Constraints to Rice Production Systems in Laos

J.M. Schiller[1*], B. Linquist[1], K. Douangsila[2], P. Inthapanya[2], B. Douang Boupha[2], S. Inthavong[3] and P. Sengxua[2]

Abstract

In 1999, total rice production in Laos was more than 2.1 million tonnes, enough to make the nation self-sufficient in rice. Over the past 2 decades, total production has increased by about 100%, with most of the increase occurring in the rainfed lowlands where production jumped from 705 000 t in 1980 to 1 502 000 t in 1999. Even though the dry-season irrigated environment has increased production by almost nine times in the past decade (from 41 000 t in 1990 to 354 000 t in 1999) and further small-scale irrigation schemes are planned to achieve a total dry-season irrigated area of about 180 000 ha by 2005, the wet-season lowland environment will remain the most important rice-producing environment for the foreseeable future. Higher yields and reduced year-to-year variability in production can be expected with further intensification of production systems in the lowlands. However, further improvements in production will depend on higher levels of inputs and continued alleviation of some production constraints. The uplands will become less important for rice production as alternative, more sustainable technologies are developed to replace the current 'slash-and-burn' and shifting cultivation practices. This paper summarizes the known main abiotic and biotic production constraints in each of Laos's rice-producing environments: wet-season lowlands, dry-season irrigated, and rainfed uplands, but not those socioeconomic constraints that can also have significant impact on farmer attitudes and production. The major production constraints in the main rice-producing environment—the wet-season lowland ecosystem of the Mekong River Valley—are drought and poor soil fertility. However, more than 10% of the wet-season lowlands in the central and southern agricultural regions are also regularly affected by flooding of the Mekong River. In these areas, flood damage is often regarded as a greater production constraint than drought. In the dry-season irrigated environment, poor soil fertility is the main abiotic constraint. Insect pests are becoming increasingly important in both these production systems. In existing production systems in the rainfed uplands, the main constraints are, in decreasing order of significance, weeds, rodents and drought. Farmers' perceptions of the relative importance of production constraints in the uplands are generally more accurate than those in the lowlands. Poor soil fertility is often not rated among the most important constraints in the wet-season lowlands and dry-season irrigated environments, despite experimental evidence that often the greatest yield increases can come from improved plant nutrition. Until recently, farmers' perceptions of the importance of insect pests in the lowlands often exaggerated their economic significance.

RICE is the single most important crop in Laos. In 1999, the area planted to rice was about 717 600 ha, representing more than 80% of the nation's cropped land. About 83% of rice production came from lowland and upland cropping during the wet season, with the lowland ecosystem accounting for about 67% of the total area and 71% of production and the upland systems for 21% of the area and 12% of production (Figure 1).

Total rice production in 1999 was more than 2.1 million tonnes (Table 1)—this was the first year that production had reached or exceeded such a number. The level was regarded as sufficient to meet the country's immediate grain needs.

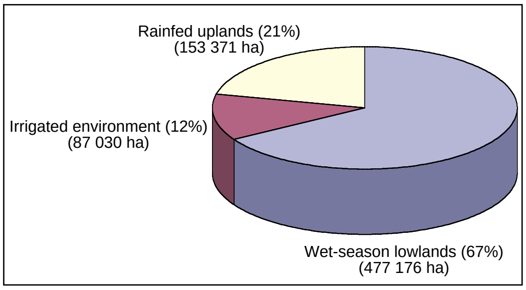
KEYWORDS: Production systems, Constraints, Abiotic, Biotic, Technologies.

---

[1] Lao–IRRI Project, Ministry of Agriculture and Forestry, Vientiane, Laos
[2] National Agriculture and Forestry Research Institute, Ministry of Agriculture and Forestry, Vientiane, Laos
[3] Agriculture and Forestry Services Office, Savannakhet Province, Laos
E-mail: J.M.Schiller@cgiar.org
*Corresponding author

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

(a) Area planted to rice in Laos, 1999



(b) Rice production in Laos, 1999

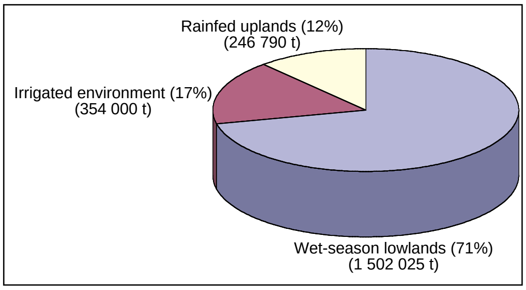


Figure 1. Area planted (a) and production (b) in the rice-growing environments of Laos, 1999.

Between 1976 and 1999, the area planted to the main wet-season lowland crop increased by 50%, from about 317 000 to about 477 000 ha. Production increased by more than three times, from about 455 000 to 1.5 million tonnes (Table 2). However, in percentages, the greatest expansion in area and production over this period took place in the dry-season irrigated environment, from 2700 ha, producing 3500 tonnes, in 1976 to 87 000 ha, producing 354 000 tonnes, in 1999. For the rainfed uplands, official statistics from the Lao Ministry of Agriculture and Forestry show that the area planted to upland rice reached a peak in the early 1980s (almost 300 000 ha), with a subsequent steady decline during the 1990s (Table 2). This decline partly reflects official governmental policy to replace all upland rice production based on 'slash-and-burn' and shifting cultivation systems with more sustainable production practices. In 1999, the area under upland rice cultivation was about 153 000 ha, producing almost 247 000 tonnes (about 12% of total production).

Systematic research aimed at improving productivity in the different rice production systems of Laos began in 1991 with support from the Swiss Government through the International Rice Research Institute (IRRI). In recent years, several other agencies have also supported the development of the Lao national rice research program.

The impact of the research output has been greatest through the development and adoption of improved varieties in the wet-season lowland and dry-season irrigated production systems. Between 1991 and 1999, the adoption of improved varieties in the wet-season lowlands of the main rice-producing area of Laos—provinces in the Mekong River Valley—increased from about 5% to 70% of the area (Schiller et al. 2000a). Most of these varieties are Lao improved glutinous varieties.

Research in other areas has highlighted a range of other production constraints in each rice-producing environment that, if alleviated, would probably result in substantial yield improvements and reduced year-to-year variability in production. Laos may well be able to considerably increase its rice production, thus increasing its annual rice surplus available for either export and/or the maintenance of a national rice reserve.

The main production constraints for each of the three rice-producing environments of Laos are summarized below.

Wet-Season Lowlands

About 84% of the rice-growing area in the wet-season lowlands is located in the central and southern agricultural regions, mainly in provinces lying in the Mekong River Valley (Table 1). Savannakhet Province, in the lower central agricultural region, has the largest area of wet-season lowland rice of any single province, encompassing 103 400 ha in 1999 (22% of the total area). Despite a significant expansion of the dry-season irrigated area, the wet-season lowland environment will remain the most important ecosystem for rice cultivation in the foreseeable future.

Abiotic constraints

Droughts and floods

With most of the planted area under rainfed conditions, annual rice production is highly susceptible to climatic variability. The rainfall pattern throughout the country is weakly bimodal with a minor peak in May and early June and a major peak in August and September. About 75% of the rainfall is received between May and October (Figure 2). In some of the more northern provinces (e.g. Sayabouly and Luang Prabang), the total annual rainfall drops to between 1200 and 1300 mm. In most provinces of the Mekong River Valley, rainfall ranges from about 1500 to 2200 mm. The rainfall pattern can vary from year-to-year, causing large fluctuations in rice production.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Table 1. General rice production statistics for Laos, 1999.

No:	Region and province	1999 Wet-season lowland			1998/99 Dry-season irrigated			1999 Wet-season rainfed upland			Total 1999		
		Harvested area (ha)	Yield (t ha^{-1})	Production (t)	Harvested area (ha)	Yield (t ha^{-1})	Production (t)	Harvested area (ha)	Yield (t ha^{-1})	Production (t)	Harvested area (ha)	Yield (t ha^{-1})	Production (t)
I	**Northern Region**	**73 034**	**3.30**	**241 304**	**7 925**	**3.36**	**26 650**	**113 358**	**1.62**	**183 906**	**194 317**	**2.33**	**451 860**
1	Phongsaly	5 747	3.26	18 761	115	3.13	360	15 800	1.57	24 802	21 662	2.03	43 923
2	Luang Namtha	7 485	3.30	24 692	860	3.40	2 921	11 200	1.64	18 410	19 545	2.35	46 023
3	Oudomxay	8 731	3.23	28 205	890	3.62	3 222	24 201	1.64	39 805	33 822	2.11	71 232
4	Bokeo	9 775	3.35	32 740	210	3.34	702	5 280	1.65	8 720	15 265	2.76	42 162
5	Luang Prabang	9 677	3.31	32 050	2 280	3.40	7 745	32 000	1.65	52 813	43 957	2.11	92 608
6	Huaphanh	11 285	3.30	37 252	1 525	2.99	4 557	12 657	1.58	20 050	25 467	2.43	61 859
7	Sayabouly	20 334	3.32	67 604	2 045	3.49	7 143	12 220	1.58	19 306	34 599	2.72	94 053
II	**Central Region**	**271 422**	**3.19**	**864 975**	**55 710**	**4.15**	**231 300**	**26 904**	**1.60**	**43 046**	**354 036**	**3.22**	**1 139 321**
1	Vientiane M.	47 683	3.31	158 007	16 730	4.30	71 949	0	—	0	64 413	3.57	229 956
2	Xieng Khuang	13 103	3.03	39 650	320	3.03	971	12 320	1.58	19 510	25 743	2.34	60 131
3	Vientiane	35 317	3.25	114 906	5 600	3.98	22 300	4 308	1.67	7 207	45 225	3.19	144 413
4	Borikhamxay	23 983	3.00	72 050	6 050	4.20	25 400	2 908	1.59	4 612	32 941	3.10	102 062
5	Khammouane	42 990	3.02	129 930	6 720	4.10	27 550	1 250	1.60	2 003	50 960	3.13	159 483
6	Savannakhet	103 396	3.25	336 037	20 155	4.10	82 629	4 170	1.56	6 510	127 721	3.33	425 176
7	Special Region[a]	4 950	2.91	14 395	135	3.71	501	1 948	1.64	3 204	7 033	2.57	18 100
III	**Southern Region**	**132 720**	**2.98**	**395 746**	**23 395**	**4.11**	**96 050**	**13 109**	**1.51**	**19 838**	**169 224**	**3.02**	**511 634**
1	Saravane	38 142	2.98	113 750	5 820	4.16	24 239	6 767	1.51	10 215	50 729	2.92	148 204
2	Sekong	2 788	3.10	8 641	430	3.81	1 640	3 142	1.53	4 810	6 360	2.37	15 091
3	Champassak	79 490	3.00	238 853	16 700	4.10	68 470	0	—	0	96 190	3.19	307 323
4	Attapeu	12 300	2.81	34 502	445	3.82	1 701	3 200	1.50	4 813	15 945	2.57	41 016
	Total	477 176	3.15	1 502 025	87 030	4.07	354 000	153 371	1.61	246 790	717 577	2.93	2 102 815

[a] Saysomboun Special Zone.

Source: Ministry of Agriculture and Forestry, Department of Agriculture, unpublished data, 2000.

Table 2. Rice production statistics for Laos, 1976 to 1999.

Year	Harvested area ('000 ha)				Production ('000 t)			
	Rainfed Lowland	Rainfed Upland	Dry-season irrigated	Total	Rainfed lowland	Rainfed Upland	Dry-season irrigated	Total
1976	317.7	204.1	2.7	524.5	455.5	202.0	3.5	661.0
1980	426.9	297.4	7.7	732.0	705.0	337.0	11.1	1053.1
1985	383.1	270.4	10.0	663.5	1023.3	345.3	26.5	1395.1
1990	392.4	245.9	12.0	650.3	1081.1	369.4	41.0	1491.5
1991	322.8	234.1	13.3	570.2	842.1	337.5	43.7	1223.3
1992	392.5	200.1	15.5	608.1	1153.4	293.6	55.3	1502.3
1993	350.4	188.3	13.0	551.7	921.4	283.7	45.6	1250.7
1994	380.9	219.1	11.0	611.0	1197.7	341.5	37.8	1577.0
1995	367.3	179.0	13.6	559.9	1071.3	296.1	50.4	1417.8
1996	363.1	172.6	18.0	553.4	1076.0	266.0	71.5	1413.5
1997	421.1	153.6	26.6	601.3	1299.5	247.0	113.5	1660.0
1998	430.2	134.2	53.1	617.5	1248.9	213.5	212.1	1674.5
1999	477.2	153.4	87.0	717.6	1502.0	246.8	354.0	2102.8

Source: Ministry of Agriculture and Forestry, unpublished data, 2000.

Every year, at least part of the country is affected by either drought or floods or a combination of both (Table 3). The drought problem in the Mekong River Valley (the main wet-season, lowland-rice-growing area) is aggravated by the permeable nature of the sandy soils that prevail in much of the area. Farmers throughout the central and southern regions regard drought as their most serious constraint.

Savannakhet Province has most of its soils in the sandy and sandy-loam categories and, of the provinces, suffers most from drought, either early or late in the season (Fukai et al. 1998). Early season drought usually occurs from mid-June to mid-July as the monsoons change from south-east to south-west. The effects of this drought can be reduced by appropriate crop practices, particularly by matching crop phenology with water availability (Fukai et al. 1998). Late-season drought occurs if the regular monsoon rains end early. Fukai et al. (1995) have demonstrated that late-season drought alone can reduce grain yields by an average of 30%. The use of earlier maturing, improved varieties to replace later maturing, and often lower yielding, traditional varieties can significantly reduce the potential impact of late-season drought. Fukai et al. (1998) have also demonstrated that the effect of drought on grain yield also depends on soil fertility, and that improved soil fertility increases grain yield, even in drought-affected seasons.

More than 10% of the area planted to wet-season lowland rice in the central and southern agricultural regions is affected by regular flooding of the Mekong River. During 1991 to 1999 significant areas were affected by flooding on five occasions: 1994, 1995, 1996, 1997 and 1999 (Table 4). In 1991, more than 21% (about 70 000 ha) of the total rice area was destroyed by floods. In 1995, almost 30% of the planted area in the central agricultural region was lost. Flooding of the Mekong River in 2000 has also resulted in large crop losses, with preliminary estimates of the area destroyed in the central and southern regions being about 61 000 ha (i.e. about 14%). As periods of submersion associated with the flooding of the Mekong River can often extend to 2 weeks, total crop loss usually results. Those areas that are particularly flood prone are not cropped in the wet season, being used only for dry-season irrigated production. Floods in the northern more mountainous agricultural region are usually of shorter duration but potentially capable of causing significant levels of soil erosion.

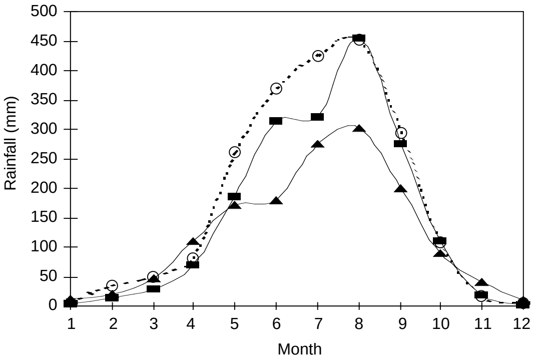


Figure 2. Annual rainfall distribution (average of 1985–1997) for the different agricultural regions of Laos: southern = -■-; Savannakhet, Saravane and Champassak Provinces; central = -○-; Vientiane and Khammuane Provinces; northern = -▲-; Huaphanh, Luang Prabang, Oudomxay, Xayaboury and Xieng Khuang Provinces (after Linquist et al. 1998).

Table 3. Occurrence of damage to rice crops by floods and drought, Laos, 1966–1998.

Year	Type of damage	Region affected[a]
1966	Severe flood	Central
1967	Drought	Central, southern
1968	Flood	Central
1969	Flood	Central
1970	Flood	Central
1971	Severe flood	Central
1972	Flood and drought	Central
1973	Flood	Central
1974	Flood	Southern
1975	Drought	All regions
1976	Flash flood	Central
1977	Severe drought	North-central (Savannakhet)
1978	Large flood	Central, southern
1979	Drought (D) and flood (F)	Northern (D), southern (F)
1980	Flood	Central
1981	Flood	Central
1982	Drought	All regions
1983	Drought	All regions
1984	Flood	Central, southern
1985	Flash flood	Northern
1986	Flood and drought	Central, southern
1987	Drought	Central, northern
1988	Drought	Southern
1989	Drought	Southern
1990	Flood	Central
1991	Flood and drought	Central
1992	Flood (F) and drought (D)	Central (F and D), northern (D), southern (F)
1993	Flood and drought	Central, southern
1994	Flood (F) and drought (D)	Central (F and D), southern (D)
1995	Flood	Central, southern
1996	Flash flood, drought	Central
1997	Flood	Central, southern
1998	Drought	All regions
1999	Flood	Central, southern

Source: Ministry of Agriculture and Forestry, Department of Meteorology, unpublished data, 2000.

Temperatures

In the wet season (May to October), temperatures are relatively stable, and within the range (20° and 30°C) regarded as suitable for rice cultivation. However, in much of the northern agricultural region, the maturity time of varieties normally grown in the central and southern regions can be extended by 20 to 40 days, as a result of significant decline in both night and daytime temperatures in the latter part of the growing period (Figure 3). The impact is believed to mainly affect maturity time rather than yield potential. However, extended maturity time can prevent the planting of a second crop under dry-season irrigated conditions. This constraint is now being reflected in the varietal improvement program, which is aiming to develop varieties more specifically adapted to the conditions of the northern region.

Table 4. Wet-season lowland crop losses (hectares destroyed) to flood damage, Laos, 1991–2000.

Region	1991[a]	1994	1995	1996	1997	2000[b]
Central						
(ha)		28 783	55 061	41 863	26 300	40 112
(%)		(13.7)	(29.0)	(17.5)	(10.2)	(13.5)
Southern						
(ha)		3 135	5 759	23 720	6 750	20 790
(%)		(2.6)	(4.9)	(18.7)	(5.2)	(14.1)
Northern						
(ha)		4 464	1 500	354	225	150
(%)		(8.3)	(2.5)	(0.5)	(0.3)	(0.2)
Total						
(ha)	70 000	36 382	62 820	65 937	33 275	61 052
(%)	(21.3)	(9.5)	(16.9)	(15.3)	(7.9)	(11.7)

[a] Regional flood damage data are unavailable.

[b] Preliminary estimates.

Sources: Unpublished reports of the Ministry of Agriculture and Forestry and the Ministry of Labour and Social Welfare.

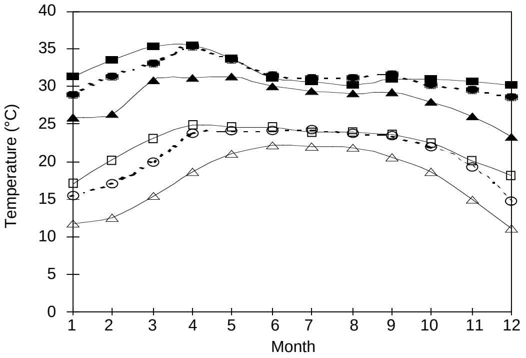


Figure 3. Mean monthly minimum (open symbols) and maximum (solid symbols) temperatures for different regions of Laos: southern (circles) = Savannakhet, Saravane and Champassak Provinces; central (squares) = Vientiane, Borikhamsay and Khammuane Provinces; northern (triangles) (after Linquist et al. 1998).

Soil fertility

The soils throughout the main lowland rice-growing areas in the central and southern agricultural areas are generally infertile, highly weathered, old alluvial deposits that comprise a series of low level terraces with an elevation of about 200 m above sea level (Lathvilayvong et al. 1996). Texturally, they are predominantly loams, sandy loams and sands. Systematic studies on the soil nutrient status and potential yield responses from fertilizer application in the wet-season lowland environment began in 1991 with the initiation of the development of a national rice research program. The studies were extended throughout the country as the rice research network expanded during 1992 to 1996.

Early studies aimed to characterize responses to N, P and K on the major soil groups, followed by quantifying the minimum input levels required to sustain yield improvements for those nutrients shown to be deficient (Lao–IRRI, unpublished technical reports for 1992, 1993, 1994, 1995 and 1996). Studies in the latter part of the 1990s were aimed at maximizing nutrient-use efficiency (particularly N and P), together with characterizing potential responses to K and S (Lao–IRRI, unpublished technical reports for 1997, 1998 and 1999). Linquist et al. (1998) summarized the main findings of the nutrient response work.

Nitrogen is the most limiting nutrient in all regions of the country, with 86% of experiment sites responding to N in the central and southern regions, and 50% in the northern region (Figure 4). The average yield response to N in the central and southern regions was 1.2 t ha^{-1} and 0.5 t ha^{-1} in the northern region. The agronomic efficiency of applied N in the central and southern regions is generally considerably greater than in the northern region (20 kg kg^{-1} in the former, and 8 kg kg^{-1} in the latter).

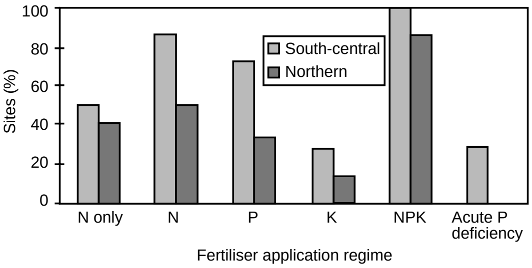


Figure 4. Percentage of sites in Laos responding significantly ($P < 0.05$) to N only, N (difference between NPK and PK treatments), P (difference between NPK and NK treatments), K (difference between NPK and NP treatments) and a combined application of NPK. An acute P deficiency is where no response to N was observed, unless P was first applied (after Linquist et al. 1998).

Phosphate was the second most limiting nutrient in all regions, with 80% of sites responding to P in the central and southern regions, and 33% in the northern region. The yield response to P averaged 0.9 t ha^{-1} in the former and 0.3 t ha^{-1} in the latter. The P-deficient soils of the north generally have higher P requirements than in the central and southern regions, probably because of higher clay contents and, possibly, different clay mineralogy (Linquist et al. 1998). In much of the central and southern regions, P deficiency is acute; 30% of sites where studies were undertaken did not respond to N application unless P was applied first (Figure 4).

Potassium was the least limiting of the nutrients tested, with 27% of sites in the central and southern regions giving a yield response to K, and 13% in the north. Responses to K and a need for K inputs are expected to increase as production is increased through double cropping (wet-season and dry-season cropping) and as rice yields increase as a result of improved varieties being used in combination with increased fertilizer inputs and improved agronomic practices.

The potential for using green manure (GM) crops as an organic source of N in the wet-season lowland production system is limited. Lathvilayvong et al. (1996) demonstrated *Sesbania rostrata* to be the GM crop with the most potential for this environment. However, the growth of *S. rostrata* in much of the Mekong River Valley has also been demonstrated to be highly dependent on the soil’s P status (Schiller et al. 1998). In studies undertaken in 1994 and 1995 in the Savannakhet and Champassak Provinces, the yield response of *S. rostrata* increased 4 to 12 times on application of P_2O_5 at 20–30 kg ha^{-1} (Figure 5). Linquist et al. (1998) demonstrated that P levels needed for optimizing potential biomass production and N inputs into the production system must be substantially higher than those needed for rice alone on the coarse-textured soils that prevail in lowland areas of much of the central and southern agricultural regions. For these and other reasons, farmers are unlikely to adopt the use of *S. rostrata* or other GM crops as a source of organic N in the wet-season lowland production systems.

Biotic constraints

Insect pests

In the wet-season lowlands, insect pests are rated by farmers as being among the top three production constraints in almost all the rice-producing provinces of the Mekong River Valley (Table 5) (Khotsimuang et al. 1995). Drought was the only factor to be consistently ranked as being more important than insect pests.

Most of the pest problems perceived are those that are highly visible, with most farmers believing that leaf-feeding insects cause yield loss (Rapusas et al. 1997). Few farmers were aware of the presence of beneficial arthropods naturally occurring in their rice

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

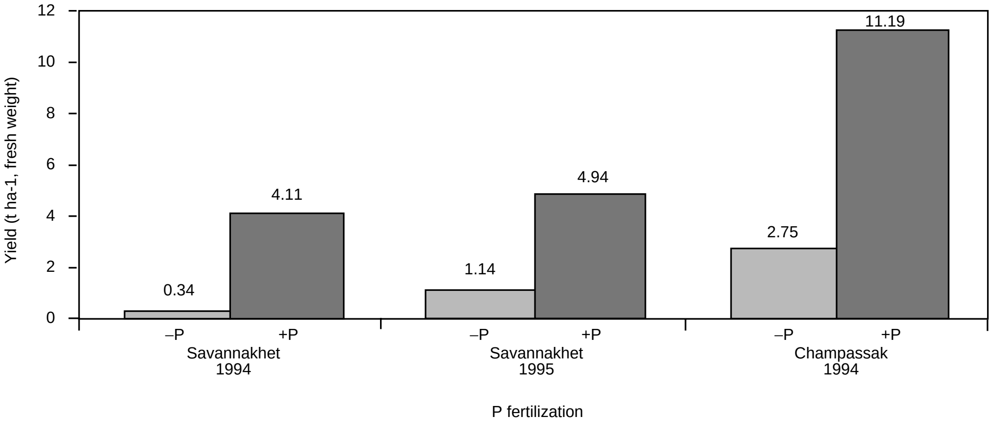


Figure 5. Yield response of *Sesbania rostrata*, a green manure crop, to phosphorus (P) fertilization, Savannakhet and Champassak Provinces, Laos (after Schiller et al. 1998).

Table 5. Farmers' ranking of the three most important of 11 potential constraints to rice production in the rainfed lowlands, Laos.

Province	District	Ranking of production constraints		
		1	2	3
Vientiane M.	Nasaythong	Drought	Weeds	Insects
Vientiane P.	Thourakhom	Insects	Drought	Weeds
Khammouane	Thakhek	Drought	Insects	Weeds
Savannakhet	Champhone	Drought	Crabs and snails	Weeds
Saravane	Vapi	Drought	Insects	Weeds
Champassak	Sanasomboune	Drought	Insects	Weeds
Champassak	Phonethong	Drought	Insects	Weeds
Sayabouly	Phiang	Drought	Insects	Weeds

Source: Khotsimuang et al. (1995).

fields. Although they were often aware of other insects and animals (spiders, crickets, dragonflies and frogs) in their fields, but not feeding on the rice, farmers generally did not know what the organisms' roles in the fields were.

However, the perception of the importance of insect pests on production is not associated with high levels of pesticide use (Rapusas et al. 1997; Heong et al., in press), even though most farmers strongly believed that insects decrease production and should be controlled with pesticides. The low use of pesticides in Laos is probably due to both the farmers' lack of resources for purchase and the unavailability of pesticides.

Although insect pests are believed to significantly limit yield, attempts to demonstrate their economic impact have usually not been successful (Lao–IRRI, unpublished technical reports for 1994, 1995 and 1996). One exception is the rice gall midge (*Orseolia oryzae*), which is economically important in some areas, particularly in the central agricultural region (Inthavong 1999). A screening program is being implemented to identify varieties and breeding lines with potential resistance to those gall midge biotypes that are important in some lowland areas of Laos.

The rice bug (*Leptocorisa* spp.) is also becoming increasingly cited by farmers as causing substantial yield loss in the provinces of the Mekong River Valley (Rapusas et al. 1997). Locally, at least, the rice bug is a problem that appears to be increasing in importance from year to year. Studies are currently under way to better understand the significance of the rice bug problem and develop appropriate control strategies.

Diseases

Although diseases are reported and recorded throughout the main rice-growing areas (leaf and neck blasts, bacterial leaf blight, brown spot and *bakanae* or "foolish seedling" disease), they are generally not of economic significance under the relatively low-input production systems that still prevail in the lowlands of Laos. However, some exceptions do occur. Parts of Phiang District of Xayaboury Province where the soils are K deficient, brown spot disease (*Helminthosporium oryzae* Breda de Haan) can significantly limit yield when inappropriate varieties are used, or the K deficiency is aggravated through the use of chemical fertilizers without a K component (Lao–IRRI, unpublished technical reports for 1997 and 1998).

Dry-Season Irrigated Environment

The area planted to rice under irrigated conditions in the 1998–99 dry season was about 87 000 ha (Table 2; Figure 1). This contrasts with 13 000 ha in 1992–93. This expansion reflects the official national policy of supporting the continued development of small-scale irrigation schemes, particularly in the main rice-growing areas of the Mekong River Valley. This expansion of irrigated production is aimed at increasing total rice production, while at the same time reducing the year-to-year variability of production resulting from the vagaries of weather in the traditional main (and wet) cropping season, when both drought and flooding can significantly affect production. By 2005, the area of dry-season irrigated rice production is expected to have expanded to about 180 000 ha and to account for about 26% of annual production.

More than 64% of the area irrigated in the 1998–99 dry season was in the central agricultural region. Provinces with the largest areas of irrigated rice were Savannakhet (20 155 ha), Vientiane Municipality (16 730 ha) and Champassak (16 700 ha) (Table 1). The adoption of improved rice production technology is highest in the irrigation scheme areas. This reflects a combination of better extension services and relatively higher farm incomes (and therefore purchasing power for inputs) in these areas.

Abiotic constraints

Temperatures

In the wet season (May to October), temperatures are relatively stable. However, dry-season temperatures are initially cool, then increase dramatically toward the end of the season (Figure 3). Critical low and high temperatures for rice are normally below 20°C and above 30°C, with considerable variability according to the crop's growth stage (De Datta 1981). The critical high temperature during panicle initiation and grain filling is 30°C; higher temperatures result in yield loss. The critical temperature for flowering is about 35°–36°C.

Within the critical limits, lower temperatures favour higher yields because of higher net photosynthesis. Low temperatures increase crop growth duration in both the vegetative and reproductive phases and lowers photorespiration. Therefore low dry-season temperatures would likely have a greater effect on rice performance in northern Laos where minimum temperatures can fall below 5°C. In southern and central Laos, high temperatures during late March and April, which can coincide with flowering and grain filling, may result in sterility and smaller grain size.

Soil fertility

More than 95% of the area used for dry-season irrigated rice cultivation is also cropped during the wet-season. The description of nutrient status and nutrient responses of soils used for wet-season lowland rice (Linquist et al. 1998) applies also to the dry-season irrigated areas. Nitrogen and phosphorus are the main limiting nutrients, with soils in provinces in the central and southern agricultural areas within the Mekong River Valley generally showing more widespread deficiencies and greater responses to nutrient inputs than soils in the northern agricultural area.

The levels of nutrient inputs recommended for dry-season irrigated cropping are generally higher than for the main wet-season crop in rainfed lowlands. For example, an application of N at about 60 kg ha^{-1} is recommended for most rainfed lowlands in the wet season, whereas N at 90 kg ha^{-1} is recommended for most areas under dry-season irrigated cultivation. The higher rates recommended for the dry season reflect the lower risk to farmers with the removal of the potential drought constraint. As with areas cropped during the wet season, an increased need for K inputs is anticipated for dry-season irrigated areas as cropping intensifies.

Biotic constraints

Insect pests

As did the farmers in the wet-season lowlands, farmers in the dry-season irrigated environment invariably perceived insect pests as being among the top three production constraints (Table 6) (Lao–IRRI, unpublished technical report for 1996).

Table 6. Farmers' ranking of the three most important constraints of 11 potential constraints to rice production in the dry-season irrigated environment, Laos.

Province	District	Ranking of production constraints		
		1	2	3
Vientiane M.	Nasaythong	Weeds	Insects	Labour
	Sikhotabong	Labour	Fertility	Weeds
	Hadsayfong	Weeds	Insects	Labour
	Saythany	Insects	Fertility	Lack water
Vientiane P.	Phonethong	Lack water	Insects	Weeds
Khammouane	Thakhek	Weeds	Insects	Labour
Savannakhet	Saybouly	Insects	Weeds	Fertility
Saravane	Saravane	Weeds	Labour	Fertility
Champassak	Champassak	Credit	Labour	Weeds

Source: Lao–IRRI, unpublished technical report for 1996.

The brown planthopper (BPH) has occasionally caused severe damage and was observed for the first time in 1979 when about 2000 ha of paddy fields in Vientiane Municipality, representing almost all the dry-season irrigated area at that time, was severely damaged (B. Somrith, unpublished data, 1991).

The last severe outbreak of BPH was in the 1990–91 dry season when more than 40% of the irrigated area was damaged. Again, this outbreak centred on Vientiane Municipality and was preceded by, and believed to be related to, a BPH outbreak and high levels of pesticide use in the central, lower northern and north-eastern regions of Thailand in the wet and dry seasons of 1989 and 1990 (B. Somrith, unpublished data, 1991).

Improved varieties with resistance to some of BPH biotypes are now available in Laos. BPH infestations are still recorded where non-resistant varieties are being used, with areas of hopper burn. However, most of the recent damage observed has been on a relatively local rather than general scale.

Many farmers in the central and southern regions of Laos believe that the stem borer is economically important in dry-season crops. Although usually observed in most areas of irrigated production, studies undertaken during 1993 to 1997 to monitor infestations in farming areas and to measure yield loss failed to demonstrate any consistent yield loss of economic significance that might require specific control measures.

Studies in Vietnam, Philippines and Indonesia indicated that the levels of deadheart and whitehead (both caused by stem borer activity) need to reach about 30% before control measures can be economically justified. In monitoring studies in most parts of the Mekong River Valley, the incidence of both deadheart and whitehead has rarely been greater than 5% (Lao–IRRI, unpublished technical report for 1998).

Golden apple snail

Of more recent significance in dry-season irrigated areas (and areas double cropped in the wet-season) is the golden apple snail (Pomacea spp.). The snail was probably introduced from neighbouring Thailand as an aquatic food to Vientiane Municipality about 1991 (Agricultural Extension 1994). Flooding in Vientiane Municipality in 1992 may have then encouraged its spread into areas of dry-season irrigation, where it quickly became established as a significant pest. In 1995, the snail was also recorded in Sing District of Luang Namtha Province, with Yunnan Province in China being the probable source.

The snail has spread to almost all irrigated areas in the central and southern regions, damaging crops shortly after transplanting, and becoming increasingly difficult to manage. Pesticides are not used for control, their use being actively discouraged by the Government. Farmers are therefore developing their own strategies for collecting and destroying the snail, including water management and the use of 'botanical' lures to attract them for easy collection and disposal.

Diseases

As with the wet-season lowlands, although the diseases blast, bacterial leaf blight, brown spot and bakanae are recorded and can occasionally be important on a local basis, they are not regarded a serious overall constraint to production.

Rainfed Uplands

Rainfed upland rice cultivation in Laos is almost exclusively based on the 'slash-and-burn' and shifting-cultivation systems. In the early 1990s, Chazee (1994) estimated that about 2.1 million ha

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

(about 8.8% of the national territory) was being used on a rotational basis for 'slash-and-burn' cultivation, most of which is rice-based. About one third of the upland rice area was believed to be 'slashed and burned' from dense forest, with the remaining area comprising a mixture of previously cropped uplands but now covered with scrub and tree regrowth, and areas where some land preparation is carried out before direct seeding the rice crop.

The northern agricultural region accounts for 74% of upland rice cultivation, with the Luang Prabang and Oudomxay Provinces having the largest areas, about 32 000 and 24 000 ha respectively (Table 1). Most upland rice cultivation is concentrated on slopes at altitudes usually ranging from 300 to 1200 m above sea level, but being as high as 1500 m. About 69% of the area used for upland agriculture has slopes of 20% or more (World Bank 1995).

Many production systems are found in the uplands, with the nature of the systems being determined by a range of factors, the most important of which are the ethnic group of the farmers (the greatest ethnic diversity is found in the uplands), population pressure, land availability, soils, topographic characteristics, food preferences, market opportunities, and past and present governmental policies (Roder 1997).

Most rice-based upland cropping is practised on a rotational basis. In most situations, a single wet-season crop is followed by a period of fallow. Critical to the stability of the system is the length of this period, which can range from 2 to 10 years, depending on population pressure and land availability. Occasionally, farmers may grow two successive rice crops on the site before moving to another. Sometimes a farmer will plant a rice crop, with a non-rice crop following in the second year. Rice is rarely monocropped, being planted with any of a range of grain and vegetable crops. Most upland farmers produce insufficient rice to meet their immediate household needs.

Abiotic constraints

Droughts

Drought is ranked by upland farmers as their third most important production constraint (Figure 6). Average annual rainfall throughout most of the upland environment is usually above 1200 mm but it fluctuates widely, with some areas receiving more

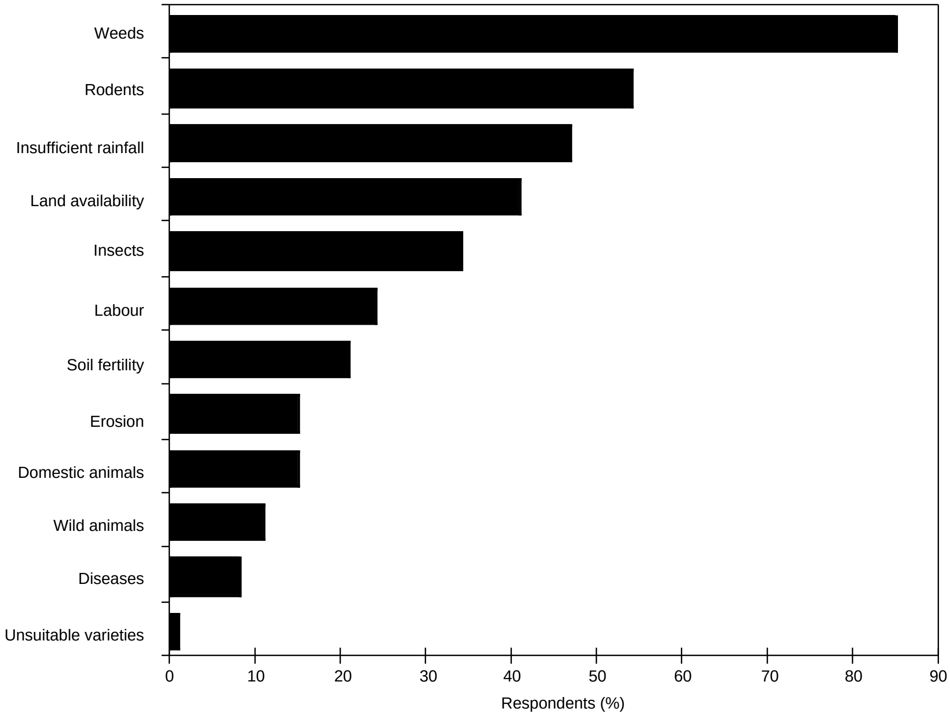


Figure 6. Farmers' perceptions of major constraints to upland rice production, Laos (after Lao-IRRI, unpublished technical report for 1992).

than 2500 mm. In the upland environment, dry conditions at or about the time of seeding (late April to May) usually has the greatest impact, by affecting crop germination and establishment. Late-season drought (i.e. when the wet-season rains end early) is not normally a concern under upland conditions because most upland crops are harvested by mid-October (30 to 50 days earlier than for lowland crops in the same region). Usually, the frequency and effects of drought in the uplands are less than in the lowlands, that is, for the decade 1990 to 1999, drought affected upland crops in the northern area in only the years 1992 and 1998 (Table 3).

Soil fertility

Soils maps of most upland areas are not yet available, but complex soils generally predominate in the hillier areas. Under the traditional 'slash-and-burn' and shifting cultivation systems that have prevailed in the past for upland rice cultivation, natural fallow rotation has been the primary means of fertility management. The restoration of soil fertility under these systems depends on the levels of biomass production of fallow crops. While traditional systems are generally sustainable with long fallows, they collapse with reduced periods of fallows because they fail to restore soil fertility levels (Sanchez and Logan 1992; Roder et al. 1997b). Between the 1950s and early 1990s, as population pressure increased, average fallow periods in much of northern Laos dropped from more than 30 to 5 years or fewer (Roder et al. 1997a, b).

Many areas of Luang Prabang Province, which has the largest area of upland rice of any single province, are currently being cropped, based on a fallow period of only 2 or 3 years. These reduced fallow periods are too short to enable soil fertility to be restored between successive rice crops. Roder et al. (1997b) report that the soil pools of organic C and total N are reduced substantially during cropping and the short fallow period. Fallow periods of 2 years are regarded as being too short to reverse the downward trend, and soil organic C and N levels are expected to decrease further with subsequent cropping-fallow cycles until an equilibrium has been reached (Roder et al. 1997b). The low upland-rice yields being recorded throughout much of northern Laos reflect, in part, this continued decline in soil fertility. Yield decline is also associated with a significant increase in the levels of weed infestation and competition under the shorter fallow periods (Roder et al. 1977a).

Although few systematic studies exist on potential rice yield responses to fertilizer inputs under the upland conditions of Laos, substantial yield increases with the application of N fertilizer have been recorded (Lao–IRRI, unpublished technical reports for 1994 and 1995). In studies conducted in Luang Prabang Province in 1994, N application (at 100 kg ha^{-1}) increased yields by over 90% at two of three sites. No responses were measured for P inputs. Large differences in yield between sites in on-farm variety trials (Lao–IRRI, unpublished technical report for 1999) can be attributed to differences in soil fertility, which, in turn, largely reflect differences in the duration of fallow between successive rice crops.

Biotic constraints

Generally, and in contrast to the lowlands, biotic constraints comprise the most important constraints to rice production in the uplands (Roder 1997). Surveys of upland rice farmers in four districts of the northern provinces of Luang Prabang and Oudomxay revealed 90% of respondents indicating weeds to be the major production constraint (Lao–IRRI, unpublished technical report for 1992). Other constraints cited (Figure 6) were rodents (54%), drought (47%), land availability (41%), insect pests (34%), insufficient labour (24%), poor soil fertility (21%) and soil erosion (15%).

Weeds

The need for weed control provides the single greatest demand on labour inputs during the cropping cycle, and the greatest constraint to labour productivity. Between 40% and 50% (140 to 190 days ha^{-1}) of an average labour input of about 300 days ha^{-1} is used to control weeds (Roder et al 1997a). This compares with an average of less than 10 days ha^{-1} through much of the lowlands (Khotsimuang et al. 1995).

The most common weed in the upland environment is *Chromolaena odorata*, which was introduced to Laos in the 1930s. Other important weeds are *Ageratum conyzoides*, *Lygodium flexuosum* and *Commelina* spp. (Table 7) (Roder et al. 1997a). Although *C. odorata* is the most abundant weed species, its growth habit allows a much easier control by hand than do other species such as *L. flexuosum* and *Commelina* sp. (Lao–IRRI, unpublished technical report for 1992).

Many of the constraints cited by farmers are interdependent (weeds, lack of land, insufficient labour, low soil fertility and soil erosion). Reduced fallow periods have been clearly associated with increased weed problems (Roder et al. 1995). In some areas, the average fallow period has shrunk from 38 years in the 1950s to about 5 years in 1992. Over the same period, the average weeding input has increased from 1.9 *weedings* in the 1950s to 3.9 in 1992.

Table 7. The most important weeds in upland-rice fields, as perceived by households surveyed in Luang Prabang and Oudomxay Provinces, Laos.

Weed species	Frequency (% of respondents)				
	Oudomxay Province	Districts of Luang Prabang Province			Average
		Viengkham	Pakseng	Xiengngeun	
Ageratum conyzoides	59	70	50	56	59
Chromolaena odorata	88	55	15	26	46
Commelina spp.	44	38	50	41	43
Panicum trichoides	34	9	40	21	26
Lygodium flexuosum	34	43	5	6	22
Imperata cylindrica	16	28	30	3	19
Pueraria thomsoni	13	36	10	15	18
Panicum cambogiense	6	38	10	18	18
Cyperus triaiatus	13	36	10	15	18
Cyperus pilosus	31	11	0	0	11
Dioscorea spp.	0	15	25	0	10

Source: Roder et al. (1997a).

Rodents

The uplands carry a high endemic rodent population. The damage rodents do to upland crops is not confined to rice, although reports of damage most often relate to this crop. This reflects the significance of rice in the uplands where it accounts for more than 75% of the cultivated land area. Upland farmers regard the rodent problem as the production constraint over which they have least control.

Although actual grain losses due to rodents have yet to be quantified, they probably account for at least 15% of the annual rice harvest. At irregular intervals, conditions favour massive population explosions of rodents, resulting in local losses of more than 50% of the rice crop. Occasionally, entire crops are lost, as was reported by some villages in the northern province of Luang Prabang, where the 1991 wet-season crop was totally lost (Singleton and Petch 1994). Other provinces that have reported similar population explosions and large grain losses in the past 10 years include parts of Sayabouly, Oudomxay, Houaphanh and Sekong.

Upland farmers associate these population explosions with mid wet-season flowering and fruiting of certain species of bamboo. The bamboo's fruiting provides an early food source for the rodents, which thereby massively increase their numbers. In the search for food for the extra numbers they move into upland rice and other annual crops.

Rodents damage rice crops not only during the period approaching harvest, but also before heading, when rodents move from nearby forested areas. In severe infestations, a rice crop can be destroyed within a couple of nights. Chronic annual losses are probably due to Mus species, while the periodic eruptions may be due to a species of Rattus (G. Singleton, pers. comm., 2000). In other upland crops, such as maize, pulses and cassava, larger rodents such as Bandicota spp. appear to cause most damage. The rodent problem in the uplands of Laos is apparently shared by the uplands of neighbouring Vietnam, Myanmar and Thailand (Schiller et al. 1999).

Insect pests

Little research has been undertaken on the role of insect pests and diseases in limiting yield of upland rice crops. A major insect pest, according to Lao farmers, is the white grub (larvae of scarab beetles), which feeds on living roots. In the tropics, the grubs have a 1-year life cycle, with the adults emerging from the soil after the first heavy rains of the wet season. They lay eggs at the same time as the farmers seed upland rice. After several months, the long-lived white grubs become sufficiently large so that two or three larvae can denude the root system of a mature rice plant. This intensity of damage is rare but wilting can occur when root loss is combined with moisture stress.

In an attempt to quantify potential white-grub damage in the uplands of Laos in 1992 and 1993, their incidence and damage was monitored in farmers' fields in the northern provinces of Luang Prabang and Oudomxay (Lao–IRRI, unpublished technical report for 1994). Although grub damage was observed as early as 3 weeks after seeding (WAS) in Luang Prabang Province and recorded in more than 50% of hills at 7 WAS, the level of

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

damage in both provinces and in both years declined significantly as the rice crops matured. No correlation was established between yield and white-grub damage, although, in drought years, white-grub damage to roots is believed to affect the plants' ability to tolerate moisture stress and to subsequently recover.

Nematodes

The increased intensity (frequency) of upland rice cropping has also been associated with increased populations of parasitic rice root-knot nematodes, which can cause significant yield losses (Plowright et al. 1990). In 1993, a survey was undertaken of upland rice fields in Luang Prabang Province to study the relationship between yield, fallow period, number of successive rice crops between fallows, major weeds and nematode population densities.

Low rice yields were found to be associated with short fallows, long successive rice cultivations, high populations of the weeds Ageratum conyzoides and Lygodium flexuosum, and root-knot nematodes, particularly the Meloidogyne spp. Galls caused by Meloidogyne were observed on the roots of A. conyzoides (Roder et al. 1998), suggesting that this nematode may be a major limitation to rice yield if the fallow duration is short and attempts are made to grow successive rice crops on the same piece of land, particularly in areas where A. conyzoides is a significant weed component (Roder 1997).

This finding is consistent with farmers' observations that, in some upland areas, successive cropping of upland rice is generally not possible for more than 2 years because of the development of 'root nodules' on rice plants in the third year. Nematodes may comprise a potential constraint in the development of alternative, technologies in which upland rice is maintained in the system but are more sustainable than shifting cultivation. Periods of fallow or cropping with selected grain legumes are known to reduce the nematode problem (Table 8).

Table 8. Effect of rice cropping and mulching treatments on nematode numbers, Laos uplands.

Treatment	Nematode *Meloidogyne graminicola*	
	No. per gram of roots	No. per cm^3 soil
Continuous rice—burnt	742	2.0
Continuous rice—mulched	187	0.7
Rice/fallow/rice—burnt	3	<0.01
Rice/cowpea/rice—mulched	1	<0.01

Source: Roder et al. (1998).

Diseases

The main disease encountered in upland rice crops is blast (*Pyricularia oryzae* Cav.), which is aggravated by high fertility (mainly N) and dry conditions. Although no reports of quantifying the economic significance of blast are known, in some years of on-farm testing of upland varieties, little yield is harvestable because of blast (Lao–IRRI, unpublished technical report for 1999).

Discussion

Although the national rice production has significantly improved over the past decade, further significant increases are possible, particularly in the wet-season lowlands. Recent research has already developed, and future research is expected to provide, technical recommendations capable of bringing further and substantial yield improvements, higher yield potential and reduced season-to-season variability in production. However, inadequately developed extension services in many areas have helped prevent widespread farmer adoption of recommended improved practices.

Wet-season lowlands

Improving plant nutrition

The level of fertilizer use in the wet-season lowlands remains low in both regional and international terms (Linquist et al. 1998; Pandey and Sanamongkhoun 1998). Research over the past decade has clearly demonstrated that, to achieve the potential benefits from the use of improved varieties and changes to some agronomic practices, increased fertilizer inputs and improved fertilizer management are required. The potential improvements to yield by the adoption of a combination of technical recommendations, rather than just improved varieties, have been clearly demonstrated at village level in farming systems in Vientiane and Champassak Provinces (Schiller et al. 2000b). Under farming conditions, average yields of between 3.2 and 3.7 t ha^{-1} were readily achievable when all recommendations were followed, that is, about 1.4 t ha^{-1} higher than when farmers adopted just improved varieties. Farmers who adopted the combination of technical recommendations more than doubled their yields and net returns in both provinces, relative to those who failed to adopt any recommendations (Figure 7).

Linquist et al. (1998) have also highlighted the importance of improved straw management as a means of maintaining soil K balance. Potassium deficiencies are expected to become more widespread as production is intensified. Under existing

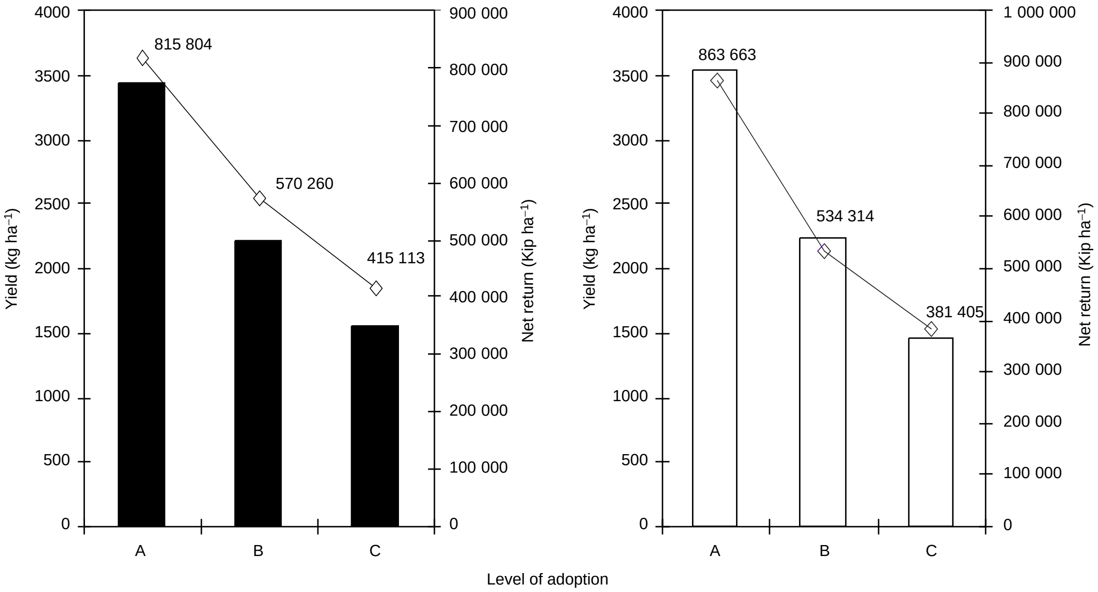


Figure 7. Relationship of yield (bars; kg ha^{-1}) and net return (lines; New Kip ha^{-1}) to the level of technology adoption in two provinces, Laos. Solid bars and symbols = Champassak Province; open bars and symbols = Vientiane Province; A = complete adoption; B = incomplete adoption; C = no adoption; exchange rate: LAK7600 = US$1, February 2001 (after Schiller et al. 2000).

cultural practices, much of the K is removed from the field as straw left over from threshing. The straw is often fed to buffalo and cattle.

Variety improvement

Until recently, the main aim of the varietal improvement program for the lowlands has been to develop higher yielding varieties with good general adaptability. Current activities in the ongoing varietal improvement program are expected to develop further varieties with more specific adaptability to particular growing conditions. New varieties would be released with the following traits: greater drought tolerance; improved resistance to gall midge, blast and bacterial leaf blight; and improved tolerance of low temperatures of the northern region. The availability and use of such varieties will help reduce season-to-season production variability.

The emphasis of past varietal improvement research had also focused on glutinous varieties on account of the Laotians' preference for this type of rice. However, with increasing consumption of non-glutinous rice in urban areas, and the increasing proportion of surplus production that will be available for export, varietal improvement research is expected to focus more and more on non-glutinous varieties and varieties with particular quality traits, such as aroma.

Minimizing the impact of drought

Fukai et al. (1998) outlined a range of strategies that can reduce the rice crop's susceptibility to drought. Potential yields from direct-seeded rice are as high as from transplanted crops, provided crop establishment is successful and weeds are controlled. The lack of standing water at optimal time for transplanting is a common problem in rainfed lowland rice. Delayed transplanting results in the use of older seedlings, with a resulting reduction in yield potential. Sometimes, the soil is too dry for transplanting and farmers may fail to grow a rice crop. These problems can potentially be eliminated, or at least alleviated, by adopting direct seeding in place of seeding and transplanting. Early planted, direct-seeded crops also mature earlier than later planted, transplanted crops (for photoperiod-insensitive varieties), thereby potentially avoiding the effects of late-season drought.

Drought problems can also be minimized greatly if supplementary water can be made available at critical times (Bhuiyan 1994). This water might come from on-farm storage tanks, underground water sources or, occasionally, streams. Such techniques have yet to be assessed under Lao conditions, although some non-governmental organizations are testing such systems.

Flood avoidance

The nature of flood damage in the Mekong River Valley makes developing varieties to reduce the impact of floods on yield unlikely. Instead, strategies will be developed for flood avoidance. Among these may be greater efforts to grow shorter and early maturing varieties that can be harvested before the most likely onset of the flood period. However, such a strategy would result in such varieties having to be harvested during the period of heaviest rainfall, with resulting problems of grain drying and poor quality grain. Direct seeding with early maturing varieties after the flood period may also provide an option. However, as national production increases, a more practical strategy may be to promote the production of other, potentially higher return, and shorter maturing crops than rice, particularly vegetables, as late wet-season crops in flood-prone areas.

Dry-season irrigated environment

Improving plant nutrition

As in the wet-season lowlands, current levels of nutrient inputs in the dry-season irrigated environment are lower than recommended, with a potential for considerable improvement in yield through a combination of higher levels of fertilizer inputs and improved management of these inputs. Technical recommendations for these changes are available.

Variety improvement

The development of improved varieties suited to the low temperatures experienced in much of the potential dry-season irrigated environment in the northern agricultural region, is the most immediate challenge of the varietal improvement program. During the 1999–00 dry season, minimum temperatures were recorded as being below 0°C in much of this area, resulting in failed crops of most of the varieties currently available. Collaborative research, facilitated by the ACIAR, and the introduction and evaluation of a range of varieties and breeding lines from other countries with low-temperature regimes during part of the production cycle, should result in the identification of varieties better adapted to the northern region.

Cultural practices

Studies in 1996 and 1997 of the impact of hill spacing on grain yield of improved varieties (Lao–IRRI, unpublished technical reports for 1996 and 1997) highlighted the importance of close hill spacing—resulting in high plant populations and improved plant nutrition. When hill spacings of 25 × 25 cm, 20 × 20 cm and 15 × 15 cm were compared under three N regimes (0, 45 and 90 kg ha^{-1}), obvious benefits occurred with closer hill spacing under each N regime. In terms of absolute yield, this benefit was greatest under the highest N application rate. In the 1996 study, under the 0 N regime, yield increase from the widest to closest hill spacing was about 900 kg ha^{-1}. Under the 90 kg ha^{-1} treatment, the corresponding yield increase was 1500 kg ha^{-1}. A similar association was demonstrated in 1997 (Table 9). The yield improvement associated with closer hill spacing was largely associated with higher panicle density.

Table 9. Relationship of yield to hill spacing and nitrogen application regime under dry-season irrigated conditions for two rice varieties, Laos.[a]

Hill Spacing (cm)	N rate (kg ha^{-1})			Mean yield
	0	45	90	
	Yield of variety ‘Thadokkham-1 (TDK1)’ (kg ha^{-1}) in 1997			
25 × 25	1392	2218	3100	2236 c
20 × 20	1866	2498	3668	2677 b
15 × 15	2279	3309	4609	3399 a
Mean	1846 c	2675 b	3792 a	
	Yield of variety ‘Namthane-1 (NTN1)’ (kg ha^{-1}) in 1996			
25 × 25	1168	2045	2923	2045 b
20 × 20	1286	2111	3077	2158 b
15 × 15	1890	2971	3989	2950 a
Mean	1448 c	2376 b	3329 a	

[a] Means not sharing common letters are significantly different at the 5% level (DMRT) between N rates and between hill spacings (N × spacing interaction was not significant for either year).

In traditional, low-input, wet-season, production systems, using traditional varieties, wide hill spacing (25 × 25 cm) has been usual. This wider spacing may have been appropriate for using the tall, lower yielding traditional varieties with limited or no nutrient inputs. Farmers have sometimes been reluctant to adopt closer spacing for improved varieties and an improved nutrient regime with an expanded area under irrigation. However, changing to higher plant populations is essential for achieving the yield potential, and the water- and nutrient-use efficiency of irrigated regimes. Similar changes are believed to be necessary (but are yet to be clearly demonstrated) for wet-season lowland production systems to maximize the yield potential of improved varieties and improved nutrient regimes.

Pest management

The rice bug (Leptocorisa spp.) is now a significant yield constraint in much of the dry-season irrigated area of the Mekong River Valley. Strategies for its management and control have yet to be developed. The problem has become the focus of current research in the integrated pest management (IPM) program in the dry-season irrigated and wet-season lowland environments. Similarly, strategies for controlling the golden apple snail have yet to be developed. As both pests are also becoming increasingly manifest in the wet-season lowlands (particularly in double-cropped areas), any management recommendations developed for the irrigated environment should be equally as applicable to wet-season conditions.

Rainfed uplands

Although national policy aims to reduce the cultivation of annual crops, including rice, in the uplands, to ensure food self-sufficiency in these areas until such time improved technologies for the uplands mean increased incomes for upland farmers who can then buy surplus rice from the lowlands, rice will have to remain part of the upland production system. However, the yield potential of traditional upland varieties does allow them to be grown on a reduced area, if the means can be found for alleviating the constraints that currently reduce yields to 1.5 t ha^{-1} and less in most upland areas.

The production constraints outlined in this paper for the rainfed upland production system relate to existing ‘slash-and-burn’ and shifting-cultivation systems. Recent research initiatives in Laos have been aimed at developing alternative, more sustainable, upland production systems to replace the traditional ‘slash-and-burn’ and ‘shifting-cultivation’ approaches to production in the uplands, in line with Lao governmental policy (MOAF 1999). The same constraints to existing production systems will probably apply to any new ‘technologies’ where annual crops such as rice are part of the production system.

Weeds are expected to remain the major constraint. Where burning is no longer practised, weed competition may increase. Rodents are also expected to continue being a major production constraint in any new production system that maintains or provides natural habitats and food sources for them. Current research to better understand the ecology of rodents in the uplands of Laos will probably help in developing strategies for better managing and controlling the populations of those rodents doing most damage in the uplands.

Among potential new constraints in the uplands is low soil fertility, particularly as cultural practices change to improve sustainability and reduce shifting cultivation. Strategies to help prevent soil erosion in the uplands will also become increasingly important.

Acknowledgments

We gratefully acknowledge the support provided by the Swiss Agency for Development and Cooperation (SDC) in the undertaking of benchmark studies and much of the research, the results of which are reported in this paper. This support was provided to the Lao National Rice Research Program through the International Rice Research Institute (IRRI).

References

Agricultural Extension, Ministry of Agriculture and Forestry. 1994. History and control of the golden apple snail. Vientiane, Lao PDR. (In Lao.)

Bhuiyan, S.I. 1994. On-farm Reservoir Systems for Rainfed Ricelands. Manila, Philippines, International Rice Research Institute (IRRI).

Chazee, L. 1994. Shifting cultivation practices in Laos—present systems and their future. In: Shifting Cultivation and Rural Development in the Lao PDR, Report of the Nabong Technical Meeting. Vientiane, Nabong College, 67–97.

De Datta, S.K. 1981. Principles and Practices of Rice Production. Manila, Philippines, International Rice Research Institute (IRRI).

Fukai, S., Rajatasereekul, S., Boonjung H. and Skulkhu, E. 1995. Simulation modelling to quantify the effect of drought for rainfed lowland rice in Northeast Thailand. In: Fragile Lives in Fragile Ecosystems, Proceedings of an International Rice Research Conference. Manila, Philippines, International Rice Research Institute (IRRI), 657–674.

Fukai, S., Sittisuang, P. and Chanphengsay, M. 1998. Increasing production of rainfed lowland rice in drought prone environments—a case study in Thailand and Laos. Plant Production Science, 1, 75–82.

Heong, K.L., Escalada, M.M., Sengsoulivong, V. and Schiller, J.M. In press. Pest management beliefs and practices of rice farmers in Laos. Crop Protection.

Inthavong, S. 1999. Ecological studies and yield loss assessment of rice gall midge, *Orseolia oryzae* (Wood-Mason) in rainfed lowland rice ecosystems of Laos. M.S. thesis. Los Baños, University of the Philippines.

Khotsimuang, S., Schiller, J.M. and Moody, K. 1995. Weeds as a production constraint in the rainfed lowland rice environment of the Lao PDR, Proceedings of 15th Asian-Pacific Weed Science Society Conference, Ibaraki, Japan. University of Tsukuba, Japan, 444–454.

Lathvilayvong, P., Schiller, J.M. and Phommasack, T. 1996. Soil limitations for rainfed lowland rice in Laos. In: Breeding Strategies for Rainfed Lowland Rice in Drought Prone Environments. Ubon Ratchathani, Thailand, ACIAR Proceedings No. 77, 74–90.

Linquist, B., Sengxua, P., Whitbread, A., Schiller, J.M. and Lathvilayvong, P. 1998. Evaluating nutrient deficiencies and management strategies for lowland rice in the Lao PDR. In: Ladha, J.K., Wade, L., Dobermann, A., Reichardt, W., Kirk, G.J.D. and Piggin, C. ed. Rainfed Lowland Rice: Advances in Nutrient Management Research. Manila, Philippines, International Rice Research Institute (IRRI), 59–73.

MOAF (Ministry of Agriculture and Forestry). 1999. The Government's Strategic Vision for the Agricultural Sector. Vientiane, Lao PDR.

Pandey S. and Sanamongkhoun, M. 1998. Rainfed Lowland Rice in Laos: A Socio-Economic Benchmark Study. Manila, Philippines, International Rice Research Institute (IRRI).

Plowright, R.A., Matias, D.M., Aung, T. and Mew, T.W. 1990. The effect of *Pratylenchus zeae* on upland rice. Revue de Nematologie, 13, 283–291.

Rapusas, H.R., Schiller, J.M. and Sengsoulivong, V. 1997. Pest management practices of rice farmers in the rainfed lowland environment of the Lao PDR. In: Heong, K.L. and Escalada, M.M. ed. Pest Management of Rice Farmers in Asia. Manila, Philippines, International Rice Research Institute (IRRI), 99–114.

Roder, W. 1997. Slash-and-burn rice systems in transition: challenges for agricultural development in the hills of northern Laos. Mountain Research and Development, 17, 1–10.

Roder, W., Phengchanh, S., Maniphone, S., Songnhikongsuauthor, K. and Keoboulapha, B. 1995. Weed management strategies aimed at reducing labour for upland rice production. In: Fragile Lives in Fragile Ecosystems, Proceedings of an International Rice Research Conference. Manila, Philippines, International Rice Research Institute (IRRI), 395–405.

Roder, W., Phengchanh, S. and Keobulapha, B. 1997a. Weeds in slash-and-burn rice fields in northern Laos. Weed Research, 37, 111–119.

Roder, W., Phenghanh, S. and Maniphone, S. 1997b. Dynamics of soil and vegetation during crop and fallow period in slash-and-burn fields of northern Laos. Georderma, 76, 131–144.

Roder, W., Keoboulapha, B., Phengchanh, S., Prot, J.C. and Mathias, D. 1998. Effect of residue management and fallow length on weeds and rice yield. Weed Research, 38, 167–174.

Sanchez, P.A. and Logan, T.J. 1992. Myths and science about the chemistry and fertility of soils in the tropics. In: Lal, R. and Sanchez, P.A. ed. Myths and Science of Soils of the Tropics. Special Publication No. 29. Soil Science Society of America (SSSA), Madison, WI, 35–46.

Schiller, J.M., Lathvilayvong, P. and Phommasack, T. 1998. Current use of and requirements for sustainable food production in the Lao PDR. In: Johnston A.E. and Syers, J.K. ed. Nutrient Management for Sustainable Crop Production in Asia. Wallingford, UK, CAB International, 321–332.

Schiller, J.M., Douang Boupha, B. and Bounnaphol, O. 1999. Rodents in agriculture in the Lao PDR—a problem with an unknown future. In: Singleton,G.R., Hinds, L.A., Leirs, H. and Zhang, Z. ed. Ecologically- based management of rodent pests. ACIAR Monograph No. 59, 372–386.

Schiller, J.M., Inthapanya, P. and Hatsadong. 2000a. Rice variety recommendations for the wet-season lowland environment of the Lao PDR. Vientiane, Lao PDR, National Agriculture and Forestry Research Institute (NAFRI).

Schiller, J.M., Phanthavong, S., Siphaphone, V., Sidavong, S. and Erguiza, A. 2000b. Impact Assessment of Improved Rice Production Technologies for the Rainfed Lowland Environment in the Lao PDR. Vientiane, Lao PDR. National Agriculture and Forestry Research Institute.

Singleton, G.R. and Petch, D.A. 1994. A Review of the Biology and Management of Rodent Pests in Southeast Asia. ACIAR Technical Report No. 30. Canberra Australia.

World Bank, 1995. Lao PDR Agriculture Sector Memorandum. Report No. 13675-LA. Washington, DC.

Economics of Lowland Rice Production in Laos: Opportunities and Challenges

Sushil Pandey[1]

Abstract

Laos is a small South-East Asian country where most of its labour force is engaged in producing its staple crop–rice. Although rice production suffered during years of internal disturbances and subsequent political changes, new liberal market policies and other initiatives have positively affected rice production in recent years. Laos has a high population growth rate for the region and its agricultural sector remains predominantly subsistence oriented. As a result, tremendous challenges lie ahead to ensure food security for Laos and, at the same time, develop a commercially oriented agricultural sector that can provide a basis for the country's sustainable economic growth. The paper gives an overview of these challenges and offers suggestions on the nature of the technological and policy interventions needed to increase rice production.

LAOS, with a population of 5 million, is a small developing country in South-East Asia. Agriculture is its major economic activity, employing more than 80% of the labour force and accounting for over 50% of the gross domestic product (GDP) (IMF 2000). With a total per capita income at US$330, the country is one of the poorest in the region (World Bank 2000). The overall poverty ratio is 46% with the incidence of poverty being higher in rural areas (53%). Although the GDP grew by 4% in 1999, relative to 1998, the population growth of 2.5% eroded much of this income growth (ADB 2000). As a result, GDP per capita grew by only 1.5% between 1998 and 1999. Population growth rates in Laos (2.5%) and Cambodia (2.6%) are much higher than in neighbouring Vietnam (1.9%) and Thailand (1.0%).

Rice production is the major agricultural activity in Laos, with rice accounting for over 75% of the gross cropped area. An essential part of the Lao diet, rice also accounts for more than 67% of total calorie consumption. Per capita consumption of milled rice is high for the region, at 163 kg. Given the economic importance of the crop in Lao agriculture, increased rice production is essential for national economic growth. This paper presents an overview of the Lao rice economy, briefly analyses the micro-economics of rice production, and discusses research and policy issues for enhancing rice production.

Rice Production in Laos

Rice ecosystems in Laos fall into three groups: upland, lowland rainfed, and lowland irrigated. Upland rice is grown mostly in the mountainous northern areas under a system of shifting cultivation. Lowland environments predominate with more than 75% of production grown in the wet season in the central and southern agricultural areas. Much of this production is rainfed-based, although some areas now have access to supplementary irrigation. Irrigated rice is grown mainly in the dry season, and mostly in provinces along the Mekong River.

In recent years, the area under upland rice had diminished as a result of governmental policies on rice production in the uplands. In 1990, upland rice was grown on 246 000 ha (or almost 38% of the total area planted to rice) and contributed to 25% of the total output (Table 1). By 1999, the area under upland rice had declined to about 153 000 ha with the share of upland rice in total output falling to

KEYWORDS: Rainfed rice, Technology adoption, Productivity trend, Research priority

---

[1] Social Sciences Division, International Rice Research Institute, Los Baños, Laguna, Philippines.
E-mail: sushil. pandey@cgiar.org

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

12%. From 1990 to 1999, the share of wet-season lowland rice, including irrigated rice, in total area planted to rice and total production increased by 22% and 39%, respectively.

During the mid-1990s, the Government of Laos launched a program to expand irrigation to increase rice production. Large investments were made to install high-capacity pumps for small-scale irrigation development, pumping directly from the Mekong River and its tributaries. Irrigated area increased seven-fold from about 12 000 ha in 1990 to about 87 000 ha in 1999. As a result, the share of irrigated rice in total rice output increased to 17%. This share is expected to increase further if the Government's target of expanding irrigated areas to 130 000 ha by 2003 is realized.

Overall, the wet-season lowland ecosystem dominates rice production in Laos, accounting for 66% of the rice area and more than 70% of total output. The rainfed lowland system is of similar importance in Cambodia and Thailand, although in Vietnam, it accounts for only 30% of the total rice area. The expansion of irrigated rice production in the Mekong Delta, which is the main rice bowl of Vietnam, has led to a reduced share for rainfed lowland rice.

The average yield of rice in Laos during 1991 and 1999 was 2.6 t ha^{-1}. Thus, in terms of average yield, Laos currently ranks second to Vietnam in the region (Table 2). The average yield in Laos is about 1.3 t ha^{-1} below that in Vietnam. Although Cambodia had slightly higher yields during 1961–1970, an absolute decline in yield especially during the years of political upheaval (1971–80) has put Cambodia behind Laos in terms of rice yield. For Thailand, where the rainfed lowland ecosystem predominates in the north-eastern region, the average yields were consistently higher than those in Laos until 1980. But a faster pace of growth in Laos subsequently has put this country ahead of Thailand in terms of average yield.

An examination of growth rates in rice yield for 1961–1999 shows that, of the four countries in the region, Laos has been able to maintain the highest average growth rate in yield of 3.45% per annum (Table 3), even though it started from the lowest average yield (Table 2). Despite this growth rate in yield, the growth rate in area planted was negative for almost two decades (1971–1990). In 1999, the area planted to rice in Laos was still below that of 1961–1970. The internal disturbances and political uncertainty are the major reasons for the decline in area planted during 1965–1975. In Cambodia, political disturbances caused a decline in area planted as well as yield. For example, during the decade 1971–1980, the area planted to rice was less than half of that planted in 1961–1970. Thus, for both Cambodia and Laos, opportunities still exist for expanding the area planted to rice. This is not the case in Vietnam where area planted is reaching a ceiling level.

As a result of overall reduction in area planted, rice output in Laos grew at the compound rate of only 2.81% per year during 1961–1999. This growth rate was barely adequate in matching the population growth rate of 2.5% per year during the late 1990s. Although the growth rate in production was almost 5% during 1991–1999, the source of more than 50% of this growth was expansion in area planted to rice. Yield growth even during 1991–1999 was only 2.59%. Thus, the challenge is to increase yield as future area expansion will most likely slow down.

Table 1. Percentage shares in area and production of different ecosystems for rice production in Laos.

Year	Area				Production			
	Total ha (thousands)	Ecosystem share (%)			Total tonnes (thousands)	Ecosystem share (%)		
		Rainfed	Upland	Irrigated		Rainfed	Upland	Irrigated
1990	650	60	38	2	1492	72	25	3
1991	570	57	41	2	1223	69	28	3
1992	608	65	32	3	1502	77	19	4
1993	552	64	34	2	1251	74	23	4
1994	611	62	36	2	1577	76	22	2
1995	560	66	32	2	1418	76	20	4
1996	554	66	31	3	1414	76	19	5
1997	601	70	26	4	1660	78	15	7
1998	618	70	21	9	1675	74	13	13
1999	718	66	22	12	2103	71	12	17
Avg.	604	65	31	4	1531	74	20	6

Source: Lao—IRRI (2000).

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Table 2. Average area, yield and production of rice in selected South-East Asian countries, 1961–1999.

Country	1961–70	1971–80	1981–90	1991–99	Overall
Cambodia					
Area (ha in thous.)	2 229	1 066	1 508	1 808	1 648
Yield (t ha^{-1})	1.20	1.15	1.33	1.63	1.32
Production (t in thous.)	2 670	1 278	2 013	2 962	2 212
Laos					
Area (ha in thous.)	752	644	645	591	659
Yield (t ha^{-1})	0.97	1.29	2.0	2.6	1.68
Production (t in thous.)	718	832	1 261	1 535	1 075
Thailand					
Area (ha in thous.)	6 654	8 101	9 403	9 329	8 347
Yield (t ha^{-1})	1.81	1.84	2.02	2.31	1.98
Production (t in thous.)	12 070	14 933	19 072	21 540	16 784
Vietnam					
Area (ha in thous.)	4 797	5 191	5 729	6 868	5 615
Yield (t ha^{-1})	1.93	2.10	2.77	3.65	2.59
Production (t in thous.)	9 245	10 887	15 930	25 221	15 066

Source: Calculated from the FAO database (2000).

Table 3. Growth rates (%) in rice area, yield and production in selected South-East Asian countries, 1961–1999.

Country	1961–70	1971–80	1981–90	1991–99	Overall
Cambodia					
Area	–0.39	–2.56	2.19	1.98	–0.29
Yield	4.28	–4.62	3.35	5.27	1.11
Production	3.84	–7.26	5.53	7.25	0.82
Laos					
Area	1.25	–0.26	–2.85	2.32	–0.65
Yield	5.33	0.66	4.89	2.59	3.45
Production	6.58	0.39	2.04	4.91	2.81
Thailand					
Area	1.38	3.19	0.19	1.67	1.23
Yield	1.17	–0.36	0.54	0.79	0.80
Production	2.55	2.83	0.74	2.46	2.04
Vietnam					
Area	0.17	1.87	0.53	2.29	1.18
Yield	–0.52	–1.42	3.42	3.16	2.13
Production	–0.34	0.45	3.95	5.45	3.30

Source: Estimated from the FAO database (2000) using a log-linear trend equation.

A feature of rice production in Laos is the high variability of production around the trend (Figure 1). Although Laos achieved self-sufficiency in rice production in 1999 with the total production of 2.1 million tons, rice output can fall dramatically below national requirements in years of drought and/or flood. This is indicated by the large deviation of production around the trend (Table 4). It reflects the uncertainty associated with rainfed rice production. The variability is similar for Cambodia where rainfed lowland systems predominate. Variability is lowest in Vietnam where the rainfed ecosystem is of relatively minor significance.

Table 4. Average percentage deviationa from the trend in rice production, South-East Asia, 1991–1999.

Country	% deviation from trend[a]
Cambodia	10.6
Laos	10.3
Thailand	4.8
Vietnam	1.5

[a] The average percentage deviation from the trend is estimated as the root mean-square error of the regression of the natural logarithm of production on a time trend.

Source: Estimated from the FAO database (2000).

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

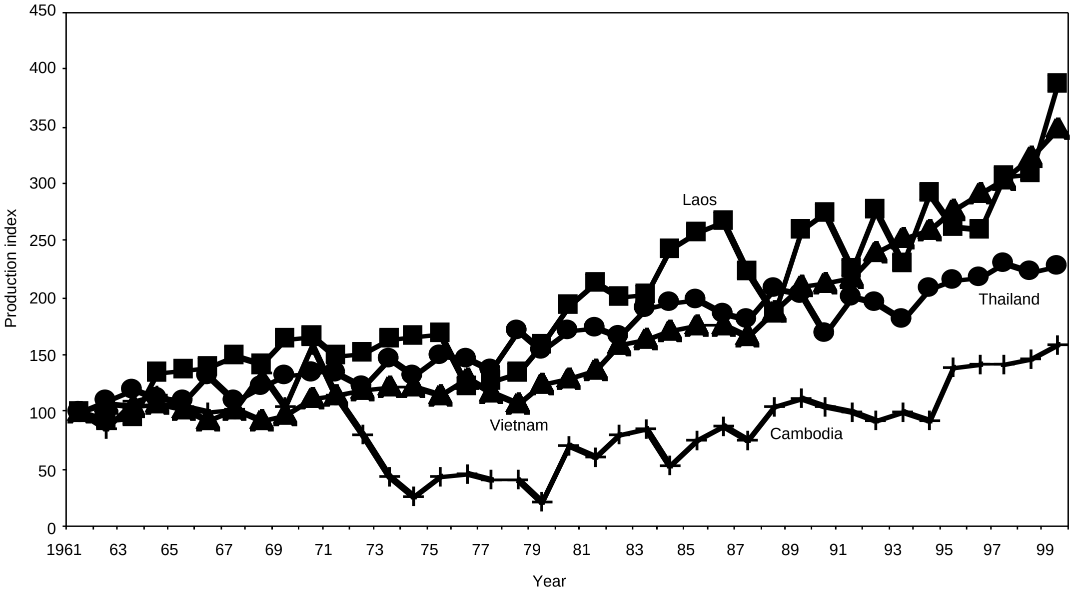


Figure 1. Trends in rice production in selected South-East Asian countries, 1961–1999.

Micro-Economics of Rainfed Lowland Rice Production in Laos

The analyses presented in this section are based on a survey of 700 rainfed rice farmers from 15 villages of Champasak and Saravan provinces of the southern plains of Laos, following survey procedures described by Pandey and Sanamongkhoun (1998). The results pertain to the 1996 wet-season rice crop.

The average farm size in the surveyed villages was 2 ha per household, with the range being from 1.3 to 3.4 ha. This is a relatively large farm size, compared with those found in more densely populated southern and south-eastern Asian countries. Because of the lower population pressure (20 persons km^{-2}) and relatively large farm size, the agricultural system of Laos is somewhat ‘extensive’.

Rice production is undoubtedly the most important economic activity in the villages surveyed. Generally, land preparation consists of two passes of ploughing and one of harrowing. Animals are the main source of draught power for land preparation. Rice is mostly established by transplanting, with seedling age varying between 3 and 8 weeks, depending mainly on the growth duration of the variety and field conditions. Harvesting starts in mid-September and is completed by the end of November. Because of labour shortage during this peak period, harvesting is staggered over several weeks. Overall, rice production is based on the use of family and exchange labour. Mechanization is limited and consists mainly of power tillers and threshers.

The average yield of rice for the sample was 1.2 t ha^{-1}, which was considerably lower than the official estimate of 2.5 t ha^{-1} for 1996 when the survey was undertaken. The lower average yield in the sample was probably the result of inundation that affected rice production in the surveyed villages. Average village-level yields varied from 0.8 to 2.1 t ha^{-1}, indicating a high variability of yield in Lao rice production environments.

Farmers may allocate their land to modern varieties (MVs) only, to traditional varieties (TVs) only, or to a combination of modern and traditional varieties. In most villages, farmers grew both MVs and TVs, with fewer than 10% of farmers growing MVs only. Although almost 60% of the farmers grew MVs, the percentage area under MVs was only 21%. This indicates that farmers who adopted MVs grew them on only a small proportion of their farm. Even in villages where almost all sampled farmers grew MVs, the area under MVs did not exceed 70%. Because the farmers in these villages had access and exposure to MVs for more than 15 years, other constraints probably operate to constrain expansion of MVs in these areas. In some villages, MVs covered only 4% of the rice area planted. Such variation in adoption patterns reflects differences in resource base, access to information and seeds, access to markets, and various farm and household characteristics.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

The use of fertilizers in Laos is very limited. Although 66% of the farmers reported using some fertilizers, the area fertilized was only 48%, indicating that fertilizers are not applied to the whole farm. About 60% of farmers had been using chemical fertilizers only since 1994. Farmers preferred to apply fertilizers mostly to sandy soil types located in higher terraces. Most farmers made a basal application of fertilizers but the average application rate for the whole sample was only 18 kg ha^{-1} of NPK combined, with N and P applied in almost equal quantities. The total application rate was as low as 3 kg ha^{-1} with farmers at the higher end applying about 50 kg ha^{-1}. This is certainly a very wide range. Obviously, those farmers who use very low quantities apply it only on seedbeds or on spots where they considered crop growth to be poor.

About 42% of farmers who grew MVs did not apply fertilizers. This proportion increased to only 57% among farmers who grew TVs. Thus, the use of chemical fertilizers does not seem strongly associated with the adoption of MVs. The yield response to fertilizer is a function of a range of variables such as the quantity of fertilizer applied, type of variety grown, soil and hydrologic properties and climatic factors. Yield response can be used to judge the economic profitability of applying chemical fertilizers. For those farmers who do not currently apply fertilizers, yield response at zero application is the relevant parameter. If this response is high, fertilizer application may be profitable, depending on the price of fertilizers relative to that of the output produced.

The estimated yield responses, using plot-level data and data aggregated at the village level, are presented in Table 5. Although a quadratic term in fertilizers was specified in the initial model, the estimated coefficient for the quadratic term was very low and statistically insignificant. Most likely, the response function is essentially linear at the low application rates applied by Lao farmers. The marginal response as measured by the coefficient of NPK ha^{-1} is 9 kg for the field-level regression and 17 kg ha^{-1} for the village-level regression. This implies that for each additional kg of NPK applied, yield increase will vary between 9 and 17 kg.

In 1996, the nutrient-to-grain price ratio in Laos was between 4.5 and 5, depending on whether urea or ammonium phosphate was considered. If farmers start applying fertilizers only when they can obtain a 100% marginal rate of return on their investment in fertilizers, the marginal response required is 9–10 kg per additional kg of nutrients applied. By this criterion, fertilizer application just breaks even for farmers who get the yield response of 9 kg per kg of nutrient applied. However, in more remote villages, the nutrient-to-grain price ratio is higher than 4.5, because of high transportation costs. Often, fertilizers are simply not available in these more remote areas. As a result, farmers may rationally choose either not to apply fertilizers or apply only a very small quantity.

Table 5. Factors explaining variations in plot-level and village-level yields of paddy rice, Laos.

Independent variables	Coefficient[a]	SE
Plot-level yield[b]		
Intercept	1.169	0.040
NPK (kg ha^{-1})	0.009***	0.001
Dummy for modern varieties[c]	0.185***	0.066
Dummy for low-lying fields[d]	–0.156*	0.070
Adj. R^2	0.13	
Number of plots	596	
Village-level yield[e]		
Intercept	1.017	0.093
NPK (kg ha^{-1})	0.017***	0.003
% area under modern varieties	0.006***	0.002
% area under clay soil	0.003**	0.001
% area on low-lying fields	–0.012***	0.003
Adj. R^2	0.96	
Number of villages	15	

[a] Significance levels: *** = 1%; ** = 5%; * = 10%.
[b] Dependent variable is the plot-level yield (t ha^{-1}) of paddy.
[c] Dummy for varieties, where 1 = modern varieties; 0 = otherwise.
[d] Dummy for low-lying land type, where 1 = low-lying; 0 = otherwise.
[e] Dependent variable is the average yield (t ha^{-1}) of paddy for each village.
Source: Pandey and Sanamongkhoun (1998).

The response to nutrients is comparable with that in Northeast Thailand, which has a similar agroclimatic environment. Other countries in the region also have responses, varying from 8 to 13 kg (Table 6). However, the nutrient-to-grain price ratio in Laos has been higher than in these other countries. For example, the ratio for Thailand was 2.5. With a similar marginal response as in Laos and with 40% cheaper fertilizers, farmers in Northeast Thailand apply only about 40 kg of N per ha. Unless the marginal response can be improved through either better technology or cheaper fertilizers through improved access, Lao farmers are unlikely to apply substantially higher rates of fertilizers.

The differential patterns of adoption of MVs and fertilizers across villages point towards the effect of accessibility in encouraging the adoption of improved technology, inputs tending to be more easily available and cheaper in more accessible villages than in remote villages. Similarly, interactions with extension agents also tend to be positively affected by accessibility.

Table 6. Nutrient use in rainfed areas in various South-East Asian countries.

Country	Marginal response[a] to N at N = 0 (kg grain per kg of N)	N-to-output[b] price ratio	Fertilizer use[b] (N per ha)
Bangladesh	13	2.0	34
Cambodia	—	6.0	18
Indonesia	11	—	—
Laos	8–17[c]	4.4[d]	17
Philippines	11	3.0	19
Thailand	8	2.5	40
Vietnam	—	4.0	—

[a] Hossain and Singh (1995). For non-linear models, the response is evaluated at the zero rate of nutrient application.
[b] IRRI (1995).
[c] Pandey and Sanamongkhoun (1998).
[d] MAF (1996).

To examine the effect of accessibility on the adoption of MVs and fertilizers, villages were grouped into different accessibility categories. Villages closer to main roads and with good feeder roads were considered as having 'good access'. Villages closer to the main road but without feeder roads were grouped as having 'medium access'. Others far away from the main road and with poor feeder roads that were mostly inaccessible during the rainy season were classified as having 'poor access'.

The different indicators of adoption are shown by accessibility in Table 7. The results show that accessibility is a major factor that affects the percentage of area under MVs, percentage of farmers growing MVs, percentage of area fertilized and average fertilizer (NPK) use. All these indicators show that adoption is lower in the more remote villages than in the more accessible ones.

Table 7. Effect of accessibility on various indicators of adoption of modern rice varieties and fertilizers, Laos.

Indicator of adoption	Accessibility[a]		
	Good	Medium	Poor
Area under modern varieties (%)	38 a	21 ab	12 b
Farmers growing modern varieties (%)	71 a	58 a	41 a
Area fertilized (%)	69 a	56 ab	28 b
NPK use (kg ha^{-1})	29 a	19 ab	7 b

[a] Figures with the same letter are not statistically significantly different at the 5% level by DMRT.
Source: Pandey and Sanamongkhoun (1998).

The extensive literature on technology adoption points to a range of field, farm and farmer characteristics as determining adoption (Feder et al. 1985; Adesina and Zinnah 1993; Bellon and Taylor 1993; Smale et al. 1994). To examine the effects of various biophysical and socioeconomic variables on the adoption of improved varieties and fertilizers, a probit model was estimated to identify the importance of these factors in Laos.

The results, presented in Table 8 (first column), indicate that the effects of farm size, access to credit, quantity of fertilizer applied and access to markets on the probability of MVs being adopted are statistically significant. Thus, farmers with larger farms, farmers who apply more fertilizers, and farmers with better access to credit and markets are more likely to adopt MVs than are farmers with small farms, or who use less fertilizers or who have less access to markets and credits. The regression results for fertilizer application are also presented in Table 8 (Column 2). Better access to markets, the adoption of MVs and the medium-lying fields have significant positive effects on the probability of adoption of fertilizer application. As expected, market access and risk have positive and negative effects, respectively. Thus, technologies that reduce risk and policies that improve access to markets are needed to encourage the adoption of MVs and fertilizers.

Production cost data for rice in Laos and neighbouring countries are presented in Table 9. Low labour costs and limited use of purchased inputs in Laos and Cambodia have kept the per unit cost of production low, relative to those in the Philippines and Thailand. Although farmers in Vietnam use more inputs, production costs for MVs are lower than for TVs due to higher yield. Overall, the differences in production costs between MVs and TVs (or between irrigated and rainfed areas) are relatively smaller in Cambodia, Laos and Thailand than in the Philippines and Vietnam. The data for Laos and Cambodia are mostly from rainfed areas. The benefits of growing currently available MVs under rainfed conditions are low as yield differences between them and TVs are small under these conditions. In Thailand, the data for irrigated areas pertain to the Northeast where the supply of irrigation is not assured. As a result, the cost advantage of irrigated relative to rainfed rice is small. Vietnam illustrates the kind of benefit that can be realized from a switch to MVs if irrigation and other complementary inputs are also applied.

Average costs and returns associated with rice production using different varieties (MVs or TVs) and fertilization practices (fertilizer applied or not applied) are presented in Table 10. These results indicate that the yield difference for TVs grown with and without fertilizers is small and statistically

Table 8. Factors influencing the adoption of modern rice varieties (MVs) and fertilizer, Laos.

Factor	Effect on probability of adoption of MVs[a]	Effect on probability of adoption of fertilizer[a]
Intercept	—	—
Dummies for:		
Low-lying fields[b]	+	—
Medium-lying fields[c]	—	+**
Clay soil[d]	+	+
Sandy soil[e]	+	+
Loamy soil[f]	—	—
Loamy sandy soil[g]	+	+
Cash income per household (US$)	+	+
Total farm holding (ha)	+**	—
Dummy for credit used for production[h]	+**	+
CV of yield computed at village level	+	—**
Dummy for extension visit[i]	+	+
Years of schooling of household head	—	+
Size of household	+	—
Dummy for good access to market[j]	+**	+**
Dummy for medium access to market[k]	+**	+**
NPK use (kg ha^{-1})	+**	
Dummy for modern varieties[l]		+**
Sample size	576	590
Value of log-likelihood function	–367	–375
Log-likelihood ratio	66***	68***

[a] Significance levels: *** = 1%; ** = 5%; * = 10%.

Dummies for:

[b] Low-lying field: 1 = low-lying field; 0 = otherwise.
[c] Medium-lying field: 1 = medium-lying field; 0 = otherwise.
[d] Clay soil: 1 = with clay soil; 0 = otherwise.
[e] Sandy soil: 1 = with sandy soil; 0 = otherwise.
[f] Loamy soil: 1 = with loamy soil; 0 = otherwise.
[g] Loamy sandy soil: 1 = with loamy sandy soil; 0 = otherwise.
[h] Credit used for production: 1 = with credit; 0 = otherwise.
[i] Extension visit: 1 = visited; 0 = otherwise.
[j] Good access to market: 1 = with good access; 0 = otherwise.
[k] Medium access to market: 1 = with medium access; 0 = otherwise.
[l] Modern varieties: 1 = modern varieties; 0 = otherwise.

Source: Pandey and Sanamongkhoun (1998).

Table 9. Rice production costs in selected South-East Asian countries (US$ t^{-1}).[a]

Country[b]	Irrigated	Rainfed	Difference (%)	Modern varieties	Traditional varieties	Difference (%)
Cambodia				104 (2.0)	110 (1.3)	6
Laos				84 (1.3)	93 (1.5)	11
Philippines	118 (3.8)	143 (2.1)	17			
Thailand	122 (2.5)	125 (1.6)	3			
Vietnam				100 (4.8)	136 (2.3)	26

[a] Figures in parentheses are yield in t ha–^{1}.

[b] Sources:

Data for year	Country	Source
1995	Cambodia	Helmers (1997).
1996	Laos	Pandey and Sanamongkhoun (1998).
1997	Philippines	Hossain (2000).
1995	Thailand	Isvilanonda and Hossain (1998).
1997	Vietnam	Hossain (2000).

Table 10. Yield, costs and returns for traditional (TV) and modern rice varieties (MV) with (+F) and without (–F) fertilizer, Laos.

Attribute	Unit	TV (–F)	TV (+F)	MV (–F)	MV (+F)
Yield[a]	(t ha^{-1})	1.18 a	1.35 a	1.23 a	1.74 b
NPK fertilizer rate	(kg ha^{-1})	0	37	0	41
Cost of fertilizers	(US\$ ha^{-1})	0	29	0	34
Total paid-out cost	(US\$ ha^{-1})	10	36	6	43
Gross revenue	(US\$ ha^{-1})	176	206	185	273
Net returns above cash cost	(US\$ ha^{-1})	166	170	179	230

[a] Means with the same letter are not significantly different at the 5% level based on DMRT.
Source: Pandey and Sanamongkhoun (1998).

insignificant. Similarly, the yield of MVs grown without fertilizers is statistically not different from that of the TVs. Rice yields are significantly increased only when MVs are grown with fertilizers. Obviously, a shift from the practice of growing TVs without application of fertilizers to the practice of growing MVs with fertilizer application would generate the highest benefit per unit area. However, farmers who are currently growing TVs without fertilizers may not achieve this transition in one step but may prefer a step-wise progression due to various constraints, including lack of capital. The current literature on the process of technology adoption indicates that farmers adopt technologies in a sequential fashion and pick simple and less cash-demanding technology first (Byerlee and Hesse de Polanco 1986). For poor farmers, returns to the incremental capital needed for the change may be more relevant than returns to land in such decisions.

Returns to incremental capital are highest for the simple change, without fertilizers, from TVs to MVs (Table 11). The benefits come from a slightly higher yield of MVs and higher price of these varieties due to better quality. This option, which is unlikely to affect rice output substantially, may be attractive to farmers who are cash constrained. For farmers who are currently growing TVs without fertilizers, the use of fertilizers without a change in varieties is the least attractive option. A very good rate of return over cash cost is indicated for farmers who are currently growing TVs with fertilizers if they change to MVs with fertilizers.

Research and Policy Issues

The average rice output of 1.5 million tons in Laos during 1995–1999 was barely sufficient to meet the national per capita requirement of 250 kg per capita. As the population grows at the rate of 2.5% per year, the total rice output must continue to increase at least at that rate to maintain the per capita food availability. Assuming that growth in area planted will soon slow down, most of this increase in rice production must come from yield improvement. The growth rate in yield during 1991–1999 has been 2.6%, which is fractionally above the population growth rate. A relatively high overall growth rate in yield during 1961–1999 in Laos resulted from a relatively low base figure for yield. With the current practices in rice production, the current rate of growth in yield will unlikely be sustained unless better rice-growing technologies are available. Improved technologies that are now ready for dissemination and those that are currently under development in Laos appear promising in this regard (Schiller et al., this volume).

At the current rate of growth, the Laotian population will increase by 64% by the end of 2020. To satisfy consumption requirements at 250 kg per capita, the total rice production needs to be increased from the 1995–1999 average of 1.5 million tonnes to 2.5 million tonnes during this period. The target output of 2.5 million tons can be considered to be the minimum production needed to avoid rice imports in less favourable years. This is indeed an important challenge for researchers and policymakers alike. Fortunately, the prospects for meeting this challenge are favourable as Laos produced a record 2.1 million tons of rice in 1999 and became self-sufficient in rice for the first time in recent decades.

Policymaking: towards self-sufficiency

What kinds of technologies and policies are needed to achieve this goal? Let me first turn to the issue of policy. Policies can be considered at two levels: macro-economic policy and agricultural policy. The macro-economic policies are designed to manipulate the exchange rate, interest rates and international trade. These parameters affect the agricultural sector indirectly by influencing its comparative advantage vis-a-vis other countries and other sectors. Agricultural policies directly affect the choice of crops grown, the levels of input used and types of technology adopted mainly by altering input/output prices.

Table 11. Incremental costs and returns (US$) associated with a change in technology from traditional varieties (TV) to modern varieties (MV), and from no fertilizer (–F) to fertilizer use (+F), Laos.

Change in technology		Incremental		
From	To	Cost ($ ha^{-1})[a]	Net return ($ ha^{-1})[a]	Rate of return (%)
TV (–F)	MV (–F)	0	8	—
TV (–F)	TV (+F)	25	4	16
TV (–F)	MV (+F)	33	64	194
TV (+F)	MV (+F)	7	60	850
MV (–F)	MV (+F)	38	51	138

[a] Our survey data indicated a slight decline in cash cost as a result of changing from TV (–F) to MV (–F). As there is no reason to believe that cash costs decline as a result of such a switch, we have assumed incremental costs to be zero. Incremental return is hence, the difference between gross revenues of TV (–F) and MV (–F).

Source: Pandey and Sanamongkhoun (1998).

For a small country like Laos, its macro-economic parameters are largely driven by the macro-economic policies of countries with which it has strong economic linkages. Thailand is a major trading partner for Laos and, as a result, the macro-economic fluctuations in Thailand are easily transmitted to Laos. This is shown by the recent economic crisis in Thailand and the resulting rapid devaluation of the Lao currency by almost 700%. Although a higher price for rice in Thailand benefited those Lao farmers in the bordering areas who had surplus rice to sell, the devaluation of the Lao currency also increased the price of inputs (such as fertilizers), which were mostly imported from Thailand. This eroded economic incentives to adopt yield-increasing inputs.

Obviously, being a small country, Laos cannot do much to influence these macro-economic shocks that arise outside its borders. Nevertheless, because these shocks do adversely affect incentives to adopt improved technology and the performance of agriculture, compensatory policies are needed to prevent erosion of agricultural incentives.

One factor closely tied with regional food security in Laos and its economic growth is infrastructure. Although initiatives have been put in place during the 1990s to improve transport infrastructure, the economies of the northern and southern areas remain somewhat fragmented because of high transport costs. These costs also create a barrier to moving surplus grain from production areas of the southern and central plains to deficit areas in the mountainous northern regions. While farmers in the southern and central plains lack incentives to increase rice output, due to excessive production, people in food-deficit areas of northern regions may find it cheaper to purchase rice produced in Thailand. Poor marketing infrastructure reduces the farmgate price of rice and increases the cost of inputs. This cost-price squeeze obviously makes it difficult to persuade farmers to adopt improved technologies even though such technologies may increase yield and output.

While marketing infrastructure is essential for the physical movement of goods, marketing institutions that permit inputs and outputs to flow freely from surplus to deficit areas are also equally important. Laos has made substantial progress in removing inefficiencies associated with the supply of credit and fertilizers by state-owned agencies. The private sector is now entering these areas. As shown by Pandey and Sanamongkhoun (1998), further actions are needed to free these markets for efficient distribution of agricultural inputs and outputs.

Rice production in Laos is currently subsistence oriented. Only a small proportion of rice produced is sold on the market. Because of the limited possibilities of obtaining food from the market, households follow the strategy of being as self-sufficient in rice as possible. However, the strategy of such self-sufficiency has its economic cost because it limits opportunities for income gains that could be realized through marketing and crop diversification. In a diversified and commercialized agriculture, rice may be grown more intensively in certain areas (such as the more favourable central and southern plains), while other income-generating activities (livestock, horticulture) are adopted in areas less suitable for rice. Such a vision of agriculture implies that it may not be necessary to develop rice production technology for marginal environments where the possibilities for technological breakthroughs are more limited.

Technological issues

Turning now to technological issues, drought and submergence are major constraints in rainfed areas of Laos. Accordingly, superior germplasm and better crop management practices to reduce the yield-depressing effects of these abiotic stresses are needed. Such technologies will help stabilize yield and encourage farmers to invest in inputs. As the papers presented in this workshop indicate, substantial progress is being made to bring the cutting edge of science to address this constraint (Jongdee; Pantuwan et al. this volume). When the traits that impart drought tolerance have been incorporated into improved rice varieties, further testing, with farmer participation, of germplasm can help rapidly identify lines with those attributes (such as taste, quality and straw yield) that farmers value.

Results from experimental work and farm-level surveys indicate that the gap between the yield that can be obtained from farmers' fields and the current average yield is substantial. The strategy of closing the yield gap may be more relevant for Laos than trying to increase the yield ceiling. One reason for high variability in yield among farmers is poor fertilizer management. As explained earlier, fertilizers are often applied in quantities that are too small to generate a good yield response. The marginal response to fertilizer application varies among farmers from 9 to 17 kg per kg of nutrient applied. We must understand the reasons for such a high variability in yield response to nutrients such as timing of fertilizer application (Linquist and Sengxua, this volume). Such scientific knowledge could then form the basis for making site-specific recommendations that are more suited to particular environmental conditions.

Relative to other Asian countries in the region, Laos, with its population density of 20 persons km^{-2}, is still sparsely populated. Accordingly, labour-intensive methods of rice production such as those practiced in the Red River Delta of Vietnam are not appropriate for Laos. With current average farm size being 2 ha (versus 0.3 ha in the Red River Delta), the agricultural system of Laos is likely to remain somewhat 'extensive' for the foreseeable future. In labour-scarce environments, farmers are more interested in maximizing returns to labour than returns to land. Hence, rice technologies that increase labour input are likely to be less attractive to farmers (even if they increase yield). This has major implications for technology design and evaluation.

Agricultural research in labour-surplus areas is generally oriented towards increasing the yield per unit area. Research approaches developed in these labour-surplus areas are inappropriate when labour is a constraining factor. Similarly, evaluation of technology should not be based merely on yield per unit area but also on yield per unit labour applied, or on other measures that reflect total factor productivity. Mechanized land preparation, direct seeding and more efficient weed control methods may be suitable to Laos as they help save labour. However, the use of mechanical land preparation and chemical weed control methods may require policy support as poor farmers cannot acquire such technologies due to limited purchasing power. Efforts to improve the effectiveness of existing tools and implements for land preparation and development of varieties that are more competitive with weeds are also desirable.

Another area of research of potential relevance to Laos is breeding for high-quality rice. As consumers with increased income switch from low to high quality rice, the demand for such rice will increase with the country's economic growth. In addition, high-quality rice can also have an export market. The environmental conditions in the southern plains of Laos are similar to those in Northeast Thailand where high-quality export rice is produced. Laos will have to face stiff competition, given that Thailand has established itself as a major exporter of high-quality rice. Nevertheless, benefits to Laos could be substantial, even if it captures only a small share of the export market. Obviously, marketing infrastructure required for export will have to be developed.

Conclusions

Laos has made good progress in increasing rice production during the 1990s. It became self-sufficient in rice with the production of 2.1 million tons in 1999. Despite this achievement, resulting mainly from improved technologies and policy reforms, the challenge to adequately feed its rapidly growing population still remains. While there are possibilities for increasing rice output through expansion of area planted, yield growth must be the ultimate source of output growth. Technologies are needed to increase and stabilize rice yield in the dominant wet-season lowland environments and good progress is being made in this regard (Schiller et al., this volume). Given the overall labour scarcity of Laos, improved technologies should not be too labour intensive. Labour-saving technologies for land preparation, crop establishment and weeding suit the labour-scarce environments of Laos well. Emphasis should be placed on reducing the substantial gap in yield between the 'best-practice' farmer and the average yield through better crop management technologies. Results of a farm survey show that yield response to fertilizers is highly variable among farmers. Such variability in response may be partly due to lack of knowledge about nutrient management. Research could help develop recommendations that are suitable to specific environmental conditions. Some of these recommendations have now been developed and are being actively disseminated (Schiller et al, this volume).

The new possibilities opened up by improved technologies cannot be exploited fully without an enabling policy environment. Poorly developed marketing infrastructure and marketing institutions remain a major handicap in commercializing the subsistence-oriented agricultural sector of Laos. As a result, the Lao agricultural economy remains somewhat fragmented, and opportunities for regional specialization based on comparative advantage are being lost. Although the Government of Laos has

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

taken initiatives to improve the marketing system, more remains to be done. With appropriate policies in place and with the technologies that are currently being developed, Laos can indeed be self-reliant in its most important staple crop.

Acknowledgments

The author gratefully acknowledges Renato Villano, Social Sciences Division, IRRI, for his assistance; and John Schiller and an anonymous reviewer for their helpful comments.

References

ADB (Asian Development Bank). 2000. Asian Development Outlook 2000, Manila, Philippines, p. 242.

Adesina, A.A. and Zinnah, M.M. 1993. Technology characteristics, farmers' perceptions and adoption decisions: a Tobit model application in Sierra Leone. Agricultural Economics, 9, 297–311.

Bellon, M.R. and Taylor, J.E. 1993. Folk soil taxonomy and the partial adoption of new seeds varieties. Economic Development and Cultural Change, 41, 763–786.

Byerlee, D. and Hesse de Polanco, E. 1986. Farmers' stepwise adoption of technological packages: evidence from the Mexican Altiplano. American Journal of Agricultural Economics, 68 (3), 519–527.

FAO 2000. Electronic database of agricultural production by commodities. Food and Agricultural Organization, Rome, Italy.

Feder, G., Just, R.E. and Zilberman, D. 1985. Adoption of agricultural innovations in developing countries: a survey. Economic Development and Cultural Change, 33, 255–298.

Helmers, K. 1997. Rice in the Cambodian economy: past and present. In: Nesbitt H.J. ed. Rice Production in Cambodia. Manila, Philippines, International Rice Research Institute (IRRI), 1–14.

Hossain, M. 2000. The impact of rice research for development for South-East Asia. Paper presented at the International Conference on the Impact of Agricultural Research for Development in South-East Asia, held 20–26 October 2000, Phnom Penh, Cambodia.

Hossain, M. and Singh, V.P. 1995. Fertilizer use in Asia: recent trends and implications for food security. Paper presented at the Final Workshop of the Projections and Policy Implications of Medium-Long-Term Rice Supply and Demand Project, held 23–26 April 1995, Beijing, China.

IMF (International Monetary Fund). 2000. Lao People's Democratic Republic: Recent Economic Developments. IMF Staff Country Report No. 3. Washington DC.

IRRI (International Rice Research Institute). 1995. World Rice Statistics 1993–94. Los Baños, Laguna, Philippines.

Isvilanonda, S. and Hossain, M. 1998. Recent changes in Thailand's rural economy: a case of six villages in the central and northeast regions. Paper presented at the Workshop on Rice Prioritization of Rice Research in Asia, held 20–22 April, 1998, International Rice Research Institute (IRRI), Los Baños, Laguna.

Lao—IRRI 2000. Wet Season 2000 Research Program. Lao—IRRI Project, Vientiane, Laos.

MAF (Ministry of Agriculture and Forestry). 1996. 20 Years Agricultural Statistics, 1976–1995. Vientiane, Lao PDR.

Pandey, S. and Sanamongkoun M. 1998. Rainfed lowland rice in Laos: a socio-economic benchmark study. Social Sciences Division, International Rice Research Institute (IRRI), Los Baños, Laguna, Philippines.

Smale, M., Just, R.E. and Leathers, H.D. 1994. Land allocation in HYV adoption models: an investigation of alternative explanations. American Journal of Agricultural Economy, 76, 553–546.

World Bank. 2000. World Development Indicators 2000. Washington DC.

Agronomic Practices for Improving Yields of Rainfed Lowland Rice in Laos

Sipaseuth[1], P. Inthapanya[1], P. Siyavong[2], V. Sihathep[3], M. Chanphengsay[4], J.M. Schiller[5], B. Linquist[5] and S. Fukai[6]*

Abstract

Agronomic research aimed at developing technologies for improving lowland rice yields in Lao PDR began in 1992. Results indicate that, to obtain high yields from rainfed lowland transplanted rice, high-yielding varieties should be sown in the early wet season (i.e. late May to early June) and seedlings should be 25 days old when transplanted. Early sowing (early June) is also important for direct-seeded rainfed lowland rice. When weed control is optimal and crop establishment is good, yields of direct-seeded rice can equal those of transplanted crops. Yield potential can be maximized under dry-season irrigated conditions by ensuring a high plant population through closer hill spacing. Transplanted rice in rainfed lowlands probably has the same requirements. The increase in potential yield achievable from improved agronomic practices for both rainfed lowland and irrigated rice depends on appropriately managing soil fertility. Technology packages for both transplanted and direct-seeded rainfed lowland rice in the wet season are also described.

In Laos, the area under rice is about 717 000 ha, representing more than 80% of the area under cultivation (Lao–IRRI2000). Of the rice ecosystems, the rainfed lowlands occupy the largest area (>60%), with one wet-season rice crop as the basic production system. According to government statistics rice yields range between 2.5 and 3.5 t ha^{-1}, but lower yields are common, particularly in the rainfed lowlands, where, under unfertilized conditions, yield can be as low as 1 t ha^{-1}. Rainfed lowland rice frequently suffers drought. Early season drought can delay sowing and transplanting, while late-season drought reduces yield, particularly in late-maturing traditional varieties.

Poor soil fertility is another important yield constraint. However, farmers generally fail to perceive these problems as a constraint, even though research has demonstrated that yields can be increased through improved N-P-K nutrition (Linquist et al. 1998).

Key management options to minimize adverse effects of drought and low-fertility soil conditions are use of suitable varieties, fertilizer application, appropriate planting time and use of seedlings of adequate age for transplanting. These options have been the focus of recent agronomic research in the Lao lowlands.

Direct-seeding technologies have also formed a research focus, reflecting an increasing labour shortage for transplanting near the larger provincial towns, and relatively high labour costs at transplanting. In Laos, direct seeding is likely to replace transplanting, although gradually, in a similar manner as to what had happened in Northeast Thailand (Naklang 1997).

Over the last decade, the area planted to dry-season irrigated rice has expanded rapidly in Laos. In 1995, this area was 13 000 ha, expanding to about 100 000 ha by 2000. Traditional photoperiod-sensitive varieties cannot be grown under dry-season irrigated conditions, thus requiring the development of suitable varieties for this environment. The Lao research program also studied appropriate planting times to maximize crop yield.

Much of the recent agronomic research in Lao lowland rice ecosystems (both irrigated and rainfed lowland) was conducted by the Lao National Rice Research Program within the National Agriculture

---

[1] National Agriculture Research Centre, Vientiane, Laos
[2] Agriculture and Forestry Office, Savannakhet, Laos
[3] Agriculture and Forestry Office, Champassak, Laos
[4] National Agriculture and Forestry Research Institute, Vientiane, Laos
[5] Lao–IRRI Project, Vientiane, Laos
[6] The University of Queensland, Brisbane, Qld., Australia
*Corresponding author: S.Fukai@mailbox.uq.edu.au

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

and Forestry Research Institute (NAFRI). The research was conducted in collaboration with the Lao–IRRI Project, and ACIAR supported projects under both on-station and on-farm conditions.

This paper summarizes the more salient outputs of these studies. Sipaseuth et al. (2000) have already published results on research on direct seeding.

Materials and Methods

Agronomic experiments on lowland rice were carried out in three locations: Vientiane Municipality (VTN), Savannakhet Province (SVK) and Champassak Province (CPK) of Laos. Experiments were conducted in both the rainfed and irrigated lowland rice systems.

Rainfed lowland rice—transplanted

Effect of sowing date on the performance of selected varieties

Studies on the effect of sowing date on the performance of several selected rainfed lowland rice varieties were undertaken in the 1994 and 1995 wet seasons at the National Agricultural Research Centre (NARC), VTN. Eight varieties were evaluated: for 1994, TDK1, Nang Nuan, Dok Tiou and RD8; and for 1995, TDK2, L161, Niaw Ubon 1 and Pongseng. Seeds were sown at about 15-day intervals between 25 May and 10 July in both years. In 1995, sowing was carried out on two additional dates after July 10, but floods destroyed the crops at the end of the growing season. In all cases, transplanting took place 25 to 35 days after sowing.

Effect of sowing date and seedling age at transplanting

Experiments were conducted at NARC, VTN, during the 1997 wet season, and at two sites in the 1998 wet season (VTN and SVK). In the 1997 study, the performance of three improved glutinous varieties (PN1, TDK1 and RD6) was evaluated. Five sowing dates at 15-day intervals were compared, using 25 or 45-day-old seedlings (Table 1). In the 1998 studies, two lines were used: IR57514-PMI-5-B-1-2 and SK12-47-2-1.

Table 1. Sowing and transplanting dates for 25 and 45-day-old rice seedlings, 1997 wet season, Vientiane, Laos.

Sowing date	Seedling age at transplanting date	
	25 days old	45 days old
25 May	20 June	10 July
10 June	5 July	25 July
25 June	20 July	10 August
10 July	5 August	25 August
25 July	20 August	10 September

Rainfed lowland rice—direct seeded

Effect of sowing date

In the 1996 wet season, studies on the effect of sowing date were conducted at the VTN, SVK and CPK sites. At each site, lines in three phenology groups, that is, early, medium and late flowering (PN1, TDK1 and RD6, respectively) were direct seeded by dibbling (three replicates) at 2-week intervals, beginning on 5 May and finishing on 5 July.

Genotype requirements for direct seeding

In the 1997 wet season, 18 genotypes were evaluated for direct seeding at two sites at the NARC, VTN, and at the Phone Ngam Research Station, CPK. All 18 genotypes were planted at VTN on 4 July 1997, whereas only 11 genotypes were planted at CPK on 12 July 1997.

Two further experiments were conducted in the 1998 wet season to investigate genotype requirements for direct seeding and weed competition. The experiments were conducted on farm at the VTN and CPK sites. Twelve genotypes (including seven that were used in 1997) were evaluated under weeded and unweeded conditions. Sowing took place on 26 June 1998 and 2 July 1998 in VTN and CPK, respectively. The same genotypes were also grown from transplanted seedlings, and yields of different genotypes were compared for crops established through direct seeding or through transplanting.

Methods of weed control in direct-seeded rice

During the 1997 wet season, a weed control experiment was conducted at the VTN, SVK and CPK sites. Comparisons were made for extent of land preparation (2 and 3 cultivations with 15 days between successive cultivations) and weeding treatment. During land preparation, the field was left without standing water. The five weeding treatments were (1) by hand, 15 days after dibbling (DAD), (2) by hand, at 15 and 30 DAD, (3) by rotary, at 15 DAD, (4) by rotary, at 15 and 30 DAD and (5) no weeding (control).

Optimal spacing for direct seeding

A study was conducted at the VTN, SVK and CPK sites in the 1998 wet season to study the effects of planting density on the grain yield of a direct-seeded crop. Two levels of weed control were compared (weeded and not weeded), with two genotypes being compared (IR57514-PMI-5-B-1-2 and IR66368-CPA-P1-3R-0-1). Planting density treatments were 25 × 25 cm, 25 × 10 cm and continuous rows with 25 cm between rows. Seed was dibbled at a rate of 80 kg ha^{-1} on 26 June in VTN, 30 May in SVK and 4 July in CPK.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Dry-season irrigated rice

Effect of hill spacing and number of seedlings per hill on grain yield

To study the relationship of yield to planting density in several selected varieties, two studies were undertaken at the NARC, VTN, in the 1994 and 1995 dry seasons. Each study compared three hill spacings (25 × 25 cm, 20 × 20 cm and 15 × 15 cm, corresponding to 16, 25 and 44 hills m^{-2}, respectively) and two seedling densities (3 and 6 seedlings per hill). In 1994, two popular varieties, TDK1 and RD10, were used, and in 1995, the varieties TDK1, RD10 and RD23 were used. A split-plot design was applied with varieties as main plots and planting densities as subplots. Fertilizer was applied at a rate of 90, 30 and 20 kg ha^{-1} of N, P_2O_5 and K_2O, respectively. Nitrogen was applied in three equal splits, at transplanting, active tillering and panicle initiation.

Effect of hill spacing and nitrogen application regime on grain yield

In the 1996 and 1997 dry seasons, we examined the effect of the N application regime (0, 45 and 90 kg N ha^{-1}) and hill spacing (25 × 25 cm, 20 × 20 cm and 15 × 15 cm, corresponding to 16, 25 and 44 hills m^{-2}, respectively) on rice productivity. Both studies were conducted on station at NARC, VTN. In 1996, the variety TDK1 was used, while, in 1997, NTN1 was used. In all cases, six seedlings per hill were transplanted. P and K were applied to all treatments

Results and Discussion

Rainfed lowland rice—transplanted

Effect of planting date on the performance of selected varieties

During the 1994 wet season, rainfall was generally favourably distributed throughout the season. However, in 1995, early season drought and late-season flooding adversely affected yields, lowering grain yield to <3 t ha^{-1} (Figure 1). Despite these differences, the effect of delayed sowing was similar in both years, and yield generally declined when the crop was sown after June 10. Yields from sowing on June 24 and July 10 were reduced by 22% and 39%, respectively, relative to the first two sowings. The lower yields associated with delayed sowing was probably due to late-season drought or pest damage (rice bug, birds and rats).

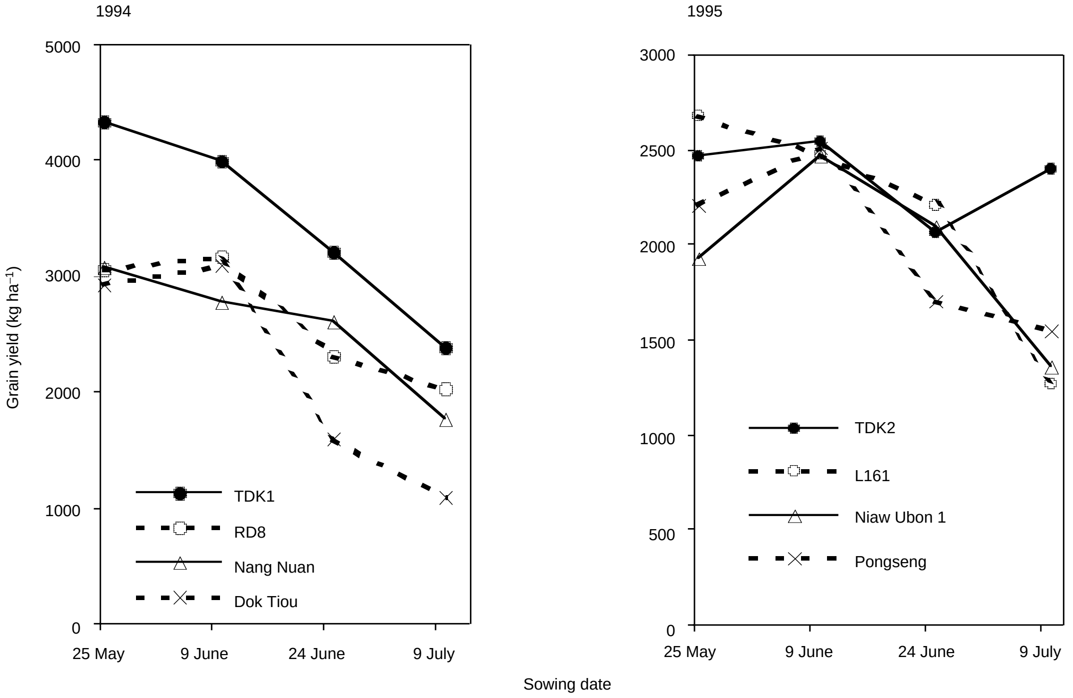


Figure 1. Grain yield of rice varieties at different sowing dates at the National Agricultural Research Centre, Vientiane Municipality, Laos, 1994 and 1995 wet seasons.

In the 1994 study, yield decline associated with delayed sowing appeared to be influenced by time to maturity. TDK1 (a photoperiod-insensitive variety) was the most affected by delayed sowing, with yield declining by 45% between the first and last sowing dates. RD8 (a highly photoperiod-sensitive variety) experienced a 33% decline, while the other two local varieties (moderately photoperiod sensitive) experienced intermediate yield decline. However, despite the large effect of sowing date, the yield of TDK1 was the highest over all sowing dates. In 1995, the effect of time to maturity on grain yield was not observed. The photoperiod-sensitive varieties (Niaw Ubon 1 and Pongseng) performed similarly to the photoperiod-insensitive varieties. Reduced yields associated with delayed sowing in 1995 may have been a result of flooding, the crops planted on last two sowing dates being completely destroyed by flooding.

Effect of sowing date and seedling age at transplanting

Yield data in the 1997 experiment showed consistent differences among varieties (Figure 2). Yield of TDK1 was 30% higher than either PN1 or RD6. Later sowing dates (25 June, 10 July and 25 July) produced significantly reduced yields. The two earlier sowing dates (25 May and 10 June) generally favoured all three varieties and both seedling ages (25 and 45 days). However, yield of 25-day-old seedlings was, on average, 460 kg ha^{-1} (22%) higher than that of 45-day-old seedlings, and the difference was consistent across sowing dates. The number of days to flowering varied between sowing dates, particularly for photoperiod-insensitive varieties. The time to flowering was longer when rice was sown early.

A similar effect of planting time was also obtained at VTN in 1998. However, planting an early maturing cultivar (SK12-47-2-1) in May and early June resulted in low yield at CPK in 1998 (Figure 3) because this cultivar flowered in August and early September during peak wet-season rainfall. Cultivars and planting dates should therefore ensure that flowering takes place after mid-September. In areas of favourable soils and rainfall, early planted and early harvested rice might allow a second crop.

Rainfed lowland rice—direct seeded

Time of direct seeding

Although, in general, sowing in late May to early June produced the highest yields (Figure 4), for short and intermediate-maturing varieties, it may result in the crop flowering during peak wet-season rainfall, with subsequent detrimental effects on yield. Later maturing variety was not suitable because of late-season drought and rice-bug damage.

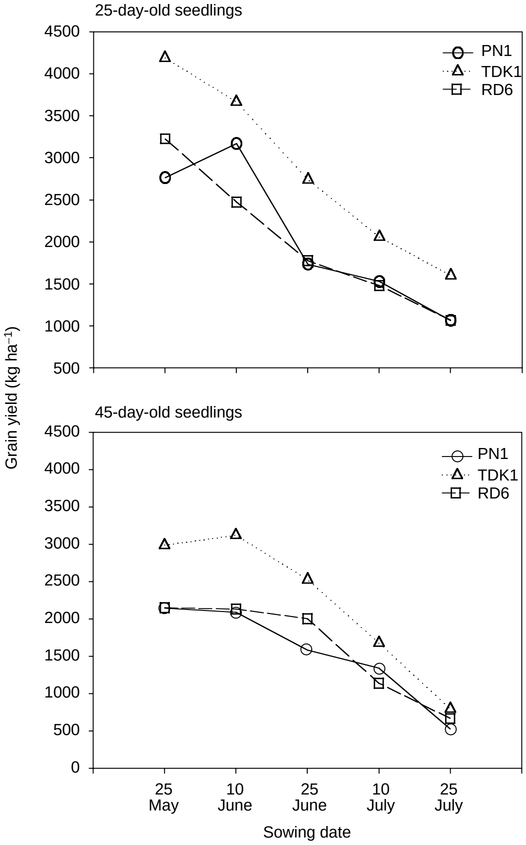


Figure 2. Effect of different seedling ages (25 and 45 days after sowing) at transplanting and sowing date on grain yield of three rice varieties with different phenologies.

These results for direct seeding are similar to those for transplanting mentioned earlier. Thus, overall, early sowing (late May-June) is advantageous in that it avoids adverse growing conditions in the wet season. These results confirm earlier reports (Inthapanya et al. 1997) that late-season varieties do not produce high yields because of the effects of late-season drought.

Genotype requirements for direct seeding

In both the 1997 and 1998 wet seasons, interaction between genotype and crop establishment method was observed. In the 1997 Vientiane experiment, tall genotypes (e.g. Ea-khao) had much lower yields

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

under direct seeding than under transplanting because of a high tendency to lodge (data not shown). An advanced line, IR46343-CPA-5-2-1-1, performed better under transplanting than under direct seeding. In Champassak, Ea-khao and IR46343-CPA-5-2-1-1 did not perform well under direct seeding, compared with Hom Nang Nuan, a local variety.

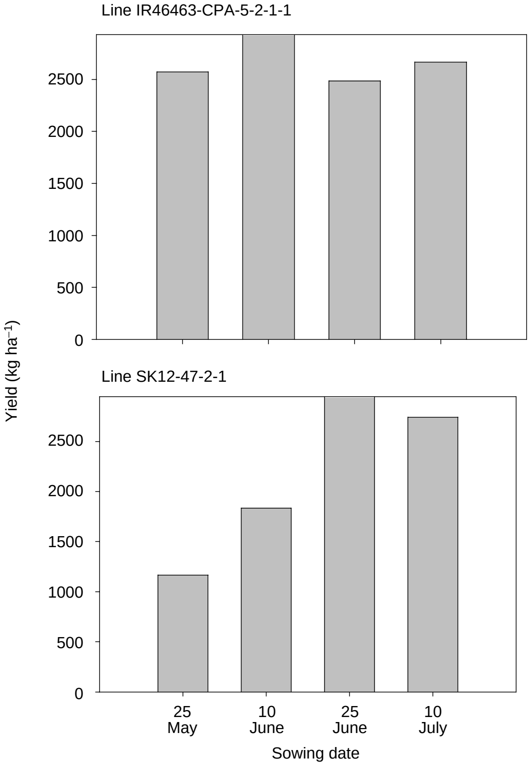


Figure 3. Effects of sowing date on rice grain yield in Champassak Province, Laos, during the 1998 wet season.

In the 1998 study, weeds heavily invaded direct-seeded rice, and a significant interaction was observed between variety and planting method (direct seeding versus transplanting) (Figure 5). Some tall genotypes, IRUBN-8-4-TDK-1-1 (5) and NSG 19 (8), had much lower yields under direct seeding because of a high tendency to lodge. Lodging is a major problem with direct seeding because the higher planting density, commonly used in direct seeding, causes excessive stem elongation. Some flowered rather late and did not lodge, even though they were tall. Flowering was delayed for several days in the unweeded treatment. Varieties responded differently to weeding, and the reduction in yield due to weeds was rather small for some varieties (Table 2).

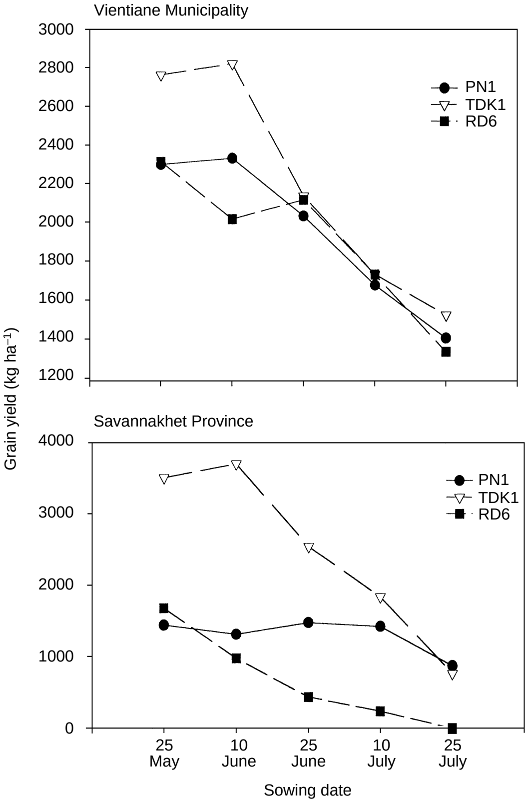


Figure 4. Effect of sowing date on grain yield of direct-seeded rice in Vientiane Municipality and Savannakhet Province, Laos, in the 1996 wet season.

Fukai (2000) suggested several genotypic traits are required in rainfed lowland rice for conditions of direct seeding. Some of these traits may also be required for transplanted rice as well, such as appropriate phenology to avoid drought and general adaptation to low soil fertility. Traits needed more for direct-seeding conditions are short to intermediate plant height to prevent lodging, ability to compete with weeds and ability to establish under adverse soil conditions. Yield of direct-seeded rice can be as high as that of transplanted rice, provided improved crop establishment and weed-free conditions prevail.

Methods of weed control in direct-seeded rice

Results of the 1997 experiments showed that grain yields among the three sites were different, partly because of weed competition. Savannakhet gave the highest yield, followed by Champassak in the weed competition experiment. Preparing land two or three times did not change yields significantly (Table 3a). Weed growth was small at 15 days after sowing, and

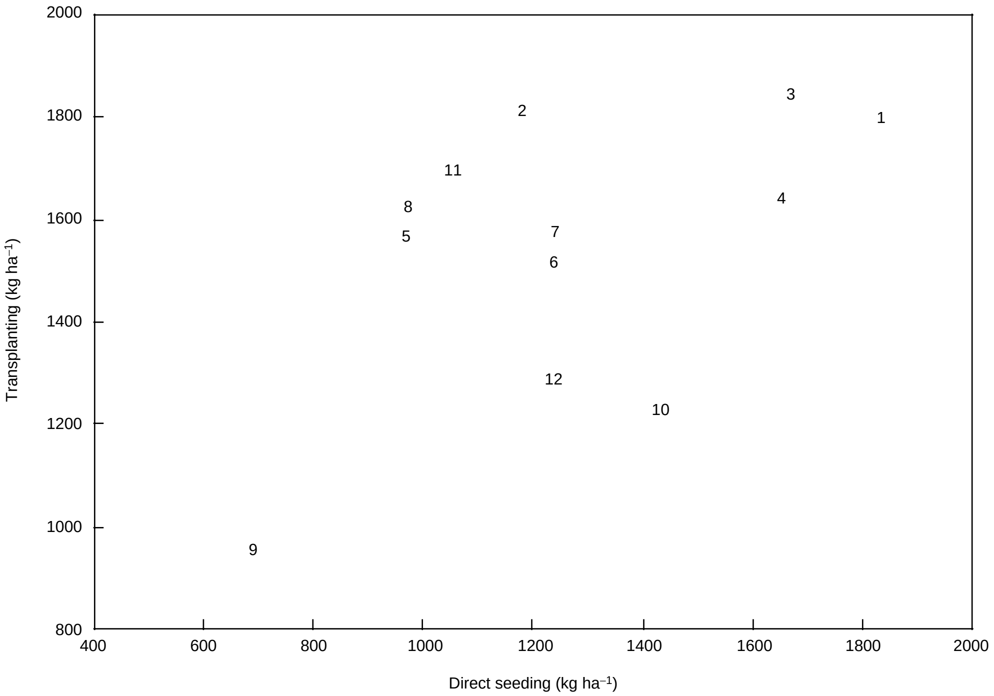


Figure 5. Relationships between grain yield of transplanted versus direct-seeded rice, wet season, Laos, 1998. (Numbers refer to genotype listed in Table 2.)

Table 2. Yields of 12 rice genotypes (kg ha^{-1}) established under direct seeding and grown under weeded and unweeded conditions, 1998 wet season, Vientiane Municipality and Champassak Province, Laos.

Code no.	Genotype	Vientiane		Champassak	
		Weeded	Not weeded	Weeded	Not weeded
1	IR68102-TDK-B-B-33-1	2470 a	1821 a	1456 de	1019 bcd
2	IRUBN4-TDK-1-2-1	2246 a	1184 abc	1973 a	899 bcd
3	TDK1	2660 a	1683 abc	1959 a	809 d
4	IR57514-PMI-5-B-2-1	2514 a	1642 ab	1914 ab	940 bcd
5	IRUBN-8-TDK-1-1	2217 a	978 bc	1707 bc	917 bcd
6	Dokmay	2621 a	1200 abc	1924 ab	1082 b
7	RD6	2227 a	1198 abc	2123 a	1299 a
8	NSG 19	2014 ab	975 bc	1318 e	1008 bcd
9	IR58821/IR58821/CA-7	1313 b	639 c	1629 cd	814 cd
10	Mahsuri	2129 a	1423 abc	2007 a	1062 b
11	IR49766-KKN-52-B-23	1851 ab	1060 abc	1971 a	1028 bcd
12	Hom Nang Nuan	1858 ab	1230 abc	1478 de	1054 bc

Means with the same letters are not significantly different at the 5% significance level.

weed management at this stage had no effect on fresh weed weight at all three sites. However, weed management methods (e.g. by hand two times) had an effect in VTN and CPK (Table 3b). A second weeding at 30 days after dibbling effectively reduced grass weed weight in CPK. In VTN, weeds reduced grain yield by as much as 47%. Rotary weeding had similar effects on weed control in both locations. More importantly, it reduced labor requirement for weeding in row planting.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Table 3a. Grain yield (kg ha^{-1}) of direct-seeded rainfed lowland rice when land was prepared two or three times before sowing at three sites, Laos, 1997.

Land preparation	Site[a]		
	VTN	SVK	CPK
Two times	2090	3671	2936
Three times	2175	4013	2640
$\text{LSD}_{0.05}$	ns	ns	ns

Table 3b. Yield (kg ha^{-1}) of direct-seeded rainfed lowland rice under different weed control measures, obtained at three sites, Laos, 1997.

Weed control treatment	Site[a]		
	VTN	SVK	CPK
Nil	1121	3823	2419
Hand weeding once	2131	3654	2795
Hand weeding twice	2280	3895	2917
Rotary weeding once	2457	3969	2857
Rotary and hand weeding	2670	3853	2948
$\text{LSD}_{0.05}$	294	ns	ns

[a] VTN = Vientiane Municipality; SVK = Savannakhet Province; CPK = Champassak Province.

Optimal spacing for direct seeding

Results suggest that the conventional spacing of 25 × 25 cm used in transplanting is unlikely to be the optimal spacing for direct seeding (Table 4). Dibbling at 25 × 10 cm is effective for achieving high yield and weed control, but requires considerable labour. A sound method for continuous row planting, where a simple tool can be used, should therefore be established.

At all three sites, the 25 × 25 cm spacing resulted in having the heaviest invasion of weeds and produced the lowest yields. In SVK Province, the 25 × 10 cm spacing produced higher yields than did continuous rows, as too many rice seeds were planted in the continuous rows at this site. In CPK, yields for the 25 × 10 cm spacing and continuous rows were similar under both weeded and unweeded conditions.

Broadcasting, as commonly practised, makes weed control very difficult, whereas the regular row planting pattern facilitates manual and mechanical weed control. Continuous row system where seeds are dropped into shallow furrows 25 cm apart may facilitate weed control. It also requires less labor for planting, compared with dibbling. Wide spacing between hills, however, is likely to encourage weeds. Yields were higher for row planting than for 25 × 25 cm or 25 × 10 cm spacings under weeded conditions, except in SVK where sown seeds were crowded together.

Dry-season irrigated rice

Effect of hill spacing and number of seedlings per hill on grain yield

The effect of hill spacing and seedling number per hill on grain yield for each variety is shown in Figure 6. Although average yields in both years were similar at 3.3 t ha^{-1}, yield of individual treatments ranged from 2.3 to 4.9 t ha^{-1}. In 1994, TDK1 yields were 26% greater than for RD10, while in 1995, RD10 yields were 20% higher than for TDK1. Yields of RD23 were similar to that of TDK1. Yields were consistently higher when hill densities were high. On average, across all treatments and years,

Table 4. Grain yield (kg ha^{-1}) of two rice lines grown at three different spacings (cm) and under direct seeding at three sites, 1998 wet season, Laos.

Site[a]	Spacing	Line IR57514-PMI-5-B-1-2		Line IR66368-CPA-3R-O	
		Weeded	Not weeded	Weeded	Not weeded
VTN	25 × 25	2235	2083	1754	1152
	25 × 10	1741	2114	2356	2147
	25 cm row	2594	2053	3623	1796
SVK	25 × 25	1775	1591	1928	1476
	25 × 10	2207	2375	3120	2175
	25 cm row	2095	1764	1835	1262
CPK	25 × 25	1446	854	1551	942
	25 × 10	2067	1145	1761	1060
	25 cm row	2097	947	1909	1054

[a] VTN = Vientiane Municipality; SVK = Savannakhet Province; CPK = Champassak Province.

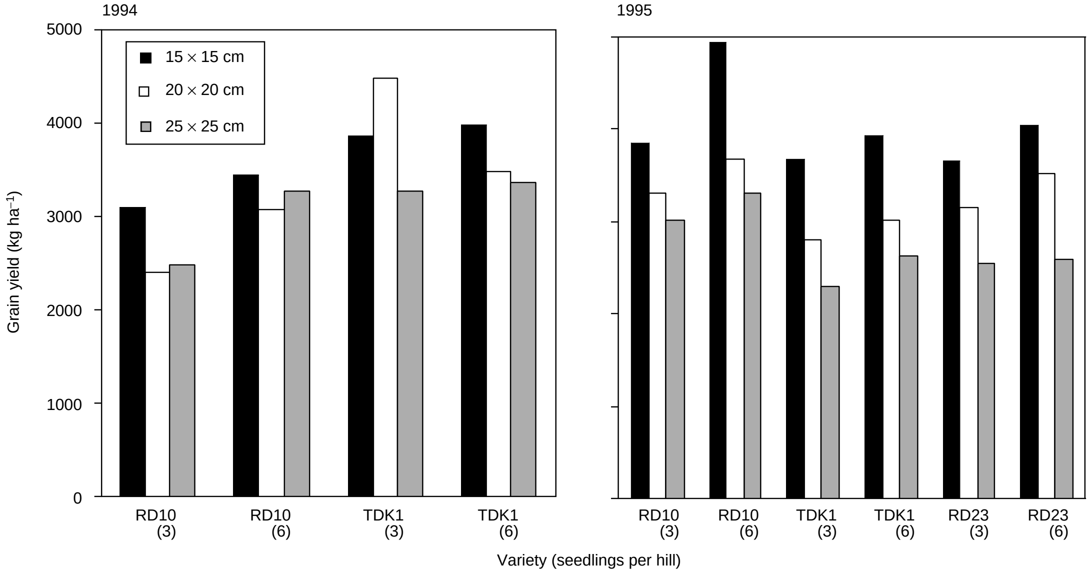


Figure 6. Effect of hill spacing and number of seedlings transplanted per hill on grain yields of selected rice varieties during the 1994 and 1995 dry seasons, Laos.

increasing hill density from 16 hills m^{-2} (25 × 25 cm) to 25 and 44 hills m^{-2} increased yields by 13% and 31%, respectively. Doubling the number of seedlings per hill from 3 to 6 also resulted in a consistent increase in yield, averaging 9%. Increasing planting density, either by spacing hills more closely or planting more seedlings per hill, increased panicle density (data not shown), resulting in higher yields.

Effect of hill spacing and nitrogen application regime on grain yield

Responses to hill spacing and N treatment were similar in both years, with yield increasing linearly with the amount of N applied at each hill spacing (Figure 7). Yields for TDK1 in 1996 were higher than for NTN1 in 1997, because of seasonal or varietal effects. When no N was applied, increasing planting density from 16 (25 × 25 cm) to 44 hills m^{-2} (15 × 15 cm) increased yields by 0.8 t ha^{-1} (a 63% increase), averaged across years. This suggests that, at higher planting densities, the crop can better exploit native soil N. Furthermore, applied N fertilizer was used more efficiently at the higher planting density than at the lower in both years. With 44 hills m^{-2}, the yield increase per kg N applied was 24 kg, compared with 18 and 12 kg for densities of 25 and 16 hills m^{-2}.

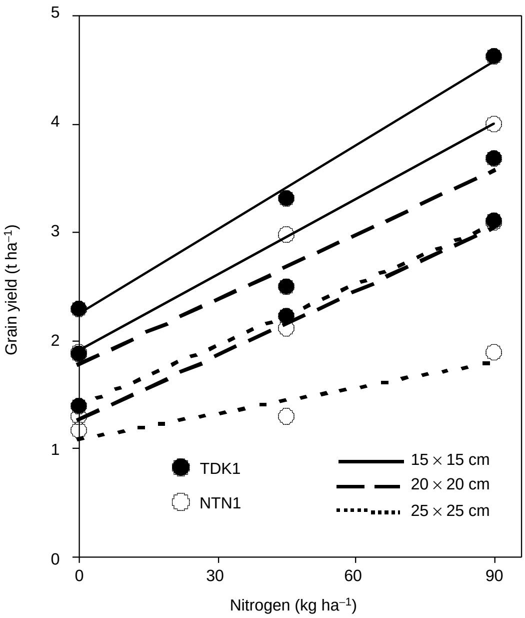


Figure 7. Effect of hill spacing and nitrogen fertilizer application regime on yields of rice varieties TDK1 and NTN1.

Results from the spacing studies discussed above are consistent with other reports. For example, Nguu and De Datta (1979) found that, under low N conditions, rice yields increased progressively with increased planting density because high planting density tends to compensate for the adverse affects on yield of low tiller number with low soil fertility. In our studies, even at the highest N rates applied (90 kg ha^{-1}), N was limiting.

These data and the data from Figure 6 illustrate the benefits of closer plant spacing under less than optimal soil N conditions. Farmers typically space their hills about 20 cm apart during the dry season and up to 25 cm apart during the wet season. This may be a reflection of labour availability, which is typically less during the wet season with more area being under cultivation. The benefits of higher densities need to be weighed against the additional cost of seed, extra labour required for a larger seedbed and more transplanting. Furthermore, in the wet season, high planting densities may predispose the crop to drought.

Technology Packages

Technology packages have been developed for rainfed lowland rice for both transplanting and direct seeding. Further work is required before a technology package can be developed for irrigated dry-season rice.

Rainfed lowland rice—transplanted

Improved varieties

Since 1993, nine improved glutinous rice varieties have been released for the wet-season lowlands (Lao–IRRI 2000). In much of the Mekong River Valley, when appropriate fertilizer management and cultural practices are followed, these varieties can raise average yields by at least 100%. The choice of varieties also depends on sowing date (see next section).

Appropriate sowing date

Sowing date depends on seasonal rainfall conditions. Sowing seed in the nursery should wait until the main fields are sufficiently wet. Sowing in late May to June is probably optimal for high yields under most conditions. Unless the main fields are located in low-lying areas, sowing in July is likely to result in reduced yield with the crop maturing too late. Early maturing varieties should not be sown early (late May to early June), as the crop is likely to flower during the wet-season peak.

Transplanting with young seedlings

Transplanting date depends on the conditions of the main fields, as the fields must be sufficiently wet if transplanting is to be successful. If water is available, transplanting should be conducted while seedlings are young. Transplanting with 25-day-old seedlings is likely to produce the highest yields.

Fertilizer application

The rate and timing of fertilizer application depend on many factors, including socioeconomics and risks. Farmers are usually recommended to apply nitrogen in three splits: transplanting, active tillering and panicle initiation. The total amount would depend on whether the fields are irrigated (90 kg ha^{-1}) or rainfed (60 kg ha^{-1}). Phosphorus is required in many locations, and 20–30 P_2O_5 kg ha^{-1} is recommended for sandy to sandy loam soils in the first season of application (Linquist et al. 1998). In subsequent seasons, an application of the amount removed by the previous crop is sufficient (Linquist et al. 2000). Although K is limiting on fewer soils, a moderate amount of K (20 to 30 kg K_2O ha^{-1}) is recommended as part of a sustainable management practice (Linquist et al. 1998).

Rainfed lowland rice—direct seeding

This new technology of direct seeding may be applicable under two conditions: that the costs and availability of labour are such that using the traditional transplanting method is difficult; and that rainfall is low at the beginning of the wet season, so that transplanting at the appropriate time may be difficult and the crop is likely to fail or produce low yields. The two key factors for successful direct seeding are good crop establishment and weed control. The technology package for direct seeding for Laos is detailed in Sipaseuth et al. (2000), and is summarized below.

Suitable sites

Lowland fields with heavy soils, poor drainage or in low-lying areas are generally not suitable for direct seeding as the fields are likely to be too wet for successful crop establishment. Fields with weeds should not be used, as the problem is likely to become worse under direct seeding.

Thorough land preparation

Because establishment is more difficult and weeds are a major problem in direct seeding, fields need to be prepared more thoroughly to establish an adequate seedbed. Early land preparation at the beginning of the wet season is recommended. Land levelling within a lowland field may be necessary for good establishment of the crop.

High-yielding varieties

Varieties from the appropriate maturity group and which are high yielding under transplanting are also usually suitable for direct seeding. With earlier seeding, improved, photoperiod-insensitive varieties are likely to be suitable. However, tall traditional varieties are often not suitable because of their tendency to lodge.

Appropriate sowing date

Sowing date depends largely on water availability. The general recommendation is to sow when the soil is moist but the field is not flooded. Seed may be soaked for a day before sowing to encourage rapid germination and establishment. If soil conditions are favourable, late May to early June is optimal for early sowing under most conditions. As for the transplanted crop, sowing date also depends on the variety to be used.

Planting pattern

If water conditions are favourable and weed problems are not expected, broadcasting may be adopted. Otherwise, planting in 25-cm-wide rows is recommended, and seed may be placed in shallow furrows. Row planting facilitates weeding.

Conclusions

The results presented in this paper provide some basic understanding of lowland rice management for Laos. The rainfed lowland ecosystem is likely to remain the most important rice production system in Laos, and efforts should be continued to develop sound technology packages appropriate for this ecosystem. The NAFRI–ACIAR–IRRI group is conducting new research to understand drought development patterns and water movement in rainfed lowland ecosystems. This may lead to an understanding of the risks involved in planting upland crops after harvesting rice.

NAFRI scientists, in association with the ACIAR project, will also work on dry-season irrigated rice. This system has expanded rapidly in different provinces of Laos, and variety requirements and optimal planting times must be found for each province. These need to be considered in relation to wet-season rice planting and harvesting so that the combined yield from wet and dry seasons is maximized. A key element of the work is to identify the effect of low temperature at sowing, particularly for northern Laos. Intergrated direct-seeding technology packages that are being developed for the rainfed lowlands in the wet season may need to be modified for the dry season. In fact, direct seeding may be adopted more readily for irrigated conditions because of the ease of controlling water in the dry season.

Acknowledgments

The Australian Centre for International Agricultural Research (ACIAR) and the Swiss Development Cooperation (SDC) finance, through the Lao–IRRI Project, much of the agronomic research currently being undertaken within the Lao National Rice Research Program.

References

Fukai, S. 2000. Cultivar requirement for direct seeding in rainfed lowland rice. In: Proceedings of Direct Seeding Technology for Lowland Rice, Bangkok, 2000.

Inthapanya, P., Sipaseuth, Sihathep, V., Chanphengsay, M. and Fukai, S. 1997. Drought problem and genotype requirement for rainfed lowland rice in Laos. In: Fukai, S., Cooper M. and Salisbury, J. ed. Proceedings of an International Workshop held at Ubon Ratchathani, Thailand, 5–8 November 1996. ACIAR Proceedings No. 77, 74–80.

Lao–IRRI (International Rice Research Institute). 2000. Annual Technical Report for 1999. Vientiane, Laos.

Lao–IRRI (International Rice Research Institute). 2000. Rice Variety Recommendation for the Wet-Season Lowland Environment of the Lao PDR. Vientaine, Laos, 23 p.

Linquist, B.A., Sengxua, P. and Whitbread, A. 2000. Residual phosphate availability in lowland rice ecosystems of Laos. In: International Rice Research Conference, Los Baños, Philippines, March 31–April 3, 2000.

Linquist, B.A., Sengxua, P., Whitbread, A., Schiller, J. and Lathvilayvong, P. 1998. Evaluating nutrient deficiencies and management strategies for lowland rice in Lao PDR. In: Ladha, J.K., Wade, L.J., Dobermann, A., Reichardt, W., Kirk, G.J.D. and Piggin, C. ed. 'Rainfed Lowland Rice: Advances in Nutrient Management Research'. Proceedings of the International Workshop on Nutrient Research in Rainfed Lowlands, 12–15 Oct. 1998, Ubon Ratchatathani, Thailand, IRRI, 59-73.

Naklang, K.1997. Direct seeding for rainfed lowland rice in Thailand. In: Fukai, S., Cooper, M. and Salisbury, J. ed. Breeding Strategies for Rainfed Lowland Rice in Drought-Prone Environments. ACIAR Proceedings No. 77, 126–136.

Nguu, N.V. and De Datta, S.K. 1979. Increasing efficiency of fertilizer nitrogen in wetland rice by manipulation of plant density and plant geometry. Field Crops Research, 2, 19–34.

Sipaseuth, Sihavong, P., Sihathep, V., Inthapanya, P., Chanphengsay, M. and Fukai, S. 2000. In: 'Development of Direct Seeding Technology Packages for Rainfed Lowland Rice in Laos'. Proceedings of Direct Seeding Technology for Lowland Rice, Bangkok, 2000.

Rice Production Systems in Cambodia

Ouk Makara[a,*], Men Sarom[a] and H.J. Nesbitt[b]

Abstract

After suffering decades of grain deficits, Cambodia has had, for the last 5 years, a national surplus of rice, resulting from expanding area under cultivation and improved yields. Most Cambodian rice is grown in subsistence production systems found in rainfed lowlands (84%) and uplands (2%), and under dry season (11%) or deepwater (3%) conditions. Traditional rice varieties, which are photoperiod sensitive, are commonly grown in the rainfed lowlands, with early, intermediate and late-maturing varieties grown in upper, medium and lower fields, respectively. Deepwater and floating rice is grown to a decreasing extent along the edges of the Great Lake (Tonle Sap) and along rivers. Upland rice-growing areas are scattered around the country. Modern rice varieties, especially IR66, are common in areas with supplementary irrigation or grown as recession rice. They are also replacing certain late-maturing selections. Most Cambodian rice is grown on ancient alluvial soils that are poorly drained, often impoverished and leached. Multicropping in rainfed areas is therefore infrequent, although double cropping is increasing on the more fertile soils and in areas with supplementary or full irrigation. Small areas of cash crops are grown almost exclusively in uplands and under irrigation on young alluvial soils. For the last decade, farmers have been using results of recent research to increase productivity. Potential for further increasing the productivity of Cambodian rice ecosystems is strongly linked to improving availability of on-farm water, and to farmers using earlier maturing varieties and following soil-specific fertilizer recommendations.

Cambodia lies between longitudes 102° and 108° east, and latitudes 10° and 15° north. The country is rimmed on three sides by mountains, which surround a large central plain supporting the Tonle Sap, the largest freshwater lake in South-East Asia, and accompanying river complex. The central plain is extremely flat, with an elevation difference of only 5 to 10 m between south-eastern Cambodia and the upper reaches of the Tonle Sap in the north-west, a distance of more than 300 km. The plain resulted from long-term deposition from the mountains and from sediments carried into the plain by the Mekong River. The river crosses the country from north to south-east by passing through Phnom Penh. At Phnom Penh, the Mekong River meets the Bassac River, which flows south, and the Tonle Sap River, which flows north-west or south-east, depending on the season. Between May and October, melting snow in China and rainfall in the upper reaches of the Mekong River cause water levels to rise. During this period, water flows north-west from the Mekong to the huge reservoir of the Tonle Sap through the Tonle Sap River. This reservoir can expand tenfold in area to about 25 000 km^2. In late October, when the water level in the Mekong subsides, the water flows back from the reservoir into the Mekong and Bassac Rivers. The Mekong River rises and falls about 9 m every year.

Cambodia is close to the centre of origin of rice, and farmers in the region have been growing rainfed rice for at least 2000 years, and possibly longer in the case of upland rice. Natural selection has contributed significantly to the evolution of various rice varietal types for different environments. Irrigated

---

[a] Cambodian Agricultural Research and Development Institute (CARDI), Phnom Penh, Cambodia
[b] Cambodia–IRRI–Australia Project (CIAP), Phnom Penh, Cambodia
*Corresponding author: E-mail: pbreed@bigpond.com.kh

KEYWORDS: Rice production, Deepwater, Dry season, Rainfed lowland, Upland

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

rice production technologies were introduced 1500 years ago (Chandler 1993) and were widespread during the Angkorian period. The centrepiece of the irrigation system was the great reservoir and canals around Angkor Wat, and this system has remained workable for supplementary irrigation until today. At present, fully irrigated areas contribute to a very small proportion of rice-growing areas in Cambodia.

Since 1995, Cambodia has achieved a rice surplus each year, although the national yield averages 1.8 t ha^{-1}. This yield is low, compared with other rice-growing countries, because most rice is produced in rainfed lowland ecosystems, which suffer severe climatic and edaphic constraints. The challenge of increasing rice production remains a major objective of the Cambodian Government and its scientists.

Current Production Status

Before 1970, Cambodia was one of the world's largest rice exporters, shipping as much as 500 000 tons per annum. In 1967, the area under cultivation reached 2.5 million ha and total production was 3.8 million tons after a steady increase from about 1.6 million tons in 1950. Production decreased rapidly after 1974 and remained low during the Pol Pot period (1975–1979). After the war, production and the total area under rice began increasing to their current status. From 1980 through to 1999, total rice area increased from 1.4 million to 2.0 million ha and rice production increased from 1.7 million to 4.0 million t (Table 1).

Harvested areas, grain production and average yields in wet and dry seasons increased from 1993 to 1999 (Figure 1). Harvested areas in the wet season varied from 1.40 million to 1.85 million ha between 1993 and 1999. In 1994, the harvested area was affected by flood and drought, while in 1998 and 1999, increased areas may have resulted from cultivating two crops (rice–rice). Wet-season grain production increased significantly from 2.0 million tons in 1993 to over 3.4 million tons in 1999. Better management, improved availability of fertilizer in the markets and higher yielding varieties released by the Cambodia–IRRI–Australia Project (CIAP) significantly contributed to the increased production. Wet-season grain yield steadily increased from 1.2 t ha^{-1} in 1993 to 1.8 t ha^{-1} in 1999 as farmers shifted from growing late-maturing varieties to growing intermediate-maturing traditional varieties and high-yielding modern varieties.

With the release of the modern variety IR66 and other early maturing varieties developed by the CIAP, the harvested areas in the dry season increased from about 0.15 million ha in 1993 to 0.24 million ha in 1999. During this period, grain yield steadily increased from 2.67 t ha^{-1} to 3.1 t ha^{-1} in 1993 and 1999, respectively. Similarly, grain production increased about twofold. The national grain yield (wet- + dry-season crops) increased from 1.32 t ha^{-1} in 1993 to 1.94 t ha^{-1} in 1999.

Climate

Situated in the tropics, Cambodia experiences a monsoonal climate with distinct wet and dry seasons. The wet season extends from May to October, while the dry season runs from November to April. The long-term distribution map presented in Figure 2 indicates good rainfall during May to October. However, rainfall is extremely erratic and 'mini' droughts may be experienced during any of these months. Because of these 'mini' droughts, farmers preferentially cultivate traditional photoperiod-sensitive varieties. Most rice-growing areas receive between 1250 and 1750 mm rainfall annually.

Minimum and maximum temperatures vary from 21°C to 37°C and the relative humidity fluctuates between 60% and 80% throughout the year. The least humid days are experienced during the lead-up to the break of the wet season. Evaporation is also greatest during this period, with water evaporating

Table 1. Area planted to rice, grain production, yield and population, Cambodia, 1900–1999.

Year	Area planted (000 ha)	Rice production (000 t)	Grain yield (t ha^{-1})	Human population (millions)	Export rice?
1900[a]	400	560	1.40	2.0	Yes
1950[a]	1657	1576	0.95	4.3	Yes
1960[a]	2150	2335	1.09	5.5	Yes
1970[a]	2399	3184	1.33	7.0	Yes
1980[a]	1441	1715	1.19	6.3	No
1990[a]	1890	2500	1.32	8.7	No
1999[b]	2085	4073	1.95	12.0	Yes

[a] Source: FAO electronic database (2000).
[b] Source: Agricultural Statistics (1999–2000).

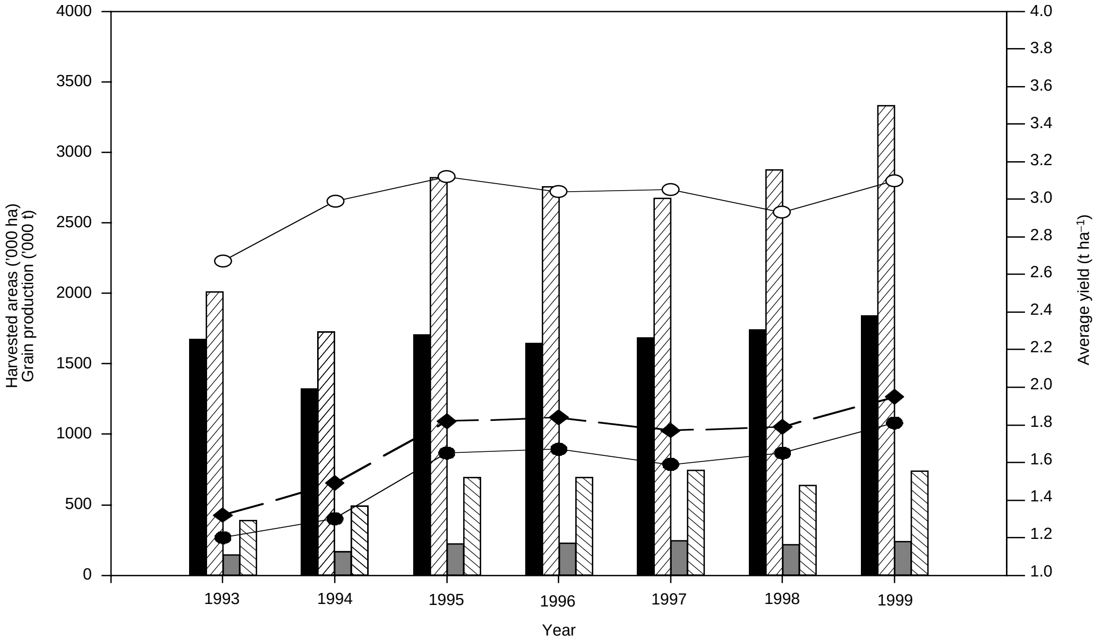


Figure 1. Wet- and dry-season rice production, Cambodia, 1993–1999. ■ = harvested areas in wet season; ▨ = production in wet season; ▬ = harvested areas in dry season; ▧ = production in dry season; —●— = average yield in wet season; —○— = average yield in dry season; —◆— = national yield.
(After MAFF 2000 Rice statistics 1993–1999.)

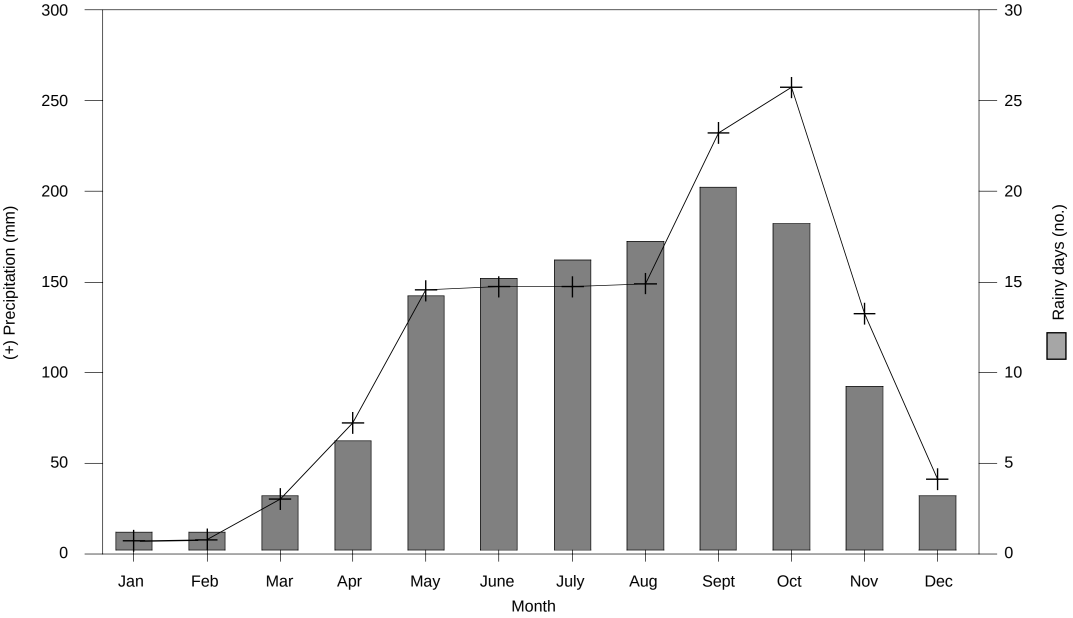


Figure 2. Monthly rainfall and number of rainy days at Phnom Penh, Cambodia (mean over 56 years).

from an open surface at a rate of more than 250 mm per month, which is greater than the average precipitation for each month. Annual evaporation expected from a free-standing surface is almost double that of the annual rainfall in Phnom Penh. Cambodia is not located in the typhoon belt and strong winds are generally not a problem.

Although Cambodia is situated between latitudes 10° and 15° north of the equator, it still experiences changing day length. The longest day of the year (June 21) lasts about 13 h 12 min, diminishing to 12 h 30 min in August, and to 11 h 30 min in December. Fluctuations in day length dramatically affects flowering in many crops, including rice.

Sunshine hours are highest during December through February when most days are sunny. The cloud cover increases as the wet season approaches, with the number of sunshine hours decreasing. Potential rice yields are therefore much higher during the dry season.

Rice Soils

The productivity of rice soils in Cambodia varies greatly, with unfertilized rice yielding from 600 to 2600 kg ha^{-1} (White et al. 1997). Most soils are generally of low fertility as a result of continuous cultivation without adequate replenishment of lost nutrients. The soils are not sufficient in nitrogen, phosphorus and often potassium. Iron toxicity is observed in some soils. In general, soil fertility increases from the higher fields to the lower fields. However, most soils are low in organic matter and cation exchange capacity. The Prateah Lang soil type, for example, described by White et al. (1997), covers 25%–30% of the rice-growing area and is considered as a difficult soil to manage. Other soil types require high rates of P to increase yield to sufficient levels.

To fertilize the Prateah Lang soil, the most commonly cultivated in the rainfed ecosystem, rates recommended per hectare are 40–60 kg N, 23–29 kg P_2O_5, 20–30 kg K_2O and 0–10 kg S (White et al. 1997). To replace nutrients lost in the previous crop, Cambodian farmers traditionally apply organic and inorganic fertilizer to the fields, for example, about 82% of rainfed lowland farmers apply fertilizer (Jahn et al. 1996; Rickman et al. 1995).

Application of organic fertilizer (manure) is limited and farmers use it mainly for seedbeds. About one third of farmers apply manure to seedbeds at about 1.6 t ha^{-1}. Lando and Solieng (1994a) reported the application rates vary from 200–300 kg to 25 t of farmyard manure per hectare of nursery. The actual amount depends on the availability of manure. About 18% of farmers apply manure to the main fields at an average of 1.9 t ha^{-1}, and about 5% apply manure at tillering stage.

A large number of farmers apply inorganic fertilizer between the seedling and booting stages (Table 2; Jahn et al. 1996). Sources of inorganic fertilizer were urea, di-ammonium phosphate (DAP) and 16–20–0 of N–P–K.

The amount of applied fertilizer is still low for the rainfed lowland soils. Farmers primarily apply N and P. Most rainfed lowland farmers apply fertilizer only once for late-maturing rice and two or three times for intermediate and early maturing rices. The number of applications depends on the fields' water status, in that farmers do not apply fertilizer when fields are dry or contain too much water.

Table 2. Inorganic fertilizer used in rainfed lowland rice of Cambodia, according to a survey of 1223 farmers in eight provinces. Note that no K_2O was applied.

Rice-growing stage	Fertilizer source[a]	Farmer applying fertilizer (%)	Nutrient rate (kg/ha)	
			N	P_2O_5
Seedling	Urea	17.2	7.7	0.0
	16-20-0	34.0	0.6	15.6
Transplanting	Urea	8.1	17.0	0.0
	DAP	20.4	9.8	25.0
Tillering	Urea	36.0	20.4	0.0
	DAP	33.2	9.0	23.0
	16-20-0	5.2	82.0	10.0
Booting	Urea	23.0	21.6	0.0
	DAP	6.7	7.5	19.0
	16-20-0	1.0	8.3	10.0

[a] DAP = di-ammonium phosphate.
Source: Modified from Janh et al. (1996, Table 9).

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Rice Ecosystems

Rice grows in a range of ecosystems in Cambodia, including rainfed lowlands and uplands, and under conditions of floating and/or deep water and dry seasons (Table 3). By far the highest percentage of the rice-growing area is found in the rainfed lowlands (84% in 1999). Early, intermediate and late-maturing varieties are located in upper, medium and lower fields, respectively, to match the maximum water depth that the crop would experience. The characteristics of these varieties are well described by Javier (1997 cited in Nesbitt 1997). Over the past decade, farmers have steadily shifted away from cultivating late-maturing (flowering after 15 November) rice varieties to growing intermediate-maturing types (120–150 days if photoperiod insensitive, and flowering between 15 October and 15 November if photoperiod sensitive). The cultivation of late-maturing rice decreased from 1.57 million ha to 0.60 million over a 32-year period. A significant increase in areas of early and intermediate-maturing varieties under cultivation played a major role in increasing rice production during this period.

Table 3. Production areas (%) of different rice ecosystems in Cambodia.

Ecosystem	Production area (%)			
	1967[a]	1981[a]	1995[b]	1999[b]
Wet season	**93.8**	**93.4**	**91.7**	**88.9**
Rainfed lowland	77.9	86.7	85.7	84.0
Early	2.9	15.6	17.4	17.2
Medium	12.4	17.0	35.4	38.9
Late	62.6	54.1	32.9	27.9
Deepwater	15.9	6.7	4.1	2.6
Rainfed upland	—	—	1.9	2.2
Dry season	**6.2**	**6.6**	**8.3**	**11.1**
Total ('000 ha)	**2508.2**	**1441.0**	**2038.1**	**2153.9**

[a] Source of data: MAFF (1993).

[b] Source of data: Agricultural Statistics (1995–1996, 1999–2000).

Less than 3% of the Cambodian rice area is currently planted to deepwater and/or floating rice. Small areas of upland rice are found in north-eastern Cambodia, mainly under shifting agriculture. Dry-season production is increasing in both area and yield. Of the three types of dry-season rice, most is recession rice, that is, it is planted when the water level in the rivers recede. The other two rice types are both dry season, but one receives supplementary irrigation and the other full irrigation. While they represent only a small proportion of dry-season rice, itself contributing only 18% of the nation's total production in 1999, they are of increasing importance to Cambodia's food security and economic growth.

Rice Cultivation Practices

Rice-farming practices vary considerably between the rainfed lowlands and uplands, and deepwater and dry-season areas. Farmers in the rainfed lowland ecosystems begin applying farmyard manure to their fields in April and May every year. In the event of a shortage, preference is given to applications on paddies cultivated as seedling nurseries to soften the soil for ploughing and to improve seedling viability.

When there is sufficient rain to prepare the nursery, the soil is ploughed twice and harrowed once or twice to level the plot. The soil is ploughed diagonally across the field to improve drainage. The prepared nursery is immediately broadcast with presoaked (24–36 h) rice seed. Sowing rates vary from 50–70 kg per 0.1 ha of nursery, depending on soil fertility. Nurseries occupy 15%–25% of the total farm area and are preferably located close to a water supply for supplementary watering during the year and are often located close to the farmer's house.

The first mainfield ploughing is usually after the first rains, which soften soils. Because the soils compact easily, the second ploughing, usually followed by harrowing, is practised one day before or on the day of transplanting. On sandy soils, harrowing is not practised and farmers transplant seedlings immediately after the second ploughing. Preference is given to fields with free-standing water for ease of transplanting and improved survival of seedlings. Thus, seedling ages vary greatly from 20 days for the early maturing and photoperiod-insensitive varieties to 100 days for the late-maturing, photoperiod-sensitive varieties.

The process of transplanting varies considerably. Some farmers apply fertilizers basally, whereas others dip roots in a mixture of fertilizer and cow manure. Transplanting sticks may be necessary on sandy soils, and transplanting densities can range from 80 000 to 800 000 hills per hectare. The recommended transplanting rate for modern varieties is at 250 000 hills per hectare.

Broadcasting of rainfed rice is commonly practised in north-western Cambodia. Jahn et al. (1996) reported 11% and 32% of farmers broadcast rice in the wet and dry seasons, respectively. This is generally achieved by ploughing the soil once or twice, broadcasting dried seed and possibly harrowing once after sowing. Labour involved with establishing and managing a nursery plus transplanting is thereby eliminated. Weeds are a problem with this broadcasting technique and often farmers will plough the crop once 6 to 8 weeks after emergence to kill the weeds. The rice is tall enough to partially survive, and new shoots and roots develop from the first node on the culm. The plant can then continue to growing to maturity.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Spot weeding of rainfed fields is a common practice and farmers regularly drain or re-bund their fields during the wet season to improve weed control. Harvesting is by hand, with a sickle, and bundles are regularly stacked on bunds to dry before threshing. Once dried, the bundles are generally carted or carried to the farmhouse and threshed at leisure over the dry season. Grain is stored permanently in above-ground silos or in temporary jute bags before selling. The rice straw is heaped in a pile (usually around a post) to be fed to animals during the wet season when there is little pasture to graze.

After harvest, the stubble is grazed by cattle and other animals. They may be tethered or free-range fed under the eye of a herd boy. Some farmers burn off the stubble during the first quarter of the year to assist land preparation and kill off residing pests and diseases. This practice decreases the quantity of roughage for grazing animals. At the onset of the first rains, germinating weeds increase the availability of green feed in rainfed and deepwater rice fields. Legume pastures are developed on the bunds and on other ground not flooded in the wet season. There is potential for improving this pasture as a source of animal feed with the application of P and introduction of improved species (White, F.P., pers. comm. 1999). As transplanting progresses and the land available for grazing diminishes, cattle are often taken to upland sites to feed or are fed by hand near the house. Freshly cut material is supplemented with straw collected after threshing.

Early maturing varieties are grown in shallow water (0–20 cm), intermediate-maturing varieties are grown in medium water depth (20–40 cm) and late-maturing varieties in water as deep as 50 cm. The cultivation schedules of these maturity groups are illustrated in Figure 3. In areas with shallow and medium water depths, farmers cultivate rice more intensively. In shallow-water fields, some farmers cultivate dry-season rice with supplementary ground water after the wet-season crop is harvested (Figure 3a). In some medium-depth fields, two crops can be cultivated in the wet season, using ground water for supplementary irrigation. The first, early maturing, rice crop is planted in mid-March with supplementary irrigation, while the second, intermediate-maturing, rice crop is transplanted usually 2 weeks after harvesting the first crop (Figure 3c). Some farmers cultivate crops such as beans, cucumbers and watermelons before or after the rice crop.

Floods, droughts and pests are major constraints to production in rainfed lowlands. Heavy local rains cause flash floods, whereas long-term floods are caused by increased water levels in the Mekong River. Droughts can damage rice at any time during the growing period. In the 1999 wet season, for example, floods and drought damaged 50 400 and 9100 ha of rice, respectively (DAALI, 2000). Uneven fields, which may lead to poor water management result in part of the field flooded while others droughted. Common pests are rats and the brown plant hopper (BPH).

Upland rice is cultivated in two ways: shifting cultivation, and monocropping for several seasons. In shifting cultivation, existing forest cover in the area slashed and burned, then upland rice seed is usually dibbled into the ground with a sharp stick (Figure 3e). Sowing follows early season rains and harvesting is between August and December. Fertilizer is not applied. Crops may be pure stands or intercropped with maize, cassava, cucumber, watermelon, eggplant and beans. Weeds are more problematic for upland rice, with weeding being needed 2 or 3 times for a monocrop. Upland rice fields, cultivated on a regular basis, are located on small hills with gentle slopes. Where rice is rotated with other crops (e.g. beans, sugar cane and peanut), the sequence of crop rotations depends on demand.

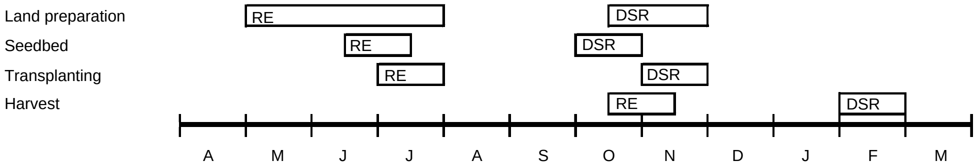
Land preparation for deepwater rice begins immediately before the wet season breaks when farmers burn the previous year’s stubble. Two ploughings and one harrowing follow immediately. Dry seed is then broadcast at a rate of 120 to 150 kg ha^{-1} (Figure 3f). However, if the rains are unusually late, some farmers may broadcast the rice seed and plough it in, or broadcast it over single-ploughed soil. Fields are not bunded and weed incidence is prolific. Animals regularly graze the fields before flooding. Some farmers weed their fields but few apply herbicides or other pesticides.

Once the floodwaters recede, the crop is harvested by cutting stems immediately below the panicle. The bundles are returned to the village for threshing. Fertilizers are rarely applied to deepwater rice fields.

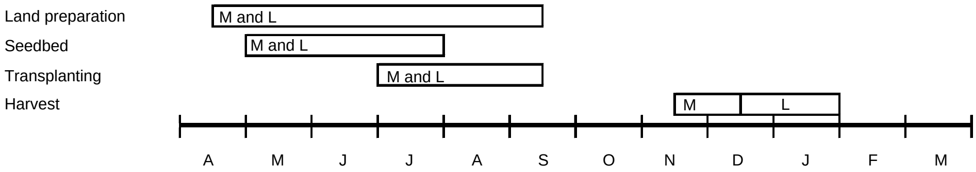
Most dry-season rice is cultivated in flood recession areas (Figure 3g). As such, it receives regular nutrient supplementation from silting and fertilizer is applied in the form of urea as a top dressing only. The first available fields are used as nurseries. Transplanting takes place when the receding water level in the fields is at an appropriate depth for transplanting. Water is pumped up from rivers and recession ponds. Modern, photoperiod-insensitive varieties are grown and recommended practices for these are followed. Transplanting is spread over December to March. Transplanting is commonly practised and some farmers in Phnom Krom (Siem Reap) throw seedlings instead of transplanting. Broadcasting is increasingly practised, with a seed rate as high as 200 kg ha^{-1}. Vietnamese farmers had recently introduced this high seed rate technology. In some areas,

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

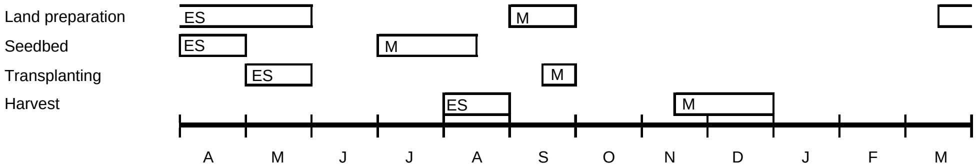
a. Rainfed lowland, early maturing rice (RE) and dry-season rice with supplementary irrigation (DSR)



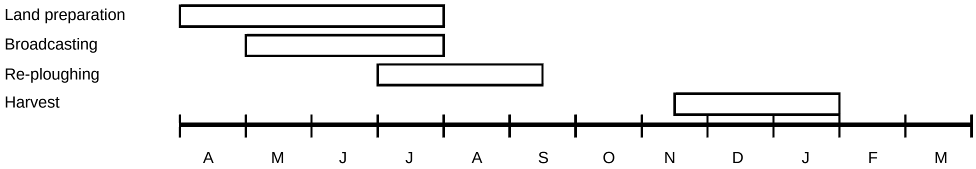
b. Rainfed lowland rice: intermediate (M) and late (L) maturing



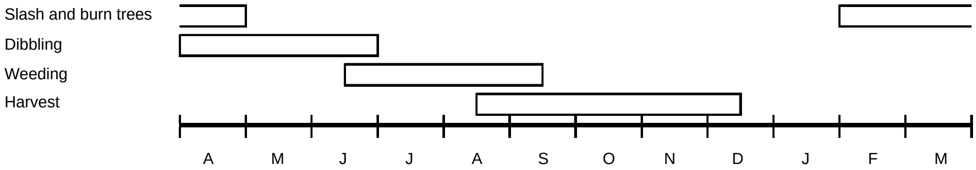
c. Rainfed lowland rice with supplementary irrigation in medium water depths.
ES = early maturing rice with supplementary irrigation; M = intermediate-maturing rice



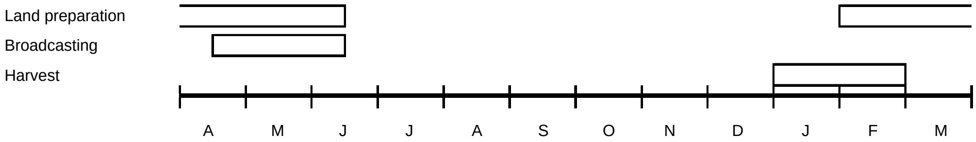
d. Rainfed lowland rice: broadcasting



e. Rainfed upland rice



f. Rainfed deepwater rice



g. Dry-season recession rice

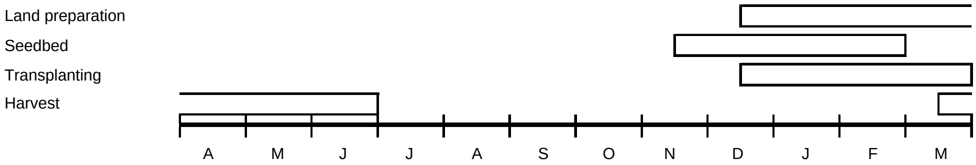


Figure 3. Common schedules for rice cultivation in different agroecosystems in Cambodia.

supplementary irrigation is pumped up to crops at the beginning of the wet season.

The cultivation schedule for dry-season rice with supplementary irrigation in rainfed shallow water is presented in Figure 3a. Under full irrigation, farmers cultivate 2 or 3 crops per annum, depending on water sources and market price. They can be in a sequence of irrigation–rainfed, rainfed–irrigation, and irrigation–rainfed–irrigation. Intermediate-maturing and photoperiod-sensitive varieties are commonly used under rainfed conditions.

Rice–Animal–Fish Interactions

Most farm households possess a small number of domestic animals. These include chickens, ducks, pigs and cattle. The first two are usually raised for domestic egg and meat consumption, whereas pigs and cattle provide a valuable source of cash when sold. Chickens, ducks and pigs are reared on household scraps and rice bran and scavenge around the village.

Children are often responsible for tending the cattle. During the dry season, they drive them to rice paddies, uncropped areas and grassed roadsides. After transplanting, cut-and-carry techniques are more often employed to avoid the cattle breaking from their tethers into crops. During this period, flooding has reduced the grazing area and rice straw is hand fed to the animals as roughage.

At night, the animals are sheltered under the houses or in nearby sheds. It is from here that the manure is collected for application on vegetable patches or on rice nurseries and main paddies.

Cattle and water buffaloes provide draught for most farm households. Lando and Solieng (1994a, b, c) observed that, although farmers owned an average of 3 animals, the distribution was uneven and in one survey in the rainfed lowlands, 21% of farmers did not own draught animals (Rickman et al. 1995). These farmers hired animals from neighbours, resulting in delays in farming activities. Lower crop yields consequently result from poorly timed practices.

Although fish farming in small ponds has increased in popularity over recent years, only a few farmers have experimented with raising fish in the rice fields. The procedure is to dig trenches around or through the paddies. As the water level drops, the fish are able to retreat into the trenches in the paddy. Control of predatory fish is difficult and rainfed paddies often dry out completely during the ‘mini’ droughts of the wet season. However, properly prepared fields can result in farm surpluses of fish, which can provide a valuable source of income.

Other Farming Enterprises

Diversification of farming enterprises is restricted because farmers live away from their fields in villages situated on higher ground. However, recently, isolated cases of farmers are constructing ‘ditch-and-dike farming systems’, fish ponds and developing watering ponds for crop (rice, vegetable and fruit trees) irrigation. This intensification needs to increase as the land is placed under further population pressure.

Household Labour

An average Cambodian farm is about 1.6 ha in area, although size varies widely across ecosystems (CARDI, 1998 unpublished data). The common household comprises 5 or 6 persons. Table 4 provides

Table 4. Labour requirements for rice production on a one-hectare farm in Cambodia. The example of the Phum Run Family, Takeo Province.

Activity	Gender	Days (no.)	Persons (no.)	Total labour (person-days)
Seedbed				
Harrowing and ploughing	Male	1.5	1	1.5
Sowing	Female	1	1	1
Rice field				
Harrowing and ploughing	Male	10	1	10
Pulling seedlings	Both	1	15	15
Transplanting	Both	1	37	37
Crop maintenance	Male	1	10	10
Harvesting	Both	5	6	30
Threshing	Both	3	2	6
Storage	Both	1	2	2
Total labour requirements				112.5

Source: CARDI (Cambodian Agricultural Research and Development Institute). 1998. Unpublished survey.

an example of rice labour needed to complete all tasks, on 1 ha of land, for the Phum Run Family in Samrong District, Takeo Province. As with most farmers, this family uses more labour for pulling, transplanting and harvesting than for seedbed and land preparation. Transplanting and harvesting required 37 and 30 person-days, respectively. Ploughing and harrowing of the main field required 10 person-days, and pulling seedlings 15 person-days. While most activities involve both males and females, ploughing and harrowing are done by males.

Conclusions

Rice production in Cambodia relies heavily on the rainfed lowland ecosystem. Thus, the amount of rainfall substantially affects rice productivity. Floods and droughts are major constraints to increases in productivity. The impact of these factors can be reduced in two ways: by constructing expensive irrigation and drainage canals throughout this ecosystem, including the levelling of paddy fields; or by developing varieties that tolerate floods and droughts while maintaining a higher yield potential. These developed varieties must also be tolerant of major pests such as the BPH and be of good quality to meet demand. Such improvements, combined with educating farmers on such issues as appropriate planting times and fertilizer application, are the major challenges that the Cambodian rice research program must accept.

References

Agricultural Statistics. 1999–2000. Statistic Office. Department of Planning, Statistics and International Cooperation. Ministry of Agriculture, Forestry and Fisheries. Phnom Penh, Cambodia.

Agricultural Statistics. 1998–1999. Statistic Office. Department of Planning, Statistics and International Cooperation. Ministry of Agriculture, Forestry and Fisheries. Phnom Penh, Cambodia.

Agricultural Statistics. 1997–1998. Statistic Office. Department of Planning, Statistics and International Cooperation. Ministry of Agriculture, Forestry and Fisheries. Phnom Penh, Cambodia.

Agricultural Statistics. 1996–1997. Statistic Office. Department of Planning, Statistics and International Cooperation. Ministry of Agriculture, Forestry and Fisheries. Phnom Penh, Cambodia.

Agricultural Statistics. 1995–1996. Statistic Office. Department of Planning, Statistics and International Cooperation. Ministry of Agriculture, Forestry and Fisheries. Phnom Penh, Cambodia.

Agricultural Statistics. 1994–1995. Statistic Office. Department of Planning, Statistics and International Cooperation. Ministry of Agriculture, Forestry and Fisheries. Phnom Penh, Cambodia.

Agricultural Statistics. 1993–1994. Statistic Office. Department of Planning, Statistics and International Cooperation. Ministry of Agriculture, Forestry and Fisheries. Phnom Penh, Cambodia.

Chandler, D.P. 1993. A History of Cambodia, 2nd ed. Boulder, CO, Westview Press.

FAO (Food and Agriculture Organization of the United Nations). 2000. Electronic database.

Jahn, G.C., Sophea, P., Bunnarith, K. and Chanthy, P. 1996. Farmers' Pest Management and Rice Production Practices in Cambodian Lowland Rice. Baseline survey report, No. 6. Phnom Penh, Cambodia, Cambodia–IRRI–Australia Project (CIAP).

Lando, R.P. and Solieng, M. 1994a. Cambodian Farmers' Decision Making in the Choice of Traditional Rainfed Lowland Rice Varieties. Research Paper Series, 151. International Rice Research Institute (IRRI), 17 p.

Lando, R.P. and Solieng, M. 1994b. Deepwater Rice in Cambodia: A Baseline Survey. Research Paper Series, 153. International Rice Research Institute (IRRI), 29 p.

Lando, R.P. and Solieng, M. 1994c. Rainfed Lowland Rice in Cambodia: A Baseline survey. Research Paper Series, 152. International Rice Research Institute (IRRI), 20 p.

MAFF (Ministry of Agriculture, Forestry and Fisheries), Department of Planning and Statistics. 1993. Bulletin of Agricultural Statistics and Studies No. 2. Phnom Penh, Cambodia.

Nesbitt, H.J. ed. 1997. Rice Production in Cambodia. Manila, Philippines, International Rice Research Institute (IRRI), 112 p.

Rickman, J.R., Pyseth, M., Sothy, O., Theavy, K.S. and Sokha, N. 1995. Farm Mechanization and Crop Production in Cambodia. Baseline survey No. 5. Phnom Penh, Cambodia, Cambodia–IRRI–Australia Project (CIAP).

White, P.F., Oberthur, T. and Sovuthy, P. 1997. Soils and Rice in Rice Production in Cambodia. Manila, Philippines, International Rice Research Institute (IRRI), 21–29.

Crop Intensification of Rice-Based Farming Systems in Cambodia

Sareth Chea[1, 2,*], Rob Cramb[2], Harry Nesbitt[1], Shu Fukai[2], Phaloeun Chan[3] and Peter Cox[1]

Abstract

Before introducing technology packages, agricultural researchers must first thoroughly understand the farming system that the technology will affect. That is, if researchers are to find encouraging innovation by farmers worthwhile they must know those factors affecting the targeted farming system: climate, water sources, flood or drought incidence, crop–animal–forest interactions and socioeconomics (e.g. labour shortages, input costs, availability of markets and knowledge and skills of farm household members). This study of Cambodian farming conditions focuses on the rainfed lowland agroecosystem and its different cropping models to demonstrate an approach intended as a precursor to increasing the productivity of rainfed ecosystems in Cambodia. A recently begun case study on double cropping rice at a specific site will explore those factors that encourage or constrain farmers from double cropping rice or crop intensification. Further studies, supported by the ACIAR, will determine whether double cropping rice is possible in other areas and if it is economically and socially justified.

AGRICULTURE involves 80% of the Cambodian population, providing the major source of income for rural dwellers. The agricultural sector is therefore a major contributor to the national economy. Until the late 1960s, Cambodia regularly produced a rice surplus for export. The quantity of milled rice shipped abroad at that time was as high as 250 000 to 400 000 tonnes p.a. (Helmers 1997).

Rice exports during the 1970s and 1980s were non-existent because rice production was below local requirements almost every year. According to statistics from the Cambodian Ministry of Agriculture, Forestry and Fisheries (MAFF), total rice production began decreasing in the early 1970s until the late 1980s, when they began increasing again. Meanwhile, the country's population had dropped from more than 7 million in 1968 to just above 6 million after the Khmer Rouge regime collapsed in 1979. Rice consumers (nearly everybody in Cambodia) increased to 11.8 million in 1998 with a growth rate of 2.4% p.a. (MPA 1998).

Poor rice yield is a major constraint to agricultural production, resulting in food shortages. Javier (1997) points out that erratic rainfall, pests, poor soils, traditional varieties, small farm size, and inadequate labour, farm power and capital all cause rice productivity in Cambodia to be the lowest in Asia. Low agricultural production is a result of both natural factors and socioeconomic constraints (such as labour shortage, input costs, lack of markets and inappropriate knowledge and skills of farm household members), which slow down the adoption of new technologies.

The cultivation of one rice crop in the wet season is the commonest practice, although non-rice crops may yield good incomes. Wet-season rice currently occupies 88% of the rice-growing area in Cambodia, 83% of which is found in rainfed lowlands (MAFF 2000). Moreover, low-yielding traditional varieties are used. Javier (1997) states that, although many traditional varieties have low yields, farmers remain satisfied with them because of their good grain

---

[1] Cambodia-IRRI-Australia Project, Phnom Penh, Cambodia
[2] The University of Queensland, Brisbane, Qld., Australia
[3] Cambodian Agricultural Research and Development Institute, Phnom Penh, Cambodia
*Corresponding author: E-mail: csareth@yahoo.com.au

KEYWORDS: Agricultural development, Research planning, Rice double cropping

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

qualities or adaptability to specific abiotic stresses. Consequently, rice yields are often less than 1 t ha^{-1}. Yields are particularly low on very acid soils without fertilizer (CIAP 1998).

Limited potential exists for increasing the area under rice in Cambodian rainfed lowlands. Farmers badly need new ways therefore to produce enough food for year-round consumption and for sale. To meet domestic requirements, the first priority for national development, farmers could select a variety of short-cycle crops that can be cultivated more than once a year in the same field. Farmers could also improve soil fertility by growing legumes, thus increasing total production. Cultivation of green manure crops may also increase rice yields. Earlier experiments by the Cambodia–IRRI–Australia Project (CIAP), working with MAFF, have shown that growing green manure before rice cultivation can increase rice yields by 40% (Nesbitt and Chan 1997).

In this paper, the term ‘intensification’ refers to the practice of growing more than one crop a year. Crops can be grown in different seasons in the same year or two crops may be grown in one season. Because rice is the staple food for all Cambodians, it becomes the base crop for intensification. Other crop options include vegetables, cereals, beans and possibly fruits. While final selection of options depends on farmer preferences, farm type and climate, short-cycle annual crops are critical for crop intensification systems. Modern rice varieties have short cycles and are photoperiod insensitive. They can be cultivated more often than traditional varieties and so help ensure food supply (Lipton and Longhurst 1989). In Cambodia, IR66 (duration within 110 days) and other photoperiod-insensitive varieties enable farmers to grow two to three rice crops per year on the same land.

This paper first reviews the rainfed lowland agroecosystem in Cambodia, then provides an overview of the advantages, constraints and economics of double-cropping rice.

Double Cropping in Rainfed Lowland Agroecosystem

The rainfed lowlands include most of Cambodia’s farmland. It stretches from the country’s north-west to south-east, excluding alluvial flood zones. This flat land is narrow in central Cambodia, becoming wider towards the north (Ministry of Education 1985). Nesbitt (1997) states that the annual rainfall has been recorded as ranging between 1250 and 1759 mm in most rice-growing areas. Standing floodwater from rainfall can be between 0 and more than 25 cm deep over long periods but, in short periods, may be as deep as 50 cm or more (Javier 1997). Rainfed lowland rice paddies are categorized into three levels: upper, middle and lower fields, each with typical depths of standing water: 20–30 cm, 20–40 cm and deeper than 50 cm, respectively (Lando and Mak 1991; Nesbitt 1997).

Rainfall in lowlands is lower than that in coastal and upland zones, and is the only source of water for crop production in most lowland areas. Nevertheless, the rainfed lowlands are still considered to form the country’s rice bowl. Javier (1997) states that rainfed lowland conditions are found in all provinces, but mainly in the central plain provinces around Tonle Sap (‘the Great Lake’), Bassac River and Mekong River, adjacent to outer margins of alluvial flood zones. Because water availability is limited, most rice is produced in the wet season. A survey, conducted in 1994–1995 by MAFF’s Department of Agronomy (DOA, 1995, cited by Javier 1997), showed that the area for wet-season rice is 10 times larger than for dry-season rice, that is, 1 747 000 ha versus 169 000 ha.

Of the wet-season production areas, the middle-level fields, usually planted with intermediate maturing rice varieties, take the largest share, followed by lower level fields (with late-maturing varieties) and upper level fields (with early maturing varieties). Regardless of the varietal maturity groups, single cropping (i.e. one rice crop per year) is common practice in most parts of the rainfed lowlands because of erratic rainfall and limited water (CIAP 1998). Supplementary sources of water and irrigation systems are scarce. Cambodian farmers therefore leave their land fallow for the entire dry season, although grazing may be possible for a couple of months after harvest while rice stubble is available.

However, double cropping has begun in certain areas of the rainfed lowlands where supplementary water is available (CIAP 1998). Double cropping may be (Figure 1):

1. Rice–rice (one rice crop in the wet season and another in the dry, or one in the early wet and another also in the main wet),
2. Rice before other crops and
3. Other crops before rice.

In addition, parts of the rainfed lowland fields of progressive farmers are being remodelled for additional cash crops in either the wet or dry season (Nesbitt and Chan 1997). Non-rice crops are cultivated in two different systems in the rainfed lowlands: with and without supplementary irrigation. Vegetables, beans, tuber crops and squash are commonly seen in systems with supplementary irrigation, but vegetables and tuber crops are occasionally seen in non-irrigated systems.

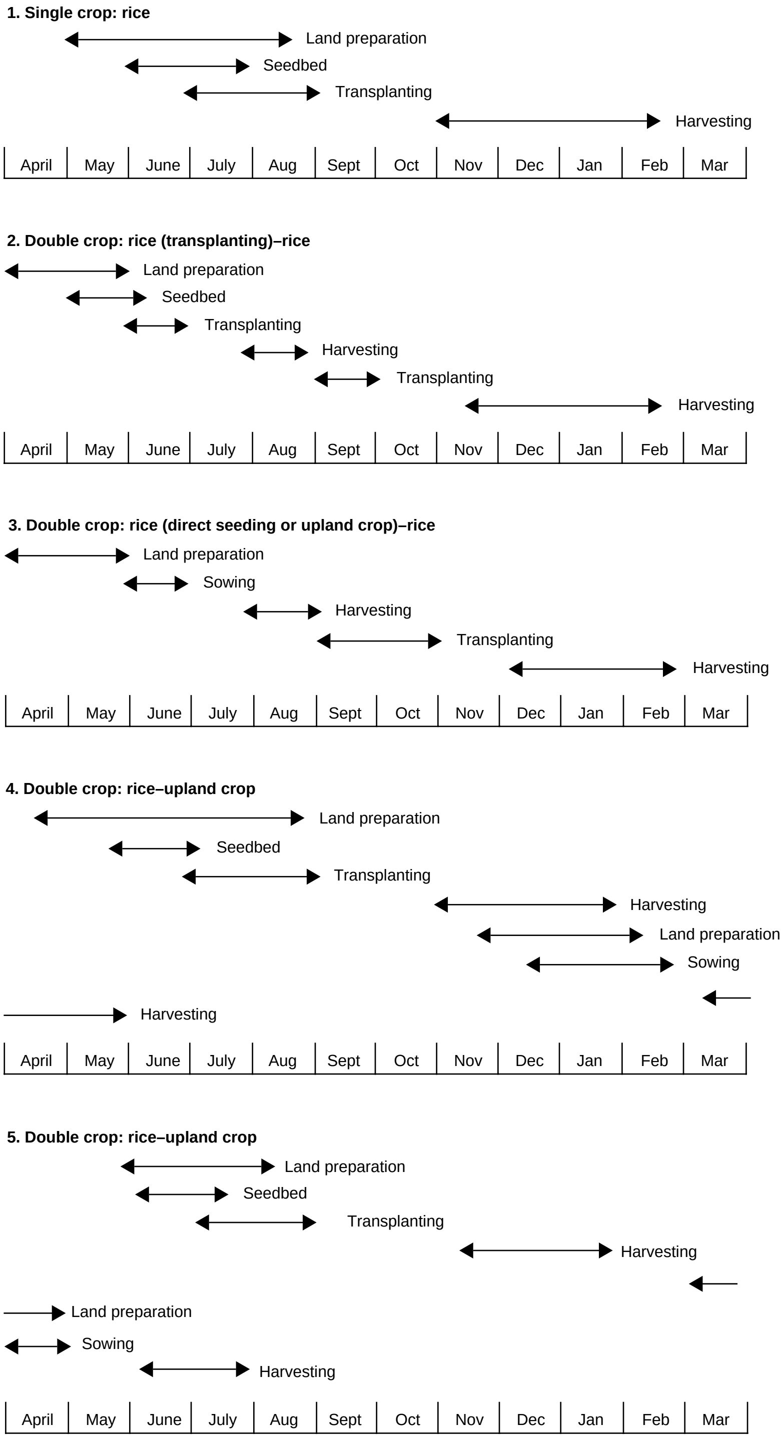


Figure 1. Rice-based cropping systems in the rainfed lowlands of Cambodia.

In 1998, CIAP conducted an experiment on growing mung bean before wet-season rice. The first crop was severely damaged by drought shortly before harvest, following the pattern of pre-wet-season rice crops planted in rainfed lowlands and which often failed to produce good yields without underground water (CIAP 1999). Even though the mung bean crop failed, the crop had contributed nutrients to rice fields, thus indirectly benefiting farmers.

In Prey Kabas District, Takeo Province, rice farms characteristically have infertile soils with low water-holding capacity. Because only one, low-yielding, rice crop could be planted, farmers in this area experienced frequent food shortages (CIAP 1999). Yet, farmers in this District have successfully changed their fields into double-cropping systems by developing supplementary irrigation, using tube wells (CIAP 1998), and improving the poor soil by applying fertilizer—especially green manure and cow manure (CIAP 1998).

Crop intensification reduces food deficits and increases household income (Table 1). Sengkea (1998) demonstrated that farmers who cultivated mung bean before rice increased their farm incomes by 9%, compared with the practice of just growing single rice crop. Non-rice crops planted before wet-season rice included beans, vegetables and other annual cash crops (CIAP 1999).

Rice crops, such as IR varieties, have also been cultivated before the wet-season rice crop, using available underground water as supplementary irrigation. The Deputy District Governor of Prey Kabas District, Meys Sorn, previously grew only one wet-season crop a year, but now with supplementary irrigation from a tube well, he can grow as many as three crops per year (ADB 1997). He estimates that, with supplementary underground water, at least 3000 ha could support more than one crop.

Together with tube-well irrigation, the development of modern rice varieties that are short cycle and photoperiod insensitive will help farmers grow two or three crops in one year. Rice production statistics from the DOA indicate that dry-season rice farmers, who grow IR varieties on their rainfed lowland fields during the early wet season, have expanded both growing area and production of IR varieties from 35 980 ha and 66 561 t in 1987 to 81 040 ha and 194 496 t in 1997 (DOA, 1998, cited by Cambodia-IRRI-Australia Project (CIAP) 1998).

However, IR varieties are not widely used by Cambodian farmers in rainfed lowland rice agro-ecosystems. Until 1995, traditional varieties were still planted on about 94% of the total 1.75 million ha of rainfed lowland paddies (Javier 1997). The modern photoperiod-insensitive short-cycle rice varieties such as IR5, IR8, IR20 and IR22 (but not IR66), which were developed and released at IRRI, were first tested in the 1970s in Cambodia at the Toul Samrong and Bek Chan rice research stations in Battambang Province (Javier 1997). Between 1987 and 1990, IRRI provided Cambodia IR66 seed through CIAP and other agencies, and directly to provincial agricultural staff in 1987 until CIAP started, more than a year later (Cox and Mak in press).

In certain areas, farmers grow IR varieties in the wet season, for example, Kandal Steng and Angsnoul Districts of Kandal Province and Treang and Angkor Borei Districts of Takeo Province (CIAP 1997). Although Cambodian farmers plant any or some of 17 IR varieties, most prefer IR66 (73% share of preference), because of its short cycle (appropriate to field size and water availability in fields), resilience when grown on poor soils with erratic rainfall (CIAP 1997; Cox and Mak (in press)) and, in particular, best adaptation to growing in the dry season (i.e. 60% of

Table 1. Costs and returns on rice and mung bean production in two ecosystems, Cambodia. These illustrative examples of average figures were obtained from a survey (n = 15) conducted in two provinces.

Province	Mung bean production[a]				Rice production[a]			
	Yield kg ha^{-1}	Gross income	Variable costs	Gross margin[b]	Yield kg ha^{-1}	Gross income	Variable costs	Gross margin[b]
		US$ ha^{-1}				US$ ha^{-1}		
Takeo[c]	90	49	18	31	2000	240	83	157
Kandal[d]	422	192	46	146	2300	292	71	221

[a] Exchange rate: US$1 = 3900 riels.
[b] Gross margin = gross income minus variable costs (including actual monetary expenses, non-labour inputs and family labour inputs).
[c] Rainfed lowland ecosystems.
[d] Alluvial flood ecosystems.
Source: Sengkea (1998).

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

dry-season land surveyed was planted to IR66) (Jahn et al. 1998).

Because of its short cycle, photoperiod insensitivity and resilience, IR66 can be planted in the early wet season with or without supplementary water or other sources of irrigation. Mak (in press) states that early wet-season rice farmers access different sources of water: 35% depend entirely on rainfall; 37% on supplementary irrigation; 8% on tube wells; 3% on lakes or tributaries; and 18% on river flooding. Of the eight provinces where CIAP conducted a survey, the percentage of farmers who used supplementary water for early wet-season rice was highest in Takeo Province and least in Prey Veng Province where rainfall remained the main irrigation source (Mak in press).

Results of yield experiments (Cox and Mak, in press; IRRI-Cambodia Project, 1990) between 1990 and 1993 showed that IR66 provided the highest yields in the shortest time: 4.3 t ha^{-1} in only 109 days versus 4.0 t ha^{-1} for IR Kru and IR72 in 113 days and 115 days, respectively, and 3.6 t ha^{-1} for the local check variety (IR42) over a longer period (136–146 days). Moreover, IR66 was the only variety recommended for rainfed lowlands (early wet season) and irrigated areas. Mak (in press) claims that the early wet-season rice has a lower risk of suffering pests than dry-season rice.

In summary, rainfed lowland agroecosystem comprises the largest rice-growing area, being about 86% of total area (Javier 1997). But, it is relatively unproductive farmland because of soil infertility, lack of irrigation, poor rainfall patterns (erratic, unevenly distributed and low quantity) and, in particular, the practice of traditional cultivation methods, involving traditional varieties and single rice-cropping patterns. Over the last couple of years, farmers have begun diversifying from single cropping to double cropping, including rice–rice and rice with other field crops. Modern photoperiod-insensitive and short-cycle rice varieties, in particular IR66, are starting to be grown across the rainfed lowlands. Research on the value of double cropping (rice–rice) at certain sites is critical for the prospect of applying crop intensification in other rainfed lowlands.

The ACIAR has recently begun funding research on intensified rice-based cropping systems in the Cambodian rainfed lowlands. The aims are to (1) determine the benefits and risks associated with various rice-based double-cropping systems, and (2) develop further the most appropriate system for increased crop production in selected areas of the Cambodian rainfed lowlands. The 5-year project commenced in 2000. This research will contribute to the better understanding of the issues surrounding the shift from single to double cropping in Cambodia and the opportunities for extending this practice to other areas. As the first stage of the project, a case study on rice-double cropping was conducted in Prey Kabas District in Takeo Province.

Double Cropping Rice in Rainfed Lowland Agroecosystem in Cambodia: A Case Study

Although double cropping of rice (with one rice crop in the early wet season, followed by another in the main wet season) is not yet widely adopted by farmers living in the rainfed lowlands, it has, as discussed before, recently been increasing wherever supplementary irrigation is available. The practice of growing two crops in the same year is the result of introducing photoperiod-insensitive rice varieties such as IR66, and poor yields in the wet season with its erratic rainfall. To maintain sufficient food supply, farmers are forced to explore alternative cultivation methods (CIAP 1999). They also want to increase household income and establish free markets where rice can be traded, either to satisfy local markets or for export to Vietnam and other countries (CIAP 1999).

Study goals

The goals of this case study are to:

1. Identify the reasons for adopting double cropping of rice.
2. Identify the constraints that prevent farmers from adopting double cropping, including both biophysical and socioeconomic factors.
3. Assess the impact of double cropping of rice on the use of farm resources, including labour (and gender), land and capital.
4. Assess the impact of double cropping of rice on net farm income.

Study area

The study is being conducted in Tungke Village, Snao Commune, Prey Kabas District, Takeo Province. The village, situated in lowlands, is about 60 km south of Phnom Penh, and 10 km from Highway 2. The absence of major rivers means that farming in this province depends entirely on rainfall. Annual rainfall ranges from 1250 mm to 1750 mm and, even though drought is a constraint, rice constitutes the Province’s principal agricultural output.

Tungke encompasses more than 170 families, and is one of five villages of the Snao Commune. Farmers of this village find getting water from canals or ditches to their rice fields difficult because the fields are located too far away from the original source of surface water. As in other villages, almost

99% of Tungke's population depend on farming. Each family has rights to some farming land, which varies from 0.5 ha to 1.5 ha of good land, but also includes 1–2 ha of unfavourable land, which is flooded every year. Just over 50% of families double crop rice.

Methodology

A general discussion was held with the village head to explain the purpose of the study and to ask for information about the number of families and their jobs in the village. With cooperation from the village head, 10 farming families—five families double cropping and another five single cropping—were randomly selected. Several days before the main interview, we visited the selected farming families to obtain their consent, and to make appointments. Appointments were sometimes re-made when the families were busy with their farms when we visited.

We had developed a questionnaire with 60, mostly open-ended, questions about the household, farming practices and decision making. The questionnaire was completed during the 2-hour interview. We also chatted, smoked cigarettes or drank tea, these being highly fruitful interviewing techniques that helped interviewees feel relaxed and ensured they did not get bored. Considerable time was spent on such questions as dates for land preparation, planting, weeding, fertilizer application and harvesting; rates of fertilizer used; and the costs of those inputs. Although the questionnaire was completed during the first interview, we made further one-day visits, at least once a week, for 2 months to obtain missing data, check dubious answers and make recorded information more transparent to the farmers.

In addition to the interviews, we conducted field measurements if either the farmers or the village head (who was responsible for recording land statistics) were doubtful on field size. Using field size, inputs and yields (converted into tonnes per hectare) and market prices, we calculated costs and returns. To facilitate farmer interviews and field monitoring, a village map, showing field layout, was developed with the village head's help.

Preliminary results and discussion

We present results for the first, or early wet season, crop only, because the main crop (i.e. the second or main wet season) has not yet been harvested, making impossible comparisons between the first and second crops, or between yields, variable costs, gross incomes and gross margins of single-cropping farmers versus double-cropping farmers. All farmers used the variety IR66. Yields for the first crop ranged from 3.3 to 3.8 t ha^{-1}, except for one farmer who could not irrigate and received less than 2 t ha^{-1}. Gross incomes from early wet-season rice are high, varying from about US\$170 to more than US\$415 ha^{-1} (Table 2).

Various gross margins (GMs) were calculated. If actual monetary expenses (inorganic fertilizers, insecticides, herbicides, fuels and harvesting contract costs) only are subtracted from gross incomes, the gross margin (GM1) remains high because monetary expenses are small (Table 3). GM2, which is derived from GM1 by subtracting non-labour inputs produced on the farm such as seed, cow manure and threshing costs, is still positive for all families, including the family who obtained less than 2 t ha^{-1}. If family labour costs (land preparation, planting, fertilizer application, weeding and harvesting) are included, the gross margin (GM3) is dramatically down, compared with GM1 and GM2. Although yields among the farmers do not differ much, results show wide variation in GM3, which may be negative when low crop yields coincide with high variable costs, for example, Farmer 5 with <2-t yields has a negative gross margin (Table 2).

Table 2. Costs and returns of early wet-season rice production of five families in Tungke Village, Cambodia, 2000.[a]

Family farm	Transplanting					Broadcasting				
	Yield t ha^{-1}	GI	GM1	GM2	GM3	Yield t ha^{-1}	GI	GM1	GM2	GM3
		US\$ ha^{-1}					US\$ ha^{-1}			
1	3.4	374	325	286	195	—				
2	3.3	297	218	131	22	—				
3	3.7	396	297	152	22	—				
4	3.8	418	395	250	67	3.75	413	342	210	84
5	1.9	209	174	91	–17	1.60	171	146	64	–16

[a] GI = gross income; GM = gross margin; GM1 = GI minus actual monetary expenses; GM2 = GI minus actual monetary expenses and non-labour input; GM3 = GI minus total variable costs (actual monetary expenses, non-labour input and family labour input); exchange rate: US\$1 = 3900 riels.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Table 3 shows that costs for non-labour inputs and family labour are much higher than the monetary expenses. Farmers 4 and 5 have very high costs of non-labour inputs because they applied a very high rate of cow manure (more than 10 t ha^{-1}). The more cow manure farmers applied, the higher their variable costs (if these are costed at market prices), so that the farmer with the <2-t ha^{-1} yield had a negative gross margin. However, farmers can collect this nutrient from their home yards. Labour would be also costly if it were calculated according to the labour hire charge, but farmers either used their families or their informal labour exchange. However, resources provided by the farm household do have economic value and some attempt to estimate their opportunity cost should be made, even if it is less than as indicated by market prices and wage rates.

Several factors encourage farmers to adopt double cropping. Four of the five farmers who practised double cropping had their own tube wells and pump, and their yields were also higher than those of the fifth family who could not access underground water. This suggests that the availability of irrigation water, particularly underground water, not only permits cultivation of the early wet-season crop but also reduces the risk of yield loss. The village farmers had not experienced shortages of underground water, even in dry periods. Farmers without a tube well may still be able to grow early wet-season rice but they encounter poor yields or possibly complete crop loss. The high risk of poor yield or crop loss tends to discourage farmers without tube wells from attempting two crops.

In addition to underground water, labour is also needed for farmers to cultivate two crops a year. While most Cambodian farmers cannot pay for labour for crop production (from land preparation to harvesting), they do have at least one labourer per household available for labour exchange. The use of hired labour would result in the gross margin being very small or possibly negative, particularly when yields are less than 2 t ha^{-1}.

According to farmers, double cropping provides food security for a couple of months before harvesting the main wet-season crop. Previously, they had frequently experienced food shortages during that period. Early wet-season rice was said to be a better income source than other non-rice crops for the same plot of land and for the time spent. Another benefit of early wet-season rice is that it provides a source of seed for the coming year, that is, for the next early wet-season crop. This overcomes a disadvantage of IR66, whose seed quickly loses its germinability if stored in the traditional way.

Although the early wet-season crop has many advantages, nearly 50% of village farmers stick to single cropping in the wet season because they lack investment capacity. The installation of a tube well and pump is too costly for many to afford. A tube well may cost from US$56 to US$85, while a pump costs US$215 to US$350. According to farmers, they can take underground water free of charge from those of their neighbours who possess tube wells. However, farmers still have to invest in pumps to make use of existing tube wells.

Credit is available through a credit scheme operated by the ACLEDA Bank Limited (of the Association of Cambodian Local Economic Development Agencies). The interest rate of 4% per month is considered high and the debt has to be cleared within 10 months. Borrowers have to deposit valuable documents such as land titles as security. If a farmer is one day late in paying off the loan, he will be fined 1% of the total loan and his property may be confiscated. According to many farmers in the village, nobody takes a loan from the credit scheme because no one knows how to manage a loan with such a high interest rate since repaying might be difficult. Farmers can borrow money from other rich villagers, but these are considered loan sharks. Those village farmers who owned tube wells and pumps did not borrow but had purchased outright.

Growing the first crop (early wet-season rice) without supplementary water is a high-risk activity.

Table 3. Inputs and costs (in US$ ha^{-1}) of early wet-season rice production in Tungke Village, Cambodia, 2000.

Family farm	Costs		Non-labour inputs		Family labour inputs		Total variable costs	
	Direct seeding	Trans-planting	Direct seeding	Trans-planting	Direct seeding	Trans-planting	Direct seeding	Trans-planting
1	—	49	—	39	—	91	—	179
2	—	79	—	87	—	109	—	275
3	—	99	—	145	—	130	—	374
4	71	23	132	145	126	182	328	351
5	30	35	82	84	80	108	192	226

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Shortage of labour is also a constraint that prevents farmers from double cropping. Other job opportunities, which generate higher incomes than growing rice, discourage farmers from adopting early wet-season rice. All five single-cropping farmers selected for the study had regular non-farm employment.

Conclusions

Both physical and economic factors affect the shift from growing a single wet-season crop to double cropping. First, supplementary irrigation (particularly with underground water) is needed for consistent high yields. Second, short-cycle photoperiod-insensitive varieties, such as IR66, are needed because the first crop must be harvested by late July or early August to start the second crop on time. Farmers are already experimenting with extra-short-cycle varieties from Vietnam. Third, growing two crops may be difficult for those who encounter family labour shortage because of opportunities for employment in non-agricultural sectors. Fourth, the chance of reduced yields through pests may increase if only few families cultivate early wet-season rice, so the shift to double cropping may best be managed on a community basis. Last, infrastructure and marketing also influence the adoption of double cropping: roads and transportation are needed to ship surplus products to markets where those crops are traded.

The impact of practising double cropping should also be taken into consideration. These include problems of possible excessive use of water, pests and maintenance of soil fertility. Extensive use of underground water as supplementary irrigation may reduce the supply of water from the aquifer. Crop intensification that does not permit farmlands to fallow may cause soil infertility. Pest outbreaks, for example, rats, are likely to get worse because crop intensification creates a continuous supply of food. Double cropping may make excessive demands on scarce labour resources within the household. The increased income from double cropping—for those families who can afford to it—may increase inequity in wealth and access to other resources. However, double cropping rice is feasible in many areas and often worthwhile. Already, together with the adoption of IR66, this farming system is starting to contribute to Cambodia's agricultural development.

Acknowledgments

The authors thank both the Australian Agency for International Development (AusAID) and the Cambodia–IRRI–Australia Project (CIAP) for their financial and other support. The authors also express their gratitude to the farmers who sacrificed their time and contributed their ideas and experience.

References

ADB (Asian Development Bank). 1997. Technical Report, 1996: Pre-feasibility Assessment of the Shallow Groundwater Resources of Cambodia and Proposal for Groundwater Pilot Project. In: Ta No. 2554-Cam: Community Irrigation Rehabilitation Project. Phnom Penh, Cambodia.

CIAP (Cambodia-IRRI-Australia Project). 1997. Annual Research Report 1996. Phnom Penh, Cambodia.

CIAP (Cambodia-IRRI-Australia Project). 1998. Annual Research Report 1997. Phnom Penh, Cambodia.

CIAP (Cambodia-IRRI-Australia Project). 1999. Annual Research Report 1998. Phnom Penh, Cambodia.

Cox, P. and Mak, S. Estimating the Impact of Agricultural Research for Development: The Effect of Boundary Assumptions. (In press).

Helmers, K. 1997. Rice in the Cambodian economy: past and present. In: Nesbitt, H.J. ed. Rice Production in Cambodia. Manila, Philippines, International Rice Research Institute (IRRI), p. 1–14.

IRRI-Cambodia Project 1990. Annual Research Report 1989. Phnom Penh, Cambodia, p. 33-45.

Jahn, G.C., Peng, S., Khiev, B. and Pol, C. 1998. Farmers' Pest Management and Rice Production Practices in Cambodian Lowland Rice. A Baseline Survey Report No. 6. Manila, Philippines, International Rice Research Institute (IRRI).

Javier, E.L. 1997. Rice ecosystems and varieties. In: Nesbitt, H.J. ed. Rice Production in Cambodia. Manila, Philippines, International Rice Research Institute (IRRI), p. 39-81

Lando, R.P. and Mak, S. 1991. Srey Ampal: A baseline survey of dry season rice in Cambodia. Baseline Survey Report, No. 4. Phnom Penh, Cambodia, Cambodia-IRRI-Australia Project (CIAP).

Lipton, M. and Longhurst, R. 1989. Modern varieties and the poor: consumption and nutrition. In: New Seeds and Poor People. London, Unwin Hyman Ltd.

MAFF (Ministry of Agriculture, Forestry and Fisheries). 2000. Government Statistics. Phnom Penh, Cambodia.

Mak, S. Continued innovation in a Cambodian rice-based farming system: farmers testing and recombination of new elements. Agricultural Systems, (In press)

Ministry of Education. 1985. The waterways in Cambodia. In: Geography Manual. Phnom Penh, Cambodia, p. 26–37.

MPA (Ministry of Public Affairs), Department of Census. 1998. National Census. Phnom Penh, Cambodia.

Nesbitt, H.J. 1997. Topography, Climate, and Rice Production. In: Nesbitt, H.J. ed. Rice Production in Cambodia. Manila, Philippines, International Rice Research Institute (IRRI).

Nesbitt, H.J. and Chan, P. 1997. Rice-based farming systems. In: Nesbitt, H.J. ed. Rice Production in Cambodia. Manila, Philippines, International Rice Research Institute (IRRI). p. 31–37.

Sengkea, H. 1998. Evaluation of the Legume-Rice Cropping Systems in Prey Kabas and Saang Districts. Phnom Penh, Cambodia, Royal University of Agriculture.

Direct Seeding of Rice in Cambodia

J.F. Rickman*, Meas Pyseth, Som Bunna and Poa Sinath

Abstract

Direct seeding is a cost-effective way of establishing rice crops, provided in-crop weeds can be controlled. Well-managed direct-seeded crops have similar grain yields to those of transplanted crops. They also mature faster and require less labour to establish. Good land preparation and levelling reduce weed burdens, but crop lodging is a major problem with existing varieties. A screening program is needed to select high-yielding varieties, suitable for direct seeding.

MORE than 30% of the rice-growing area in Cambodia is direct seeded (CIAP 1996). The largest areas are in the northern provinces where more than 80% is normally direct seeded. Direct seeding is also undertaken in the irrigated, deep water and recession areas (CIAP 1997). (Recession areas are those that are available for crop production after the floodwaters have receded.) Depending on the agroecosystem and location, farmers use one of two techniques to direct seed their crops.

Direct Seeding Systems

The two direct seeding systems are:

Dry seeding

In the northern provinces, dry seed is broadcast onto dry soil and partially incorporated during the final pass. In a normal wet season, 80%–90% of rice fields in these provinces are dry seeded (CIAP 1998). The fields are very uneven and, in some districts, no attempt is made to control the water with bunds. Seeds germinate with the onset of the wet season and establishment rates are generally low and uneven. Weeds are a major problem and, when there is standing water in the fields and the crop is 400–500 mm high, many farmers plough the crop to control weeds and improve plant tillering (CIAP 1999). This practice is also popular in many other parts of Asia (Mazid et al. 2000).

Wet seeding with pre-germinated seed

In the southern provinces, where there is better water control and supplementary water is often available, pre-germinated seed is sown into puddled fields, which have been recently drained, or into standing water. Where the seed is broadcast into standing water, the fields are prepared 24–48 h before planting. This allows the soil surface to consolidate, which reduces the chance of the seed sinking below the soil surface and also helps clear the water. When seed is sown into standing water, the fields are normally drained after 48 h. The use of pre-germinated seed is very common in nurseries, recession areas and irrigated areas. In some deep-water areas, large seedlings, up to 15 cm long, are broadcast directly into water-covered puddled fields. Large seedlings are used because the encroaching waters rise rapidly and sufficient labour is either not available or not affordable for transplanting (CIAP 2000).

Materials and Methods

For the last 5 years, the Cambodia–IRRI–Australia Project (CIAP) conducted studies to examine ways of improving crop production, using direct seeding to establish crops (CIAP 1996, 1997, 1998, 1999, 2000). Both on-station and on-farm studies were conducted to examine the relationships between crop establishment techniques and other crop parameters such as plant populations, weed burdens, crop lodging, crop maturity, grain yields and labour requirements. Land preparation methods, including

---

Cambodia–IRRI–Australia Project, Phnom Penh, Cambodia
*Corresponding author: E-mail: J.Rickman@cgiar.org

KEYWORDS: Direct seeding, Land levelling, Weeds

Table 1. A summary of locations, main treatments for rice crop establishment and measurements taken at each trial site, Cambodia.

Year	Province	Major treatments (no. of trials)	Factors measured
1995	Kandal	Wet direct seeding (1) Machine seeding (1)	Plants established
1996	Kandal Kampong Speu	Seeding rates (1) Planting technique (1) Planting technique and fertilizer placement (1)	Plants established Crop yield Plant tillering
1997	Kandal Svey Rieng	Land preparation and planting technique (2) Plant establishment and soil type (laboratory study; 1) Planting technique and fertilizer placement (2)	Plants established Crop yield
1998	Battambang Banteay Meanchey Kandal Kampong Thom	Planting technique and weed management (1) Planting technique and mechanical seeding (1) Planting technique and crop lodging (1)	Plants established Crop lodging Crop yield
1999	Kandal Battambang Banteay Meanchey Prey Veng Kampong Chhanang	Planting technique and weed population (2) Planting technique and land preparation (2) Planting technique (small plot; 1)	Plants established Weed mass Weed type Crop yield

levelling, were also examined in relation to crop establishment techniques.

Seventeen replicated trials (Table 1) were conducted in eight provinces to examine the relationship between crop establishment techniques, crop production and impact on farm management

Quadrat sampling was used to determine the number of plants established and weed biomass in each field. Plant counts were taken at least 20 days after establishment and weed biomass was measured at panicle initiation. Crop yields were determined by manually harvesting the whole treatment area and then machine threshing. Yield comparisons were made on a 14% moisture basis.

Crop lodging was determined by visual assessment of the whole plot. Land levelness was determined by taking the standard deviation of all points measured in a 10 × 10 m grid topographic survey of each field.

Results

Plant populations

The number of direct-seeded plants established (as a proportion of seeds sown) in large field trials, conducted from 1995 to 1997, was 7%–21%, with a mean of 14%. A summary of the range in plant establishment rates for each year's trials is presented in Table 2.

Table 2. The range in plant establishment percentages for each year's trials on direct-seeded rice.

Year	Trial type	Establishment (%)
1995	Large fields	12–16
1996	Large fields	9–15
1997	Large fields	7–21
1998	Laboratory	18–31
1999	Small plot	29–48

In station trials at the Cambodian Agricultural Research and Development Institute (CARDI) in 1999, plant establishment ranged from 29% (for dry seeding into dry soil + follow-up irrigation) to 45% (for pre-germinated seed sown into water) and 48% (for machine planting and follow-up irrigation).

Laboratory studies on five soil types in 1998, using pre-germinated seed, showed plant establishment percentages ranging from 18% on soil with a higher clay content to 31% on soils with higher sand contents. In the same experiment, dry-seeding establishment percentages were 8%–16%. When seed was placed 12 mm under the soil surface, the highest establishment percentage achieved was 9% for the sandy soil type, with a mean of 3% for all soil types.

A survey of five provinces in 1995 found that farmers broadcast 137 kg ha^{-1} of seed when direct seeding and use the equivalent of 103 kg ha^{-1} of seed when transplanting. For transplanted crops, this equated to an establishment rate of 28%.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Weed burdens

Direct-seeded crops had more weeds than transplanted crops. In on-farm weed trials at the Bek Chan in 1999, non-weeded, dry-seeded fields had 1.85 t ha^{-1} of weed biomass at panicle initiation while non-weeded transplanted fields had 1.23 t ha^{-1} of weed biomass. At Phnom Penh Thmey research site, the weed biomass in non-weeded direct-seeded fields was 2.23 t ha^{-1}, whereas non-weeded transplanted fields produced 0.19 t ha^{-1} of weed biomass (Table 3). In the manually weeded fields, the weed biomass for the direct-seeded and transplanted treatments were 0.14 t ha^{-1} and 0.10 t ha^{-1}, respectively.

Table 3. Weed biomass and rice grain yields at Phnom Penh Thmey, Kandal Province, Cambodia, 1999.

Treatment	Weed mass (t ha^{-1})	Mean grain yield (t ha^{-1})[a]
Broadcast + no weeding	2.23	1.85 b
Broadcast + herbicide	2.05	2.14 b
Broadcast + manual weeding	0.14	3.20 a
Transplant + no weeding	0.19	3.73 a
Transplant + herbicide	0.12	3.47 a
Transplant + manual weeding	0.10	3.51 a

[a] Means followed by a common letter are not statistically different at the 5% level.

Studies at CARDI and Phnom Penh Thmey showed a strong negative relationship between weed biomass at panicle initiation and crop yields (Figure 1).

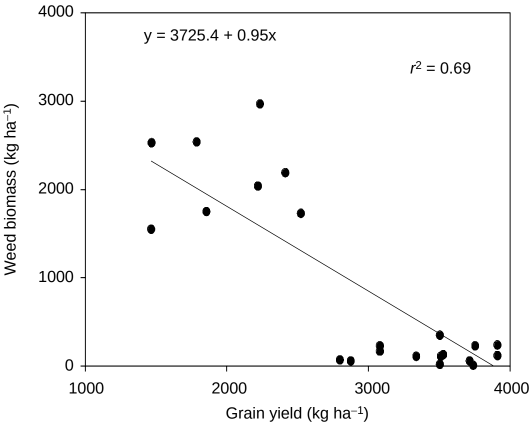


Figure 1. The effect of weed biomass on yields of direct-seeded and transplanted rice crops grown at Phnom Penh Thmey, Kandal Province, Cambodia, 1999.

The type of weeds present depended on the water level in the field. At Bek Chan, which had periods of low water coverage, *Paspalum distichum* L. made up 95% of the weed biomass. At Phnom Penh Thmey, which had good water coverage in the fields, *Echinochloa colona* (L.) contributed 75% of the weed biomass. In both locations, the use of a postemergent herbicide, thiobencarb (Saturn®), at 30 days after plant establishment failed to significantly control *Echinochloa colona*, *Cyperus deformis* L. *Cyperus iria* L.

Crop lodging

Crop lodging was a major problem with direct-seeded crops. Studies at CARDI in 1998 showed that traditional or locally improved varieties are much more susceptible to lodging than are imported modern varieties when direct seeded (Table 4).

Table 4. Yield and lodging potential of modern and traditional rice varieties.

Variety	Transplanted		Broadcast	
	Yield (t ha^{-1})	Lodged (%)	Yield (t ha^{-1})	Lodged (%)
Modern	2.5	0	2.5	0
Traditional	1.8	8	1.7	33

All varieties showed susceptibility to lodging when grain yields exceeded 3 t ha^{-1}. Results from 1996 showed that ‘IR66’ lodged badly, 10 days after flowering, when yields exceeded 4 t ha^{-1}. Similar findings occurred with ‘Santepheap 2’ at CARDI and Phnom Penh Thmey from 1995 to 1998. In one direct-seeded field, at CARDI in 1998, crop lodging caused an estimated 25% or 0.80 t ha^{-1} reduction in yield. In high-yielding crops, the plants lodge from the crown rather than the stem.

Crop lodging was reduced when the seed was partially incorporated by harrow or drilled by machine. A study in 1998 showed lodging was reduced to less than 10% when ‘Santepheap 2’ was machine drilled and to 15% when seed was partially incorporated into dry soil, using drag harrows after broadcasting. In the same trial, 45% of the crop lodged in the treatments involving dry seed broadcast onto dry soil.

Crop maturity

Direct-seeded crops matured 5%–10% faster than transplanted crops. In 1995, ‘Santepheap 2’, which normally takes 140 days to mature when transplanted, was ready for harvest in 120 days when direct seeded. Similarly in 1996, ‘IR66’, which is normally ready for harvest in 105 days, could be harvested 95 days after being direct seeded. In 1999, 'Santepheap 2' seed was sown in the nursery the same day that it was broadcast into the larger fields. The broadcast crops were mature in 124 days while the transplanted crop took 148 days to mature.

Crop yields

While yield differences were recorded in some locations in some years, no significant difference in crop yields between transplanted and direct-seeded crops were observed over the 4 years of study. Results from 10 studies, conducted in seven locations where broadcasting and transplanting were compared as major treatments, are presented in Table 5. All fields were larger than 0.1 ha and the treatments were replicated in each location.

Labour

Direct seeding reduced the time and labour requirements for crop establishment. At CARDI, pulling and transplanting seedlings take 30–33 person-days per hectare. This was reduced to 5 person-hours ha^{-1} for broadcasting pre-germinated seed into water and 3 person-hours ha^{-1} for broadcasting dry seed onto dry soil. In studies at Bek Chan in 1998, 1.25 ha was broadcast with dry seed in 3.75 h. In similar studies in Svey Rieng Province in 1997, 1 ha of flooded fields was seeded in 3 h. Results from a farm-mechanization survey in 1995, found that farmers spent 33 days establishing their crops by transplanting and 1.5 days when these were direct seeded.

Land levelling

The degree of land levelness also had a significant impact on weed burdens and crop yields. A trial conducted at CARDI in 1998, compared yields between fields that were established by broadcasting pre-germinated seed onto fields with different degrees of levelness. All the comparisons were made in large fields (0.25 ha), using the same rice variety and the same fertilizer inputs. A strong correlation was found between the land levelness (expressed as the standard deviation of the land height within the field) and crop yields (Figure 2). Similar results were also obtained from a study conducted at a different location in 1995.

Table 5. Yields for transplanted and direct-seeded rice crops in Cambodia, 1996–1999.

Year	Location	Variety	Transplanted (t ha^{-1})	Broadcast (t ha^{-1})	Comparisons (no.)
1996	Kandal	Improved	3.04	4.05	6
1997	Kandal	Improved	1.85	1.20	9
1997	Kandal	Improved	2.39	2.76	6
1997	Svey Rieng	Improved	1.00	1.51	9
1997	Battambang	Improved	4.12	3.87	12
1998	Kandal	Improved	2.30	2.45	6
1998	Kandal	Traditional	1.82	1.69	13
1998	Battambang	Traditional/improved	3.37	3.24	14
1999	Kandal	Improved	3.79	3.20	6
1999	CARDI	Improved	1.69	2.21	8
Mean			2.54	2.62	89

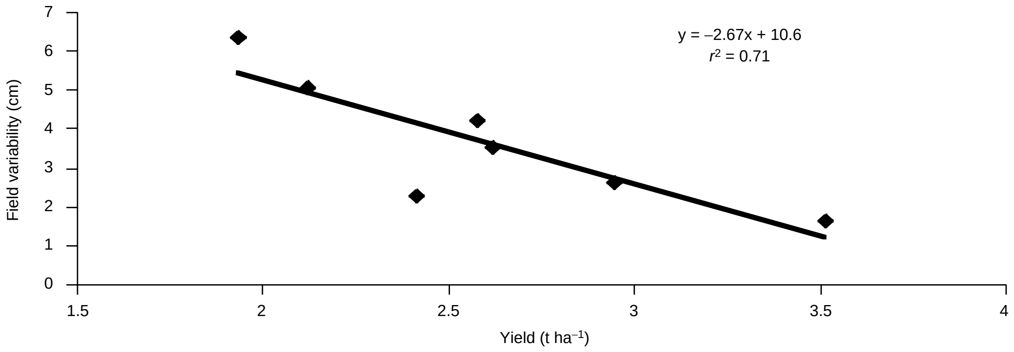


Figure 2. The effect of land levelness on rice crop yields at the Cambodian Agricultural Research and Development Institute (CARDI), 1998.

Visual observations of farm fields showed that weed burdens were much higher in the non-levelled fields. In land preparation trials at CARDI in 1999, which were direct seeded but not weeded, levelled fields yielded 2.48 t ha^{-1} of rice and produced 0.85 t ha^{-1} of weeds at panicle initiation. The non-levelled fields yielded 1.95 t ha^{-1} of rice and produced 1.46 t ha^{-1} of weeds at panicle initiation.

Studies in dry-seeded and transplanted fields in north-west Cambodia in 1998 found that land levelling and improved weed management significantly increased grain yields. Studies were conducted on 14 farms, where comparisons were made between non-levelled fields, levelled fields and levelled fields where weeds were controlled by either using herbicides or controlling water levels in the fields (Table 6).

Table 6. Mean crop yields (t ha^{-1}) from 14 levelled and non-levelled fields in Battambang, Cambodia, 1998.

Field reatment	Grain yield (t ha^{-1})[a]	
	Dry broadcast	Transplanted
No levelling	1.78 a	2.40 a
Levelling	2.47 ab	2.86 ab
Levelling + weed control	3.24 b	3.37 b
Mean	2.50	2.87

[a] Treatments followed by the same letters are not statistically different at the 5% level.

Discussion

Direct seeding can be a highly efficient way of establishing a crop if weeds can be controlled.

While grain yields are similar for well-managed direct-seeded and transplanted crops, direct seeding offers other benefits: crops mature faster, requiring less water and permitting later planting, which is important if the monsoons are late. In double cropping and recession areas, direct seeding is advantageous because the time available for land preparation and crop growth is restricted. Reduced time for crop establishment and growth reduces pumping costs, improves water-use efficiency (when water can be limited early in the season) and enables the crop to mature before floodwaters rise later in the season.

Direct-seeded crops required less labour to establish. This is very important in north-west Cambodia, where landholdings are large and rural labour scarce. In these areas, the savings made by reducing labour costs for planting must be offset against the cost of increased weed burdens. In these situations, farmers either do not weed their crops, or plough again after establishment to control weeds. This second ploughing does help reduce weed populations but, more importantly, it stimulates plant tillering which helps the crop establish a competitive advantage over weeds.

Land levelling reduces weed burdens and improves crop yields (Rickman et al. 1995). Farmers commented that weed burdens were lower and less labour was required to weed the levelled fields manually. CIAP studies confirmed that weeds were reduced by 40% after land levelling. Appropriate herbicides could also be used to control in-crop weeds and would reduce dependence on manual weeding. Better land preparation techniques have improved crop yields by reducing the number of weeds being carried over from fallow into cropping. A more aggressive last *working* from a rotovator, or the use of chemicals at this stage, may also help reduce the carryover of fallow weeds.

Lodging is a problem in high-yielding direct-seeded crops. The plants lodge from the crown, not the stem, and the traditional or locally improved varieties appear to be more susceptible to lodging than the imported modern varieties (Fukai 2000). Machine planting may overcome this problem in dry-seeded crops as studies have shown that direct drilling of seeds reduces lodging. Varietal screening would help identify higher yielding varieties that may be better suited to direct seeding. At present, no varieties have been specifically selected or recommended for direct seeding.

Crop establishment percentages are low in direct-seeded fields and nurseries. Rice seeds are highly susceptible to oxygen deprivation when incorporated below the soil surface and also when field water is muddy during establishment (Tran Van My et al. 2000). Better grading and cleaning techniques may help improve seed vigour and subsequent establishment rates on farm. Seed priming, which increases the rate of germination, may help improve establishment in wet-seeding situations.

Conclusions

The migration of labour from rural areas to urban centres in Cambodia will increase farmers' dependence on direct seeding as a technique for establishing their rice crops.

These studies have shown that transplanted and direct-seeded crops give similar yields when weeds are controlled. Lack of in-crop weed control is probably the most important constraint to the widespread adoption of direct seeding. Manual weeding, more thorough land preparation, herbicide applications, and land levelling are all activities that can be used to help reduce weeds.

A second constraint to the adoption of direct seeding is the lack of varieties that do not lodge. No rice varieties have so far been selected or screened specifically for direct seeding in Cambodia. If this situation is not addressed, the potential yield ceiling for direct-seeded rice crops is about 3 t ha^{-1}.

References

CIAP (Cambodia–IRRI–Australia Project). 1996. Annual Research Report 1995. Phnom Penh, Cambodia.

CIAP (Cambodia–IRRI–Australia Project). 1997. Annual Research Report 1996. Phnom Penh, Cambodia.

CIAP (Cambodia–IRRI–Australia Project). 1998. Annual Research Report 1997. Phnom Penh, Cambodia.

CIAP (Cambodia–IRRI–Australia Project). 1999. Annual Research Report 1998. Phnom Penh, Cambodia.

CIAP (Cambodia–IRRI–Australia Project). 2000. Annual Research Report 1999. Phnom Penh, Cambodia.

Fukai. S. 2000. Rice cultivar requirements for direct seeding in rainfed lowlands. Paper presented at the International Workshop on Dry-Seeded Rice Technology, held in Bangkok, 25–28 January.

Mazid, M.A., Bhuiyan, S.I., Mannan, M.A. and Wade, L.J. 2000. Dry-seeded rice for enhancing productivity of rainfed drought-prone lands: lessons from Bangladesh and Philippines. Paper presented at the International Workshop on Dry-Seeded Rice Technology, held in Bangkok, 25–28 January.

Rickman, J.F., Pyseth, M., Sothy, O., Theavy, K. and Sokha, N. 1995. Farm Mechanization and Crop Production in Cambodia. Baseline Survey Report No. 5. Phnom Penh, Cambodia, Cambodia–IRRI–Australia Project.

Tran Van My, To Phuc Toung, Vo-Tong Xuan and Nguyen Thanh Nghiep. 2000. Dry seeding rice for increased cropping intensity in Long An Province, Vietnam. Paper presented at the International Workshop on Dry-Seeded Rice Technology, held in Bangkok, 25–28 January.

Field Screening for Drought Resistance

G. Pantuwan[a,*], S. Fukai[b], M. Cooper[b], S. Rajatasereekul[c] and J.C. O'Toole[d]

Abstract

Because drought frequently reduces yields in Northeast Thailand, we studied variation in grain yield among rainfed lowland rice genotypes and the association between traits and yield under different drought conditions in the region. We found considerable genotypic variation for grain yield under both irrigation and drought. Depending on timing, duration and severity of plant water deficit and on sowing time, grain yield of genotypes under drought, compared with under irrigation, was reduced by up to 81%. However, a significant G × E interaction was found for grain yield across different drought environments, with genotypes responding according to timing and severity of drought. Genotypes that could maintain high panicle water potential (PWP) during drought that developed just before flowering produced higher grain yield, harvest index, filled-grain percentage, and fertile-panicle number per m^2. Drought tended to delay flowering, and a larger delay in flowering was associated with a higher reduction in grain yield, harvest index and percentages of fertile panicles and filled grains. Higher drought scores (leaf death) in the dry season were associated with lower grain yield under drought in the wet-season experiments. The association, however, was significant only under particular wet-season conditions, that is, when patterns and severity of drought in both seasons were similar. The dry-season screening conditions for the drought score screen should be managed to correspond to relevant types of drought conditions in the wet season in targeted areas. According to the results of this study, a breeding program should select for high grain yield under drought conditions relevant to target areas. The breeding station's and selection environments and their relationships with targeted on-farm environments should be characterized. Selection of genotypes for high PWP and minimal flowering delay under drought should be practised at the same time as yield testing. Some evaluation and selection of early generation breeding materials for low drought score could be conducted in the dry season before high grain yield genotypes are selected under irrigation and drought in the wet season.

PHENOTYPIC variation for grain yield in rainfed lowland rice is usually more influenced (based on relative size of variance components) by environment and genotype-by-environment (G × E) interactions than by genotype (Cooper and Somrith 1997; Fukai et al. 1999). The presence of G × E interactions and the low heritability of wet-season grain yield of rainfed lowland rice results in a high level of uncertainty in the selection of drought-resistant genotypes (Blum 1993; Fukai and Cooper 1995). A further consequence of G × E interactions is that selected genotypes that yield well under one type of drought environment may not perform well in other drought environments. Hence, G × E interactions reduce the realized response to selection (Cooper et al. 1999a, b). Consequently, selection for drought resistance with the direct use of grain yield under drought as a selection index may be inefficient when practised on a limited sample of target population of environments.

KEYWORDS: Rice, Rainfed lowland, Drought, Yield reduction, Water potential, Flowering delay

---

[a] Ubon Ratchathani Rice Research Centre, Ubon Ratchathani, Thailand
[b] School of Land and Food Sciences, The University of Queensland, Brisbane, Qld., Australia
[c] Chum Phae Rice Experiment Station, Khon Kaen, Thailand
[d] The Rockefeller Foundation, Regional Office, Bangkok, Thailand
*Corresponding author: E-mail: grienggrai@doa.go.th

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

To accommodate the effects of G × E interactions and improve selection efficiency, genotypes may be evaluated in many experiments over years and sites with different drought intensities to increase the heritability and realized response to selection (Nyquist 1991; Fukai and Cooper 1995). These evaluation processes are costly and increase the time of selection in the breeding program. Consequently, indirect selection methodology has aroused considerable interest in the search for more efficient breeding strategies for rainfed lowland rice (Falconer 1989; Fukai and Cooper 1995).

Morpho-physiological traits that confer drought resistance may be used as indirect selection criteria to improve grain yield under drought. For example, Fischer et al. (1989) used specific physiological traits as indirect selection criteria for improving maize (*Zea mays* L.) yield under drought. In rice, O'Toole (1982), Fukai and Cooper (1995) and Nguyen et al. (1997) proposed several putative drought-resistant traits that may contribute to grain yield under drought in rainfed lowlands. These traits should be evaluated for their contributions to adaptation under drought and on how they might be used to improve the efficiency of rice-breeding programs. If they can be evaluated with rapid reliable techniques in the early generations of genetic improvement, then using these traits as indirect selection criteria may enhance the rate of improvement of drought-resistant cultivars.

Our study aims to:

1. Examine genotypic variation for grain yield under various types of drought conditions in targeted drought-prone areas in Northeast Thailand;
2. Examine genotypic expression of putative drought-resistant traits and their contributions to grain yield under drought; and
3. Evaluate the use of the dry-season screening for drought resistance to estimate grain yield under drought in the wet season.

Experiment Procedures and Growth Conditions

Four sets of experiments, giving a total of nine field experiments, were conducted under lowland conditions in the upper (Chum Phae) and lower (Ubon Ratchathani) regions of Northeast Thailand. These two regions differ in the amount and pattern of rainfall they receive. Amount of annual rainfall is smaller and the growing season is shorter in Chum Phae than in Ubon Ratchathani. The first three sets of irrigated (control) and drought experiments conducted in the wet season were used to investigate genotypic variation for grain yield and putative drought-resistant traits in the wet season. Randomly sampled sets of 50 to 128 recombinant inbred lines derived from four biparental crosses were used for all experiments.

To increase the chance of achieving drought, experiments were sown later in the wet season than is normally practised in the region. Different levels of drought were imposed on each set of experiments, that is, mild drought during grain filling in experiment 2, severe drought just before flowering in experiment 4, prolonged severe drought during the reproductive to grain-filling stages in experiment 6 and prolonged but mild drought during the vegetative and grain-filling stages in experiment 7. Experiments 1, 3 and 5 were controls, that is, all were well-watered (Table 1). Flowering time, above-ground total dry matter at anthesis (TDMa) and maturity (TDMm), grain yield and harvest index of all genotypes were determined. Predawn (0230–0600 hours) panicle water potential (PWP) of all genotypes in experiment 4 was determined at flowering.

The fourth set of two experiments (experiments 8 and 9) were conducted over two dry seasons to examine genotypic variation for drought score (leaf death score) and assess the reliability of using the drought score measured in the dry season to estimate grain yield measured under drought in the wet season. Drought score (De Datta et al. 1988) of genotypes in experiments 8 and 9 was visually estimated. Soil water deficit in experiment 8 developed slowly and thus the drought score of genotypes was relevant for mild stress only (Table 1). In contrast, soil water deficit in experiment 9 developed rapidly and genotypes experienced severe drought (high drought score) by the end of the experiment.

Results and Discussion

Genotypic differences for growth and yield across environments

The mean responses of all genotypes in terms of above-ground total dry matter at anthesis (TDMa) and maturity (TDMm), grain yield and harvest index in all experiments are summarized in Table 1. In different experiments, the crops experienced drought at different times, duration and severity. Thus, the effect of drought in the different experiments on the mean above-ground TDM and yield was variable. For example, the mean grain yield under drought, compared with that under irrigation, was reduced by 18% in experiment 2, 55% in experiment 4, 81% in experiment 6 and 52% in experiment 7 (Table 1). Although there were differences in the effect of drought on mean grain yield, the genotypes heritability for grain yield under each drought treatment was high, that is, h^2 = 0.80, 0.70, 0.70 and 0.74 for experiments 2, 4, 6, and 7, respectively.

Table 1. Four sets of seven wet-season experiments and two dry season experiments conducted in rainfed lowland rice-growing areas in Ubon Ratchathani (experiments 1–4; 8–9) and Chum Phae (experiments 5–7) in Northeast Thailand. Data show mean and standard error for total above-ground dry matter at anthesis (TDMa) and maturity (TDMm), grain yield (GY) and harvest index (HI) of all genotypes used in each experiment. na = data not available.

Experiment	Growing conditions	TDMa		TDMm		GY		HI	± SEM
		(t ha^{-1})	± SEM	(t ha^{-1})	± SEM	(t ha^{-1})	± SEM		
Wet season									
Experiment set 1									
1	Well-watered	na	—	na	—	3.36	± 0.22	na	—
2	Grain filling, mild drought	na	—	na	—	2.72	± 0.21	na	—
Experiment set 2									
3	Well-watered	7.41	± 0.43	8.89	± 0.45	3.75	± 0.45	0.42	± 0.02
4	Flowering, short severe drought	5.39	± 0.37	5.73	± 0.38	1.69	± 0.19	0.30	± 0.03
Experiment set 3									
5	Well-watered	5.30	± 0.40	6.56	± 0.48	2.94	± 0.22	0.45	± 0.01
6	Flowering and grain filling, prolonged severe drought	3.28	± 0.42	3.12	± 0.40	0.55	± 0.15	0.16	± 0.03
7	Vegetative and grain filling, prolonged mild drought	2.25	± 0.19	3.15	± 0.21	1.41	± 0.11	0.45	± 0.02
Dry season									
Experiment set 4									
8	Mild drought at the vegetative stage	—	—	—	—	—	—	—	—
9	Severe drought at the vegetative stage	—	—	—	—	—	—	—	—

Source: Adapted from Pantuwan et al. (2001c).

Yield reduction due to drought in each environment was generally correlated with reduction in filled-grain number and percentage. The most severe loss in grain yield existed in experiments 4 and 6 because drought developed during the critical growth period of flowering time. Yield reduction was small under mild drought stress during grain filling in experiment 2. The prolonged mild drought in experiment 7 also had a smaller effect on yield reduction, compared with drought at flowering at the same site (81% yield reduction in experiment 6). These smaller effects of drought on yield may have occurred because the growth of the genotypes may have been affected less by drought during the vegetative stage and grain filling.

Genotypes expressed significant ($P < 0.05$) differences for drought score as measured in both experiments 8 and 9. However, while both experiments were conducted in the dry season, little association ($P > 0.05$) was found between the drought scores of genotypes determined in each experiment. This suggests that the patterns of development of plant water deficit and also the severity of water stress in experiments 8 and 9 were different.

Factors affecting variation in grain yield of genotypes under drought

Grain yield of genotypes decreased mainly because of increased spikelet sterility when drought developed at flowering. A schematic representation of the factors affecting genotypic variation in grain yield under drought in these experiments is illustrated in Figure 1.

Genotypic variation in maintaining internal plant water status at flowering was associated with significant difference in grain yield under drought. In experiment 4, in which plant water deficit developed just before flowering, genotypes that could maintain high panicle water potential (PWP) had higher grain yield, harvest index, filled-grain percentage, and fertile-panicle number and percentage (Figure 2). This evidence suggests that a capacity to maintain high internal plant water status during drought is an important character for rainfed lowland rice to minimize damage to grain yield due to drought. This result is consistent with findings by Jongdee (1998).

The mechanisms controlling internal plant water status may involve water uptake and/or water conservation by the plant and also internal plant water conductance during stress. Pantuwan et al. (2001a) indicated that rapid water uptake exhausted the available water in the soil and, hence, reduced PWP at a later stage of crop development, resulting in increased spikelet sterility, which decreased grain yield. Here, in experiment 4, genotypes that extracted a larger amount of water during the early stage of drought subsequently exhausted the available water more rapidly (data not shown) and grain yield was affected more severely because the plants

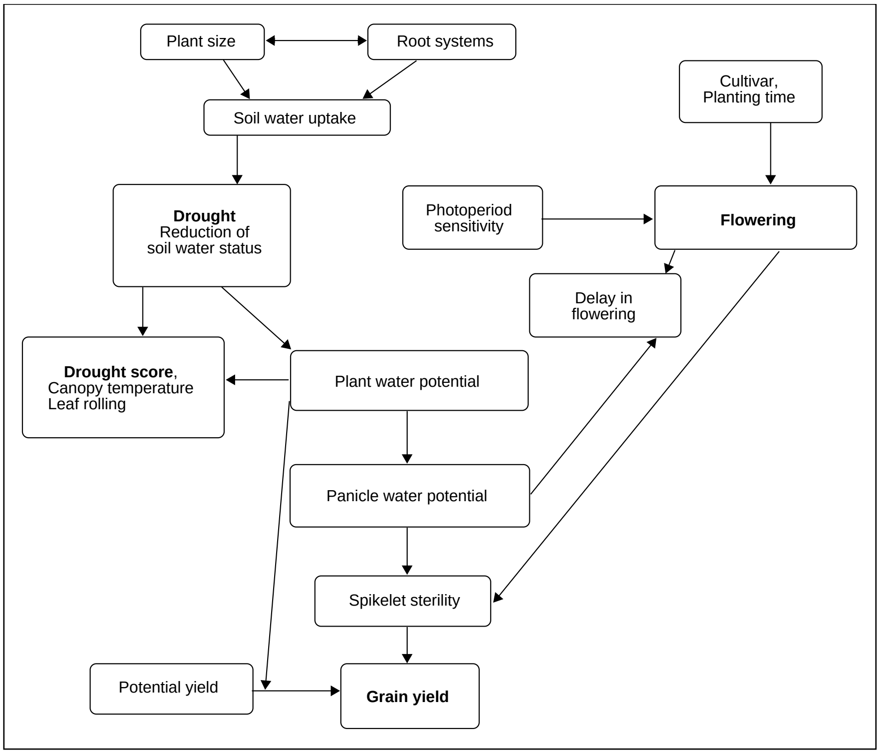


Figure 1. Schematic summary of the major effects of drought on grain yield when drought develops at around flowering (Pantuwan 2000).

experienced a larger water deficit during late stage of drought. Genotypes that extracted less water at booting could conserve water for use around flowering, resulting in these genotypes achieving higher grain yield and harvest index.

Yield potential obtained under non-stress conditions appears to have an influence on grain yield when drought was mild. In experiment 2, in which mild drought developed during grain filling, grain yield of genotypes was positively associated with grain yield under well-watered conditions in experiment 1 (*r* = 0.63**). The influence of genetic yield potential on performance under drought has been found in other studies, for example, Fischer and Maurer (1978), Blum (1983) and Bidinger et al. (1982), where drought stress was not severe and yield was only slightly reduced, relative to grain yield under favourable conditions. However, under the prolonged severe drought of experiment 6, no association was found between yield potential and yield under stress

Under severe drought, genotypes with large plants were disadvantaged because they used more water and experienced higher water deficit than did smaller plants. When genotypes used more water and the soil profile was not recharged during drought, their PWP was reduced, leading to yield reduction (Pantuwan et al. 2001a). Under short severe drought (experiment 4), the genotypes that yielded well had a smaller TDMa. They were also shorter plants when grown under irrigation. However, these characteristics of small TDMa and short plants under irrigation may not always be useful when severe drought stress does not develop. Larger TDMa was positively associated with higher grain yield under irrigation in experiments 3 and 5. This association was also observed in late sown crops under mild drought, for example, in experiments 2 and 7, when crop growth was limited because of a shortened vegetative phase.

Drought escape in early flowering genotypes is an important character for terminal drought. Terminal drought is common in North-East Thailand where the seasonal rainfall ends abruptly. The usefulness of early flowering was observed in experiment 6, where drought stress was severe because of low rainfall. In this experiment, grain yield was reduced to 1.5 t ha^{-1} in early flowering genotypes and to almost 0 t ha^{-1} in the latest flowering genotypes. Time to flowering was negatively associated with grain yield (*r* = -0.83**), number of filled grains per panicle (*r* = –0.77**) and filled-grain percentage (*r* = –0.80**).

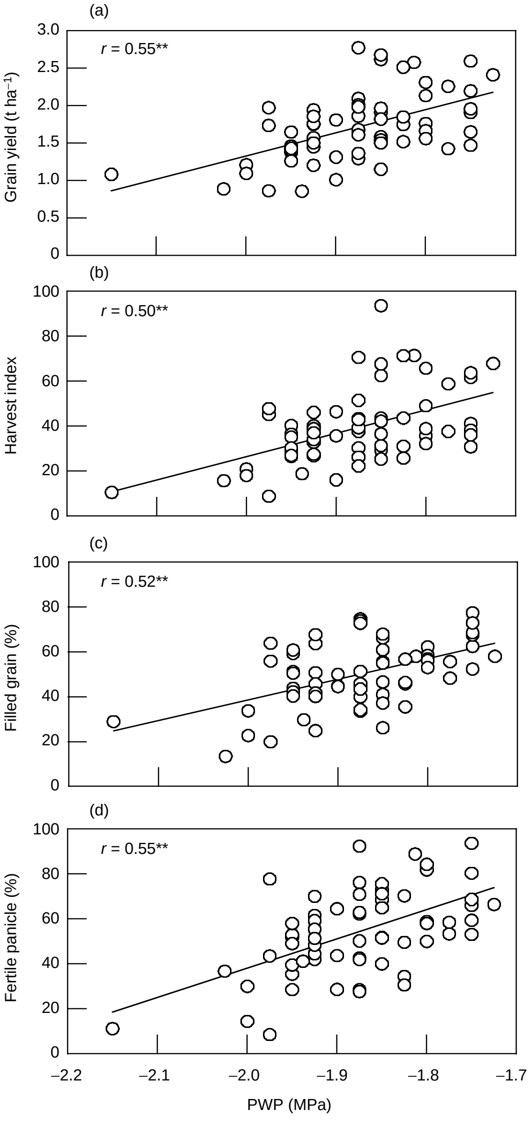


Figure 2. Relationships between predawn panicle water potential (PWP) at flowering and (a) grain yield, (b) harvest index, (c) filled-grain percentage and (d) fertile-panicle percentage of genotypes in experiment 4 (Pantuwan et al. 2001a).

Under water deficit at the reproductive stage, genotypes varied in delaying flowering, reflecting variation in susceptibility to the effects of drought. Genotypic differences in delay in flowering time were consistently observed under different drought treatments in experiments 4 (no delay to 10-day delay) and 6 (delay of 2 to 22 days). Under these conditions, genotypes that delayed more to flower were further disadvantaged because they would have experienced a larger water deficit at flowering because soil moisture decreased with time. In both experiments 4 and 6, increased delay in flowering was associated with increased reduction in grain yield (*r* = –0.43** and *r* = –0.71** respectively; Figures 3a and 3b), harvest index (*r* = –0.33* and *r* = –0.65**, respectively, data not shown), fertile-panicle percentage (*r* = –0.39**) and filled-grain percentage (*r* = –0.35* and *r* = –0.76**, respectively). In experiment 4, delay in flowering was strongly associated with low PWP (*r* = –0.39**) (data not shown), hence genotypes with a longer delay in flowering tended to experience more stress under drought because they flowered when available soil water was lower. Yield reduction of genotypes in both experiments resulted from a large increase in spikelet sterility.

Consistency of response of genotypes to drought environment

Strong G × E interactions were found for most traits among the seven wet-season experiments that were conducted across environments. Different genotypic responses for grain yield were observed between drought and well-watered conditions among drought experiments, and even between the two well-watered experiments at the different sites. The large G × E interaction among the drought experiments may have resulted partly from differences in the drought development pattern.

However, genotypic variation for grain yield was also inconsistent when drought was absent, that is, no relationship existed between grain yield under irrigation in experiment 3 at Ubon Ratchathani and experiment 5 at Chum Phae. Only in the two irrigated experiments at the same site (Ubon Ratchathani) did a significant correlation (*r* = 0.42**) occur among genotypes. Given the large G × E interaction due to site, even under well-watered conditions, the inconsistency of grain yield of particular genotypes in the drought experiments (some of which were conducted at different sites) may also have been a result of other environmental factors varying among the experiments, rather than a result of differences in drought conditions per se. Genotypes may have had differences in specific adaptations to uncontrolled variables

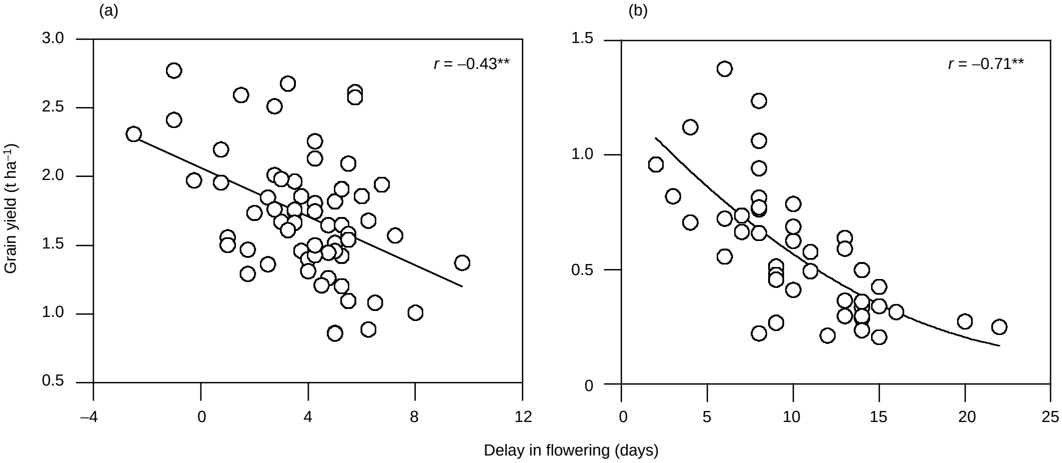


Figure 3. Relationships between delay in flowering and grain yield under (a) drought that developed rapidly just before flowering in experiement 4, and (b) prolonged severe drought at flowering and grain filling in experiment 6 (after Pantuwan et al. 2001a, b).

of the particular growing environments, for example, soil fertility and its effects on plant nutrition.

These findings suggest that types of drought stress (as well as other key environmental constraints) in target areas should be characterized and identified so that particular (drought resistant) genotypes may be selected according to grain yield under managed drought conditions that are appropriate to the target areas. The feasibility of using such an approach will depend on the heterogeneity and complexity of the target population of drought environments in Northeast Thailand.

Using the drought score to select for drought resistance in target areas

Large components of genotypic variation for drought score at the vegetative stage were expressed in experiments 8 and 9 when conducted in the dry season. However, no relationship was found between the drought scores of genotypes determined in these two experiments. Different patterns of development and severity of drought in these two experiments, that is, slow development and mild plant water deficit in experiment 8 and fast development and severe plant water deficit in experiment 9, were identified as the major contributors to the genotypes' different response patterns. The higher drought score in the dry-season experiments was associated with lower grain yield under specific drought conditions in the wet season, but the association was weak to moderate and significant only under particular drought conditions (Table 2).

In most cases, a significant phenotypic correlation between drought score in the dry season and grain yield in the wet season existed only in experiments where there were similar patterns of drought. For example, grain yield under mild stress during grain filling in experiment 2 correlated with drought scores in experiment 8 where drought was also slow to develop, but did not correlate with drought scores in experiment 9, where drought developed rapidly and drought scores were large (Table 2). Grain yield of genotypes that were largely affected by severe drought in experiment 4 correlated with drought scores in experiment 9, but not with those of experiment 8.

These findings indicate the importance of characterizing key types of drought environment in the targeted areas and the environments used for yield evaluation by the breeding program. The dry-season environments used to measure genotypic variation for drought scores should be managed to correspond to relevant types of drought conditions frequent in the wet season. There were advantages and disadvantages of both indirect selection (using drought scores measured in the dry season) and direct selection (using grain yield under drought in the wet season).

The efficiency of using drought scores as an indirect selection criterion for improving grain yield under drought was lower than direct selection for grain yield. However, using drought scores as a selection index, a larger number of genotypes can be evaluated than using grain yield in the wet season, making the application of higher selection intensities

Table 2. Phenotypic correlation coefficient between drought scores in experiments 8 and 9, and grain yield (GY) in experiments 2 and 4 at Ubon Ratchathani, and experiments 6 and 7 at Chum Phae, Northeast Thailand.

Experiment		Drought score in Exp 8			Drought score in Exp 9		
No.	Description	Stress 1 (DS = 1.7)	Stress 2 (DS = 2.3)	Stress 3 (DS = 3.4)	Stress 1 (DS = 2.9)	Stress 2 (DS = 6.5)	Stress 3 (DS = 7.5)
2	GY[a] (grain filling, mild drought)	–0.26	–0.34*	–0.31*	–0.06	0.06	0.09
4	GY[a] (flowering, short severe drought)	–0.14	0.02	0.16	–0.26**	–0.19*	–0.15
6	GY[b] (flowering and grain filling, prolonged severe drought)	0.06	0.14	0.20	0.17	0.12	0.28*
7	GY[b] (vegetative and grain filling, prolonged mild drought)	–0.19	–0.35*	–0.35**	0.34*	0.34*	0.16

[a] n = 128, [b] n = 50.

* = significant at $P \leq 0.05$; ** = significant at $P \leq 0.01$; DS = mean drought score of all genotypes.

possible. Even in the current breeding program in Thailand, where drought scores can be used to evaluate five times the number of lines that can be tested for grain yield (in the wet season), the dry-season indirect selection strategy is still less effective than the wet-season direct selection for grain yield for the experimental conditions sampled in this study. Comparing the likelihood of drought incidence in the wet and dry seasons, it is potentially easier to manage the development of plant water deficit in the dry season. The experience gained from evaluating the dry-season drought screen in this study provides useful recommendations for conducting this screening nursery:

1. The dry-season drought screen should be repeated under differently managed drought conditions to permit the evaluation of drought score responses of genotypes across a range of patterns and severity of droughts in any one dry season. Screening environments conducted at the high positions in the toposequence are expected to impose conditions of rapid and severe stress, while screening environments positioned lower in the toposequence will impose conditions of more gradual stress. The breeder can thus manipulate the duration and severity of stress imposed on the test genotypes by manipulating the toposequence position of the screen.
2. The pattern of development and severity of drought must be characterized for the dry-season drought screening environments to thus evaluate the relevance of screening conditions to the drought conditions encountered in target wet-season environments.
3. A common set of reference or probe genotypes (Cooper and Fox 1996; Wade et al. 1996) should be included in the dry-season screen and wet-season experiments to facilitate comparison of wet-season and dry-season environments. This experimental methodology would assist the quantification of the relevance of dry-season screening environments to key wet-season environments.

Conclusions and Recommendations for a Breeding Program

Direct selection for drought-resistant cultivars, using grain yield as a selection criterion

A promising screening method for drought resistance against late-season drought is the use, as selection criterion, of grain yield under drought in the wet season. The presence of a reasonably high heritability for grain yield under drought for Ubon Ratchathani (experiment 4) and Chum Phae (experiment 6) provided some evidence of the high selection efficiency under these specific conditions. Because cultivars usually have specific responses to particular types of drought rather than consistent responses that give broad adaptation to every drought condition, drought screening should be conducted under drought conditions with quantified relevance for target areas. The feasibility of combining components of specific adaptation to improve broad adaptation (Cooper 1999) was not considered in this study and has yet to be determined.

High yield potential under non-stress conditions was found to contribute to high grain yield under mild drought. Whether or not the stress is mild or severe, selected genotypes should have reasonably high yield potential under non-stress rainfed conditions to ensure they can respond to favourable conditions when they occur, which, according to this study and others (Jearakongman et al. 1995; Cooper and Somrith 1997; Romyen et al. 1998), occur with reasonable frequency in Northeast Thailand (Cooper and Somrith 1997; Cooper et al. 1999b). Selection for high yield potential should therefore be made as early as selecting parents for crossing because parents with low yield potential are unlikely to improve grain yield per se under the range of drought conditions common in Northeast Thailand. A further priority research area is to quantify the frequency of occurrence of different types of drought environments.

Indirect selection for drought-resistant cultivars, using plant traits as selection criteria

A major determinant of grain yield of rainfed lowland rice cultivars in Northeast Thailand is their phenology. Cultivars must have an appropriate phenology to match their growth and development with the predominant rainfall pattern in the region to achieve high grain yield, particularly when annual rainfall finishes early. Cultivars with good yield performance across environments are likely to possess the trait combination of early maturity and high yield potential. However, although early flowering genotypes can escape late-season drought, genotypes that are too early are unlikely to produce high yields under favourable conditions because they will not be able to produce sufficient TDMa with their short vegetative phase.

Genotypic variation for PWP and the contribution of high PWP to high grain yield under drought were demonstrated in this study. Screening for genotypes that have high PWP under drought is likely to be useful in identifying breeding materials with adaptation to drought. Although the measurement of PWP is time consuming (about 50 samples per hour), high value information on adaptation to drought can be obtained. The scope for developing quicker PWP measurement procedures warrants further investigation, particularly if a measurement methodology is developed that could be applied to early generations and larger numbers of lines.

Delay in flowering under drought was found to be a reliable indicator of drought susceptibility. Genotypes can be evaluated for delay in flowering in the same experiment as screening for PWP. To measure delay in flowering under drought, an irrigated control with the same sowing date as for the drought treatment must be grown.

Screening for drought resistance at the vegetative stage, using the drought score, can be applied to many early generation materials in the dry season. While the results of the present study indicate that the response to selection for drought score was less efficient than direct selection for grain yield under drought, this strategy could be used as part of a screening strategy to discard a large number of drought-susceptible genotypes before screening in the wet season for traits that are more time consuming to measure. Genotypes that show susceptibility to drought at the vegetative stage are unlikely to perform well under drought at the reproductive stage (Mackill et al. 1996). However, given the observation in this study of a lack of association between grain yield and drought score of genotypes across different types of drought stress, this suggestion requires further investigation to evaluate the causes and effects of these G × E interactions for drought score.

Acknowledgments

This paper is based on a collaborative study carried out by the Thai Department of Agriculture, the Australian Centre for International Agricultural Research (ACIAR) and the Rockefeller Foundation. The authors thank the above-mentioned organizations for their financial support of this research.

References

Bidinger, F.R., Mahalakshmi, V., Talukdar, B.S. and Alagarswamy, G. 1982. Improvement of drought resistance in pearl millet. In: Drought Resistance in Crops with Emphasis on Rice. International Rice Research Institute (IRRI), Los Baños, Philippines, 357–375.

Blum, A. 1983. Breeding programs for improving crop resistance to water stress. In: Kramer P.J. and Raper, Jr, C.D. ed. Crop Reactions to Water and Temperature Stress in Humid, Temperate Climates. Westview Press, USA 373 p.

Cooper, M. 1999. Concept and strategies for plant adaptation research in rainfed lowland rice. Field Crops Res. 64: 13-34.

Cooper, M. and Fox, P.N. 1996. Environmental characterisation based on probe and reference genotypes. In: Cooper, M. and Hammer, G.L. ed. Plant Adaptation and Crop Improvement. Wallingford, UK, CAB International, 529–547.

Cooper, M., Rajatasereekul, S., Immark, S., Fukai, S. and Basnayake, J. 1999a. Rainfed lowland rice breeding strategies for Northeast Thailand. I. Genotypic variation and genotype × environment interactions for grain yield. Field Crops Research, 64, 131–151.

Cooper, M., Rajatasereekul, S., Somrith, B., Sriwisut, S., Immark, S., Boonwite, C., Suwanwongse, A., Ruangsook, S., Hanviriyapant, P., Romyen, P., Porn-uraisanit, Skulkhu, E., Fukai, S., Basnayake, J. and Podlich, D.W. 1999b. Rainfed lowland rice breeding strategies for Northeast Thailand. I. Comparison of intrastation and interstation selection. Field Crops Research, 64, 133–176.

Cooper, M. and Somrith, B. 1997. Implications of genotype-by-environment interactions for yield adaptation of rainfed lowland rice. Influence of flowering date on yield variation. In: Breeding Strategies for Rainfed Lowland Rice in Drought-prone Environments. Proceedings of an International Workshop held at Ubon Ratchatani, Thailand, 5–8 November 1996. ACIAR, Canberra, 104–114.

De Datta, S.K., Malabuyoc, J.A. and Aragon, E.L. 1988. A field screening technique for evaluating rice germplasm for drought tolerance during the vegetative stress. Field Crops Research, 19, 123–134.

Falconer, D.S. 1989. Introduction to Quantitative Genetics. New York, Longman Scientific & Technical, 438 p.

Fischer, K.S., Edmeades, G.O. and Johnson, C.E. 1989. Selection for the improvement of maize yield under moisture deficits. Field Crops Research, 22, 227–243.

Fischer, R.A. and Maurer, R. 1978. Drought resistance in spring wheat cultivars. I. Grain yield response. Australian Journal of Agricultural Research 29, 897–912.

Fukai, S. and Cooper, M. 1995. Development of drought-resistant cultivars using physio-morphological traits in rice. Field Crops Research, 40, 67–86.

Fukai, S., Pantuwan, G., Jongdee, B. and Cooper, M. 1999. Screening for drought resistance in rainfed lowland rice. Field Crops Research, 64, 61–74.

Jearakongman, S., Rajatasereekul, S., Naklang, K., Romyen, P., Fukai, S., Skulkhu, E., Jumpake, B. and Nathabutr, K. 1995. Growth and grain yield of contrasting rice cultivars grown under different conditions of water availability. Field Crops Research, 44, 139–150.

Jongdee, B. 1998. The importance of leaf water potential and osmotic adjustment on growth and grain yield of rice (*Oryza sativa* L.) genotypes under water deficit conditions. Ph.D. dissertation. Brisbane, The University of Queensland.

Mackill, D.J., Coffman, W.R. and Garrity, D.P. 1996. Rainfed Lowland Rice Improvement. International Rice Research Institute (IRRI), Manila, Philippines, 242 p.

Nguyen, H.T., Babu, R.C. and Blum, A. 1997. Breeding for drought resistance in rice: physiology and molecular genetics considerations. Crop Science, 37, 1426–1434.

Nyquist, W.E. 1991. Estimation of heritability and prediction of selection response in plant populations. Critical Review of Plant Sciences, 10, 235–322.

O'Toole, J.C. 1982. Adaptation of rice to drought-prone environments. In: Drought Resistance in Crops with Emphasis on Rice. International Rice Research Institute (IRRI), Los Baños, Philippines, 195–213.

Pantuwan, G. 2000. Yield response of rice (*Oryza sativa* L.) genotypes to water deficit in rainfed lowland. Ph.D. dissertation. Brisbane, The University of Queensland.

Pantuwan, G., Fukai, S., Cooper, M. and O'Toole, J.C. 2001a. Yield response of rice (*Oryza sativa* L.) genotypes to drought under rainfed lowlands. 1. Severe drought stress at flowering. Field Crops Research. (submitted)

Pantuwan, G., Fukai, S., Rajatasereekul, S., Cooper, M. and O'Toole, J.C. 2001b. Yield response of rice (*Oryza sativa* L.) genotypes to drought under rainfed lowlands. 2. Prolonged severe and mild drought stress at the reproductive stage and grain filling period. Field Crops Research. (submitted)

Pantuwan, G., Fukai, S., Cooper, M. and O'Toole, J.C. 2001c.Yield response of rice (*Oryza sativa* L.) genotypes to drought under rainfed lowlands. 3. Mild drought stress during grain filling period and genotype consistency across environment. Field Crops Research. (submitted)

Romyen, P., Hanviriyapant, P., Rajatasereekul, S., Khunthasuvon, S., Fukai, S., Basnayake, J. and Skulkhu, E. 1998. Lowland rice improvement in northern and northeast Thailand. 2. Cultivar differences. Field Crops Research, 59, 109–119.

Wade, L.J., McLaren, C.G., Samson, B.K., Regmi, K.R. and Sarkarung, S. 1996. The importance of site characterization for understanding genotype by environment interactions. In: Cooper, M. and Hammer, G.L. ed. Plant Adaptation and Crop Improvement. Wallingford, UK, CAB International, 549–562.

Response of Rainfed-Lowland Rice Genotypes to Prolonged Drought and Rewatering during the Vegetative Stage

A. Kamoshita[1,*], R. Rodriguez[2], A. Yamauchi[3] and L.J. Wade[2]

Abstract

To examine water use and biomass production in rainfed lowland rice during drought and after rewatering, six diverse genotypes were tested under shorter and prolonged periods of drought in the greenhouse. Genotypes with greater seedling vigour developed a deep-root system earlier in response to drought, and consumed soil water more quickly, experiencing greater reduction in transpiration, water-use efficiency and biomass production during prolonged drought. Recovery from drought was better in these genotypes under both the shorter and prolonged stress treatments. The water-use pattern of rice seedlings examined in the greenhouse could help improve understanding of the adaptation of rainfed lowland rice to an environment with frequent early season drought.

Heterogeneous and variable drought environments have prevented rapid improvement of varieties of rainfed lowland rice. Traits that are expressed under drought conditions and that may improve adaptation to drought environments have been studied (Fukai et al. 1999; Fukai and Cooper 1995; O'Toole 1982). However, the extent of those traits' contribution to increased biomass production and yield is not clear. The rainfed lowland environment is often heterogeneous, even within a paddy, and sometimes results in large errors in data collected in field experiments, thus masking genotypic variation of physio-morphological traits such as root length or leaf-water potential (Jongdee et al. 1997; Pantuwan et al. 1997). Expression of physio-morphological traits is also influenced by the intensity and duration of water deficit. However, controlling and manipulating stress conditions in the field is not easy, as costly facilities such as rainout shelters are not always available. Greenhouse experiments can control water stress development more easily and enable one to measure physio-morphological traits with reduced errors and to quantify their effects on biomass production.

Deep-root systems and osmotic adjustment as putative drought resistant traits have been studied, with a scope to utilize in marker-assisted selection (Nguyen et al. 1997). A deep-root system may improve adaptation of rice during drought through greater capacity for water extraction, thus maintaining high plant-leaf-water status. Association between root-length density and amounts or rates of soil-water extraction has been demonstrated in upland (Lilley and Fukai 1994) and lowland (Kamoshita et al. 2000) rice. However, the advantage of deep-root systems for adaptation to drought may depend on the duration of drought and the soils' water-holding capacity. Genotype × environment interaction for deep-root characters was also reported by Kamoshita et al. (in press), suggesting the importance of characterizing drought environments, and quantifying root traits and water extraction.

Osmotic adjustment may also help plants retain higher relative water content with a given level of water potential. Although greater biomass or yield production due to higher capacity of osmotic adjustment has not been reported in rice, evidence is available for other crops (Zhang et al. 1999). If drought is

---

[1] The University of Tokyo, Midoricho, Tanashi, 188–0002, Japan
[2] International Rice Research Institute, MCPO Box 3127, 1271 Makati City, Philippines
[3] Nagoya University, Chikusa, Nagoya 464–8601, Japan
*Corresponding author:
E-mail: akamoshita@fm.a.u-tokyo. ac.jp

KEYWORDS: Drought, Drought recovery, Rainfed lowland rice, Root, transpiration

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

extended and all genotypes reduce soil-water extraction, genotypes with a higher capacity for osmotic adjustment may be advantaged for biomass production or even survival.

Drought recovery is important, particularly after early season drought. Mitchell et al. (1998) showed that recovery after drought was related, not to a genotype's resistance during drought, but to leaf area at the drought's end. Wade et al. (2000) found that genotypic variation in drought recovery was associated with seedling vigour under a progressive drought of about 20 days. If drought is further prolonged, genotypes with higher seedling vigour may become further injured and so not show superior drought recovery.

We tested six diverse rice genotypes for rainfed lowlands in the greenhouse for their expression of physio-morphological traits under progressive drought and their capacity to recover afterwards. Two periods of drought were used: 22 to 24 days, and about 30 days. Our first objective was to examine transpiration and biomass production during drought and recovery after rewatering. Our second objective was to determine the presence and influence of genotypic variation.

Material and Methods

Details of cultural practices

An experiment was conducted in the 1999 dry season in the greenhouse at the International Rice Research Institute (IRRI), Los Baños, Philippines (14° 11′ north, 121° 15′ east, 23 m altitude). A split-plot design with three replicates was used, with three water regimes (well watered, shorter and prolonged periods of stress) as the main plots and six rice genotypes as subplots. In the shorter stress treatment, ponded water was drained at 21 days after sowing (DAS) and no water was supplied until transpiration was about 3.9 kg of water, that is, 22 to 24 days after drainage, depending on genotype (shorter drought period). After the drought, 4 kg of water was replenished, then water was added daily for 7 days to keep the level of ponded water the same as in the well-watered treatment (rewatering period). In the prolonged stress treatment, drought was extended for another 7 days. Plants were then given 7 days of rewatering, as for the shorter stress treatment.

Six rice genotypes adapted to rainfed lowlands were used: CT9993-5-10-1-M (CT9993), IR62266-4-2-6-2 (IR62266), IR58821-2-3-B-1-2-1 (IR58821), IR52561-UBN-1-1-2 (IR52561), Khao Dawk Ma Li 105 (KDML105) and Nam Sa Gui 19 (NSG19). These genotypes were among eight that were selected from diverse rainfed lowland rice germplasm and differed for root system and osmotic adjustment (Shashidhar et al. 1994; Samson et al. 1995; Lilley and Ludlow 1996; Ray et al. 1996; Sarkarung et al. 1997; Azhiri-Sigari et al. 2000; Kamoshita et al. 2000).

Twenty kilos of sandy loam soil (pH = 5.7) were sieved, air-dried and placed in a plastic sleeve inside a PVC pot, with a 20-cm internal diameter and 55 cm high. The pots' sides were covered with aluminium foil to minimize increase in soil temperatures. The soil surface was covered with small cubic polystyrene after drainage and the tops of all the pots were covered with aluminium foil to minimize evaporation so that any changes in pot weight could be attributed to transpiration from plants and/or watering. An adequate amount of fertilizer was supplied, with 2.73 g of urea for nitrogen, 1.84 g of solphos for phosphorus and 1.04 g of muriate potash for potassium. Four to five pre-germinated seeds were sown in each pot on 29 January 1999, and thinned to one young seedling per pot at 12 DAS. Ponded water in the well-watered treatment was always kept at about 2 to 4 cm deep. No disease, insect or weed damage was observed.

Measurements

Meteorological data

The minimum and maximum daily air temperatures were collected by a hygrothermograph, and evaporation was measured with seven pan evaporimeters randomly placed inside the greenhouse. The average daily minimum and maximum air temperatures during the experiment were 26.5°C and 34.4°C, respectively, and average evaporation was 4.8 mm d^{-1}.

Transpiration and plant sampling

Daily transpiration was calculated, from 21 DAS until the end of the experiments, by measuring weight loss in the drought treatment and water added in the well-watered treatment. Cumulative transpiration after 21 DAS was calculated by the sum of daily increments in each water regime.

Plants were sampled at different times, according to genotype (Table 1):

1. At 21 DAS and before stress imposition;
2. When cumulative transpiration has reached about 2.0 kg, between 32 and 36 DAS;
3. When cumulative transpiration has reached about 3.9 kg, between 43 and 45 DAS;
4. 7 days after the third sampling, that is, between 50 and 52 DAS; and
5. 7 days after the fourth sampling, that is, between 57 and 59 DAS.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Table 1. Six rice genotypes adapted to rainfed lowlands were evaluated for water-use efficiency and biomass production under drought. (a) Characteristics of each growth period used in the experiment; (b) sampling times (days after sowing; DAS) and cumulative transpiration under drought (kg); and (c) according to genotype, the five sampling occasions (1–5) in terms of DAS, and the intervals (in days) between samplings for each growth period.

(a)

Characteristic	Growth period[a]			
	DR$_i$	DR$_s$	RW$_s$/DR$_{pr}$	RW$_{pr}$
Interval (days)	11–15[b]	9–12[b]	7	7
Shorter stress	DR$_i$	DR$_s$	RW$_s$	—
Prolonged stress	DR$_i$	DR$_s$	DR$_{pr}$	RW$_{pr}$
Transpiration rate during drought (mm d^{-1})	5.1	5.7	2.9	—

(b)

Parameter	Sampling occasion				
	1	2	3	4	5
Sampling time	21	32–36[b]	43–45[b]	50–52[b]	57–59[b]
Cumulative transpiration	0	1.9	3.9	4.3–4.6[b]	—

(c)

Genotype	Sampling occasion					Intervals[a]			
	1	2	3	4	5	DR$_i$	DR$_s$	RW$_s$/DR$_{pr}$	RW$_{pr}$
CT9993	21	36	45	52	59	15	9	7	7
IR62266	21	33	44	51	58	12	11	7	7
IR58821	21	32	44	51	58	11	12	7	7
IR52561	21	35	45	52	59	14	10	7	7
KDML105	21	32	43	50	57	11	11	7	7
NSG19	21	32	43	50	57	11	11	7	7

[a] DR$_i$ = initiation of drought, whether the shorter or prolonged period; DR$_s$ = shorter drought period; RW$_s$ = rewatering after shorter drought period; DR$_{pr}$ = prolonged drought period; RW$_{pr}$ = rewatering after prolonged drought period.
[b] Differs according to genotype.

Different dates were chosen for each genotype on the second and third samplings to see the genotypic differences when all the genotypes used the same amount of water, thus minimizing the confounding effects of different potential growth under the well-watered treatment. In the fourth and fifth samplings, response of all the genotypes to the same duration of 7 days of prolonged drought or rewatering was examined. To assess plant response during each stage of drought development and rewatering, growth periods during the experiment were divided into:

- Initial drought period (from the first to second samplings)
- Shorter period of drought (from the second to third samplings)
- Prolonged period of drought (from the third to fourth samplings in prolonged stress treatment), and
- Rewatering period (from the third to fourth samplings in shorter stress treatment and from the fourth to fifth samplings in prolonged stress treatment).

Transpiration rate during each drought period was calculated. Plants in both water regimes were sampled at the same time. At each sampling, total shoot biomass was determined.

Root parameters

After each sampling of above-ground plant parts, the soil mass within the plastic sleeve was slowly pulled from the PVC pots, and divided into layers of 0–5, 5–10, 10–20, 20–30, 30–40 and 40–50 cm from the soil surface. Root dry matter in each soil layer was measured, and total and deep-root dry matter below the 30-cm soil layer were calculated. Root-to-shoot ratio was estimated from total root dry matter divided by total shoot biomass. Deep-root ratio was calculated as a proportion of deep-root matter to total root matter.

Statistical analysis

Analysis of variance was conducted for each water regime and the least significant difference at the probability of 5% was determined, using Systat 7.0 (SPSS 1997).

Results

Stress development and plant response

The values presented in this section comprise the averages of all six genotypes.

Transpiration

In the stress treatments, increase in cumulative transpiration from 21 DAS was much slower than in the well-watered treatment (Table 2). The level of cumulative transpiration under drought was 67%, 31% and 19% of the well-watered treatment by the end of the initial, shorter and prolonged periods of droughts, respectively. The average transpiration rate was 5.1, 5.7 and 2.9 mm d^{-1} in the initial, shorter and prolonged droughts, respectively (cf. Table 1a). In response to rewatering, the rate of transpiration increased, and the amount of transpiration during the 7 days of rewatering was about 5.8 and 5.7 kg for the shorter stress and prolonged stress treatments, respectively.

Root growth

Total root matter and root-to-shoot ratio were always higher in the well-watered treatment than in the stress treatments (Table 2). Root-to-shoot ratio declined during drought and increased during rewatering. In stress treatments, deep-root matter and deep-root ratio increased during drought but stopped increasing after rewatering (data not shown). Deep-root ratio was 10% and 17% at the end of shorter and prolonged droughts, respectively, while it was less than 3% in the well-watered treatment at the corresponding times.

Shoot biomass

The pattern of shoot biomass production over time was similar to that of transpiration (Table 2). The level of shoot biomass under drought was 81%, 46% and 31% of well-watered treatment by the end of the initial, shorter and prolonged droughts, respectively. Water-use efficiency (WUE), calculated by the increment of shoot biomass divided by the increment of transpiration (both from 21 DAS) in the well-watered treatment, was 2.65 g kg^{-1} during the experiment. Water-use efficiency was higher under drought, with the values 3.05, 3.97 and 4.05 g kg^{-1} at the end of initial, shorter and prolonged droughts, respectively.

Table 2. Cumulative transpiration (kg) from 21 days after sowing, total root matter (g), root-to-shoot ratio (%), and shoot biomass (g) at each sampling occasion (1–5) under three water regimes.

Parameter	Sampling occasion				
	1	2	3	4	5
Transpiration (kg)					
Well-watered	0	2.93	12.36	24.03	40.24
Shorter stress	0	1.97	3.88	9.66	—
Prolonged stress	0	1.97	3.88	4.52	10.23
Total root matter (g)					
Well-watered	0.05	0.88	4.14	8.36	11.06
Shorter stress	0.05	0.48	1.09	2.80	—
Prolonged stress	0.05	0.48	1.09	1.25	2.41
Root-to-shoot ratio (%)					
Well-watered	8.7	10.6	12.1	14.0	10.5
Shorter stress	8.7	7.3	6.9	9.2	—
Prolonged stress	8.7	7.3	6.9	6.6	8.7
Shoot biomass (g)					
Well-watered	0.6	8.2	34.4	60.1	107.3
Shorter stress	0.6	6.6	16.0	30.6	—
Prolonged stress	0.6	6.6	16.0	18.9	28.1

In response to rewatering, it declined to 3.10 g kg^{-1} under the shorter stress treatment and dropped further to 2.68 g kg^{-1} under the prolonged stress treatment (data not shown).

Genotypic variation

Transpiration

Under initial drought, NSG19, KDML105 and IR58821 transpired about 2 kg of water 3 or 4 days earlier than did IR52561 and CT9993, respectively (cf. Tables 1 and 3). In the shorter drought, CT9993 and IR52561, respectively, transpired about 1.9 kg of water in 3 and 2 days earlier than IR58821. During the 7 days of prolonged drought, IR58821 and NSG19 transpired the smallest amounts of water while CT9993 and IR52561 transpired the largest amounts (Table 3). During the 7 days of rewatering periods under both shorter and prolonged stress treatments, NSG19 transpired the largest amount of water, followed by KDML105, whereas CT9993 and IR62266 transpired the least amount of water, with this genotypic variation being wider under the prolonged stress treatment. Increment of transpiration on the date of rewatering was higher for NSG19 and KDML105 (data not shown). Under the prolonged stress treatment, KDML105 and NSG19 had higher amounts of transpiration (about 0.12 kg) 3 h after rewatering.

Table 3. Cumulative transpiration in shorter and prolonged water stress treatments during each growth period for each rice genotype.

	Transpiration (kg)[a]				
Genotype	DR_i	DR_s	RW_s	DR_{pr}	RW_{pr}
CT9993	2.03	1.82	5.57	0.76	4.62
IR62266	1.95	1.96	5.32	0.65	5.06
IR58821	1.93	1.91	5.73	0.48	5.60
IR52561	1.97	1.89	5.67	0.77	5.18
KDML105	1.95	1.99	6.05	0.63	6.70
NSG19	1.98	1.92	6.32	0.53	7.14
$LSD_{0.05}$	ns	ns	ns	0.10*	1.60**

[a] See footnote a, Table 1.

** = significant at P = 0.01; * = significant at P = 0.05; ns = not significant at P = 0.05.

Root growth

Under the well-watered treatment, IR58821 had significantly higher total and deep-root matter than did the other genotypes (data not shown). At 51 DAS, the root-to-shoot ratio of IR58821 was 20% and, at 58 DAS, deep-root ratio was 7.3%. Among the other five genotypes, NSG19 and KDML105 increased deep-root matter at an earlier growth stage, whereas CT9993 and IR52561 were later.

Under the stress treatments, IR58821 had the smallest root-to-shoot ratio (5.7%) at the end of prolonged drought treatment and IR52561 had smallest total root matter during the droughts (data not shown). CT9993 always had the highest root-to-shoot ratios (9.7% at the end of prolonged drought) and largest total root matter by the end of the prolonged drought treatment. IR58821 increased root-to-shoot ratio up to 9.9% and 9.4% under the shorter and prolonged stress treatments, respectively, which were the second highest values after CT9993 (10.4% and 10.0%, respectively). Deep-root matter increased fastest in CT9993, followed by NSG19 and KDML105, and was slowest in IR52561 by about 44 DAS.

Shoot biomass production

Before stress was imposed, significant genotypic variation was observed for shoot biomass on 21 DAS, in descending order: NSG19, IR58821, KDML105, IR62266, IR52561 and CT9993 (Table 4). This genotypic ranking was, overall, retained at the end of the experiment under the well-watered treatment. During initial drought, shoot biomass increment was higher in IR52561 and CT9993 and smallest in IR62266 and IR58821, despite the fact that all the genotypes transpired almost the same amount of water. All the genotypes reduced shoot biomass production during the initial drought, compared with the well-watered treatment, but the proportion of reduction was smallest in CT9993 (96%) and KDML105 (93%). During the shorter drought treatment, shoot biomass increment was higher in KDML105 and NSG19 than in CT9993 and IR52561, despite the fact that all the genotypes transpired almost the same amount of water. During the 7 days of rewatering under the shorter stress treatment, shoot biomass increment was highest in NSG19, followed by KDML105, and smallest in IR62266. During the 7 days of prolonged drought, NSG19 and KDML105 had the smallest increase in shoot biomass, whereas IR52561 and CT9993 had the largest. During the 7 days of rewatering under the prolonged stress treatment, KDML105 and NSG19 had the greatest shoot biomass increment, whereas CT9993 and IR52561 had the least.

Discussion

Response to, and recovery from, two different drought periods

This study compared plant water use, root growth and shoot response between two periods of drought,

Table 4. Shoot biomass (g) in six rainfed-lowland rice genotypes before stress imposition and at the end of the experiment under a well-watered treatment, and increment of shoot biomass (g) during each growth period under water stress treatments for each genotype.

Genotype	Shoot biomass (g)						
	Well-watered		Stress[a]				
	First sampling	Fifth sampling	DR_i	DR_s	RW_s	DR_{pr}	RW_{pr}
CT9993	0.38	86.4	6.6	6.2	13.8	3.5	7.5
IR62266	0.59	104.5	4.9	9.7	12.6	3.3	9.2
IR58821	0.78	115.5	5.5	10.1	14.5	3.0	8.2
IR52561	0.52	97.4	6.8	7.9	14.7	3.8	7.4
KDML105	0.68	117.1	5.8	11.3	15.2	2.6	11.7
NSG19	0.87	123.0	6.5	10.7	17.0	1.5	10.9
$LSD_{0.05}$	0.20**	10.1**	1.3^+	3.8*	4.8^+	ns	2.1**

[a] See footnote a, Table 1.
** = significant at P = 0.01; * = significant at P = 0.05; + = significant at P = 0.10; ns = not significant at P = 0.10.

designated as ‘shorter’ and ‘prolonged’, and plant behaviour after rewatering. Stress intensity during the initial and shorter drought periods, as measured by transpiration rate (5.1 and 5.9 mm d^{-1}, respectively), was slightly lower than, but comparable with, findings by Kamoshita et al. (2000) (about 7.6 mm d^{-1}). During the 7 days of prolonged drought, however, the transpiration rate declined significantly to 2.9 mm d^{-1}.

Proliferation of deep roots was enhanced during drought, with the deep-root ratio being, respectively, 10% and 17% at the end of the shorter and prolonged droughts. These values were much higher than those reported by Azhiri-Sigari et al. (2000) for similar pot experiments (3% and 4%). The reason is not clear, but the polystyrene covering the soil may have slowed the rate of stress development in this study, thereby minimizing water loss through evaporation. Another reason may also have been the favourable weather conditions that allowed partitioning of assimilates to deeper soils. As the deep-root ratios in the well-watered treatment (0.3%) were comparable with values obtained by Azhiri-Sigari et al. (2000) (0.4% and 1.2%, respectively), adaptive response of deep-root development to drought may be highly affected by the characteristics of drought development.

Osmotic adjustment was about 0.5 MPa by the end of the initial drought period, and gradually increased thereafter to 0.7 MPa. Apparently, it was not associated with leaf retention or leaf elongation rate, which sharply declined during the shorter period of drought (data not shown). Reduction in shoot biomass production during drought was less than that of transpiration, because of an increased WUE.

With rewatering, the transpiration rate increased, surface root length increased, and leaf-water potential increased. Leaf growth and shoot biomass production recovered. No difference in the rate of transpiration at recovery was found between the two stress treatments, but increment of shoot biomass after rewatering after prolonged stress was 63% of that for the shorter stress treatment, showing that the prolonged drought caused greater damage to the shoots’ physiological functions.

Genotypic variation

This study demonstrated that plant size before stress was significant for subsequent response to drought and rewatering. Genotypes with higher seedling vigour such as NSG19 and KDML105 developed a deep-root system and started earlier to extract soil water from deeper layers. They also decreased leaf-water potential earlier once having exhausted the extractable soil water (data not shown). NSG19 and KDML105 had lower transpiration rates and WUE during the prolonged drought treatment, suggesting that this treatment most severely damaged growth in these two genotypes. Even so, these genotypes still retained higher shoot biomass by the end of either drought treatment. However, the drought periods in our study were not long enough to alter the ranking of shoot biomass and thus could not verify Passioura’s argument (1982) that vigorous genotypes exhaust soil water earlier and thus become more severely damaged under prolonged drought.

The relationship between root-length density and soil-water extraction rate in deeper soil layers at the end of shorter stress treatment was apparently negative (data not shown). The genotypes that developed an early deep-root system and thus had higher root-length density at the end of shorter stress treatment (i.e. NSG19 and KDML105) had started extracting soil water from deeper layers earlier and thus had smaller amounts of extractable water after 36 DAS. Although Kamoshita et al. (2000) established a positive correlation between root-length density and soil-water extraction rate from deep soil layers during drought, observations started at the beginning of soil-water extraction from these soil layers. Genotypes that more quickly develop deep roots in response to drought can take up water more quickly at first but, as the extractable water in deep soil layers decreases, the degree of deep-root length has little advantage for extracting water, unless roots are able to continue proliferating in yet deeper soil layers where extractable water would be available.

Genotypic variation in maintenance of leaf-water potential was not clear, except that leaf-water potential declined earlier in genotypes with high seedling vigour and which extracted water more quickly (data not shown) (Kamoshita et al. 2000). Genotypic variation in osmotic adjustment was observed (data not shown), with some data corroborating the results of Kamoshita et al. (2000), who showed osmotic adjustment to be high in IR52561 and low in CT9993. No relationship was found between osmotic adjustment and increment of shoot biomass in this study. To demonstrate the effect of osmotic adjustment on growth, near isogenic lines need to be developed (Zhang et al. in press). More research is needed to estimate genotypic variation for osmotic adjustment and its association with leaf-water potential (Jongdee 1998; V.Sibounheuang et al. this volume)

Recovery of shoot biomass production after rewatering was more rapid in NSG19 and KDML105, and this was more notable under the prolonged stress treatment than under the shorter stress treatment. The greater shoot biomass retained by NSG19 and KDML105 by the end of the drought periods may have been advantageous in that transpiration increased more rapidly after rewatering. Wade et al. (2000) and Mitchell et al. (1998) pointed out the importance of the extent of leaf area and leaf biomass at drought’s end for superior recovery from drought. In contrast, Blum (2000) suggested that recovery from drought was mostly affected by plant water status such as relative water content, leaf-water potential or osmotic adjustment at drought’s end. In this study, NSG19 and KDML105 had higher osmotic adjustment at drought’s end, but the relationship between leaf-water potential at the end of the stress treatments and capacity to recover was not clear.

Wade et al. (1999) related trait expression in seedlings of rice reference lines with their adaptation to diverse rainfed-lowland environments. Although the results of these greenhouse experiments need to be interpreted with caution, they do at least help us understand the adaptation of the rainfed-lowland reference lines to early season drought. At the same time, the effects of physio-morphological traits on biomass production and growth need to be quantified by using genotypes with similar genetic backgrounds, except for the traits. Experiments are being carried among genotypes selected from doubled haploid lines, which have similar seedling vigour but differ in rooting capacity.

Conclusions

In responding to drought, genotypes with higher seedling vigour developed a deep-root system earlier. This resulted in a more rapid extraction of water and reduced transpiration, WUE and biomass production, particularly during the prolonged drought treatment. Capacity to recover was always greater in NSG19 and KDML105, which are genotypes with higher seedling vigour and which retained greater biomass by the drought’s end, even when drought was prolonged and caused increased injury.

Acknowledgments

We thank Rene M. Panopio, Donato V. Lanwang and Ramon B. Masajo for helping with experimental operations, and Dr. Surapong Sarkarung for providing seeds. The Japan—IRRI Shuttle Project supported this research.

References

Azhiri-Sigari, T., Yamauchi, A., Kamoshita, A. and Wade, L.J. 2000. Genotypic variation in response of rainfed lowland rice to drought and rewatering. II. Root growth. Plant Production Science, 3, 180–188.

Blum, A. 2000. Towards standard assays of drought resistance in crop plants. In: Ribaut, J.M. and Poland, D. ed. Molecular Approaches for the Genetic Improvement of Cereals for Stable Production in Water-Limited Environments. A Strategic Planning Workshop held at CIMMYT, El Baton, Mexico, 21–25 June 1999. Mexico, Centro Internacional para Mejoramiento de Maiz y Trigo (CIMMYT), 29–35.

Fukai, S. and Cooper, M. 1995. Development of drought-resistant cultivars using physiomorphological traits in rice. Field Crops Research, 40, 67–86.

Fukai, S., Pantuwan, G., Jongdee, B. and Cooper, M. 1999. Screening for drought resistance in rainfed lowland rice. Field Crops Research, 64, 61–74.

Jongdee, B. 1998. The importance of leaf water potential and osmotic adjustment on growth and grain yield of rice (*Oryza sativa* L.) genotypes under water deficit conditions. Ph.D. dissertation. The University of Queensland, Brisbane, Qld., Australia.

Jongdee, B., Fukai, S. and Cooper, M. 1997. Genotypic variation in water relations and growth during vegetative stage among six rice lines contrasting in maintenance of high leaf water potential. In: Fukai, S., Cooper, M. and Salisbury, J. ed. Breeding Strategies for Rainfed Lowland Rice in Drought-Prone Environments. Proceedings of an International Workshop held at Ubon Ratchathani, Thailand, 5–8 November 1996. ACIAR Proceedings No. 77, 180–191.

Kamoshita, A., Wade, L.J. and Yamauchi, A. 2000. Genotypic variation in response of rainfed lowland rice to drought and rewatering. III. Water extraction during drought period. Plant Production Science, 3, 189–196.

Kamoshita, A., Zhang, J., Siopongco, J., Sarkarung, S., Nguyen, H.T. and Wade, L.J. In press. Effects of phenotyping environment on identification of QTL for rice root morphology under anaerobic conditions. Crop Science.

Lilley, J.M. and Fukai, S. 1994. Effect of timing and severity of water deficit on four diverse rice cultivars. I. Rooting pattern and soil water extraction. Field Crops Research, 37, 205–213.

Lilley, J.M. and Ludlow, M.M. 1996. Expression of osmotic adjustment and dehydration tolerance in diverse rice lines. Field Crops Research, 48, 185–197.

Mitchell, J.H., Siamhan, D., Wamala, M.H., Risimeri, J.B., Chinyamakobvu, E., Henderson, S.A. and Fukai, S. 1998. The use of seedling leaf death score for evaluation of drought resistance of rice. Field Crops Research, 55, 129–139.

Nguyen, H.T., Babu, R.C. and Blum, A. 1997. Breeding for drought resistance in rice: Physiology and molecular genetics considerations. Crop Science, 37, 1426–1434.

O’Toole, J.C. 1982. Adaptation of rice to drought-prone environments. In: Drought resistance in crops with emphasis on rice. International Rice Research Institute (IRRI), Los Baños, Philippines, 195–213.

Pantuwan, G., Fukai, S., Cooper, M., O’Toole, J.C. and Sarkarung, S. 1997. Root traits to increase drought resistance in rainfed lowland rice. In: Fukai, S., Cooper, M. and Salisbury, J. ed. Breeding Strategies for Rainfed Lowland Rice in Drought-Prone Environments. Proceedings of an International Workshop held at Ubon Ratchathani, Thailand, 5–8 November 1996. ACIAR Proceedings No. 77, 170–179.

Passioura, J.B. 1982. The role of root system characteristics in the drought resistance of crop plants. In: Drought resistance in crops with emphasis on rice. International Rice Research Institute (IRRI), Los Baños, Philippines, 71–82.

Ray, J.D., Yu, L.X., McCouch, S.R., Champoux, M.C., Wang, G. and Nguyen, H.T. 1996. Mapping quantitative trait loci associated with root penetration ability in rice (*Oryza sativa* L.). Theoretical Applied Genetics, 42, 627–636.

Samson, B.K., Wade, L.J., Sarkarung, S., Hasan, M., Amin, R., Harnpichitvitaya, D., Pantuwan, G., Rodriguez, R., Azhiri-Sigari, T. and Calendacion, A. 1995. Examining genotypic variation in root traits for drought resistance. In: Tuong, T.P. ed. Fragile Lives in Fragile Ecosystems. Proceedings of the International Rice Research Conference, 13–17 Feb 1995. International Rice Research Institute (IRRI), 521–534.

Sarkarung, S., Pantuwan, G., Pushpavesa, S. and Tanupan, P. 1997. Germplasm development for rainfed lowland ecosystems: breeding strategies for rice in drought-prone environments. In: Fukai, S., Cooper, M. and Salisbury, J. ed. Breeding Strategies for Rainfed Lowland Rice in Drought-Prone Environments. Proceedings of an International Workshop held at Ubon Ratchathani, Thailand, 5–8 November 1996. ACIAR Proceedings No. 77, 43–49.

Shashidhar, H.E., Ray, J.D., Nguyen, H.T., Sarkarung, S. and O’Toole, J.C. 1994. Genetic variation for root hardpan penetrability and restriction fragment length polymorphism survey in rice. Paper presented at International Program on Rice Biotechnology 7th annual meeting, held 16–22 May 1994, Bali, Indonesia.

SPSS Inc. 1997. SYSTAT 7.0: New Statistics. Chicago, IL. 303 p.

Wade, L.J., McLaren, C.G., Quintana, L., Harnpichitvitaya, D., Rajatasereekul, S., Sarawgi, A.K., Kumar, A., Ahmed, H.U., Sarwoto, Singh, A.K., Rodriguez, R., Siopongco, J. and Sarkarung, S. 1999. Genotype by environment interactions across diverse rainfed lowland rice environments. Field Crops Research, 64, 35–50.

Wade, L.J., Kamoshita, A., Yamauchi, A. and Azhiri-Sigari, T. 2000. Genotypic variation in response of rainfed lowland rice to drought and rewatering. I. Growth and water use. Plant Production Science, 3, 173–179.

Zhang, J., Nguyen, H.T. and Blum, A. 1999. Genetic analysis of osmotic adjustment in crop plants. Journal of Experimental Botany, 50, 291–302.

Zhang, J., Zheng, H.G., Tripathy, J.N., Aarti, Sarial, A.K., Robin, S., Nguyen, T.T., Babu, R.C., Nguyen, B.D., Sarkarung, S., Blum, A. and Nguyen, H.T. In press. Locating genomic regions associated with osmotic adjustment and root penetration ability in rice. Theoretical Applied Genetics.

Leaf-Water Potential as a Drought Resistance Character in Rice

V. Sibounheuang, J. Basnayake*, S. Fukai and M. Cooper

Abstract

Drought significantly constrains higher yield and yield stability in rainfed rice. Maintenance of high leaf-water potential (ψ_L) is associated with drought resistance, and water potential may be useful as an indirect selection criterion for improving drought resistance in rainfed rice. Rice is most sensitive to water deficit when flowering. We conducted three experiments to study (1) the genotypic variation in ψ_L and its association with spikelet sterility under drought conditions; (2) the relationship between plant water status and delay in flowering among lines under different moisture regimes; (3) whether genotypic variation for ψ_L was related to plant size and xylem anatomy; (4) the genotypic variation for water potential at given positions within the plant; and (5) the consistency of water potential across lines. The results of the field studies suggested that drought reduced ψ_L and delayed flowering. The genotypic variation of ψ_L for lowland was generally higher than upland stress conditions. The percentage of spikelet sterility of each genotype was positively associated with the delay in flowering time and negatively associated with ψ_L under both lowland and upland stress conditions. Maintenance of water potential was not always related to plant size. Water potential varied according to the position within the plant, being lowest at the leaf tip and highest at the stem base. Variation in ψ_L across lines was related to internal water conductance, xylem vessels and stem cross-section areas.

Rice (Oryza sativa L.) is a major staple food crop in the world, supplying one third of the world's population with more than 50% their calories and nearly half their protein. Rice is grown in the most diverse range of environments (Wade et al. 1999), although yield is usually low in rainfed lowland systems because of drought and drought-associated problems (Widaswsky and O'Toole 1990; Ingram 1995; Mackill et al. 1996). The lower grain yield obtained in rainfed lowlands is partly because cultivars have inadequate tolerance of drought, other abiotic and biotic stresses, poor response to inputs such as nutrients and genetically low yield potential (Singh and Dwivedi 1997).

Fukai and Cooper (1995) suggested that the timing and severity of drought affect grain yield differently, that is, a significant genotype × environment interaction for grain yield operates in drought-prone environments. O'Toole (1982) has described characteristics of drought resistance in rice. Fukai and Cooper (1995) have suggested that the efficiency of breeding programs can be improved by complementing selection for yield with selection for physiological traits that contribute to yield in important, well-defined, and targeted drought environments.

A drought's effect depends not only on the timing or severity of the water deficit but also on the developmental stage at which it hits the crop (Somrith 1997). Reduced grain yield is particularly associated with failure in processes that determine grain number (Lilley and Fukai 1994). O'Toole and Moya (1978), and Jongdee (1998) have reported genotypic variation in leaf-water potential (ψ_L) among rice cultivars

---

School of Land and Food Sciences, University of Queensland, Brisbane, Qld., 4072, Australia
*Corresponding author: E-mail: J.Basnayake@uq.edu.au

KEYWORDS: Delay in flowering, Plant size, Spikelet sterility, Vascular bundle, Water potential, Water stress, Xylem vessel size

with diverse genetic backgrounds. Fukai and Cooper (1995) have suggested that the maintenance of ψ_L may be usefully treated as a selection criterion for specific types of drought environments.

Jongdee (1998) and Pantuwan et al. (1997) have suggested some plant characters are associated with genotypic variation for leaf-water potential under water stress, including delay in flowering, spikelet sterility, pollen sterility and water conductance. Water stress could delay flowering and, subsequently, increase spikelet sterility. Plant size and water conductance have been shown to associate to some degree with spikelet sterility under water stress (Jongdee 1998). Further research is needed to verify these hypothesized associations, and to allow us to identify the major morphological and physiological mechanisms involved in maintaining high ψ_L in rice.

Among the several traits reported as associated with drought adaptation in rainfed lowland rice, ψ_L is one of the accepted indicators of water status in the plant (Jongdee 1998). It is determined by the interaction of several processes involved in the uptake, transport and loss of water from the plant. Genotypic differences probably exist in the patterns of accessing soil water and taking it up (both involving the root system); of losing water to the atmosphere (involving stomatal conductance, canopy size, leaf rolling and degree of leaf death); and, possibly, of resistance by the vascular system to water transport.

This study aimed to investigate, in rice, (1) the effect of water deficit during the reproductive stage on the expression of genotypic variation for ψ_L in terms of delay in flowering and spikelet sterility, (2) the relationships between ψ_L, delay in flowering and spikelet sterility; (3) whether an association exists between genotypic variation in ψ_L, plant size and the stem's internal anatomy; (4) the relationship between vascular anatomy and the water potential gradient within the plant; and (5) the consistency of water potential across different rice lines with contrasting ability to maintain ψ_L.

Materials and Methods

Three experiments were conducted at the University of Queensland (UQ) during 1999–2000.

Experiment 1 Water stress and delay in flowering

Experiment 1 was conducted under both lowland and upland conditions, with two moisture regimes (irrigated and water stress at flowering) from October 1999 to March 2000. The rainout shelter facility at the University's Redland Bay Farm was used to impose water stress. Water was withheld before the plants started to head and the plots were re-watered after 12 (lowland) or 13 days (upland). Control treatments were continuously irrigated.

Plants were grown in a randomized complete block design with three replicates. Each plot comprised four rows, each 1 m long and spaced at 20 cm from each other. Within each row, plants were spaced at 10 cm. Measurements were taken from the middle two rows, leaving 2 hills at each side of the plot. In total, 19 lines, with varying capacities to maintain ψ_L, were used for Experiment 1 (Table 1). Some of these lines (e.g. Lines 18–11, 57–1 and 28) were from an F5 population of a bi-parental cross of cv Lemont and BK88–BR6 (Jongdee 1998). 'Doongara', 'Illabong' and 'Calrose' are Australian commercial cultivars. Most of the other lines were introductions and had been tested for drought characteristics at the UQ. Because the lines differed in phenology, a staggered planting system was used to synchronize flowering. Seeds from each line were hand sown three times at intervals of 4 days. Fertilizer was applied at 40 kg N ha^{-1}, 48 kg P ha^{-1} and 40 kg K ha^{-1} as a basal and 40 kg N ha^{-1} at 55 and 75 days after sowing.

Flowering date was recorded for each experiment when 50% of the plants in the plot had flowered. The difference between flowering dates of the irrigated and stressed treatments was used to measure delay in flowering. At the time of imposing water stress, six stems with a similar auricle distance (2 cm) were identified in each plot. These plants were used for all measurements. Three panicles were collected at physiological maturity from plants used to take water relation measurements under each water regime. Filled and unfilled grains were counted in the separate panicles to determine spikelet sterility.

Leaf-water potential was measured, using the pressure chamber technique described by Turner (1981). Midday ψ_L (10.00 a.m.–3.00 p.m.) and predawn ψ_L (1.00 a.m.–4.30 a.m.) were measured three times during the stress period for both lowland and upland conditions.

Experiment 2 Plant size and maintenance of LWP

Experiment 2 was conducted to determine the effects of plant size on the expression of ψ_L in rice under stress. Anatomical differences in the stem in contrasting lines were studied. Four lines; cv Lemont, and Lines 36, 77 and 28 were used to study the importance of ψ_L and osmotic adjustment on growth and yield under water deficit (Jongdee 1998). Four plant sizes used were full canopy, 1/3 leaf removal, 2/3 leaf removal and tillers reduced to six in number. Two line-mixture treatments, using plants of different sizes, were also conducted: one tall (Line 77) and two short lines (Lines 36 and cv Lemont) in a mixture, and the same lines in alternate rows. The leaf removal treatments were imposed 58 days after sowing (DAS).

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Experiment 2 was conducted under upland conditions at the UQ's Redland Bay Farm during the 1999 summer. Three water environments, namely, irrigation, mild water stress and severe water stress were used. Water was withheld at 58 DAS in both the mild and severe stress environments, and the rainout shelter facility was used to continue the stress period by preventing rain landing on the plots. For the mild stress environment, water was withheld for 14 days, starting at 58 DAS, and for severe stress, for 18 days, starting at 58 DAS.

Plants were grown in a randomized complete block design with three replicates. Each replicate consisted of 18 treatments: 4 lines × 4 plant sizes + 2 line-mixture treatments with tall and short lines in alternate row arrangement. Each plot measured 1.92 m^2, comprising 6 rows per treatment spaced at 20 cm. Within each row, spacing between plants was 10 cm. Seeds were hand sown and the plants were thinned at 14 DAS to one plant per hill. Fertilizer was applied at 40 kg N ha^{-1}, 48 kg P ha^{-1} and 40 kg K ha^{-1} as a basal, and 40 kg N ha^{-1} at 55 DAS.

Plant size (mean leaf area of 4 plants) was measured before and after stress to investigate the relationship between plant size and development of midday ψ_L during the stress period. The sets of measurement were taken at 61, 67 and 71 DAS for mild stress and at 61 and 75 DAS for severe stress. Leaf-water potential was also measured in the control treatment.

For each line, stems were collected to determine the size and number of vascular bundles and xylem cells. Samples were taken from the base of the main tiller (fourth node from the base). They were preserved in a solution of 50% ethanol, 5% acetic acid, 5% formaldehyde and distilled water. A cross section of a stem was taken and observed through the microscope with a ×100 magnification to determine the size and number of vascular bundles. The total number of vascular bundles within the cross section was counted. In addition, the diameter of the xylem within a large vascular bundle was measured, using five xylem cells chosen at random. The stem's inner and outer circles were also measured to determine stem area. Total xylem area was thus calculated from both xylem diameter and number of vascular bundles.

Experiment 3 Xylem anatomy and water potential

Experiment 3 was conducted in a greenhouse at the UQ in Brisbane during the 1999–2000 summer. Greenhouse temperature varied between 28°C and 32°C, differing by 2–3°C from outside temperatures. The six lines studied were cv Lemont, and Lines 36, 77, 28, 29 and 49, which, according to Jongdee (1998) differ in their ability to maintain ψ_L levels under water stress: cv Lemont and Line 36 maintain higher levels of ψ_L than do Lines 29 and 49, which, in their turn, maintain higher levels than do Lines 28 and 77.

The six lines were planted at 2 plants per pot (30 cm in diameter and 25 cm high). Each pot was filled with 3.5 kg of sandy loam soil with uniform soil moisture conditions. Pots were allocated to four replicates and, at weekly intervals, were moved randomly within their respective replicates. Adequate amounts of fertilizer and water were applied to ensure that growth was not limited until the stress treatments began. Water stress was imposed at 79 DAS. Before that date, soil moisture content was kept constant in all pots. The control treatment (no stress), using the same lines, was planted in two replicates.

Plant-water potential (ψ) was measured five times during 10 days of stress at four positions in the plant: leaf tip, leaf base, leaf sheath and base of main stem. Before stress was imposed, primary stems were collected from plants of the six lines and preserved in a 50% alcohol medium for the microscopic study of vascular anatomy. These samples were used to determine, for each line, the number of vascular bundles, number of xylem cells within the vascular bundles, size of xylem (in a large vascular bundle from stem) and area of the stem cross section at different positions within the plant. Cross sections of the leaf tip, leaf base, leaf sheath and stem were taken and observed under the microscope with varying magnifications. Total xylem area was calculated as described for Experiment 2. Samples for ψ measurements were taken from the same positions as for the stressed plants. The rate of development of water stress in each position was estimated by taking the difference between the first and last ψ values of the stressed plant, and dividing by number of days of the stress period. Analyses of variance were conducted for each measurement time and for each of the four positions in the plant. The significance of variations among lines and positions in plants and their interaction was analysed.

Results

Experiment 1

Delay in flowering

Delay in flowering was assessed by taking the difference in days to flowering between the control (no stress) and stress treatments for upland and lowland conditions. Analysis revealed that the variation among lines for delay in flowering was significant for both upland and lowland stress conditions ($P < 0.05$), ranging from 1 to 6 days under upland conditions, and from 1 to 7 days under lowland conditions (Table 1). Some consistency was found when ranking lines for delay in flowering under upland and lowland conditions ($R^2 = 0.67$). However, line 122221 was quickly stressed under lowland conditions, showing as long a delay in flowering as did Line 28. Cultivar Lemont and line AYR657 showed least delay in flowering (1 day) under lowland conditions, whereas Line 28 was most delayed under both conditions (6 and 7 days, respectively). The association between delay in flowering and flowering date was poor under well-watered conditions.

Development of water stress in different rice lines

Under lowland stress conditions, predawn and midday ψ_L declined steadily during the 12 days of stress. They ranged from −0.85 to −2.84 MPa for midday ψ_L and −0.31 to −1.70 MPa for predawn ψ_L. Under upland stress conditions, midday ψ_L declined slowly during the first 9 days in the stress period, then dropped sharply during last 4 days. The measurements ranged from −0.85 to −2.16 MPa for midday ψ_L and from −0.17 to −0.99 MPa for predawn ψ_L. Both lowland and upland control treatments had similar levels of midday ψ_L (−0.82 and −0.90 MPa, respectively) at the end of the stress period.

The genotypic variation for midday and predawn ψ_L was significant ($P < 0.05$) for both upland and lowland stress conditions at the end of the stress period. Cultivar Lemont recorded the highest ψ_L, followed by line AYR657, under lowland stress conditions, whereas lines 122221 and 122230 recorded the lowest (Table 1). Under upland conditions, cv Lemont showed the highest ψ_L and Line 28 the lowest.

Total grain per panicle, and percentages of filled and unfilled grain

Variation among lines for the total number of grains per panicle was significant for both stress and irrigated conditions. The average grain number per panicle was 126 for upland stress conditions and 135 for lowland stress conditions. Cultivar Lemont and line AYR657 recorded the highest grain numbers per panicle under upland stress conditions, and lines AYR657 and 122221 had the highest under lowland stress conditions.

The genotypic variation for the percentage of filled and unfilled grains was also significant under both stress conditions. Under lowland conditions, the percentage of unfilled grains ranged from 25% to 75%, whereas for the upland conditions, it ranged from 33% to 69%. Generally, when the rate of water stress development was low, the variation in unfilled grain percentages among lines was higher in the lowland stress treatments than in the upland stress treatments.

Relationships between ψ_L, delay in flowering and percentage of unfilled grain

The relationship between delay in flowering and midday ψ_L (at the end of the stress period) was examined for 19 lines for both lowland and upland stress conditions. A negative association was found between midday and predawn ψ_L and delay in flowering under upland and lowland stress conditions (Figure 1). The R^2 for the linear association between ψ_L and delay in flowering was 0.54 and 0.65, respectively, for predawn and midday ψ_L in the uplands (Figure 1a).

Table 1. Delay in flowering and values for midday leaf-water potential (ψ_L, MPa) of 19 rice lines after 12 days of water stress under lowland conditions and 13 days of water stress under upland conditions in Experiment 1, Redland Bay Farm, University of Queensland, 1999–2000.

Cultivar or line	Delay in flowering		Midday ψ_L (MPa)	
	Upland	Lowland	Upland	Lowland
Lemont	1	1	–1.35	–1.63
AYR657	2	1	–1.87	–1.72
TJ4	3	4	–1.80	–3.03
M7	3	4	–2.43	–2.83
J29	3	3	–1.78	–2.60
Doongara	3	4	–2.24	–2.73
YRL39	3	4	–1.77	–3.07
122216	3	3	–1.73	–2.47
Illabong	3	3	–2.23	–2.33
Line 18–11	4	3	–2.53	–2.57
122230	4	5	–2.28	–3.37
Line 85–10	4	4	–2.53	–3.20
122227	4	5	–2.13	–3.23
ATF43	4	6	–2.27	–3.27
ATF47	4	4	–1.74	–2.91
122221	4	7	–2.10	–3.42
Line 57–1	5	5	–2.50	–3.17
Calrose	5	5	–2.77	–3.20
Line 28	6	7	–2.93	–3.13
Mean	**3.6**	**4**	**–2.16**	**–2.84**
$LSD_{0.05}$	2.4	2	0.65	0.80

Under lowland stress conditions (Figure 1b), the association was similar to that of upland stress conditions, with R^2 values of 0.52 and 0.80 for predawn and midday ψ_L, respectively. Cultivar Lemont had only a 1-day delay in flowering after 12 or 13 days of stress under lowland and upland conditions, and maintained higher ψ_L than the other lines.

A negative relationship was found between midday ψ_L and unfilled grain percentage for both upland and lowland stress conditions ($R^2 = 0.42$ and 0.56, respectively) (Figure 2). The lines able to maintain high ψ_L under water stress had a low percentage of unfilled grains than did lines with low ψ_L at the end of the stress period. Cultivar Lemont maintained a higher ψ_L than most other lines and had a low percentage of unfilled grain under both stress conditions. Conversely, Line 28 had a consistently low ψ_L and had a higher percentage of unfilled grain.

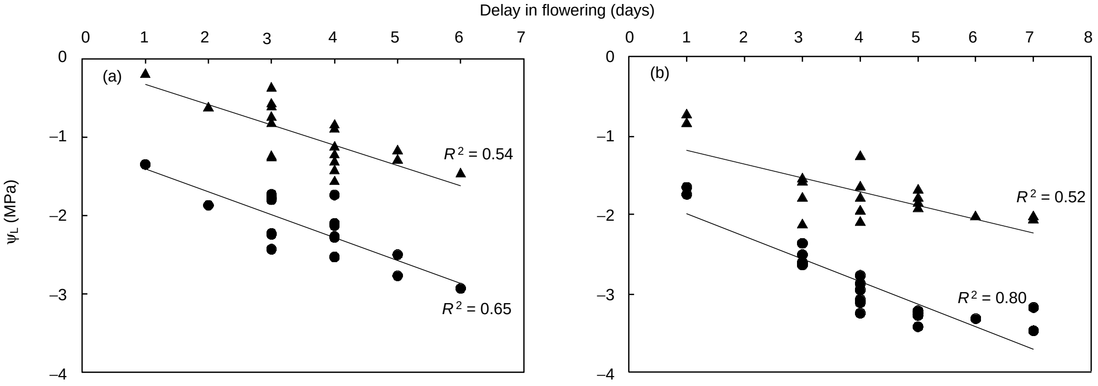


Figure 1. Relationship between delay in flowering, and midday (●) and predawn (▲) leaf-water potentials (ψ_L) in 19 rice lines after (a) 13 days under upland stress conditions, and (b) 12 days under lowland stress conditions.

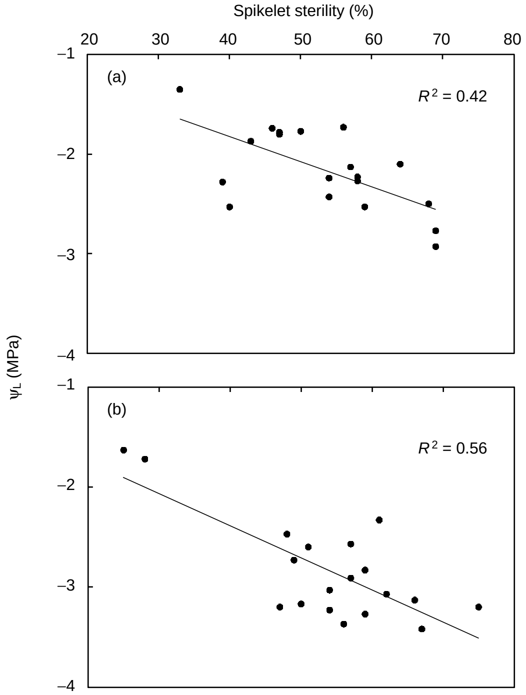


Figure 2. Relationship between spikelet sterility and midday leaf water potential (ψ_L) among 19 rice lines under (a) upland stress conditions, and (b) lowland stress conditions.

Relationship between delay in flowering and unfilled grain percentage

An association was found between delay in flowering and percentage of spikelet sterility under upland (R^2 = 0.50) and lowland (R^2 = 0.58) stress conditions (Figure 3). Lines with short delays in flowering produced the smallest unfilled grain percentages under water stress. Generally, under both stress conditions, cv Lemont delayed little in flowering and subsequently produced the lowest percentages of unfilled grain. In contrast, cv Calrose and Line 28 delayed longer in flowering and produced the highest percentages of unfilled grain.

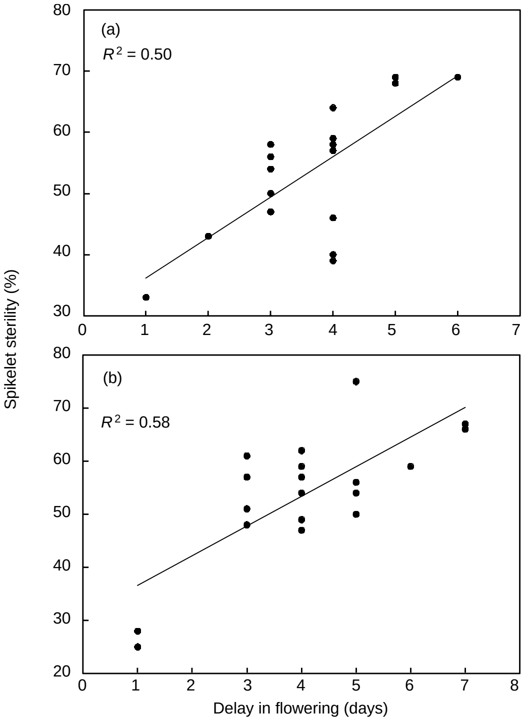


Figure 3. Relationship between delay in flowering and spikelet sterility among 19 rice lines under (a) upland stress conditions, and (b) lowland stress conditions.

Experiment 2

Canopy size and leaf-water potential

Leaf area among canopy treatments under no stress, mild stress and severe stress was significantly different ($P < 0.05$) at the beginning and end of the treatments. The mean leaf area after no, mild and severe water stress periods was 761, 603 and 556 cm^2, respectively. This indicated that differences in plant size within a given line were effectively maintained in relation to variations in ψ_L at the end of the stress period.

We found no significant line × canopy-size treatments interactions for midday ψ_L before the three water stress conditions were imposed. Midday ψ_L declined slowly during the first 9 days and sharply afterwards under both mild and severe stress. At the end of the stress period, mean ψ_L values declined from –1.23 to –2.32 MPa under mild stress and from –1.23 to –2.62 MPa under severe stress. At the end of both stress periods, significant line × canopy-size treatments interactions were found for midday ψ_L. A significant difference ($P < 0.05$) in ψ_L was observed among canopy treatments for Line 36 under mild stress, although none were seen under severe stress. Significant line × canopy-size interactions were also observed for Lines 77 and 28 under severe stress (Table 2).

Variation among lines for ψ_L was highly significant ($P < 0.01$). Lines 36, 77 and 28 maintained lower ψ_L than did cv Lemont under both mild and severe stress at the end of the stress periods (Table 2). For ψ_L, the canopy treatments within lines responded differently under water stress, particularly for Lines 77 and 28. Under severe stress, in Line 77, ψ_L did not decrease significantly ($P > 0.05$) when tillers were removed (6 tillers only), whereas, in Line 28, ψ_L decreased significantly ($P < 0.05$) when the same treatment was applied. Similarly, in Line 36, ψ_L under full canopy treatment was, overall, lower than it was under other canopy treatments under severe stress, whereas, for Line 77, it was, on the whole, higher. Furthermore, the expression of ψ_L in Line 77, cv Lemont and Line 28 in the mixture treatments was similar to that of the full canopy treatments. Although differences in ψ_L among Lines 36, 77 and 28 with full canopies were not significant ($P > 0.05$), some differences ($P < 0.05$) among these lines were identified for ψ_L under reduced canopy treatments.

Number and size of vascular bundles

Four lines showed significantly different ($P < 0.05$) numbers of large and small vascular bundles and xylem diameters. Cultivar Lemont, which maintained relatively high ψ_L, had a larger xylem diameter than did Lines 77 and 28, which both had low ψ_L (Table 3). Line 28 had a significantly lower number of large and small vascular bundles than did the other three lines. Differences in stem area and the total xylem area of the four lines were significant. Cultivar Lemont and Line 36 had the largest stem area while Line 77 had the lowest. Similarly, cv Lemont and Line 36 showed the highest total xylem area, compared with Lines 28 and 77. Maintenance of ψ_L in those lines was associated with total xylem area and the stem cross-section area. However, the association between the number of vascular bundles and the expression of ψ_L was poor.

Table 2. Values for leaf-water potential (ψ_L) of four rice lines under 18 canopy-size treatments in well-watered (control) conditions, mild stress (14 days) and severe stress (18 days) in the field Experiment 2, Redland Bay Farm, University of Queensland.

Cultivar or line, Canopy size treatment	ψ_L (MPa)		
	Control	Mild stress	Severe stress
Lemont, full canopy	–0.97	–1.83	–1.80
Lemont, 1/3 leaves removed	–1.03	–1.87	–2.00
Lemont, 2/3 leaves removed	–0.80	–1.80	–2.17
Lemont, 6 tillers only	–0.97	–1.77	–1.97
Lemont + Line 77 mixture	–0.87	–2.00	–1.67
Lemont + Line 28 mixture	–0.70	–1.83	–1.83
Line 36, full canopy	–1.20	–2.77	–2.83
Line 36, 1/3 leaves removed	–1.17	–2.30	–2.57
Line 36, 2/3 leaves removed	–1.23	–2.50	–2.50
Line 36, 6 tillers only	–1.03	–2.60	–2.87
Line 77, full canopy	–1.53	–2.10	–2.73
Line 77, 1/3 leaves removed	–1.40	–2.33	–2.70
Line 77, 2/3 leaves removed	–1.43	–2.40	–3.47
Line 77, 6 tillers only	–1.43	–2.47	–2.77
Line 77 + Lemont mixture	–1.33	–2.37	–2.67
Line 28, full canopy	–1.47	–2.60	–2.80
Line 28, 1/3 leaves removed	–1.30	–2.90	–3.07
Line 28, 2/3 leaves removed	–1.53	–2.70	–3.37
Line 28, 6 tillers only	–1.67	–2.53	–3.57
Line 28 + Lemont mixture	–1.57	–2.67	–3.03
Mean	**–1.23**	**–2.32**	**–2.62**
$LSD_{0.05}$	0.44	0.40	0.71

Experiment 3

Following the results of the field experiment, the greenhouse experiment investigated, in six lines, the relationship between ψ_L, total xylem area and stem area. In addition, the y gradient within the plant and its consistency across lines were investigated.

Table 3. Number of large and small vascular bundles per cross-section area of the stem, xylem diameter, stem area and total xylem area of the stem base of four rice lines.

Cultivar or line	Vascular bundles		Xylem diameter (μm)	Stem area (mm^2)	Total xylem area (μm^2)
	Large	Small			
Lemont	30.3	29.3	42.0	16.3	84300
Line 36	30.7	29.7	44.7	15.7	96220
Line 77	30.7	29.3	33.3	8.6	50140
Line 28	28.7	27.7	37.3	14.9	67180
Mean	**30.1**	**29.0**	**39.3**	**13.9**	**74460**
$LSD_{0.05}$	1.29	1.20	1.80	1.20	10680

Maintenance of water potential among lines

The results showed that, within lines, significant differences existed among positions for maintenance of ψ ($P < 0.05$) under stress. The ψ values of different positions of the six lines at 0 and 10 days after stress was imposed are shown in Table 4. Overall, cv Lemont maintained the highest plant ψ, whereas Line 77 maintained the lowest throughout all the locations studied. Stem-base water potential (ψ_{sb}) decreased least during the stress period. Line 77 showed the highest rate of development of stress in the stem base, which changed from −0.24 MPa at 0 days to −1.00 MPa at 10 days after stress was imposed, followed by Line 28 (from −0.24 to −0.83 MPa). This trend was consistent across the plant positions of the six lines. The rate of development of water stress was highest in the leaf tip than in the other positions. Line 77 (−0.80 to −3.55 MPa) and Line 28 (−0.79 to −2.40 MPa) recorded the lowest leaf-tip water potential (ψ_{Lt}) at the end of the stress period.

The mean value of stem-base water potential (ψ_{sb}) ranged from −0.16 MPa at 0 days to −0.58 MPa at 10 days after stress. Before water stress was imposed, the ψ among lines in the stem base, leaf sheath and leaf base were not different among lines. As water stress continued, Lines 77 and 28 could not maintain a high leaf-tip water potential (ψ_{Lt}) when transpiration demand increased. In contrast, cv Lemont showed an ability to maintain a higher ψ_{Lt} (−0.58 to −1.30 MPa) over the same period of stress.

Number of vascular bundles among lines

The number of vascular bundles at different positions, xylem diameter, stem cross-section area and total xylem area of the six rice lines are shown in Table 5. The number of vascular bundles depended on the tissue area in the position. The stem base had the largest cross section of the plant and contained a higher number of vascular bundles than did other plant positions. The leaf tip had the smallest cross section and had a relatively small number of vascular bundles. Lines varied for the number of vascular bundles in each location, except for leaf sheath (ψ_{Ls}). However, the association between plant ψ at different plant positions and number of vascular bundles in each position across lines was poor ($R^2 = 0.07$).

Plant ψ at different locations showed association with the respective xylem area (average xylem area × total xylems/stem cross section area) and stem cross-section area of each genotype. Generally, ψ_L tended to increase with increased size of xylem area (Figure 4a). When xylem area was increased from 35 000 μm^2 to 58 000 μm^2 in the stem base, ψ_{Lt} increased from −3.55 to −1.30 MPa. Usually, lines with the stem xylem area larger than 58,000 μm^2 had

Table 4. Comparison of water potential (ψ) values for stem base, leaf sheath, leaf base and leaf tip among six rice lines under control (no stress) and stress (10 days of water deficit) treatments in the greenhouse.

Cultivar or line	ψ (MPa) at 0 or 10 days after stress imposed							
	Stem base		Leaf sheath		Leaf base		Leaf tip	
	0	10	0	10	0	10	0	10
Lemont	–0.09	–0.33	–0.43	–0.78	–0.51	–1.03	–0.58	–1.30
Line 29	–0.10	–0.48	–0.38	–1.27	–0.39	–1.48	–0.55	–1.78
Line 49	–0.13	–0.43	–0.35	–1.13	–0.43	–1.52	–0.58	–1.65
Line 36	–0.18	–0.45	–0.38	–0.75	–0.44	–1.50	–0.63	–2.03
Line 28	–0.24	–0.83	–0.49	–1.57	–0.64	–1.96	–0.79	–2.40
Line 77	–0.25	–1.00	–0.64	–2.10	–0.73	–2.98	–0.80	–3.55
Mean	**–0.16**	**–0.58**	**–0.44**	**–1.27**	**–0.52**	**–1.75**	**–0.65**	**–2.12**
$LSD_{0.05}$	ns	0.34	ns	0.60	ns	0.64	0.20	0.90

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Table 5. Number of vascular bundles at different positions, namely, leaf tip (lt), leaf base (lb, fourth node), leaf sheath (ls) and stem base (sb); xylem diameter; stem cross-section area; and total xylem area of six rice lines (lv = large vascular bundles; sv = small vascular bundles).

Cultivar or line	Number of vascular bundles					Xylem diameter (μm)	Stem cross-section area (mm^2)	Total xylem area (μm^2)
	sb							
	lv	sv	ls	lb	lt			
Lemont	32.0	29.8	38.5	20.5	11.5	33.8	24.0	58100.0
Line 29	34.3	32.3	38.5	24.5	14.5	41.8	34.8	93760.0
Line 49	30.0	29.8	39.0	20.5	14.0	36.2	21.3	62580.0
Line 36	35.0	33.0	39.5	22.0	13.5	32.5	20.8	59360.0
Line 28	32.8	32.3	38.5	18.5	10.5	31.8	16.8	52080.0
Line 77	33.5	32.3	39.0	19.5	13.5	25.8	16.0	34960.0
Mean	**32.9**	**31.5**	**38.8**	**20.8**	**12.9**	**33.6**	**22.3**	**60140.0**
LSD$_{0.05}$	2.99	ns	ns	0.71	0.86	4.72	8.21	19734.0

similar ψ in all positions and expressed higher y than lines with smaller stem xylem areas.

Similarly, lines with larger stem cross-section areas could maintain higher ψ at all positions than could lines with lower stem areas (Figure 4b). When the cross section area increased from 16 to 24 μm^2, ψ_Lt tended to increase from −3.55 to −1.30 MPa. However, any increment in cross section area beyond this limit did not show further increase in y through the four positions of those lines. These results suggest that the genotypic variation in plant ψ may be associated with xylem and stem areas of these rice lines but not with the number of either vascular bundles or xylem cells in the stem.

Discussion

This study showed that ψ was associated with some yield components in rice under water stress, whether in the uplands or lowlands, and could potentially delay flowering in rice. Average delay in flowering was 4 days under both stress conditions, and its genotypic variation was associated with ψ_L and spikelet sterility. Phenology, particularly flowering date, is a major determinant of the number of filled grains per panicle under water stress. Factors such as maintenance of high ψ_L may also be important for high grain yield (Jongdee 1998). For example, cv Lemont had the same flowering dates as some lines under both upland and lowland stress conditions but had a higher filled grain percentage than did the other lines. This difference in filled grain percentage under stress could be associated with the differences in maintaining ψ_L under stress. Cultivar Lemont was also able to maintain higher ψ_L than the other lines, whereas Line 28, which had the lowest ψ_L, had a low percentage of filled grain. The results confirmed those of Jongdee (1998), who found that the maintenance of high ψ_L may help maintain high grain yield under water deficit. An association was found between spikelet sterility and delay in flowering under both lowland and upland stress conditions.

While maintenance of high ψ_L appears to favour low spikelet sterility, the influence of plant size on the expression of ψ_L showed a contrasting pattern of response among lines. The canopy study showed that the expression of ψ_L could be changed within lines where high ψ_L cannot be maintained under stress (e.g. Lines 77 and 28). Therefore, canopy size (leaf area) may have some effect on the expression of ψ_L, particularly, in lines experiencing low ψ_L under severe stress. Boonjung and Fukai (1996) reported that plants with small canopy size were able to maintain higher ψ_L and take up water more slowly than those with larger canopy size. Cultivar Lemont and Line 77 had similar canopy sizes but cv Lemont became stressed more slowly and was able to maintain higher ψ_L than could Line 77 at the end of the stress period. However, cv Lemont had a smaller canopy size than Line 28 and recorded a higher ψ_L after the stress period. The variation in ψ_L due to changes in canopy size was high within lines that expressed low ψ_L under stress. These results corroborate those of Lilley and Fukai (1994), who showed that lines with similar canopy size and total water use differ in ψ_L.

Xylem diameter and total xylem area were higher in cv Lemont and Line 36 than in Lines 28 and 77. These differences influenced water conductance within the plant during stress. It was shown that higher xylem diameter and total xylem area were associated with higher ψ_L for the four lines. A plant ψ gradient was found from stem base to leaf tip in the rice plant.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

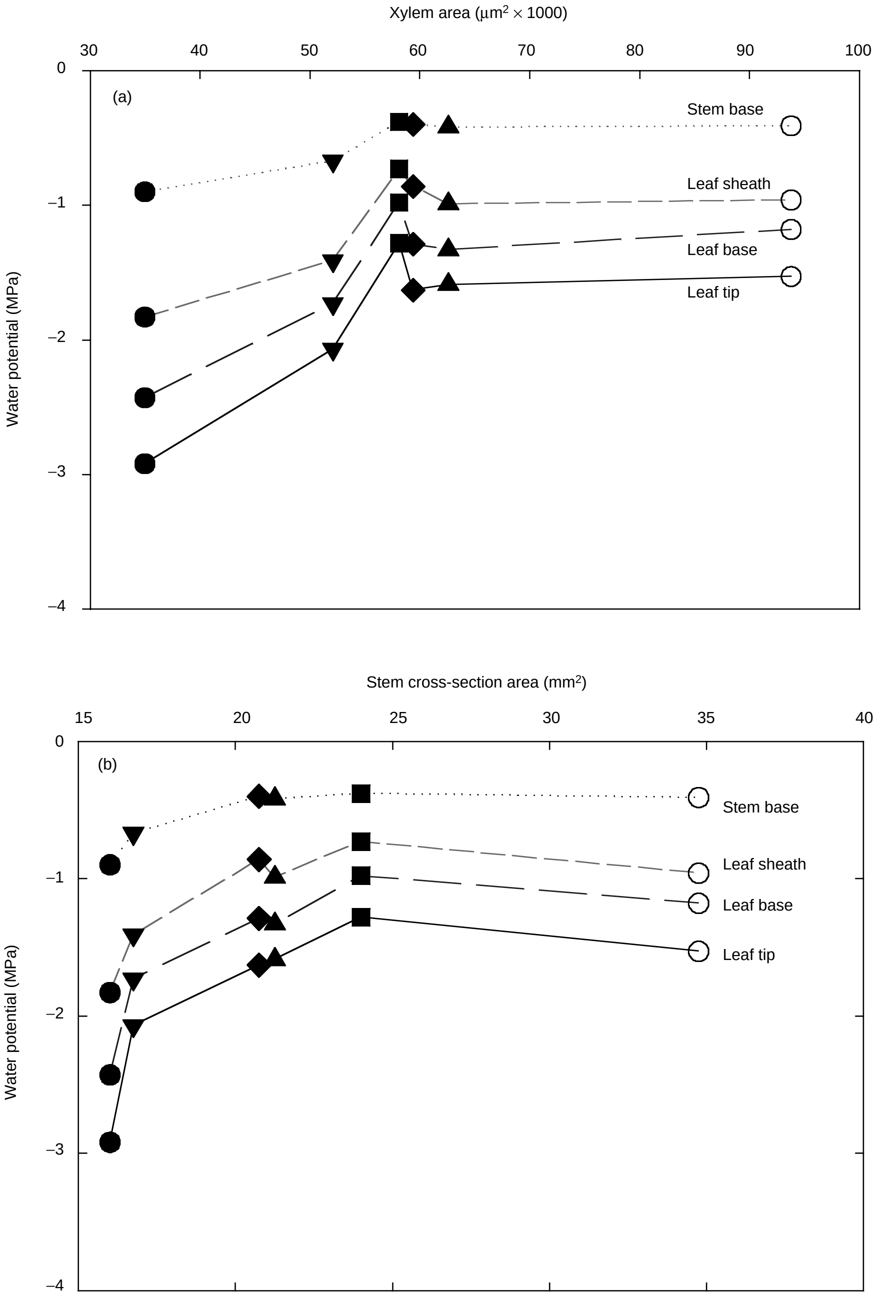


Figure 4. Comparison of different water potentials (ψ, MPa), averaged across 6, 9 and 10 days after stress imposed, at different plant locations and related to (a) xylem (µm^2, large vascular bundles), and (b) stem cross-section area (mm^2). Plant locations were leaf tip (——), leaf base (— — —), leaf sheath (- - - -) and stem base (……..). The six rice lines used were cv Lemont = ■; Line 28 = ▼; Line 29 = ○; Line 36 = ◆; Line 49 = ▲; Line 77 = ●.

While the pattern of the gradient differed among lines, the trend of expression of ψ from stem base to leaf tip was consistent. The stem maintained the highest ψ, followed by leaf sheath, leaf base and leaf tip. Turner (1982) suggested that the capacity of roots to take up water would have a limited impact on ψ_L if the stem had a high resistance to water flow. Conversely, Jongdee (1998) reported that the ψ_{sb} in rice lines was relatively high, even when gravimetric soil moisture content was low (13.6% to 18.3%) and leaf drying was observed. The current study suggests that lines vary for ψ_{sb} and, therefore, internal conductance of water from stem base to leaf tip may be an important expression of genotypic variation for ψ_L under water stress.

Acknowledgments

The financial assistance provided by the Australian Centre for International Agricultural Research is most appreciated.

References

Boonjung, H. and Fukai, S. 1996. Effects of soil water deficit at different growth stage on rice growth and grain yield under upland conditions. 1. Growth during drought. Field Crops Research, 48, 37–45.

Fukai, S. and Cooper, M. 1995. Development of drought-resistant cultivars using physio-morphological traits in rice. Field Crops Research, 40, 67–86.

Ingram, K.T. ed. 1995. Rainfed Lowland Rice Agricultural Research for High-Risk Environments. Manila, Philippines, International Rice Research Institute (IRRI), 248 p.

Jongdee, B. 1998. The Importance of Leaf Water Potential and Osmotic Adjustment on Growth and Grain Yield of Rice (*Oryza sativa* L.) Genotypes under Water Deficit Conditions. Ph.D. dissertation. Brisbane, University of Queensland, pp 238.

Lilley, J.M. and Fukai, S. 1994. Effect of timing and severity of water deficit on four diverse rice cultivars. II. Physiological response to soil water deficit. Field Crops Research, 37, 215–223.

Lilley, J.M. and Ludlow, M.M. 1996. Expression of osmotic adjustment and dehydration tolerance in diverse rice lines. Field Crops Research, 48, 185–197.

Mackill, D.J., Coffman, W.R. and Garrity, D.P. 1996. Rainfed Lowland Rice Improvement. Manila, Philippines, International Rice Research Institute, 242 p.

O'Toole, J.C. 1982. Adaptation of rice to drought-prone environment. In: Drought Resistance in Crop with Emphasis on Rice. Los Baños, Philippines, International Rice Research Institute (IRRI), 195–213.

O'Toole, J.C. and Moya, T.B. 1978. Genetic variation in maintenance of leaf water potential in rice. Crop Science, 18, 873-876.

Pantuwan, G., Fukai, S. and Cooper, M. 1997. Root traits to increase drought resistance in rainfed lowland rice. In: Breeding Strategies for Rainfed Lowland Rice in Drought-Prone Environments, Proceedings of an International Workshop held at Ubon Ratchatani, Thailand, 5–8 November 1996. Canberra, ACIAR Proceedings No. 77, 170–179.

Singh, R.K. and Dwivedi, I.L. 1997. Rice improvement for rainfed lowland rice ecosystems: Breeding methods and practices in Eastern India. In: Breeding Strategies for Rainfed Lowland Rice in Drought-Prone Environments, Proceedings of an International Workshop held at Ubon Ratchatani, Thailand, 5–8 November 1996. Canberra, ACIAR Proceedings No. 77, 50–57.

Somrith, B. 1997. Cultivars improvement for rainfed lowland rice in Thailand. In: Breeding Strategies for Rainfed Lowland Rice in Drought-Prone Environments, Proceedings of an International Workshop held at Ubon Ratchatani, Thailand, 5–8 November 1996. Canberra, ACIAR Proceedings No. 77, 36–42.

Turner, N.C. 1981. Techniques and experimental approaches for the measurement of plant water status. Plant and Soil, 58, 339–366.

Turner, N.C. 1982. The role of shoot characteristics in drought resistance of crop plants. In: Drought Resistance in Crop with Emphasis on Rice. Los Banos, Philippines, International Rice Research Institute (IRRI), 115–134.

Widaswsky, D.A. and O'Toole, J.C. 1990. Prioritizing the Rice Technology Research Agenda for Eastern India. New York, Rockefeller Foundation.

Improving Water-Use Efficiency in Rice-Based Cropping Systems Using Permanent Raised Beds

Andrew K. Borrell[1,*] and Donald E. Van Cooten[2]

Abstract

A major challenge for the next 20 years is to develop genetic and agronomic solutions to combat water shortages for rice production and to develop ecosystems that better match crop growth with water supply. Experiments were conducted in northern Queensland, Australia (1989–1992) and eastern Indonesia (1993–1999) to develop a cropping system based on raised beds and saturated soil culture (SSC), whereby rice could successfully be grown in rotation with several field crops. Advantages of the SSC system include improved efficiencies of water use, energy savings, enhanced timeliness of field operations and reduced soil compaction. The northern Queensland studies indicated that double cropping rice and field crops on permanent raised beds provides additional synergistic and logistic benefits over those found in the traditional rice/fallow system. Subsequent experiments in West Timor found that various crops, as well as rice, can be grown on raised beds during the wet season, thus overcoming the problem of waterlogging. Moreover, if raised beds were constructed before the wet season in lowland areas, crops could be sown at the onset of the wet season, thus avoiding end-of-season drought and permitting significant increases in crop yields. Reforesting of eroded upland cropping areas with perennial tree species was also possible, provided the intensive lowland production met the subsistence farmers' basic food and/or cash crop requirements. By increasing the probability of year-round crop production, this system, overall, can help enhance food security for South-East Asian subsistence farmers.

GLOBALLY, water for irrigated rice (*Oryza sativa* L.) production is becoming increasingly scarce due to greater urban and industrial demand (DuPont 2000). Water, more than any other resource, also limits rainfed rice production throughout the world. The challenge is to develop rice ecosystems that use less water and improve water-use efficiency (WUE) by better matching crop growth to water supply. This paper summarizes a series of studies that were undertaken initially in northern Australia (1989–1992), then in West Timor (1993–1999), to develop a raised-bed cropping system in which rice could successfully be grown in rotation with a range of other field crops. These concepts are equally applicable to lowland rice production in South-East Asia.

Options for decreasing water use and increasing WUE for irrigated rice were first investigated in north-eastern Queensland, Australia, because of the high costs of water in the Burdekin River Irrigation Area (BRIA). In addition to improving economic returns to growers, it was believed that increasing the WUE for irrigated rice production would have long-term environmental benefits by lowering water tables and reducing salinization in irrigation areas (Gardner and Coughlan 1982; Borrell et al. 1997).

In the northern Queensland studies, it was hypothesized that WUE (g m^{-2} mm^{-1}) of field-grown rice could be increased by implementing an agronomic system known as saturated soil culture (SSC). This system was initially developed for soybean production on raised beds in the greenhouse (Hunter et al. 1980; Nathanson et al. 1984) and later in the field (Wright et al. 1988; Troedson et al. 1989; Garside et al. 1992a). Plants were grown on raised beds that were 0.2 m high and 1.2 m wide, with water

---

[1] Hermitage Research Station, Department of Primary Industries, Warwick, Queensland, Australia
[2] Service Fellowship International, Bali, Indonesia
*Corresponding author: E-mail: borrela@dpi.qld.gov.au

KEYWORDS: Saturated soil culture (SSC)

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

maintained in furrows, which were 0.3 m wide and about 0.1 m below the bed surface. Water-use efficiency (WUE) was increased by reducing water use without reducing dry matter production. The Queensland studies aimed to reach similar efficiencies for rice grown under SSC.

Both northern Queensland and eastern Indonesia are characterized by a typical monsoonal rainfall pattern with hot, humid, wet seasons from November to April and cooler dry seasons from May to October. Improved WUEs for rice production with SSC in tropical Australia indicated that similar benefits might be realized with this method of irrigation in West Timor. It was also thought that permanent raised beds would reduce the incidence of soil erosion, the most significant environmental problem facing Timor today (Duggan 1991).

To ensure food security in eastern Indonesia, a cropping system is required that will enable subsistence farmers to produce sufficient nutritious food, despite the lack of rainfall between May and October. Maximum crop production depends on efficient use of rainfall during the wet season and of stored soil water during the dry season, that is, on matching crop growth with water supply. The development of any new cropping system should be considered in the context of the region's existing agricultural production systems. Simpson (1995) highlighted five production systems that commonly exist side by side within a single farm in West Timor: (1) swidden (shifting/slash and burn) cultivation of rainfed crops, mainly maize (*Zea mays* L.); (2) the cultivation of rainfed or irrigated rice in lowland areas; (3) house gardens with rainfed maize, cassava (*Manihot esculenta* Crantz) and beans (*Phaseolus* spp.) intercropped with tree crops; (4) cattle production, including the use of the breeding herd for rencah system, in which cattle are herded into flooded rice fields to puddle the soil in preparation for rice planting); and (5) harvesting forest products such as tamarind (*Tamarindus indica* L.), candlenut (*Aleurites moluccana* (L.) Wild.), sandalwood (*Santalum album* L.) and fuel wood.

All these systems are constrained by drought and, at times, waterlogging. The incompatibility of upland crops such as maize and soybean with flooded rice culture hindered the development of rice-based cropping systems in both northern Queensland (Garside et al. 1992b) and West Timor (Van Cooten and Borrell 1999). The key to overcoming this inherent incompatibility was SSC on raised beds.

Northern Queensland

Garside et al. (1992b) report the development of a rice-based cropping system for tropical Australia that included the double cropping of rice, soybean and maize. They discuss a series of experiments conducted at Millaroo Research Station (20° 03′ south, 147° 16′ east) in the BRIA, between 1989 and 1992. Such a system, based on rice production under SSC on permanent raised beds, was shown to improve productivity and to have considerable advantages over the traditional rice/fallow system, such as greater WUEs, energy savings, improved timeliness of field operations and reduced soil compaction.

To develop a viable and practical rotation, Garside et al. (1992b) identified and examined in isolation those cultural and management components most likely to inhibit the system. Three key areas were identified:

1. Incompatibility of irrigation practices for flooded rice and furrow-irrigated upland crops (Borrell et al. 1991, 1993, 1997).
2. Impact of cultural changes on timeliness of operations (Braunack et al. 1995; McPhee et al. 1995a, b, c); and
3. Effects of crop and irrigation practice on soil chemistry and nutrient availability (Borrell 1993; Dowling 1995; Ockerby et al. 1999a, b).

Development of an irrigated rice-based cropping system for tropical Australia was driven by both economic and environmental imperatives. At the time of research, water and nitrogen fertilizer accounted for about 40% and 20%, respectively, of the variable costs of growing a rice crop (Bourne and Norman 1990), highlighting the need to improve the efficiencies with which these resources were used. Previous studies in the BRIA had also found that deep drainage losses from rice fields ranged from 50 to 240 mm per crop, depending on the permeability of the B horizon (Gardner and Coughlan 1982). Therefore, it was considered likely that increasing the area of flooded rice production would lift the regional water table, possibly leading to soil salinization in some areas. It was thought that SSC, an alternative irrigation strategy, may obviate this problem. In addition, there was increasing pressure for nitrogen fertilizer inputs to be reduced to prevent drainage of excess nitrate from agricultural enterprises into coastal rivers and, eventually, into the Great Barrier Reef (Prove et al. 1990).

Irrigation practices

Field crops such as maize and soybean are not suited to the anaerobic environment associated with flooded rice production. Therefore, rice would need to be grown under a different cultural system to improve compatibility between rice and field crops. Experiments were conducted to examine alternative methods of irrigating rice. The responses of biomass production and yield in rice (cv. Lemont) to five methods of irrigation were examined in a wet and dry season in northern Australia (Borrell et al. 1997). Permanent floods at sowing (PF-S), at the three-leaf stage (traditional, PF-3L) and before panicle initiation (PF-PI) were compared with two unflooded methods: SSC and intermittent irrigation at weekly intervals. The objective of these studies was to maximize grain yield by optimizing its functional components: water use, plant water-use efficiency for biomass production and harvest index.

These studies found that flooding rice is not necessary to obtain high grain yield and quality (Borrell et al. 1997). Although the trend across all water regimes was for yield to increase with water supply, no significant difference in yield and quality was found between SSC and traditional flooding (PF-3L), even though SSC used about 32% less water in both seasons (Table 1). Transpiration would have been small during the first 30 d of crop growth. Therefore, higher water losses during this period in flooded (290 mm) than unflooded (160 mm) treatments suggest that evaporation, seepage and percolation losses were higher with ponded water. These factors were not measured separately in this study, but their combined values support earlier findings that percolation increases with increasing depth of ponded water due to the imposition of a larger gradient in hydraulic head (Ferguson 1970; Sanchez 1973; Wickham and Singh 1978). Alternative irrigation strategies comprising lower depths of ponded water such as SSC, are likely to be most advantageous in relatively porous, non-swelling soils where flooding simply creates a greater hydraulic head which, in turn, increases percolation.

In the dry season, there was a trend for increased WUE for grain production (WUE_g) in SSC, compared with the other treatments (Table 1). In the wet season, WUE_g was higher in PF-S and SSC than in the other treatments. The Australian studies pointed out that the selection of an optimal irrigation method for rice production in tropical environments should not be based on the criterion of WUE, but rather on the dual criteria of WUE_g and total water use. Had selection been based on WUE_g alone, both SSC and PF-S would have been acceptable in the wet season, despite significantly higher water use in PF-S (about 35% more). With increasing water scarcity, the urgent issue is to select a system that encompasses both improved efficiency and lower water use. Based on these dual criteria, SSC was the optimal treatment in the Australian experiments.

For rice grown as a row crop on permanent raised beds, irrigation water can be supplied to the furrows at a constant rate, maintaining the water level at about 0.1 m below the bed surface. Alternatively, water can be supplied at regular intervals (e.g. twice weekly) to rice grown on raised beds within bunded fields, maintaining the water at an average level of 0.1 m below the bed surface. While SSC was initially developed for irrigated crop production, the principles still apply to rainfed rice production within bunded fields during the wet season, although water levels cannot be controlled to the same extent as for irrigated production.

Table 1. Water use (mm), grain dry mass (g m^{-2}) and efficiency of water use for grain production (WUEg, g m^{-2} mm^{-1}) for two seasons and five methods of irrigation.

Irrigation method[b]	Water use	Grain dry mass	WUE_g
Dry season			
PF-S	1351 d	875 b	0.65
PF-3L	1320 d	822 b	0.63
PF-PI	1170 c	789 b	0.67
SSC	904 b	734 b	0.82
II	764 a	507 a	0.66
Mean	1102	746	0.69
$LSD_{0.05}$	94	177	ns
Wet season			
PF-S	1286 d	612 c	0.48 b
PF-3L	1228 c	456 b	0.37 a
PF-PI	1075 b	421 ab	0.39 a
SSC	833 a	402 ab	0.48 b
II	873 a	363 a	0.41 ab
Mean	1059	451	0.43
$LSD_{0.05}$	49	64	0.07

[a] Means within a column and season followed by differing letters are significantly different ($P < 0.05$). ns = not significant at $P < 0.05$, F-test.

[b] PF-S = permanent floods at sowing; PF-3L = at three-leaf stage; PF-PI = before panicle initiation; SSC = saturated soil culture; II = intermittent irrigation.

Source: Adapted from Borrell et al. (1997).

Controlled traffic

At the same experiment site (Millaroo Research Station, BRIA), but separately from the irrigation studies, timeliness and trafficability were studied. The potential of controlled traffic was assessed for irrigated double cropping of soybean and maize in northern Australia (McPhee et al. 1995c). Timeliness measures the ability to perform operations such as planting and harvesting at optimal time. Two controlled traffic treatments, using direct drilling and conventional tillage between the traffic lanes, were compared with a conventional tillage system. (Controlled traffic is defined as the separation of the traffic zone from the crop growth zone.) Controlled traffic with direct drilling improved timeliness, creating earlier planting opportunities in all seasons examined, compared with controlled traffic for both cultivation and conventional tillage. Raised beds under SSC in the irrigation studies were observed not to degrade, suggesting that no obvious limitation was present to prevent the combination of SSC, permanent beds and controlled traffic.

Eastern Indonesia

Van Cooten and Borrell (1999) discussed the development of a rice-based cropping system for eastern Indonesia, arguing that crop production on permanent raised beds enables growth to be better matched to water supply. To develop a viable and practical system based on permanent raised beds, Van Cooten and Borrell (1999) first identified, then examined, the following components: (1) compatibility of raised beds for rice and upland cropping; (2) timeliness of operations; (3) water harvesting and drainage; (4) using stored soil water; (5) mechanization; (6) weed control; (7) erosion control; (8) an integrated approach to food and cash cropping; (9) living fences; and (10) availability of labour. Those components directly related to improved WUE in rice-based cropping systems are discussed later in this paper (see ‘Developing Rice-Based Cropping Systems for South-East Asia’).

Improving rice management

Three field experiments were conducted at Batu Plat, Kupang, West Timor (10.2° south, 123.9° east), between 1993 and 1995 to improve rice production in this region (Borrell et al. 1998). The primary objectives of these studies were to examine the effects of irrigation method (raised beds under SSC v. flooded system), irrigation frequency (daily v. twice weekly) and rice genotype (traditional v. improved) on crop yield and yield components. Secondary objectives were to examine the response of rice grown on raised beds to sowing time and nitrogen fertilization. Higher WUEs for rice grown under SSC in tropical Australia suggested that similar benefits might be realized with this irrigation method in West Timor. The West Timor experiments were conducted within a low-external-input system, and all experiments were affected by drought. The key issue was to match crop growth with water supply to ensure adequate quantity and quality of grain production at the end of the season.

Time of sowing

An improved lowland rice cultivar (cv. Lemont) was sown early (15 December) and late (15 January) to examine the impact of sowing time on grain yield in the wet season. Crop growth was better aligned with the available water resources in the early sowing, since yield potential (indicated by grains m^{-2}) was similar for both sowings, yet more water was available to complete grain filling in the early sowing, resulting in higher grain quality (indicated by grain size) for this sowing time (Borrell et al. 1998). Permanent raised beds, such as those used in SSC, provide a mechanism for sowing crops immediately after the onset of wet-season rains, thereby minimizing the risk of drought late in the grain-filling period. The SSC therefore provides a means of better matching crop growth with water supply by enabling farmers to sow at optimal time.

Water management

Irrigation method (SSC v. flooded rice) was split for irrigation frequency (daily v. twice weekly applications), which was again split for genotype (traditional upland v. improved lowland). No difference in grain yield between rice grown on raised beds and rice grown in flooded bays was found, suggesting that yield can be maintained in an unflooded system, using SSC (Table 2; Borrell et al. 1998). Nor did irrigation frequency have impact on grain yield, highlighting the advantage of irrigating twice weekly rather than irrigating daily or flooding. Although water use was not monitored in these studies, reductions under SSC compared with traditional flooded production may have occurred, as for the northern Australian studies (Borrell et al. 1997).

Other benefits of raised beds are enhanced drainage, particularly in the wet season. Although drought is the main limitation to crop yield in eastern Indonesia, excess rainfall is common between January and February when the north-west monsoons peak. Poor drainage can result in crops being waterlogged for several weeks, following cyclonic activity. Pellokila et al. (1991) define the ideal cropping area as one that has sufficient drainage to prevent waterlogging but is capable of storing adequate moisture to minimize water stress during drought. Ideal cropping areas are rare, however such areas can be created by constructing fields of permanent raised beds, which provide excellent drainage during periods of intense rainfall in the wet season, yet capture and store water during periods of low rainfall.

The growth of rice on raised beds also opens the way for other crops to be grown in rotation with rice. Field crops such as maize and soybean are not suited to the flooded soil conditions used for rice production, but these crops do grow well on raised beds in rotation with rice (Garside et al. 1992b). The development of a rice-based cropping system on permanent raised beds would enable farmers to produce food and cash crops, thereby meeting the criteria of food security and income generation highlighted by Pellokila et al. (1991).

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Table 2. Grain dry mass, above-ground dry mass, harvest index, grain number per m^2, mass per grain, panicle number per m^2, grain number per panicle, plant number per m^2 and panicle number per plant for two irrigation methods, two irrigation frequencies and two rice genotypes.

Treatment	Grain dry mass (g m^{-2})	Above-ground dry mass (g m^{-2})	Harvest index	Grain number per m^2	Mass per grain (mg)	Panicle number per m^2	Grain number per panicle	Plant number per m^2	Panicle number per plant
Irrigation method									
Raised beds	150	487	0.28	6374	21.8	228	29	119	2.3
Flooded	154	353	0.44	6180	24.9	210	32	84	2.0
LSD$_{0.05}$	ns	ns	ns	ns	ns	ns	ns	ns	ns
Irrigation frequency									
Daily	163	465	0.36	6696	24.1	224	32	104	2.2
Twice weekly	140	375	0.35	5858	22.6	214	29	98	2.1
LSD$_{0.05}$	ns	ns	ns	ns	ns	ns	ns	ns	ns
Rice genotype									
Traditional	127	371	0.34	5546	21.9	163	35	102	1.6
Improved	176	469	0.37	7008	24.8	275	26	101	2.8
LSD$_{0.05}$	ns	ns	ns	ns	1.5	50	ns	ns	0.2

Source: Adapted from Borrell et al. (1998).

Traditional versus improved genotypes

The performance of an improved short genotype (cv. Lemont) was compared with that of a taller traditional rice from the neighbouring island of Alor in a dry and wet season (Borrell et al. 1998). The traditional genotype appeared to have an advantage over the improved genotype when growth was limited by water during grain filling. The choice of traditional versus improved genotypes, and their associated ‘input’ packages, requires careful consideration. Experience from other parts of Indonesia has shown that rice production can be significantly increased with improved resources. However, the cost is high and the appropriateness of these high-input systems needs to be fully examined (Pellokila et al. 1991). There is a need to better examine the world’s genetic stocks of crops and forages that are well suited to eastern Indonesia (Barlow and Gondowarsito 1991). Pellokila et al. (1991) are now identifying early maturing rice varieties that are disease resistant, adapted to the environment and able to flower during the wet season, thus avoiding a potential end-of-season drought.

Developing Rice-Based Cropping Systems for South-East Asia

Below we briefly discuss some of the cropping system components identified by Van Cooten and Borrell (1999) in terms of their applicability to the development of rice-based cropping systems for South-East Asia.

Compatibility of raised beds for rice and upland cropping

The successful growth of rice on raised beds in northern Australia (Borrell et al. 1997) and in eastern Indonesia (Borrell et al. 1998) opens the way for upland crops to be grown in rotation with rice. In northern Australia, wet-season soybean was grown on raised beds in rotation with dry-season rice, and dry-season maize was grown in rotation with wet-season rice (Garside et al. 1992b; Borrell 1993). This concept has been extended to eastern Indonesia where soybean, maize, sorghum (*Sorghum* spp.), garlic (*Allium sativum* L.), mung bean (*Vigna radiata* L.) and cassava have been grown on raised beds in rotation with rice in West Timor (Van Cooten and Borrell 1999). Similarly, a range of crops could be grown in rotation with rice on raised beds in Cambodia and Laos.

Timeliness of operations

The single largest constraint to cropping in eastern Indonesia is late planting of the wet-season crop (Borrell et al. 1998; Van Cooten and Borrell 1999). Delayed sowing reduces yield because growth is poorly aligned with water availability, resulting in the crop experiencing end-of-season drought. A related factor is staggered plantings as farmers wait for cattle or tractors to become available for cultivation. Late-planted crops are more likely to run into moisture stress and, in addition, they are more likely to suffer yield reduction due to the build-up of pests from earlier crops (Pellokila et al. 1991). Raised beds provide a mechanism for sowing crops immediately after the onset of wet-season rains, thereby reducing the risk of drought during grain filling. Crops of rice (Borrell et al. 1998) and soybean (R.M. Kelly, pers. comm., 2000) sown in December yielded more than comparable crops sown in January. Therefore permanent raised beds enable farmers to sow at optimal times, providing a means of better matching crop growth with water supply and phenology.

Water harvesting and drainage

Water shortage, a major constraint to agricultural production in eastern Indonesia and throughout South-East Asia, can be defined as the under-exploitation of available water resources and continued dependence on rainfall with all of its uncertainties (Duggan 1991). Waterlogging can also occur for a number of weeks following cyclonic activity, particularly if drainage is poor. Further, rainfall within the wet season can be highly variable, resulting in patches of intermittent water deficit between periods of intense rainfall. However, the effects of intermittent drought can be minimized by harvesting and storing more water from the intense rainfall periods. Thus, during subsequent dry periods, the crop will have increased availability of water. Within bunded fields, furrows between raised beds can capture water during high rainfall events without causing waterlogging, while providing extra water for the crops in dry spells.

Using stored soil water

Capturing, storing and using soil water is one key to successful dry-season cropping. In eastern Indonesia, rainfed crops sown at the end of the wet season will need to rely almost exclusively on stored soil water for growth since, on average, less than 5% of rainfall occurs during the dry season. Potential still exists for dry-season cropping via improved agronomy (raised beds) and plant selection (drought-resistant species). If wet-season crops are sown on raised beds before mid-December as proposed by Borrell et al. (1998), they can be harvested at the end of March. This opens the way for drought-resistant crops such as sorghum [*Sorghum bicolor* (L.) Moench] to be sown into the beds in late March or early April. Rainfall data for the 10 years preceding 1995 (Table 3) shows that, on average, 214 and 72 mm of rain fell in the months of March and April, respectively, although only 42 mm fell during the following 6 months. This suggests that, on average, sorghum can be planted into a near-full soil water profile at the start of the dry season. Experiments have shown that drought-resistant sorghum lines can yield over 2 t ha^{-1} in southern India (Borrell et al. 1999) when grown on stored soil water under severe water deficit. Relay cropping of sorghum or mung bean immediately after wet-season rice or soybean is an effective means of using stored soil water (Van Cooten and Borrell 1999).

Weed control

Another critical issue for raised-bed cropping is the extent to which weeds will colonize this system, compared with a flooded rice-based system. Weed growth in unflooded systems is usually higher than in flooded systems (De Datta et al. 1973; Borrell et al. 1997), although this is not always the case (Tabbal et al. 1992). Rotational cropping systems have the potential to reduce weed growth since the environment for the survival of any particular weed species is constantly being changed, preventing the build-up of any one species. We have observed that,

Table 3. Total monthly rainfall (mm) from January to December recorded at Kupang, West Timor, between 1985 and 1995.

Year	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
1985	203	163	196	49	0	8	0	0	4	92	101	57	873
1986	640	299	129	45	5	0	95	0	0	0	47	1075	2335
1987	1075	416	52	0	0	0	0	0	0	0	250	375	2168
1988	544	122	243	12	0	0	0	0	0	0	378	321	1620
1989	272	202	264	0	9	20	21	0	0	0	26	114	928
1990	187	386	337	55	29	0	0	0	0	0	113	252	1359
1991	554	456	50	274	0	0	5	0	0	0	180	95	1614
1992	314	395	200	154	0	0	0	2	9	16	42	58	1190
1993	453	250	189	0	14	5	0	0	43	13	30	150	1147
1994	265	318	236	66	0	0	0	0	0	0	7	82	974
1995	427	569	460	141	59	2	0	0	0	20	179	266	2123
Mean	449	325	214	72	10	3	11	0	5	13	123	259	1485

Source: Adapted from Van Cooten and Borrell (1999).

in West Timor, wet-season soybean, when well established, quickly reach full canopy, choking out competing weeds. The subsequent dry-season sorghum crop is drought-resistant, competing well with weeds in this arid environment. Combining stringent herbicide use, mechanical cultivation, manual weeding and rotational cropping systems should adequately control weeds on permanent raised beds in South-East Asia.

Erosion control

Using permanent raised beds can reduce erosion in two ways. First, raised beds on clay soils in the lowlands increases the stability of the system because the beds are permanent and can provide all-year ground cover. Hence bare soil is not exposed to high rainfall at the beginning of the wet season. Second, upland cropping on steep slopes can be replaced by a variety of tree species, providing additional food, fodder, firewood and medicines while reducing erosion. This is possible because the crops currently grown in upland fields (e.g. maize) can instead be grown on raised beds in the lowlands since waterlogging is not a problem on the raised beds. Replacement of upland cropping areas with forests, however, assumes that all the farmers' basic food and cash crop requirements can be met by growing a diverse intercrop on large raised beds, interspersed by smaller raised beds planted to monocultures of rice or soybean in the wet seasons and sorghum or mung bean in the dry season (see below 'An Integrated Approach …').

Availability of labour

To reduce the risk of crop failure, farmers may cultivate three or four swidden gardens, 5 to 10 km apart, as well as cultivate rice. Widely dispersed fields increase the chance that at least one field receives enough rain at the right time for a successful harvest (Simpson 1995), but they also increase the labour and time required for walking to and fro. The availability of labour, especially for land preparation, weeding and guarding of gardens from livestock intrusion, bird damage and stealing, is a major factor affecting crop production in eastern Indonesia (Pellokila et al. 1991). The permanent raised bed system proposed by Van Cooten and Borrell (1999) combines both upland swidden gardening with rice cultivation in the one field, thus reducing the labour and time involved in walking between widely dispersed fields and therefore increasing the farmers' opportunities for protecting their crops from livestock, birds and thieves. The higher water-holding capacity of the lowland soils and the ability to store excess water in the furrows better uses rainfall, reducing the need for widely dispersed gardens. Intercropping and crop rotation can also reduce the labour requirements for weeding. However, the initial establishment of raised beds and furrows requires considerable labour, that is, farmers adopting this system will need to work together or be helped with a revolving credit scheme that will enable them to hire additional labour or use machines.

An Integrated Approach to Food and Cash Cropping

Subsistence farmers' most important concern is to provide sufficient nutritious food for their families. Only after household needs are met can farmers consider the feasibility of entering the cash economy. Income generated from cash cropping is required for housing, health care and education. Food security is paramount in regions such as West Timor, and the cropping systems evolved in these areas aim to reduce total crop failure through drought or flooding (Pellokila et al. 1991). Cropping systems in South-East Asia must therefore meet the criteria of food production (food crops) and income generation (cash crops).

Recent experiments in West Timor have shown that rice (Borrell et al. 1998) and soybean (Van Cooten and Borrell 1999; R.M. Kelly pers. comm., 2000) can be grown successfully on raised beds in the wet season. Rice is an important food crop, supplying energy in the form of complex carbohydrates (Eggum 1979). However, rice production in eastern Indonesia is severely limited by drought (Borrell et al. 1998), and N and P deficiencies in the soil also limit yield (Pellokila et al. 1991). In contrast, soybean yields particularly well on soils depleted in both N and P, indicating the suitability of this grain legume to the harsh environment and poor soils of eastern Indonesia (R.M. Kelly pers. comm., 2000). Soybean is also an excellent source of protein, complementing the carbohydrates supplied by various cereals.

Garlic, an important cash crop, is grown mainly in the highlands of West Timor during the south-east monsoons (Pellokila et al. 1991; Simpson 1995). Garlic can be grown on raised beds in rotation with other crops (Simpson 1995). We also found that, when planted between April and June, garlic grew well on raised beds in the lowlands near Kupang. We observed that sequential cropping on raised beds of wet-season rice, soybean or cassava followed by dry-season sorghum, garlic, cassava or mung bean was a viable system that provided a balance of food (carbohydrates and protein) and cash income. Peanut (*Arachis hypogaea* L.) comprises another important cash crop in West Timor, being grown mainly as a monocrop in small areas (Pellokila et al. 1991).

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Intercropping is an example of risk-aversion management used by subsistence farmers to maximize rainfall use, and is an important part of existing cropping systems in south-eastern Indonesia (Simpson 1995). Although yields may be lower for individual crops within this system, total crop production is optimized, regardless of the type of wet season (Pellokila et al. 1991). Intercropping in Timor usually involves crops that mature after the maize harvest and can grow on residual soil moisture (Pellokila et al. 1991), that is, cassava, sorghum and pigeon pea (*Cajanus cajan* (L.) Millsp.). The effects of intercropping peanut and maize on maize yields have been studied in some detail by Bahtier et al. (1989), Salam Wahid et al. (1989a, b) and Zubachtirodin (1989). They conclude that crops such as peanut with similar growing seasons to that of maize should not be intercropped because they compete for available resources, reducing the potential maize yield and therefore the amount of food available to the household.

Intercropping on large raised beds was evaluated in the village of Oenesu, West Timor, during the 1997/98 wet season (Van Cooten and Borrell 1999). Maize, yam bean (*Pachyrrhizus erosus* (L.) Urban), cassava, traditional sorghum and pigeon pea were intercropped on raised beds that were 0.5 m high and 4 m wide. Between the large beds, rice and soybean were grown on smaller beds, 0.2 m high and 1.3 m wide. The surface of the large beds was flat (3 m), with sloping edges (0.5 m) into which yam bean was planted. Sorghum was planted along the edge of the beds with maize, pigeon pea and cassava intercropped in the centre of the beds. Maize, pigeon pea and cassava were sown in the first week of December at the start of the wet season (Figure 1). Sorghum was planted in the third week in December, followed by yam bean in the first week in January. The crops were harvested sequentially as they matured, beginning with maize at the end of March (2.6 t ha^{-1}). Yam bean (0.8 t ha^{-1}), sorghum (1.8 t ha^{-1}) and cassava (2.3 t ha^{-1}) were harvested in June, and pigeon pea (0.3 t ha^{-1}) in the second week of July.

The yields quoted were fresh weights, as the village had no drying facilities. These experiments highlighted the fact that it is possible to grow crops other than rice on the lowland clay soils in the wet season and, more importantly, that the total yield of this system per unit land area (7.8 t ha^{-1} fresh weight) is far greater than that achieved with rice monoculture (about 1.5 t ha^{-1} dry weight, Borrell et al. 1998). Moreover, crops could be harvested from late March to early July, guaranteeing continuity of food supply over this time. Periods of intermittent drought affected some crops more than others, but all crops yielded something at the end of the season.

Raised-bed cropping in Timor would also provide a mechanism for farmers to plant a traditional mixture of crop species on the more fertile alluvial soils, thus improving the output of the traditional system and ensuring the survival of species diversity. In a survey on the ethnobotany of Alor, eastern Indonesia, Van Cooten (1999) reported 57 plant species of importance to the Abui people. These species are used for food, medicines, poisons and dyes (Kelly and Van Cooten 1997).

Conclusions

The permanent raised bed system proposed in the northern Australian (Garside et al. 1992b; Borrell et al. 1997) and Indonesian (Borrell et al. 1998; Van Cooten and Borrell 1999) studies recommends modifications to the current agricultural systems in these regions, to obtain a more sustainable system with higher annual production.

Collectively, the complementary studies conducted in northern Queensland between 1989 and 1992 indicate that the double cropping of rice and field crops in rotation is feasible and may provide additional synergistic and logistic benefits over those found in the traditional rice/fallow system (Garside et al. 1992b). The key to integrating the various system components seems to depend on developing SSC technology for rice production. Regardless of where this technology is adopted in the tropics, acceptance of SSC by rice growers would lead to decreased water use and more efficient use of water. In addition, adoption of permanent raised bed concepts and controlled traffic would improve the timeliness of farm operations, facilitate the change from one crop to the next, and greatly improve the reliability of achieving multiple crops per year. This would lessen the probability of unproductive fallow periods. Incorporation of a grain legume such as soybean would improve the N economy of the system, and P requirements for field crops following rice may be reduced by growing rice under SSC.

Experiments undertaken in West Timor between 1993 and 1999 have shown that a range of crops, in addition to rice, can be grown on raised beds during the wet season, overcoming the previous limitation of waterlogging to crop growth. Initial construction of raised beds before the wet season in lowland areas, and maintenance of permanent structures thereafter, enables crops to be sown at the onset of the wet season, thereby avoiding end-of-season drought and significantly increasing crop yields. Appropriate mechanization in the form of a two-wheeled hand-tractor and associated bed-maker can be used to construct and maintain the beds. Early sowing and harvesting of the wet-season crop opens the way to plant a drought-resistant species such as

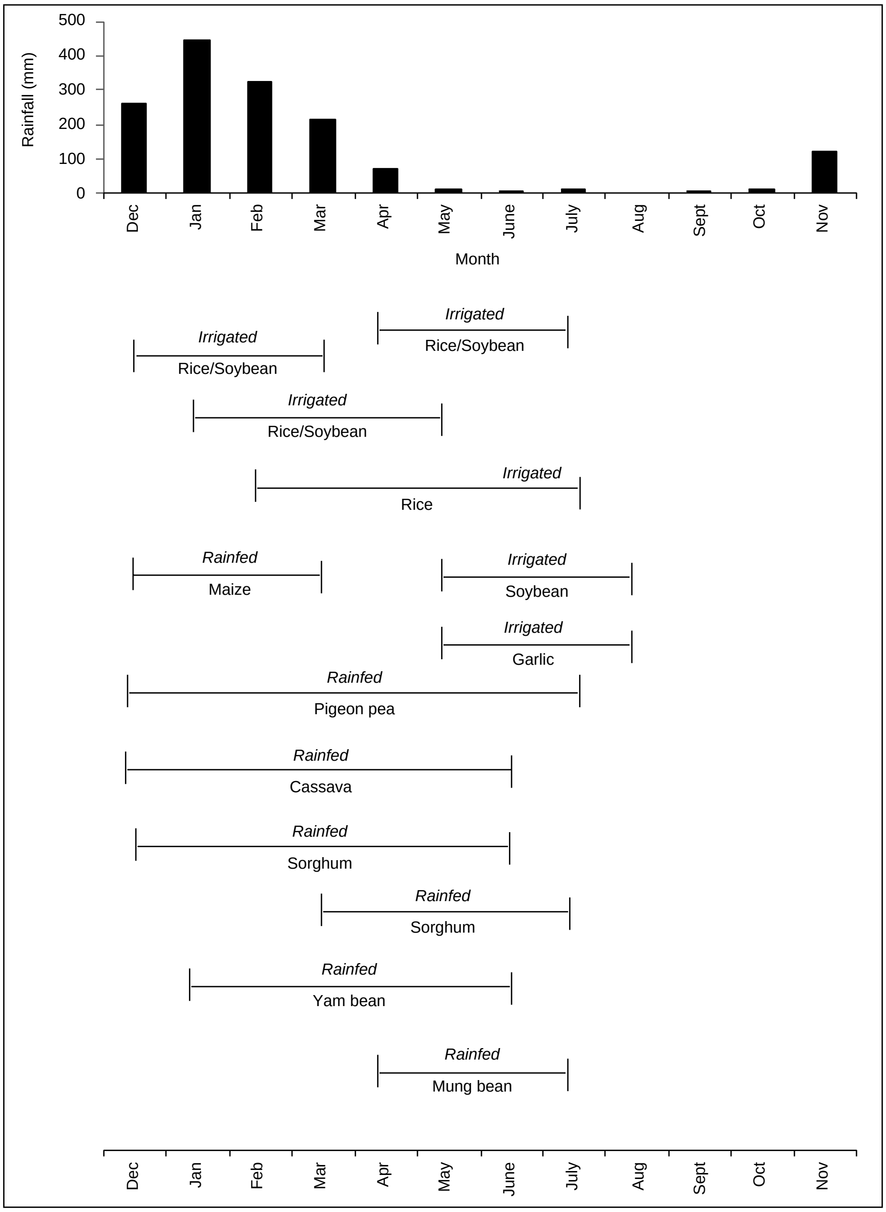


Figure 1. Cropping calendar for a raised-bed farming system in West Timor. Horizontal bars denote the length of the growing season for various crops. Each crop is also classified as either *irrigated* or *rainfed*. The total monthly rainfall was recorded at Kupang, West Timor, and is the mean of a 10-year period from 1985 to 1995.

sorghum in late March or early April, better using stored soil water from the end of the wet season. This system greatly increases the probability of attaining both wet- and dry-season crops each year, thus enhancing food security for subsistence farmers in eastern Indonesia. It also opens up the possibility of reforesting eroded upland cropping areas with a range of perennial species that would provide food, fodder, firewood, building materials and medicines, assuming that the subsistence farmers' basic food and/or cash crop requirements can be met by intensive lowland production.

Together, the studies conducted in northern Queensland and eastern Indonesia provide a framework for using less water and increasing the WUE in rice-based cropping systems throughout South-East Asia. Saturated soil culture on permanent raised beds is the key technology underpinning these improved efficiencies.

References

Bahtier, Zubachtirodin and Subandi. 1989. Pengaruh tumpangsari jagung kacang-kacangan dan populasi jagung terhadap pertumbuhan gulma dan hasil. Laporan Komponent Technologi Tanaman Pangan, 1988/89. [The influence of maize and legume intercropping and maize population on the growth of weeds and on yields. Report of the Food Crops Technology Component, 1988/89.] Kupang, Timor, NTASP. (Nusa Tenggara Agricultural Support Project)

Barlow, C. and Gondowarsito, R. 1991. Socio-economic features and potentials. In: Barlow, C., Bellis, A. and Andrews, K. ed. Nusa Tenggara Timur: The Challenges of Development. Political and Social Monograph 12. Canberra, Australian National University, 15–30.

Borrell, A.K. 1993. Improving efficiencies of nitrogen and water use for rice in semi-arid tropical Australia. Ph.D. dissertation. Brisbane, The University of Queensland.

Borrell, A.K., Bidinger, F.R. and Sunitha, K. 1999. Stay-green associated with yield in recombinant inbred sorghum lines varying in rate of leaf senescence. International Sorghum and Millets Newsletter, 40, 31-34.

Borrell, A.K., Fukai, S. and Garside, A.L. 1991. Alternative methods of irrigation for rice production in tropical Australia. International Rice Research Newsletter, 16 (3), 28.

Borrell, A.K., Fukai, S. and Garside, A.L. 1993. Saturated soil culture: a new concept for irrigated rice production in tropical Australia. In: Proceedings of the 7th Australian Agronomy Conference, 19–24 September 1993. South Australia, The University of Adelaide, 100–102.

Borrell, A.K., Garside, A.L. and Fukai, S. 1997. Improving efficiency of water use for irrigated rice in a semi-arid tropical environment. Field Crops Research, 52, 231–48.

Borrell, A.K., Kelly, R.M. and Van Cooten, D.E. 1998. Improving management of rice in semi-arid eastern Indonesia: responses to irrigation, plant type and nitrogen. Australian Journal of Experimental Agriculture, 38, 261–71.

Bourne, A. and Norman, K.L. 1990. Burdekin irrigated field crops costs and returns: 1990/1991. Report No. RQM90003. Brisbane, Queensland Department of Primary Industries, 50 p.

Braunack, M.V., McPhee, J.E. and Reid, D.J. 1995. Controlled traffic to increase productivity of irrigated row crops in the semi-arid tropics. Australian Journal of Experimental Agriculture, 35, 503–13.

De Datta, S.K., Krupp, H.K., Alvarez, E.I. and Modgal, S.C. 1973. Water management practices in flooded tropical rice. In: Water Management in Philippine Irrigation Systems: Research and Operations. Los Baños, Philippines, International Rice Research Institute, 1–18.

Dowling, A.J. 1995. Phosphorus dynamics in soils that undergo alternating periods of flooding and draining. Ph.D. dissertation. Brisbane, The University of Queensland.

Duggan, K. 1991. Land and environment in NTT. In: Barlow, C., Bellis A. and Andrews, K. ed. Nusa Tenggara Timur: the Challenges of Development. Political and Social Monograph 12. Canberra, The Australian National University, 31–8.

DuPont, A. 2000. Food, water and security: what are the connections? In: Food, Water and War: Security in a World of Conflict. Record of a conference conducted by the Crawford Fund for International Agricultural Research, Parliament House, Canberra, 15 August 2000. ACIAR Monograph No. 73. Canberra, 39–59.

Eggum, B.O. 1979. The nutritional value of rice in comparison with other cereals. In: Proceedings of the Workshop on Chemical Aspects of Rice Grain Quality. Los Baños, Philippines, International Rice Research Institute, 91–111.

Ferguson, J.A. 1970. Effect of flooding depth on rice yield and water balance. Arkansas Farm Research, 19, 4.

Gardner, E.A. and Coughlan, K.J. 1982. Physical factors determining soil suitability for irrigated crop production in the Burdekin-Elliot River area. Agricultural Chemistry Branch Technical Report No. 20. Brisbane, Queensland Department of Primary Industries, 49 p.

Garside, A.L., Lawn, R.J. and Byth, D.E. 1992a. Irrigation management of soybean (*Glycine max* (L.) Merrill) in a semi-arid tropical environment. III. Response to saturated soil culture. Australian Journal of Agricultural Research, 43, 1033–49.

Garside, A.L., Borrell, A.K., Ockerby, S.E., Dowling, A.J., McPhee, J.E. and Braunack, M.V. 1992b. An irrigated rice-based cropping system for tropical Australia. In: Hutchinson, K.J. and Vickery, P.J. ed. Proceedings of the 6th Australian Agronomy Conference, held at The University of New England, Armidale, 259–61. Armidale, NSW. Australian Society of Agronomy.

Hunter, M.N., de Jabrun, P.L.M. and Byth, D.E. 1980. Response of nine soybean lines to soil moisture conditions close to saturation. Australian Journal of Experimental Agriculture and Animal Husbandry, 20, 339–345.

Kelly, R.M. and Van Cooten, D.E. 1997. Useful Plants of Alor. YBM Monograph 1. Kupang, Timor, Yayasan Bina Mandiri.

McPhee, J.E., Braunack, M.V., Garside, A.L., Reid, D.J. and Hilton, D.J. 1995a. Controlled traffic for irrigated double cropping in a semi-arid tropical environment:, Part 1: Machinery requirements and modifications. Journal of Agricultural Engineering Research, 60, 175–82.

McPhee, J.E., Braunack, M.V., Garside, A.L., Reid, D.J. and Hilton, D.J. 1995b. Controlled traffic for irrigated double cropping in a semi-arid tropical environment, Part 2: Tillage operations and energy use. Journal of Agricultural Engineering Research, 60, 183–89.

McPhee, J.E., Braunack, M.V., Garside, A.L., Reid, D.J. and Hilton, D.J. 1995c. Controlled traffic for irrigated double cropping in a semi-arid tropical environment, Part 3: Timeliness and trafficability. Journal of Agricultural Engineering Research, 60, 191–99.

Nathanson, K., Lawn, R.J., De Jabrun, P.L.M., and Byth, D.E. 1984. Growth, nodulation and nitrogen accumulation by soybean in saturated soil culture. Field Crops Research, 8, 73–92.

Ockerby, S.E., Garside, A.L., Adkins, S.W. and Holden, P.D. 1999a. Prior crop and residue incorporation time affect the response of paddy rice to fertiliser nitrogen. Australian Journal of Agricultural Research, 50, 937–944.

Ockerby, S.E., Adkins, S.W. and Garside, A.L. 1999b. The uptake and use of nitrogen by paddy rice in fallow, cereal, and legume cropping systems. Australian Journal of Agricultural Research, 50, 945–952.

Pellokila, C., Field, S. and Momuat, E.O. 1991. Food crops for Nusa Tenggara Timur. In: Barlow, C., Bellis, A. and Andrews, K. ed. Nusa Tenggara Timur: The Challenges of Development. Political and Social Monograph 12. Canberra, The Australian National University, 121–43.

Prove, B., Truong, P. and Evans, D. 1990. Reduced tillage may help protect the Great Barrier Reef. Agrarian (Newsletter of INCITEC Agribusiness), 10, 1–2.

Salam Wahid, A., Fadahly, A.F., Supadmo, H. and Djamaluddin. 1989a. Pengaruh jarak tanam dalam barisan dan jumlah tanaman jagung tiap rumpun terhadap hasil tumpangsari jagung dengan kacang tanah. Laporan Komponent Technologi Tanaman Pangan, 1988/89. [The influence of planting distances in rows and the number of maize seedlings per cluster on the results of maize and peanut intercropping. Report of the Food Crops Technology Component, 1988/89.] Kupang, Timor, NTASP. (Nusa Tenggara Agricultural Support Project)

Salam Wahid, A., Zubachtirodin, Momuat, S. and Subandi. 1989b. Pengaruh waktu tanam kacang tanah pada sistem tumpangsari dengan jagung. Laporan Komponent Technologi Tanaman Pangan, 1988–89. [The influence of planting time of peanuts on the intercropping system with maize. Report of the Food Crops Technology Component, 1988/89.] Kupang, Timor, NTASP. (Nusa Tenggara Agricultural Support Project)

Sanchez, P.A. 1973. Puddling tropical rice soils. 2. Effects of water losses. Soil Science, 115, 303–308.

Simpson, S.L. 1995. Post construction activities to support ground water development for subsistence communities in West Timor, Indonesia. (Unpublished report, Nusa Tengarra Timur Water Resources Development Service Program, Kupang)

Tabbal, D.F., Lampayan, R.M. and Bhuiyan, S.I. 1992. Water-efficient irrigation technique for rice. In: Murty, V.V.N. and Koga, K. ed. Soil and Water Engineering for Paddy Field Management. Bangkok, Asian Institute of Technology.

Troedson, R.J., Lawn, R.J., Byth, D.E. and Wilson, G.L. 1989. Response of field-grown soybean to saturated soil culture. 1. Patterns of biomass and nitrogen accumulation. Field Crops Research, 21, 171–87.

Van Cooten, D.E. 1999. Collecting baseline data on the ethnobotany of Nusa Tenggara Timur, Indonesia. In: Domestication of Trees in Southeast Asia Special Issue. FACTRR. (Forest, Farm and Community Tree Research Reports)

Van Cooten, D.E. and Borrell, A.K. 1999. Enhancing food security in semi-arid eastern Indonesia through permanent raised-bed cropping: a review. Australian Journal of Experimental Agriculture, 39, 1035–1046.

Wickham, T.H. and Singh, V.P. 1978. Water movement through wet soils. In: Soils and Rice. Los Baños, Philippines, International Rice Research Institute, 337–357.

Wright, G.C., Smith, C.J. and Wilson, I.B. 1988. Growth and yield of soybeans under wet soil culture and conventional furrow irrigation in south-eastern Australia. Irrigation Science, 9, 127–142.

Zubachtirodin. 1989. Pengendalian gulma pada tumpangsari jagung dengan kacang tanah. Laporan Komponent Technologi Tanaman Pangan, 1988–89. [Weed control by intercropping maize and peanuts. Report of the Food Crops Technology Component, 1988–89.] Kupang, Timor, NTASP. (Nusa Tenggara Agricultural Support Project)

Low Temperature Tolerance in Rice: The Korean Experience

Moon-Hee Lee

Abstract

In 1980 and 1993, low temperatures seriously damaged the Korean rice crop. Grain yield decreased by 26% and 9.2%, respectively, compared with the national average of other years. Low temperatures cause the rice plant to suffer poor and slow vegetative growth, spikelet sterility, delayed heading and poor grain filling. Rice varieties differ significantly in their capacity to tolerate low temperatures at various growth stages. Tongil types (Indica/Japonica hybrids and high-yielding rices), for example, are more susceptible to low temperatures than are Japonica varieties, needing temperatures that are 2.5° to 3.0°C higher. Reliable screening methods have been developed, using a phytotron, growth chambers and low water temperatures, and significantly improving cold-tolerant selections. For year 2000, 57% of varieties released in Korea were highly tolerant of low temperatures. Management of cultural practices is another method for improving cold tolerance in rice. For example, optimal application of nitrogen can maximize yields and reduce damage by low temperatures. If leaf nitrogen content is too high, then, under low temperatures, spikelet sterility increases significantly—by 3.5% in Tongil and 2.5% in Japonica varieties. In 1993, in cool mountainous regions, applying organic matter during low temperatures significantly increased grain yield. Deepwater (20 cm) irrigation during the reproductive stage can increase grain yields by 10% to 14%, compared with rice growing in shallow water.

RICE is Asia's most important staple, and its consistent production is vital for food security. Most rice-growing countries are faced with climate-induced stresses that significantly reduce rice productivity: droughts, floods, low temperatures and winds. Low temperatures comprise a major climatic problem for rice growing in 25 countries, including Korea and Japan, and even in tropical countries such as the Philippines and Thailand (Kaneda and Beachell 1974).

The Korean peninsula is located in the Far East, between latitudes 33° 06′ and 43° 01′ north and between longitudes 124° 11′ and 131° 53′ east, in the northern temperate climatic zone. Summers are hot and humid and winters severely cold. Rice is therefore a summer crop, grown between April and October. In the northern, mountainous regions, the rice plant can suffer from low temperatures at any stage between germination and maturity. In years of extreme low temperatures, all rice-growing areas are susceptible to cold at the reproductive stage. For example, in 1980 and 1993, low temperatures seriously damaged the Korean rice crop, with grain yields dropping by 26% and 9.2%, respectively, compared with the national average yield on either side of these years (MOAF 1994).

This paper discusses the damage caused by low temperatures in Korea in recent years and the development of new varieties and cultural practices for cold tolerance. Developing cold-tolerant varieties and suitable cultural practices is of great concern for the future because these will lead to consistently high yields in cold regions, particularly in the highlands and cooler regions of the subtropics.

Geo-Climatic Conditions

The geography of the Korean peninsula is characteristically hilly or mountainous. Three regions can be distinguished: (1) alpine: northern and eastern

---

International Rice Research Institute (IRRI), PBGB, MCPO Box 3127, 1271 Makati, Philippines.
E-mail: m.lee@ cgiar.org

KEYWORDS: Cold tolerance, Low temperatures, Low temperature damage, Rice, Sterility

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

peninsula, featuring a high and long mountain range known as the Hamgyong and Taebaeg Range; (2) mid-altitudes: located mid-peninsula and extending north to south; and (3) coastal plains: mostly western and southern peninsula. The mountainous topography reduces arable land to about 21.7% of the nation's total land area (KOIS 1993).

The Korean peninsula has four distinct seasons: a cold winter, spring, a warm and humid summer and autumn. The average annual temperature is around 12°C, averaging between 12° and 15°C in the south, 10° and 12°C in the central region, and 5° and 10°C in the north. Temperatures range from 0°C in the coldest month (January) to 25°C in the warmest month (August) (NCES 1990).

Temperature, solar radiation and water are the three critical requirements for growing rice. Over summer (the rice-growing season), the mean monthly air temperature gradually increases from 11°C in April to 25°C in August, then declines to below 13°C in October (Figure 1). Temperatures vary, however, according to year and region, for example, the southern and coastal areas usually have higher temperatures than do the northern and inland regions.

Average annual rainfall in Korea is about 1250 mm, with some regional variation. However, 70% of total rainfall occurs in the summer, from June to September, with 330 mm falling in July. As are autumn and winter, spring is often a dry season, frequently delaying transplanting of rice in rainfed areas. In the autumn dry period, the crop receives sufficient solar radiation between physiological maturity and harvest to permit ripening and therefore adequate yields.

Low Temperature Damage in Korea

The Korean rice industry has suffered many climate-induced disasters, including low temperatures, strong winds, droughts and floods. Winds cause severe and frequent lodging (Table 1). However, low temperatures comprise the biggest threat to the Korean rice industry in terms of area and degree of damage. In 1980 and 1993 summers, for example, 783 000 and 208 000 ha were damaged, respectively, by low temperatures during the rice crop's critical vegetative and reproductive stages.

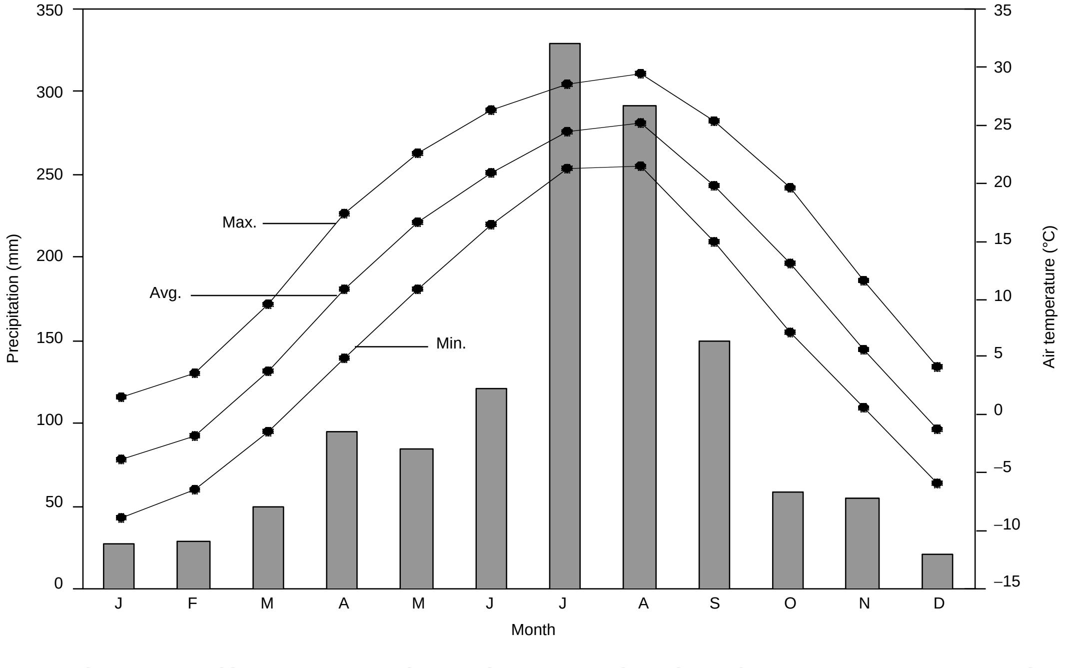


Figure 1. Changes in monthly air temperatures (lines) and precipitation (bars) during the rice cropping season (Kim and Kim in press).

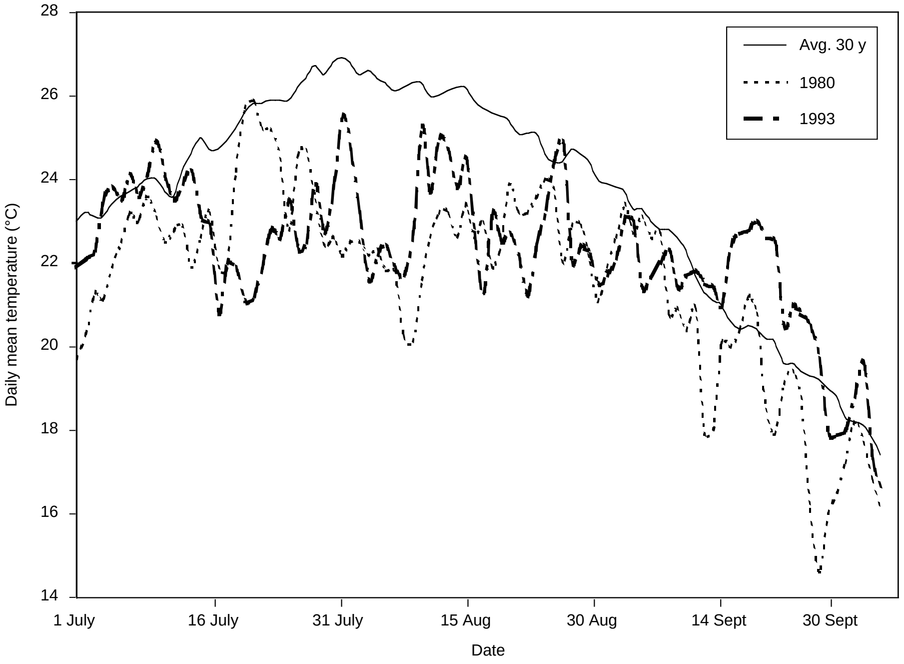


Figure 2. Daily mean temperatures from June to August of 1980 and 1993, and the average of the last 30 years, Korea.

Table 1. Area of paddy fields damaged by unfavourable climatic factors in Korea, 1965 to 1998.

Year	Unfavourable climatic factor			
	Drought (10^{-3} × ha)	Wind (10^{-3} × ha)	Low temp. (10^{-3} × ha)	Others (10^{-3} × ha)
1965	574	48	—	—
1970	—	172	—	67
1975	24	50	—	—
1980	5	105	783	7
1985	—	111	—	3
1990	—	122	—	—
1993	—	39	208	9
1995	7	84	—	—
1998	—	235	—	67

Source: MOAF (1999).

The daily mean air temperatures during reproductive and maturing (July–September) in 1980 and 1993 were lower compared with the 30-year average (Figure 2). During the 1980 season, the spell of low temperatures started late July and continued until late August, whereas, in 1993, cool weather was prevalent between mid-July and early August, that is, 2 weeks earlier, but 2° to 3°C warmer.

The low temperatures in 1980 and 1993 decreased rice production significantly, compared with Korea's national average in other years. Yields in 1980 averaged 2.89 t ha^{-1}, representing a 26% decrease, compared with the national average in the previous 5 years and, in 1993, yields averaged 4.18 t ha^{-1}, representing a 9.2% decrease (Figure 3; MOAF 1999). These rice production data suggest that a significant difference in rice production existed between 1980 and 1993. The improvement may have been due to improved cold-tolerant varieties and cultural practices, and to the degree and extent of low temperature damage. Following the cold weather in 1980, three research substations were established in both the alpine and mid-altitude regions to develop low-temperature-tolerant varieties and improve cultural practices.

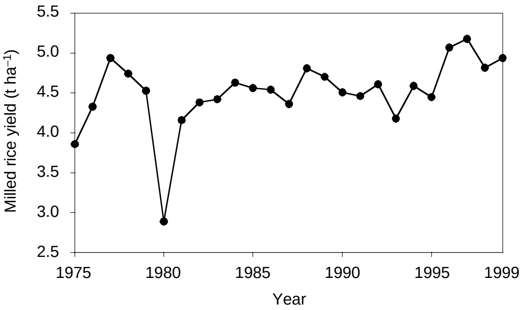


Figure 3. Average milled rice yield from 1975 to 1999, Korea (MOAF 2000).

Conditions for Low Temperature Damage

For successful rice production in Korea, air temperature should average more than 13°C for 150 days. Too cool air and water temperatures cause damage at crop establishment, while low air temperature by itself affects the rice plant at the reproductive and grain-filling stages. Research on breeding cold-tolerant varieties and cultural practices did not begin until 1970. Since then, it has been strengthened, particularly when the Tongil types (Indica/Japonica hybrids and high-yielding rices) were found to be highly susceptible to low temperatures.

Research findings on critical low temperatures and symptoms of resulting damage are summarized in Table 2 (NCES 1990). The critical temperature for rice is usually below 20°C and varies according to growth stage, for example, for germination, the critical temperature is 10°C and for the reproductive stage, it is 17°C. Nishiyama (1985) and Yoshida (1978) report that the critical low temperature differs according to variety, duration of low temperature and the plant's physiological development.

Table 2. Type and symptoms of cold damage in rice, Korea.

Growth stage	Critical temp. (°C)	Type and/or symptoms of cold injury
Germination	10	Poor, delayed
Seedling	13	Retarded seedling growth Leaf discolouration Seedling rot
Vegetative	15	Inhibited rooting, growth and tillering Delayed panicle initiation
Reproductive	17	Inhibited panicle development Degenerated spikelets Disturbed meiosis and pollen formation Delayed heading
Heading	17	Poor panicle exsertion Inhibited anther dehiscence and pollination
Maturity	14	Poor grain filling and quality Early leaf senescence

Source: NCES (1985).

The usual symptoms of low temperature damage in Korea are poor and delayed germination, stunted seedling growth and leaf yellowing during early growth, and inhibited rooting and tillering during the vegetative stage. The rice plant is most sensitive to low temperatures during the reproductive stage, showing inhibited panicle initiation and development, spikelet degeneration and disturbed pollen formation. Near maturity, low temperatures induce poor grain filling and rapid leaf senescence.

Results of NCES research show that, under controlled conditions and at 10°C, germination rate was very low, compared with the rates at 12° and 15°C (Table 3). However, germination rates were significantly different between the Japonica (74%) and Indica/Japonica (12%) varieties, 20 days after sowing at 10°C. Jun et al. (1987) also reported that Japonica rice varieties germinated well, compared with Indica/Japonica crosses under the same low temperatures.

Table 3. Differences of germination rates (%) between Japonica and Indica/Japonica rice lines according to temperature.

Line group	Varieties (no.)	Temperature[a]					
		10°C		12°C		15°C	
		15 D	20 D	15 D	20 D	15 D	20 D
Japonica	5	45	74	85	88	93	95
Indica/Jap.	7	2	12	51	64	72	97

[a] D = days after sowing.

Source: NCES (1977).

Seedling growth is highly variable under different temperature regimes (Table 4). At the vegetative stage, temperatures lower than 15°C reduce plant height, tillering, root growth and dry weight of the rice plant. Hue (1978) and other studies suggest that Japonica rice varieties can tolerate low temperatures much better than Indica/Japonica varieties, with the latter requiring 2.5°–3.0°C higher temperatures than do Japonica rice varieties for effective growth between germination and maturity.

Table 4. Effect of temperature on seedling growth and rooting in the Indica/Japonica rice variety Milyang 23.

Temperature (°C)	Plant height (cm)	Tillers (no. per hill)	Roots (no. per plant)	Dry weight (g per 10 plants)
20	64	9.6	84	25.1
12	12	2.6	10	0.7
25–12[a]	59	3.1	32	3.3
15–25[b]	40	4.5	22	7.1
Control (Natural)[c]	36	13.2	83	17.8

[a] Grown for 10 days at 25°C and for 20 days at 12°C.

[b] Grown for 10 days at 15°C and for 20 days at 25°C.

[c] Natural : Field temperature condition

Source: NCES (1970).

Within the reproductive stage, booting is the stage at which rice is most sensitive to low temperatures, particularly 10 days before heading, leading to panicle degeneration and empty grains at harvest. Yoshida (1978) and Satake (1976) found that low temperatures most affect the young microspore stage, at about 10 or 11 days before heading. A recent phytotron experiment compared two varieties (Tongil, i.e. Indica/Japonica type, and Jinheung, i.e. Japonica type) exposed to low temperatures at different times before heading. The lowest filled grain ratios were 30% for Tongil and 70% for Jinheung at 10 days before heading (Figure 4).

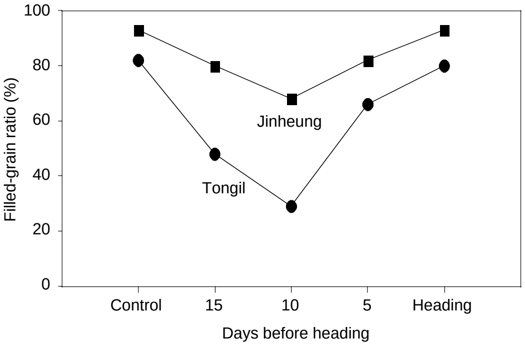


Figure 4. Filled-grain ratio for Jinheung (Japonica rice type) and Tongil (Indica/Japonica rice type) varieties exposed to low temperatures on different days before heading (after Lee et al. 1987a).

Developing Cold-Tolerant Rice Varieties

Breeders aim to develop rice germplasm that can produce high and stable yields in regions where low temperatures are found. Specific objectives include integrating qualities of other varieties into leading varieties. Traits include short-cycle maturity, medium stature, multiple resistance to pests and diseases and good grain quality.

Screening

Screening for low temperature tolerance in rice is highly complex, because responses to low temperatures differ between varieties, growth stages and actual temperatures used. For effective selection, the standard screening methods and facilities used need to be reliable in providing the required low air and water temperatures. A list of standard screening and testing methods for low temperature tolerance developed in Korea is given in Table 5. To screen effectively for adapted cultivars, low temperature treatment and duration differ according to growth stage, for example, at germination, a 7-day treatment of air and water cooled to 13° to 15°C is imposed; at the 3-leaf stage, a 10-day treatment of 12°/10°C (day/night air) is used; at booting, 10 days of air and water at 18°C; and at grain filling, 20°/15°C (day/night air) for 20–30 days, using the phytotron or greenhouse. The simultaneous use of controlled facilities such as the growth chamber or phytotron

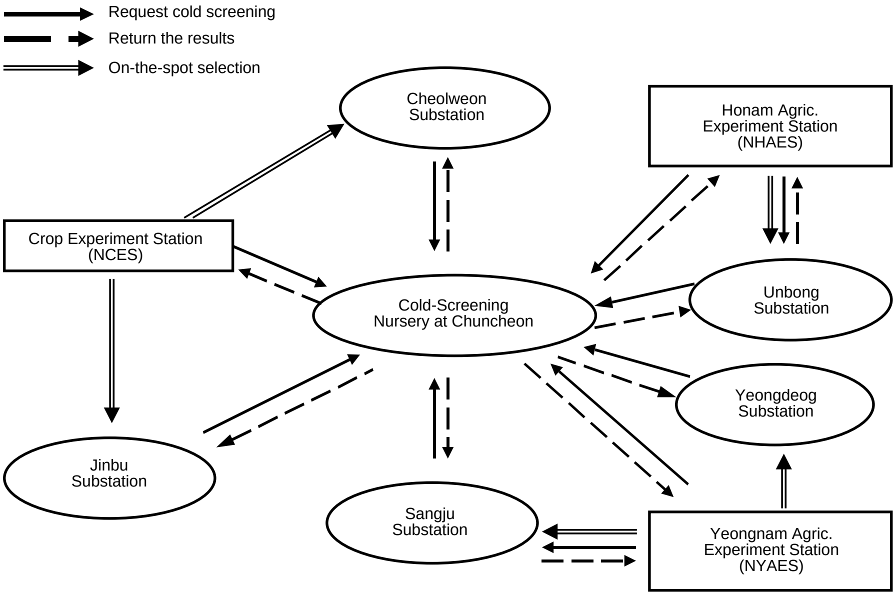


Figure 5. Cooperative system between three experiment stations and their five substations for screening and selecting cold-tolerant rice varieties, Korea (after NCES 1985).

and mass screening in the field is required for efficient selection.

For mass screening, the cold-water screening system works efficiently, especially for combined cold tolerance throughout the entire plant growth. The screening system consists of planting lines in 12-m-long rows, and irrigating them with a 7°C gradient in water temperature over 10 m from inlet to outlet. The paddy field is constantly irrigated with cold water from 20 days after transplanting to maturity. This screening system allows researchers to determine the response of various agronomic traits associated with cold damage, and to identify varietal differences.

Breeding system

To solve low temperature problems in rice, the National Crop Experiment Station (NCES) established facilities in 1978 at the Chuncheon Substation. After the extreme low temperature events in 1980, four substations were established in the highland and mid-altitude regions: Jinbu at the NCES, Unbong at the National Honam Agricultural Experiment Station (NHAES), and Sangju and Yeongdeog at the National Yeongnam Agricultural Experiment Station (NYAES). Research facilities consist of a field screening system, using cold water, and greenhouse screening.

A model of the collaborative breeding system between the three experiment stations (NCES, NHAES and NYAES), involving five of their substations has been developed (Figure 5). Most of the cultivars selected for low temperature tolerance have been tested, using the cold-water field-screening system at the Chuncheon Substation. Based on preliminary results from Chuncheon, very early maturing material is then sent to Jinbu Substation. Short-season cultivars, selected for their adaptability to mountainous areas, are sent to the Cheolweon Substation, located in the mid-altitude areas of Korea’s central region. Selections from the early maturing materials from the NHAES are sent to the Unbong Substation in the mid-altitude regions in the southern part of the peninsula. Materials sent from the NYAES to the Sangju and Yeongdeog Substations are for mid-altitude areas in southern and eastern coastal areas.

To maximize breeding efficiency and develop highly cold-tolerant varieties, using the research facilities, the shuttle breeding system was established between the stations (Figure 6). The idea was to incorporate cold tolerance and other desirable traits (multiple disease resistance) into commercial varieties, using three-way bridge crossing or single and back crossing at the stations. Selected F_2 populations and F_3 lines are sent to the Chuncheon Substation to screen for low temperature tolerance at the cold-screening nursery. Selections from the F_4 and F_5 generations are conducted according to maturity type, spikelet sterility and phenotypic acceptability under natural conditions. Very early maturing lines are selected from the F_6 and F_7 generations at Jinbu and Yeongdeog. However, the F_6 and F_7 lines, which are early maturing and possess desirable agronomic traits, are selected at the Cheolweon, Unbong and Sangju Substations. Subsequently, the selected F_8 lines are tested for adaptability to local conditions at the substations and on farm. The selected elite lines are then nominated for release as new varieties.

Rice-breeding techniques for low-temperature tolerance have led to the release of significantly improved new cultivars during the last 30 years. Cold-tolerant varieties usually have short cycles, are

Table 5. Methods and facilities for screening cold tolerance in rice, Korea.

Types of damage	Screening procedure[a]	Facilities
Germinability	Water and air at 13°–15°C for 7 days	Germinator
Seedling		
Chilling injury	Water and air at 5°C for 2–3 days at 2-leaf stage	Growth chamber
Growth and	Cool-air treatment at 12°/10°C (D/N) for 10 days at 3-leaf stage	Phytotron
Discolouration	Cold-water treatment at 13°C for 10 days at 3-leaf stage	Cold-water flowing test at Chuncheon
Delayed heading	18°/10°C (D/N air) for 10 days at 10–20 days after transplanting	Phytotron
Sterility	18°/18°C (air/water) for 10 days at meiosis	Phytotron and greenhouse
	10°/23°C (air/water) for 10 days at heading	Phytotron and greenhouse
Combined type	Cold water at 17°C and flowing for the whole growing period from 20 days after transplanting	Cold-water irrigation screening nursery at Chuncheon
Grain filling	20°/15°C (D/N air) for 20–30 days	Phytotron

[a] D/N = day/night;
Source: NCES (1990).

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

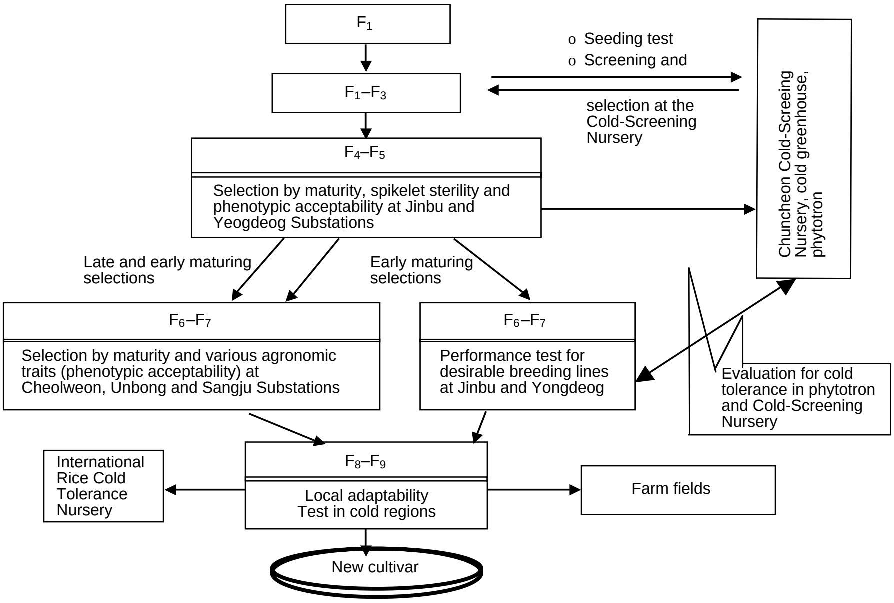


Figure 6. Shuttle system for breeding cold tolerance rice, Korea (after NCES 1990).

short and have a high yield potential and good grain quality. By year 2000, 101 rice varieties have been recommended to farmers in Korea. Of the recommended varieties, 86% have short cycles and 65% have intermediate cycles; these were all identified as being tolerant of low temperatures (Table 6). The cold tolerance program has identified 60% of released varieties as being highly resistant.

Developing Cultural Practices

In years of low temperatures, the use of cold-tolerant varieties and implementation of appropriate cultural practices (e.g. fertilizer and water management) are important for minimizing low temperature damage.

Fertilizer application

Good crop establishment is an advantage for rice during cold conditions. Fertilizer applications are needed for plant maintenance as well as for nourishing and accelerating plant growth. The relationship between applied fertilizer and cold damage has been thoroughly studied and the nutritional balance is critical to varietal tolerance. For example, during booting, nitrogen concentration in the plant should be low while temperatures are low (Amano 1984; Lee et al. 1987b). On studying the relationship between N concentration in the leaf blade at panicle initiation with the filled-grain ratio under low temperatures, the NHAES (1985) found that the filled-grain ratio decreased with increasing N levels (Figure 7).

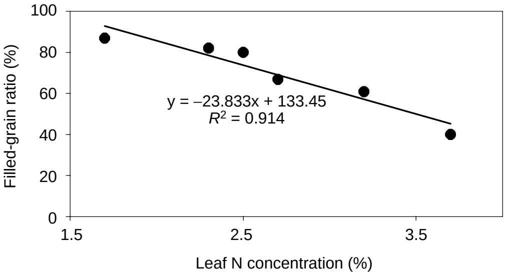


Figure 7. Effect of leaf nitrogen concentration at panicle initiation on the filled-grain ratio under low temperatures (after NHAES 1985).

The effects of N application are well illustrated by Sasaki and Wada's findings (1975). When they used artificial climate chambers, they found that the relationship between N and fertility differed in 1977 and 1980 because of low temperatures (Figure 8). The 1980 low temperatures caused a sharp decline in the filled-grain ratio with increased N, compared with the stable response from 1977. Shiga et al. (1977) reported that top-dressing with N at panicle formation increased spikelet sterility. Top dressing at the flag-leaf stage during lower temperatures therefore increases the risk of damage to the rice crop.

Table 6. Degree of low-temperature tolerance in recommended rice varieties, Korea.

Maturity	Varieties (no.)	Degree of tolerance				
		High	Moderately high	Fair	Moderately susceptible	Susceptible
Early	30	20	6	2	—	2
Intermediate	38	13	12	7	1	5
Late to intermediate	33	—	7	19	4	3
Total	101	33	25	28	5	10

Source: RDA (1998).

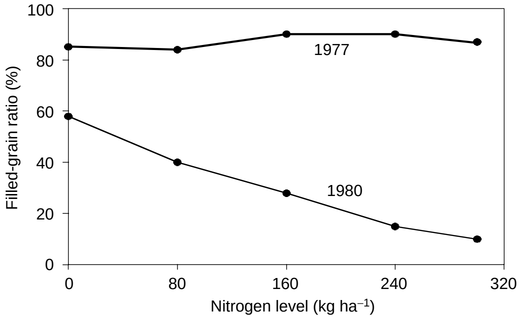


Figure 8. Effect of nitrogen level on filled-grain ratio of the 1977 and 1980 rice crops, Korea (RDA 1981).

Phosphorus is another important nutrient in cold regions. When sufficient phosphate is applied, low temperature damage is reduced. When the amount of phosphate is increased from 100 to 200 kg ha^{-1}, milled rice yield increases by 12% as the grain number and filled-grain ratio increase (Table 7; Chungbuk RDA 1980).

Table 7. Effect of phosphate application on rice under low temperatures.

Phosphate (kg ha^{-1})	Grains (no. in 10^{-3} m^{-2})	Filled-grain ratio (%)	Milled rice yield (t ha^{-1})
100	27.5	87.0	3.89
150	28.6	89.0	4.16
200	31.1	90.4	4.49

Source: Chungbuk RDA (1980).

The application of organic matter, compost, rice straw and barnyard manure is widespread in the northern and mountainous rice-growing areas of Korea. Farmers believe that applying organic matter improves the physiological strength of rice and prevents low temperature damage, particularly in mountainous areas. Onodera (1936) reports that, from practical experience, applying compost and barnyard manure reduces cool weather damage in Japan. Amano (1984) shows that applications of compost reduces sterility and improves root health, both in morphological and physiological terms, compared with plots without compost application. The mechanism providing the favourable effects of compost on yield has not yet been fully elucidated. These observations were confirmed by an experiment conducted at Jinbu Substation during the 1993 low temperature year. The optimal N–P–K-supplied plot had low yields, compared with the plot treated with rice straw, animal residue and compost (Table 8). Using the findings of this study, we found that applying reduced synthetic fertilizer and adding an organic source led to improved yield at low temperatures.

Water management

When the air temperature is low enough to damage rice crops at panicle initiation or early booting, deep-water irrigation (15–20 cm) is an effective way of protecting panicle formation and increasing the filled-grain ratio. A yield increase of 14% and 11% was recorded in Sangjubyeo and Yeongdeog, respectively (Table 9).

Table 8. Effect of organic matter on rice grain yield under low temperatures at Jinbu, Korea, 1993.

Treatment[a]	Heading date in August	Filled-grain ratio (%)	Brown rice yield (t ha^{-1})
N–P–K (optimum)	12	10.3	0.44
50% + rice straw	10	58.1	2.33
50% + animal residue	9	49.8	2.36
50% + compost	9	52.5	2.31
50% + compost + animal residue	9	54.2	2.58

[a] 50% = 50% of N–P–K optimum.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Table 9. Effect of shallow (5 cm) and deep (15–20 cm) irrigation on grain yield of rice growing under low temperatures at two sites, Korea.

Site	Water depth (cm)	Filled-grain ratio (%)	Milled-rice yield (t ha^{-1})
Sangjubyeo	5	59.9	4.09
	15–20	71.9	4.66
Yeongdeogk	5	59.3	4.12
	15–20	80.3	4.57

Source: NYAES (1993).

Conclusions

Rice researchers and farmers in Korea found that two periods of severe low temperatures damaged rice crops in 1980 and 1993. These experiences led to the establishment of research facilities, five research substations, a phytotron and greenhouses, and a research program plan to develop highly resistant varieties and appropriate cultural practices. Of the released rice varieties, 57% were identified as highly resistant to low temperatures. Appropriate cultural practices for fertilization and water management were developed to minimize low temperature damage. The research programs will continue focusing on low temperature resistance, both in breeding and agronomy, to stabilize rice production under Korea's unpredictable climate.

References

Amano, T. 1984. Studies on cool weather damage with special reference to improvement in rice cultivation technique. Report of the Hokkaido Prefecture Agricultural Experiment Station, 46, 1–67.

Chungbuk RDA (Chungbuk Province Rural Development Administration). 1980. Annual Research Report. Cheongju, Korea.

Hue, H. 1978. Studies on physiological and ecological characteristics of Indica/Japonica rice varieties. Research Report of Agriculture RDA (Crops), 1–48.

Jun, B.T., Cho, S.Y. and Lee, J.H. 1987. Test of germination ability of new breeding variety and line of rice under low temperature condition. Research Report on Phytotron Experiment, II. Suwon, Korea, National Crop Experiment Station, 5–18.

Kaneda, C. and Beachell, H.M. 1974. Breeding rice for cold tolerance. Saturday Seminar Paper 9. Los Baños, Philippines, International Rice Research Institute (IRRI).

Kim, J.K. and Kim, Y.S. In press. Labor-Saving Cultivation Technologies of Rice in Korea: Direct Seeding and Machine Transplanting. Bangkok, Asia-Pacific Association of Agricultural Research Institutions (APAARI).

KOIS (Korean Overseas Information Service). 1993. A Handbook of Korea. Seoul, Korea.

Lee, M.H., Lee, D.J., Park, S.K., Rho, Y.D., Lee, J.H. and Park, R.K. 1987a. Varietal differences in low temperature damage at the reproductive, heading and ripening stages of the rice plant. Research Report on Phytotron Experiment, II. Suwon, Korea, National Crop Experiment Station, 38–59.

Lee, M.H., Oh, Y.J., Lee, J.H. and Ham, Y.S. 1987b. Physiological relationship between nitrogen fertilizer and cold tolerance at low temperature of rice plant. Research Report on Phytotron Experiment, II. Suwon, Korea, National Crop Experiment Station, 60–69.

MOAF (Ministry of Agriculture and Forestry). 1994. Agricultural Statistics. Seoul, Korea.

MOAF (Ministry of Agriculture and Forestry). 1999. Agricultural Statistics. Seoul, Korea.

MOAF (Ministry of Agriculture and Forestry). 2000. Agricultural Statistics. Seoul, Korea.

NCES (National Crop Experiment Station). 1970. Annual Research Report (Rice). Suwon, Korea.

NCES (National Crop Experiment Station). 1977. Annual Research Report (Rice). Suwon, Korea.

NCES (National Crop Experiment Station). 1985. Rice Varietal Improvement in Korea. Suwon, Korea.

NCES (National Crop Experiment Station). 1990. Rice Varietal Improvement in Korea. Suwon, Korea.

NHAES (National Honam Agricultural Experiment Station). 1982. Annual Research Report (Rice). Iksan, Korea.

NHAES (National Honam Agricultural Experiment Station). 1985. Annual Research Report (Rice). Iksan, Korea.

Nishiyama, I. 1985. Physiology of Cool Weather Damage to the Rice Plant. Sapporoo, Japan, Hokkaido University Press.

NYAES (National Yeongnam Agricultural Experiment Station). 1993. Annual Research Report (Rice). Milyang, Korea.

Onodera, I. 1936. Cool summer injury to rice plant and fertilizer application. Agriculture and Economy, 3, 896–907.

RDA (Rural Development Administration). 1981. Report of Low Temperature Damage in 1980 and Its Comprehensive Technological Countermeasures of Rice, Suwon, Korea.

RDA (Rural Development Administration). 1998. List of major recommended crop varieties. Suwon, Korea.

Sasaki, K. and Wada, S. 1975. Effect of nitrogen, phosphoric acid and potassium apply on the incidence of sterility in rice plant. Proceedings of the Crop Science Society of Japan, 44, 250–254.

Satake, T. 1976. Determination of the most sensitive stage to sterile-type cold injury in rice plant. Research Bulletin of the Hokkaido National Agricultural Experiment Station, 113, 1–43.

Shiga et al. 1977. Methods of Applying Nitrogen Fertilizers for Higher yields in the Cool Temperature Region, 2. Top-dreesing of Nitrogen at the Panicle Formation and Flag Leaf Emergence Stages of Rice Plants. Research Bulletin of Hokkaido National Agricultural Experiment Station, 117, 31-44.

Yoshida, S. 1978. Fundamentals of Rice Crop Science. Los Baños, Philippines, International Rice Research Institute (IRRI).

Response of Growth and Grain Yield to Cool Water at Different Growth Stages in Paddy Rice

Hiroyuki Shimono, Toshihiro Hasegawa* and Kazuto Iwama

Abstract

Rice growing in cool climates and under flooding can be subjected to suboptimal water temperature (T_W) at any stage of the crop cycle. Although the response to T_w depends on the stage of crop growth, little is understood, in quantitative terms, about this stage-dependent growth response. We therefore conducted field trials for three years to determine the response of biomass and grain yield to T_w at three different stages: vegetative, reproductive and early grain filling. Cool irrigation water, under either two or three temperature regimes (16°–25°C), was used for 20 to 34 days of each period. We confirmed that grain yield was most severely reduced by low T_w (below 20°C) during the reproductive period, as a result of low spikelet fertility. Low T_w during the vegetative period also reduced grain yield by as much as 20%. Although crop growth rate (CGR) was reduced by low T_w in all stages, the magnitude differed according to period, being greatest during the vegetative period, followed by the reproductive and early grain-filling periods. Reduced CGR before heading was associated largely with decreased canopy radiation interception and limited leaf area, whereas radiation use efficiency (RUE) was relatively unaffected by T_w. Decreased CGR after heading was associated with reduced RUE, although leaf area was also reduced by low T_w. The present results can be used to quantify rice growth and grain yield as affected by T_w.

Rice (*Oryza sativa* L.) grown under flooding conditions can be subject to cool water stress at any time during growth. Water temperature (T_w) can affect various growth processes, and response to T_w can differ according to growth stage. During the vegetative period, cool water reduces the rates of tillering, leaf emergence and leaf elongation (Enomoto 1936; Takamura et al. 1960; Matsushima et al. 1964b), which, in some cases, are accompanied by leaf yellowing (Kondo and Okamura 1931). Cool water during the reproductive period, particularly around the microspore stage, substantially decreases spikelet fertility, thereby resulting in severe yield decline (Tanaka 1962; Matsushima et al. 1964a; Tsunoda 1964). Grain yield can also be reduced by low T_w during the vegetative period (Shimazaki et al. 1963).

Because cool water temperature has a large impact on grain yield, several studies have been conducted to identify the processes and factors that affect spikelet sterility during the reproductive period (*see reviews by* Nishiyama 1983 *and* Wada 1992). Takamura et al. (1960) and Matushima et al. (1964b) have also reported on the effect of T_w on vegetative growth, focusing on such processes as tillering and leaf emergence. However, understanding of the response of biomass to T_w is still limited to quantifying crop growth under suboptimal T_w at various stages of the crop cycle.

Crop growth is an integrated result of various physiological processes, including canopy radiation capture, photosynthesis and conversion of photosynthate to biomass. However, a simple linear

---

Graduate School of Agriculture, Hokkaido University, Sapporo, Hokkaido 060-8589, Japan.
*Corresponding author: Toshihiro Hasegawa, Graduate School of Agriculture, N9, W9, Kita-ku, Sapporo, Hokkaido, 060-8589; Phones: +81-11-706-2444; +81-11-706-3878; E-mail: thase@res.agr.hokudai.ac.jp

KEYWORDS: Canopy radiation interception, Cool water temperature, Crop growth rate, *Oryza sativa* L., Radiation use efficiency, Rice, Spikelet fertility

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

association has often been observed between canopy radiation interception and biomass in many crops (Montieth 1977), and the regression slope, known as radiation use efficiency (RUE), represents the capacity of plants to use the intercepted solar energy in the accumulation of biomass (*see review by* Sinclair and Muchow 1999).

This simple but physiologically sound relationship has often been used in many crop growth models (Horie 1987; Muchow et al. 1990; Amir and Sinclair 1991). It also allows us to analyse the processes limiting crop growth under various stresses. For example, Boonjung and Fukai (1996) studied the reduction of dry matter production of upland rice associated with drought stress at various growth periods, and found that reduced radiation interception was largely responsible for reduced crop growth rate (CGR) in the early growth period, but that the growth thereafter was limited by RUE. For wheat (Sinclair and Amir 1992) and sunflower (Giménez et al. 1994), both radiation interception and RUE can constrain crop growth under limited N conditions, and, for maize (Andrade et al. 1993), low air temperature (T_a). However, no such analysis has been made for rice grown under suboptimal T_w conditions.

Many attempts have been made to quantify rice growth as affected by T_a (Iwaki 1975; Horie 1987; Berge et al. 1994; Drenth et al. 1994; Hasegawa and Horie 1997), but few have taken into account the effect of T_w, even though its importance for crop growth is well known. Matsushima (1964a, b) conducted a pot experiment with factorial combinations of T_a and T_w (16°–36°C) at various growth stages, and found that growth and yield are limited more by T_w than by T_a before the mid-reproductive period. Takamura et al. (1960) also found that T_w was relatively more important than T_a in leaf emergence in early growth.

In paddy fields, T_w is different from T_a, and the difference is generally larger in a cooler climate. Tanaka (1962) monitored the difference between T_a and T_w in paddy fields at Aomori (40° 49′ north), northern Japan, and showed that the maximum and minimum T_w can be higher than T_a by as much as 10° and 5°C, respectively, with the difference decreasing with canopy development. Because T_w is higher than T_a in the first half of the growing period, deep-water irrigation has been used to protect panicle development from low T_a in a cool climate (Sakai 1949; Satake et al. 1988).

However, considering the difference between T_a and T_w and the large impact of T_w on growth, the response of biomass and yield production to T_w needs to be determined in relation to various growth parameters to evaluate the magnitude of the stress.

This paper therefore aims to determine the effects of cool T_w on dry matter production and yield during various growth periods, thereby improving our quantitative understanding of growth of field-grown rice under suboptimal T_w.

Materials and Methods

Field experiments were conducted in paddy fields at the Experiment Farm of the Faculty of Agriculture, Hokkaido University, Sapporo, Japan (43° 04′ north) in 1996, 1997 and 1998. Germinated seeds of rice cultivar Kirara 397 were sown in late April (3 seeds per pot) and seedlings raised under a polyhouse. They were transplanted in late May (Table 1). The number of leaves on the main culm at the transplanting time was 4.4 in 1996 and 5.2 in 1997 and 1998. Planting density was 13 × 33 cm except for 1997 (16 × 33 cm). Each plot received equal amounts of basal fertilizers (9.6, 9.6 and 7.2 g m^{-2} for N, P_2O_5, and K_2O, respectively).

Table 1. Sowing and transplanting dates and harvest at days after transplanting for the 1996, 1997 and 1998 rice crops, Sapporo, Japan.

Year	Sowing	Transplanting	Harvest
1996	18 Apr	21 May	126
1997	23 Apr	27 May	115–129
1998	22 Apr	26 May	121–129

The treatment was conducted for three growth periods: vegetative (from 17–21 days after transplanting [DAP] to panicle initiation [PI]), reproductive (from PI to full heading), early grain filling (from full heading to 20 d after full heading). The trial area received cool (about 15°C) irrigated water between 0600 and 1800 h at a rate of about 300 L min^{-1} (Table 2). A temperature gradient from the water inlet was used to set either two or three T_w regimes for each period. The size of each plot was between 64 and 72 m^2, enclosed with plastic boarding 30 or 45 cm high.

The water level was maintained at 10 cm above the soil surface until about 20 days after full heading (86–95 DAP), except for the reproductive period in 1996 where deep-water irrigation at 20 cm deep was conducted.

Each treatment was assigned two letters, the first representing the period (i.e. V for vegetative, R for reproductive and G for early grain filling), and the second, the water temperature (L = low; M = middle). The plot with the highest T_w for all three growth periods was designated as ‘control’. In 1996 and 1997, the plot with intermediate T_w was treated

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

continuously for all three periods and was designated as 'CM'. The treatment was not replicated because the random assignment of the plots was difficult.

Table 2. Periods (days after transplanting) of water temperature treatments and developmental stages of the 1996, 1997 and 1998 rice crops, Sapporo, Japan.

Year	Treatment[a]	Treatment period	Panicle initiation	Heading
1996	Control	—	—	—
	VL	21–48	—	—
	RL	49–74	—	—
	GL	75–94	—	—
	CM	21–94	—	—
1997	Control		39	64
	VL	21–45	46	71
	RL	42–74	39	73
	GL	66–85	39	63
	CM	21–85	43	75
1998	Control		39	66
	VL	17–38	47	73
	VM	17–38	42	70
	RL	39–72	39	80
	RM	39–72	39	76
	GL	73–92	39	66
	CM	73–92	39	66

[a] V = vegetative stage; R = reproductive stage; G = early grain filling; C = continuous treatment throughout crop's life cycle; L = low water temperature; M = intermediate water temperature.

To show variation of data, the standard error or pooled standard error was used. Water and soil temperatures were measured at the centre of each plot by thermocouples placed 5 cm below either the water surface or soil surface (Copper-Constantan, 0.6 mm in diameter), and recorded in the data logger (IDL-3200, North Hightech, Sapporo) at 10-min intervals. The daily mean temperature was expressed as the average of the daily maximum and minimum temperatures. On-site T_a at 1.5 m above the ground and global solar radiation (S) were also recorded. Photosynthetically active radiation (PAR) was estimated as $0.5 \times S$.

Plants with an average number of tillers were sampled from each plot at seven growth stages, including from the beginning and end of each treatment for five (1996, 1997) or four hills (1998). Plants within two rows of the edge of each plot were not sampled to avoid the border effect.

Leaf area was measured with an automatic area meter (AAM-7, Hayashi Denko, Tokyo), and the dry weight for each organ was determined after drying for more than 72 h at 80°C. Leaves were ground, then subjected to Kjeldahl analysis for N determination.

At maturity, 20 hills (four rows × five hills) were sampled at four (1998) or five (1996, 1997) places in each plot between 115 and 129 DAP, to determine yield and its components. In 1996, the number of grains per panicle and 1000-grain weight were not measured. Percentage of ripened spikelets was determined with ammonium sulfate solution of 1.06 specific gravity. Spikelet fertility was measured for the panicles on the three tallest culms (1996) and those on all culms (1997, 1998) of five (1996, 1997) or four (1998) plants in each plot. Anther length and number of engorged pollen grains were measured for the third, fourth and fifth spikelets growing on the first, second and third primary branches on the three main culms of three hills per plot in 1996, following the method of Kariya et al. (1985). Plant height, tiller number and leaf number on the main stem were measured weekly for 10 hills per plot until heading (1997 and 1998).

In 1998, canopy PAR transmittance was measured under diffuse radiation conditions about twice a week with a PAR sensor (LI-250, LI-COR, Lincoln, NE, USA) attached to the top of a 1-m stainless steel pole. We measured PAR below the canopy at 20–30 points by moving the sensor at about 7 cm intervals, perpendicularly to the rows. Immediately after reading the below-canopy PAR, the above-canopy PAR was determined to obtain the percentage of PAR transmittance.

Results

Climatic conditions, water temperatures and developmental stages

Average air temperature (T_a) during the vegetative period ranged from 16.4° to 18.8°C (Table 3), and was generally higher in 1997 than in 1996 and 1998. Air temperature (T_a) during the reproductive period was also higher in 1997 than in the other 2 years, but none of the experimental years showed, for this period, T_a below 20°C, the critical temperature for damage from mid-season coolness (Wada 1992). During early grain filling, however, T_a in 1997 was lower than in the other 2 years. Solar radiation (S) in all 3 years showed similar yearly variation to T_a, where S during the vegetative and reproductive period was slightly higher in 1997 than in 1996 and 1998, and vice versa in early grain filling.

Average water temperature (T_w) ranged from 15.6° to 24.6°C, and differed by 3.6° to 6.7°C between Treatment L and control in each period tested. Yearly variation was observed for T_w associated with T_a and S, where T_w in 1997 was relatively high in the vegetative and reproductive periods. Soil temperature at 5 cm below the surface showed a smaller diurnal change than did T_w, and the daily mean was 1° to 2°C lower than that of T_w. Although cool water was supplied during the day, water and soil temperatures were consistently lower in L and M (data not shown).

Table 3. Average water temperatures, air temperatures and global solar radiation (± standard deviations) during the vegetative, reproductive and early grain-filling periods of the 1996, 1997 and 1998 rice crops, Sapporo, Japan.

Period	Treatment[a]	1996	1997	1998
		Water temperature (°C)		
Vegetative	Control	20.4 ± 1.7	23.2 ± 1.7	21.8 ± 2.5
	VL	16.6 ± 1.8	17.7 ± 1.5	16.8 ± 1.3
	VM	—	—	19.2 ± 2.0
	CM	18.0 ± 1.7	20.5 ± 1.5	—
Reproductive	Control	23.3 ± 1.9	24.6 ± 2.6	23.3 ± 1.2
	RL	16.9 ± 1.2	17.9 ± 1.5	16.5 ± 1.1
	RM	—	—	19.5 ± 1.6
	CM	18.4 ± 1.6	19.3 ± 1.6	—
Early grain filling	Control	22.1 ± 1.5	20.3 ± 2.4	21.2 ± 1.1
	GL	18.5 ± 1.3	16.0 ± 2.0	15.6 ± 0.8
	GM	—	—	16.1 ± 0.8
	CM	19.5 ± 1.3	17.3 ± 2.0	—
		Air temperature (°C)		
Vegetative		16.4 ± 1.8	18.8 ± 2.1	16.7 ± 2.5
Reproductive		20.4 ± 2.2	21.9 ± 2.4	20.3 ± 2.2
Early grain filling		21.2 ± 2.0	19.8 ± 2.6	20.5 ± 1.8
		Solar radiation (MJ m^{-2} d^{-1})		
Vegetative		14.7 ± 6.5	16.2 ± 6.9	15.1 ± 8.5
Reproductive		14.0 ± 6.4	16.2 ± 7.1	14.7 ± 7.6
Early grain filling		14.1 ± 6.4	11.6 ± 6.0	13.9 ± 5.9

[a] V = vegetative stage; R = reproductive stage; G = early grain filling; C = continuous treatment throughout crop's life cycle; L = low water temperature; M = intermediate water temperature.

Low T_w substantially delayed all developmental stages (Table 2). Panicle initiation (PI) in VL was delayed by 7–8 days because of low T_w during the vegetative period, while the time from PI to heading was similar for both VL and control. Low T_w during the reproductive period also had a large impact on the time between PI and heading: the crop under RL reached heading 9–14 d later than it did under control.

Yield and its components

Grain yield was largely affected by low T_w during all growth periods, but the magnitude of yield loss differed considerably with the period tested (Table 4), as reported elsewhere. Yield was most severely reduced (by almost 100%) under CM in 1996 and under RL in all 3 years—these treatments received water at temperatures below 19°C during the reproductive period. The CM during the reproductive period in 1997, when T_w averaged at 19.3°C, also had severely reduced yields (58%). The substantial decrease in spikelet fertility suggested that low T_w during the reproductive period apparently causes a typical sterility-type cool injury. In addition, the 1000-grain weight was lower than in the control, while the number of spikelets was not affected.

A yield loss of 14%–20% was also recorded in the treatments during the vegetative period in all 3 years. Treatments VL and VM had fewer panicles—numbers were reduced by 9% to 14%—which accounted for most of the yield reduction. The 1000-grain weight was slightly higher under VL and VM than under control. The effect of low T_w during early grain filling was not consistent across the years. In 1996, while GL negatively affected yield, little difference was observed between GL and control in 1997 and 1998.

Dry matter production

The crop growth rate (CGR) was significantly reduced by cool water treatments in all the periods tested (Table 5), and the magnitude of the effect appeared different according to the stage, the most severe reductions (up to 74%) occurring under treatments VL and VM in all the years studied. Treatments during the reproductive and early grain-filling periods resulted in similar reductions in CGR. Under CM, CGR was reduced by 13% to 33% for the three growth periods, except the vegetative in 1997.

The mean leaf area index (mLAI) was reduced by low T_w during almost all periods. Low T_w during the vegetative period resulted in the largest reduction (as much as 50%), followed by RL. Even after heading, low T_w decreased LAI by about 10%–20%, indicating faster senescence under cool water conditions. The response of the relative leaf growth rate (RLGR) to T_w is illustrated in Figure 1. Note that, for the reproductive period, data from PI to booting were used to calculate RLGR because LAI in some treatments reached the maximum value at booting. For all the periods tested, RLGR responded linearly within the temperature range tested. As usually occurs with other crops, RLGR decreased in the present study, but the dependence on temperature was similar between the vegetative and reproductive periods, being about a 50% decrease in RLGR with a 5°C decrease in T_w. Moreover, the relationship was well conserved over the years under different S and T_a conditions.

The RLGR in the vegetative period was positively correlated with the relative rate of tillering (rTiller) and leaf emergence rate (LER) on the main culm

Table 4. Yield, and its components, of the 1996, 1997 and 1998 rice crops grown under different water temperature regimes in Sapporo, Japan.

Year	Treatment[a]	Yield ($g\ m^{-2}$)	Panicles (m^{-2})	Spikelets per panicle	Spikelets ($10^3\ m^{-2}$)	1000-grain weight (g)	Fertile spikelets (%)
1996	Control	633	468	—	—	—	88.6
	VL	504	401	—	—	—	91.4
	RL	0	478	—	—	—	0.0
	GL	522	385	—	—	—	94.8
	CM	0	459	—	—	—	0.0
	SE	26	59	—	—	—	1.0
1997	Control	533	427	57.8	24.7	22.7	96.4
	VL	460	381	59.5	22.6	22.9	93.1
	RL	45	366	60.8	21.9	18.1	31.0
	GL	565	436	57.8	25.2	22.8	97.0
	CM	223	362	57.5	20.7	20.5	62.1
	SE	45	59	3.4	3.0	0.3	6.2
1998	Control	652	565	61.3	34.6	22.5	94.3
	VL	528	503	53.9	27.2	23.7	93.7
	VM	539	516	52.0	26.9	23.0	94.2
	RL	1	710	45.0	31.9	14.5	4.7
	RM	96	658	57.6	37.6	19.2	16.7
	GL	693	609	60.1	36.6	22.8	94.5
	GM	568	520	52.8	27.4	23.0	95.9
	SE	38	35	3.2	2.3	1.2	5.0

[a] SE = pooled standard error.

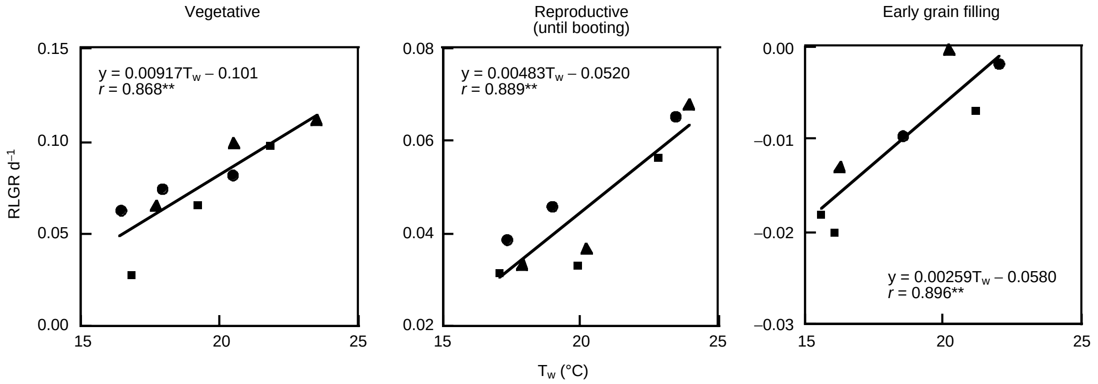


Figure 1. Relationship between relative leaf growth rate (RLGR) and water temperature (Tw) in the 1996, 1997 and 1998 rice crops, Sapporo, Japan. ** = significant at 1% level. ●, 1996; ▲, 1997; ■, 1998.

(Figure 2), indicating that the limiting effect of low T_W on leaf area development appeared through both processes. In the reproductive period, RLGR could no longer be related with rTiller because few new tillers appeared, but LER still had a positive influence on RLGR. Interestingly, a single regression line effectively expressed the relationship between RLGR and LER in both vegetative and reproductive periods, possibly providing a reliable basis for estimating leaf area development under various T_W.

To convert LAI to the canopy gap fraction, the radiation extinction coefficient (k) needs to be known. We therefore ascertained if the k value varies with Tw. Figure 3 illustrates the close association between PAR transmittance (logarithm) below the canopy and LAI measured during the vegetative and reproductive periods in 1998. We observed no significant differences in the slope of the regression line between the treatments in both periods, which allowed us to use the single and constant k value of 0.4 to estimate radiation interception of the canopy. This agrees with the response of the k values of other crops to such stresses as drought for barley (Goyne et al. 1993) and wheat (Robertson and Giunta 1994)

Table 5. Crop growth rate (CGR), mean leaf area in index (mLAI), mean daily canopy PAR interception (PARi) and radiation-use efficiency (RUE) of rice grown under different temperatures in the vegetative, reproductive and early grain-filling periods.[a]

Period	Year	Treatment[a]	CGR (g m^{-2} d^{-1})	mLAI	PARi (MJ m^{-2} d^{-1})	RUE (g MJ^{-1})
Vegetative	1996	Control	4.36	0.53	1.77	2.46
		VL	2.00 (0.46)	0.26 (0.49)	0.86 (0.48)	2.34 (0.95)
		CM	3.24 (0.74)	0.40 (0.75)	1.36 (0.77)	2.38 (0.97)
	1997	Control	4.13	0.42	1.68	2.47
		VL	2.54 (0.62)	0.28 (0.67)	1.02 (0.61)	2.49 (1.01)
		CM	4.36 (1.06)	0.43 (1.02)	1.65 (0.98)	2.65 (1.07)
	1998	Control	4.49	0.67	1.52	2.97
		VL	1.18 (0.26)	0.30 (0.45)	0.65 (0.43)	1.81 (0.61)
		VM	2.56 (0.57)	0.46 (0.68)	0.84 (0.55)	3.05 (1.03)
Reproductive	1996	Control	15.2	2.81	4.62	3.29
		RL	14.0 (0.92)	2.18 (0.78)	4.01 (0.87)	3.50 (1.06)
		CM	13.2 (0.87)	1.95 (0.69)	3.67 (0.80)	3.58 (1.09)
	1997	Control	17.8	2.31	5.45	3.27
		RL	12.5 (0.70)	1.75 (0.76)	4.03 (0.74)	3.09 (0.94)
		CM	12.0 (0.67)	1.82 (0.79)	3.61 (0.66)	3.32 (1.01)
	1998	Control	17.8	2.56	5.63	3.17
		RL	13.0 (0.73)	2.41 (0.94)	4.68 (0.83)	2.78 (0.88)
		RM	14.4 (0.81)	2.62 (1.02)	4.90 (0.87)	2.95 (0.93)
Early grain filling	1996	Control	23.1	3.93	5.76	4.02
		GL	18.7 (0.81)	3.78 (0.96)	5.67 (0.98)	3.29 (0.82)
		CM	18.3 (0.79)	3.48 (0.89)	5.47 (0.95)	3.35 (0.83)
	1997	Control	18.8	3.22	4.35	4.33
		GL	11.7 (0.62)	2.83 (0.88)	4.07 (0.94)	2.87 (0.66)
		CM	15.3 (0.81)	2.63 (0.82)	4.33 (1.00)	3.54 (0.82)
	1998	Control	18.5	3.81	5.66	3.27
		GL	17.0 (0.92)	3.45 (0.91)	5.44 (0.96)	3.12 (0.96)
		GM	17.0 (0.92)	3.38 (0.89)	5.55 (0.98)	3.07 (0.94)

[a] Values in brackets are relative to those of control.

[b] V = vegetative stage; R = reproductive stage; G = early grain filling; C = continuous treatment throughout crop's life cycle; L = low water temperature; M = intermediate water temperature.

and nitrogen deficiency for sunflower (Giménez et al. 1994). Canopy PAR interception (PAR$_i$) in 1996 and 1997 was therefore derived from PAR, measured leaf area and the k value of 0.4.

The PAR$_i$ was reduced by 39% to 57% in VL and 13% to 26% in RL, which results are similar to those observed for CGR (Table 5). As a result, radiation use efficiency (RUE), defined as the quotient of CGR over PAR$_i$, was mostly unaffected by low T$_w$ in both periods, except for the VL in 1998 where RUE was reduced by about 40%.

During early grain filling, poor correlation existed between PAR transmittance and leaf area, and PAR$_i$ did not change with time in any treated plot, even though LAI decreased by as much as 22%. Accordingly, because the reduced LAI during early grain filling did not affect PAR$_i$, a reduced RUE was responsible for the reduced CGR.

Low T$_w$ during any period also affected dry matter after treatment (e.g. see 1998 data in Figure 4). Notably, lower T$_w$ during the vegetative period led to a wider gap in dry weight during the reproductive period than in the vegetative period, resulting in a smaller biomass during early grain filling, although the longer duration for RL and RM narrowed the difference at harvest.

Discussion

Despite many studies conducted on rice growth at suboptimal temperatures (Kondo and Okumura 1931; Enomoto 1936; Takamura et al. 1960; Tanaka 1962; Shimazaki et al. 1963; Matsushima et al. 1964a, b; Tsunoda 1964; Sato 1972a, b, 1974), few have reported on the response of the crop biomass to water temperature (T$_w$) under field conditions.

We found that cool T$_w$, imposed at any growth period, reduced CGR by at least 8% to as much as 74%, even after the meristem emerged above the water surface in mid-reproductive period (Table 5). Reduction was severest under low T$_w$ in the vegetative period, causing the largest influence on biomass

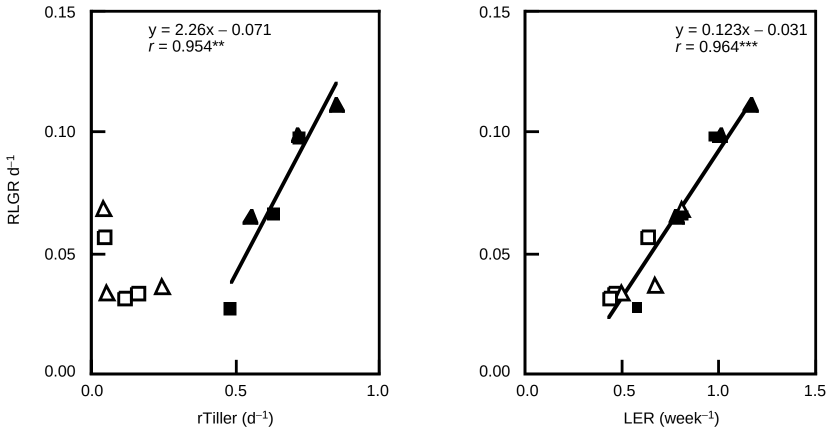


Figure 2. Relationships between relative leaf growth rate (RLGR), relative tillering rate (rTiller) and leaf emergence rate (LER) in the vegetative (closed symbols) and reproductive (open symbols) periods of the 1997 (△) and 1998 (□) rice crops, Sapporo, Japan. For the reproductive period, data from panicle initiation to booting were used. ** = significant at 1%, *** = significance at 0.1%.

production after treatment. The reduced crop size in VL and VM during treatment apparently decreased canopy radiation interception, compared with the control, after treatment. The result was an even larger difference in biomass between control and VL and VM during the reproductive and early grain-filling periods, although time to heading was prolonged (Table 2).

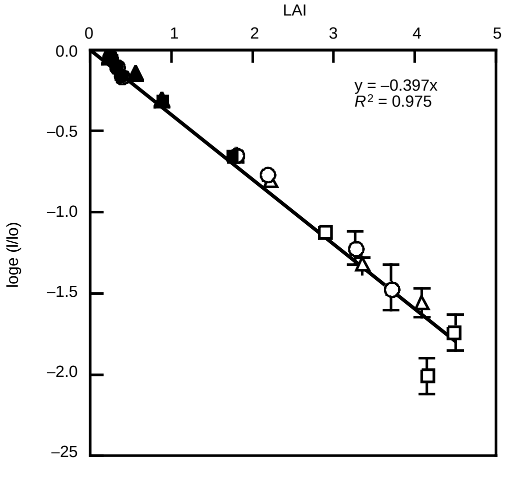


Figure 3. Relationship between logarithm of photosynthetically active radiation (PAR) transmittance below the canopy (loge (I/Io)) and leaf area index (LAI) during the vegetative (closed symbols) and reproductive (open symbols) periods in the 1998 rice crop, Sapporo, Japan. □ = control; ○ = low water temperature; △ = intermediate water temperature. I = PAR below canopy; Io = PAR above canopy; *** = significance at 0.1%; vertical bar = standard error.

This after-effect decreased not only shoot mass at harvest, but also grain sink capacity, which is known to depend largely on crop size during the mid-reproductive period (Wada 1969). In our study, we also observed a close linear association between shoot dry weight at booting and spikelet number per unit land area ($r = 0.882$, $P < 0.01$). A smaller biomass at this stage in VL, that is, 31%–55% smaller than the control, reduced spikelet number between 9% and 23%. As a consequence, grain yield decreased by 3.4% with a 1°C decrease in T_w in the temperature range of 16° to 23°C during the vegetative period (Figure 5).

During the reproductive period, reductions in CGR were smaller than in the vegetative period, ranging from 8% to 30%, but grain yield was most severely reduced by the treatments. The finding that grain yield was most highly sensitive to T_w during the reproductive period agrees with the findings of many earlier studies (Enomoto 1936; Tanaka 1962; Matsushima et al. 1964a; Tsunoda 1964).

Lower temperatures during the reproductive stage (notably at the microspore stage) have been long known to reduce anther size and the number of engorged pollen grains (Hayase et al. 1969; Nishiyama 1983). In our study, a substantial decrease in anther length was observed with decreasing T_w during the reproductive period, and almost no engorged pollen grains in RL (measured only in 1996). This resulted in a relative grain yield response to T_w (Figure 5) that was similar to what was observed in the yield—T_a relationship (NIAS 1975; Wada 1992), where yield drops sharply at temperatures below 20°C. Apparently, spikelet fertility is

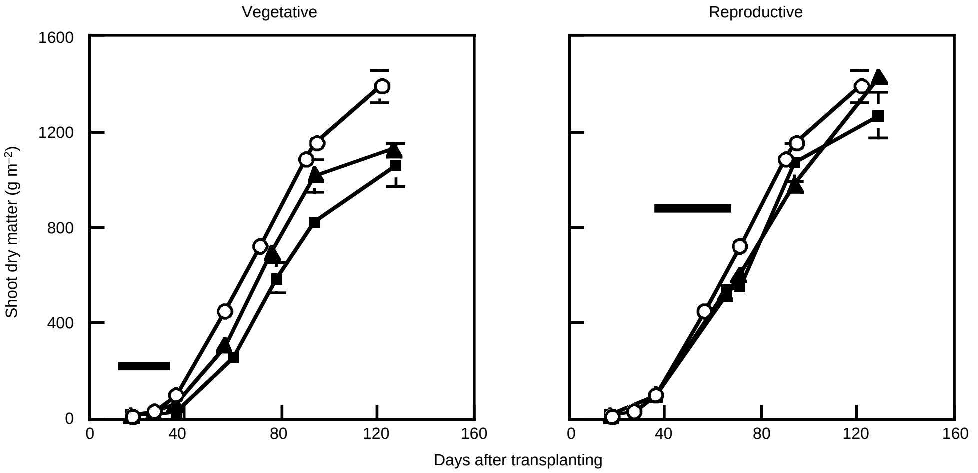


Figure 4. Changes in shoot dry matter accumulation for the whole growth period in the 1998 rice crop, Sapporo, Japan. Thick lines = treatment period; vertical bars = standard error. ○ = control; ▲ = intermediate water temperature; ■ = low water temperature.

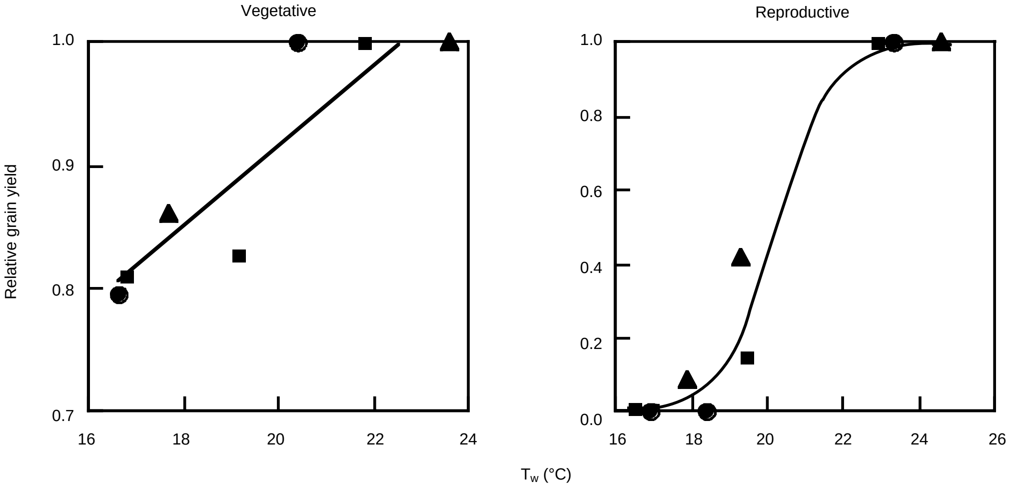


Figure 5. Relationship between grain yield (relative to control) and water temperature (T_w) during the vegetative and reproductive periods of the 1996 (●), 1997 (▲) and 1998 (■) rice crops, Sapporo, Japan.

more sensitive to T_w than is CGR, which overrides the T_w effect on CGR for grain yield. However, biomass production during the reproductive period can be an important determinant for spikelet number and the level of carbon reserves at flowering (Wada 1969). For varieties that better tolerate sterility-type cool injury, biomass reduction with low T_w may have a significant impact on grain yield.

Even after heading, CGR was reduced by low T_w in all years to an extent similar to that of the low T_w treatment during the reproductive period, while the effect on grain yield was not clear. Matsushima et al. (1964a) and Tsunoda (1964) found that the effects of T_w during grain filling on yield and its components were negligible, compared with those of T_a, based on the pot experiment with factorial combinations of T_w and T_a ranging from 16° to 31°C. During grain filling, the increase in panicle grain weight depends on current assimilate supply and carbon stored before heading.

Under water stress, in early grain filling, Kobata and Takami (1979, 1981) found that grain weight of stressed rice increased at a similar rate to that of control rice, despite heavily reduced dry matter production. Further, Takami et al. (1990) demonstrated that grain growth in rice was limited only where total assimilate supply (current assimilates and stored carbon) was below grain demand for carbon. Hence, dry matter production, restricted by low T_w in our study, probably did not decrease the level of total assimilate supply below the grain demand for carbon.

Under low T_w before heading, any reduction in CGR was caused mostly by reduced canopy PAR interception (PAR_i), which resulted from limited leaf area (Table 5). Leaf growth is well known to be sensitive to various environmental stresses such as low T_a (Sato 1972a), drought (Boonjung and Fukai 1996) and nitrogen deficiency (Hasegawa and Horie 1997). The present study also showed that leaf area was largely responsible for limited growth under low T_w.

Relative leaf growth rate (RLGR) is known to be closely associated with T_a (Miyasaka et al. 1975), a finding borne out by our study, including for grain filling. Water temperature (T_w) is generally considered to strongly influence rice growth in the first half of the growing season, but our results also suggest a strong influence of T_w on both leaf area development and senescence, which influence was consistent over the years under different radiation and T_a conditions.

Leaf area growth is an integrated result of tillering, leaf emergence and leaf elongation. While several studies have been conducted to find the effect of T_w on each process (Takamura et al. 1960; Matsushima et al. 1964b), few have tried to relate them to each other to give a dynamic and quantitative relationship. In the vegetative period, both rTiller and LER are apparently responsible for reduced leaf area, while the association of RLGR with rTiller diminished in the reproductive period because few new tillers appeared.

Although we did not measure individual leaf lengths, ample evidence exists for limited elongation of the leaf under low T_w (Matsushima et al. 1964b), which might also have reduced the RLGR in our study. Even though several processes are involved in leaf area growth, we found a close association between RLGR and LER across years and growth periods. Because the interval of leaf emergence can be easily expressed as a function of T_w (Ellis et al. 1993; Sie et al. 1998), the present finding will provide a solid basis for modelling leaf area, which is the major determinant for crop growth under low T_w.

In contrast to leaf area and PAR_i, RUE was relatively unaffected by low T_w during the vegetative and reproductive periods. Radiation use efficiency (RUE) is generally considered as a stable parameter under various environments, but some reports showed that low T_a decreased RUE in maize (Andrade et al. 1993) and peanut (Bell et al. 1992). The limited response of RUE to T_w may indicate the small impact of T_w on photosynthetic rates. In rice, the photosynthetic rate has been reported to decrease with T_a (Ishii et al. 1977; Huang et al. 1989; Makino et al. 1994). Only a few studies investigated the response of photosynthesis to T_w, but, in tomato, Shishido and Kumakura (1994) found no apparent change in the photosynthetic rates, with the soil temperature ranging from 10° to 22°C.

In our experiment, the T_w range of 16°–25°C may not have strongly affected the photosynthetic rate in the vegetative and reproductive periods. It should also be noted that the treatments conducted in this study were ‘long term’ so that the plants had probably acclimatized to low T_w. In fact, as a result of limited leaf area growth, leaves became thicker during the treatments (before heading) and leaf N content on an area basis increased, which probably reduced the negative effect on RUE. ‘Short-term’ treatments may possibly lead to different responses. Changes in physiological parameters under low T_w need to be evaluated to clarify this point.

Flooding conditions of irrigated paddy fields can promote rice growth under cool climates because the warmer T_w in the first half of the growth period can serve as a ‘water blanket’ to protect the shoot base and developing panicles. In addition, unlike T_a, T_w can be managed in various ways, including by warming ponds and canals.

The present study revealed that a slight difference in T_w affects CGR in all growth periods, with the magnitude depending on the given growth stage. The largest reduction due to low T_w was observed in the vegetative period, followed by the reproductive and early grain-filling periods, while grain yield was most severely reduced in the reproductive period, as found elsewhere. During the vegetative and reproductive periods, limited leaf area and PAR_i were the major reasons for reduced CGR, while RUE was relatively unaffected. The decrease in CGR during early grain filling was associated with a reduced RUE, although leaf area was also reduced by low T_w.

These responses to T_w obtained in the present study will be useful for identifying the magnitude of temperature stress and for evaluating the impact of water management on growth and grain yield of irrigated paddy rice.

Acknowledgments

We thank Dr. K. Kariya at the Hokkaido National Agricultural Experiment Station for instruction on measuring anther length and pollen grain numbers. Thanks are also due to N. Moki and S. Ichikawa, Faculty of Agriculture, Hokkaido University, for their help with field management. The collaboration of H. Asaishi, A. Itoh, C. Kashiuchi and S. Fujimura are gratefully acknowledged.

References

Amir, J. and Sinclair, T.R. 1991. A model of the temperature and solar-radiation effects on spring wheat growth and yield. Field Crops Research, 28, 47–58.

Andrade, F.H., Uhart, S.A. and Cirilo, A. 1993. Temperature affects radiation use efficiency in maize. Field Crops Research, 32, 17–25.

Bell, M.J., Wright, G.C. and Hammer, G.L. 1992. Night temperature affects radiation-use efficiency in peanut. Crop Science, 32, 1329–1335.

Berge, H.F.M. ten, Wopereis, M.C.S., Riethoven, J.J.M. and Drenth, H. 1994. Description of the ORYZA—0 modules (version 2.0). In: Drenth, H., Berge, H.F.M. ten and Riethoven, J.J.M. ed. ORYZA Simulation Modules for Potential and Nitrogen Limited Rice Production. Los Baños, Philippines, Simulation and Systems Analysis for Rice Production (SARP), 43–56.

Boonjung, H. and Fukai, S. 1996. Effect of soil water deficit at different growth stages on rice growth and yield under upland conditions. 1. Growth during drought. Field Crops Research, 48, 37–45.

Drenth, H., Berge, H.F.M. ten and Riethoven, J.J.M. 1994. Description of the ORYZA—N modules (version 2.0). In: Drenth, H., Berge, H.F.M. ten and Riethoven, J.J.M. ed. ORYZA Simulation Modules for Potential and Nitrogen Limited Rice Production. Los Baños, Philippines, Simulation and Systems Analysis for Rice Production (SARP), 7–42.

Ellis, R.H., Qi, A., Summerfield, R.J. and Roberts, E.H. 1993. Rate of leaf appearance and panicle development in rice (*Oryza sativa* L.): a comparison at three temperatures. Agricultural and Forest Meteorology, 66, 129–138.

[a]Enomoto, N. 1936. Effects of cool irrigation on growth and yield. Agriculture, 662, 10–20.

Giménez, C., Connor, D.J. and Rueda, F. 1994. Canopy development, photosynthesis and radiation-use efficiency in sunflower in response to nitrogen. Field Crops Research, 38, 15–27.

Goyne, P.J., Milroy, S.P., Lilley, J.M. and Hare, J.M. 1993. Radiation interception, radiation use efficiency and growth of barley cultivars. Australian Journal of Agricultural Research, 44, 1351–1366.

Hasegawa, T. and Horie, H. 1997. Modeling the effect of nitrogen on rice growth and development. In: Kropff, M.J., Teng, P.S., Aggarwal, P.K. et al. ed. Applications of Systems Approaches at the Field Level. Dordrecht, Netherlands, Kluwer Academic, 243–257.

Hayase, H., Satake, T., Nishiyama, I. and Ito, N. 1969. Male sterility caused by cooling treatment at the meiotic stage in rice plants. II. The most sensitive stage to cooling and the fertilizing ability of pistils. Proceedings of the Crop Science Society of Japan, 38, 706–711.

Horie, T. 1987. A model for evaluating climatic productivity and water balance of irrigated rice and its application to Southeast Asia. Southeast Asian Studies, 25, 62–74.

Huang, L.K., Wong, S.C., Terashima, I., Zhang, X., Lin, D.X. and Osmond, C.B. 1989. Chilling injury in mature leaves. I. Varietal differences in the effects of chilling on canopy photosynthesis under simulated Dry Cold Dew Wind conditions experienced in South-East China. Australian Journal of Plant Physiology, 16, 321–337.

Ishii, R., Ohsugi, R. and Murata, Y. 1977. The effect of temperature on the rates of photosynthesis, respiration and the activity of RuDP carboxylase in barley, rice and maize leaves. Japanese Journal of Crop Science, 46, 516–523.

Iwaki, H. 1975. Computer simulation of vegetative growth of rice plants. In: Murata, Y. ed. JIBP SYNTHESIS, volume 11. Tokyo, Tokyo University, 105–118.

[a]Kariya, K., Satake, T. and Koike, S. 1985. The easy method of measuring the engorged pollen number in rice. Japanese Journal of Crop Science, 54 (2), 230–231.

[b]Kobata, T. and Takami, S. 1979. The effects of water stress on the grain-filling in rice. Japanese Journal of Crop Science, 48, 75–81.

[b]Kobata, T. and Takami, S. 1981. Maintenance of the grain growth in rice (*Oryza sativa* L.) subject to water stress during the early grain filling. Japanese Journal of Crop Science, 50, 536–545.

[a]Kondo, M. and Okamura, T. 1931. Response of rice growth to water temperature. Agriculture and Horticulture, 6, 517–530.

Makino, A., Nakano, H. and Mae, T. 1994. Effects of growth temperature on the responses of ribulose-1, 5-bisphosphate carboxylase, electron transport components, and sucrose synthesis enzymes to leaf nitrogen in rice, and their relationships to photosynthesis. Plant Physiology, 105, 1231–1238.

[b]Matsushima, S., Tanaka, T. and Hoshino, T. 1964a. Analysis of yield-determining process and its application to yield-prediction and culture improvement of lowland rice. LXX. Combined effects of air-temperatures and water-temperatures at different stage of growth on the grain yield and its components of lowland rice. Proceedings of the Crop Science Society of Japan, 33, 53–58.

[b]Matsushima, S., Tanaka, T. and Hoshino, T. 1964b. Analysis of yield-determining process and its application to yield-prediction and culture improvement of lowland rice. LXXI. Combined effects of air-temperatures and water-temperatures at different stage of growth on the growth and morphological characteristics of rice plants. Proceedings of the Crop Science Society of Japan, 33, 135–140.

---

[a] In Japanese.

[b] In Japanese, with English summary.

Miyasaka, A., Murata, Y. and Iwata, T., 1975. Leaf area development and leaf senescence in relation to climatic and other factors. In: Murata, Y. ed. JIBP SYNTHESIS, volume 11. Tokyo, Tokyo University, 72–85.

Monteith, J.L. 1977. Climate and the efficiency of crop production in Britain. Transactions of the Royal Society of Philosophy (London), series B, 281, 277–294.

Muchow, R.C., Sinclair, T.R. and Bennett, J.M. 1990. Temperature and solar radiation effects on potential maize yield across locations. Agronomy Journal, 82, 338–343.

[a]NIAS (National Institute of Agricultural Sciences). 1975. Climate change and crop production. Miscellaneous report. Tokyo, Division of Meteorology, NIAS, 40 p.

[a]Nishiyama, I. 1983. The damage in rice plants imposed by sub- and supra-optimal temperature, particularly about spikelets sterility. Japanese Journal of Crop Science, 52, 108–117.

Robertson, M.J. and Giunta, F. 1994. Responses of spring wheat exposed to pre-anthesis water stress. Australian Journal of Agricultural Research, 45, 19–35.

[a]Sakai, K. 1949. Effects of deep irrigation water recovering yields decreased by unseasonable cool weather during meiotic stage of rice plants. Agriculture and Horticulture, 24, 405–408.

Satake, T., Lee, S.Y., Koike, S. and Kariya, K. 1988. Male sterility caused by cooling treatment at the young microspore stage in rice plants. XXVIII. Prevention of cool injury with the newly devised water management practices—effects of the temperature and depth of water before the critical stage. Japanese Journal of Crop Science, 57, 234–241.

[b]Sato, K. 1972a. Growth responses of rice plant to environmental conditions. I. The effects of air-temperatures on the growth at vegetative stage. Proceedings of the Crop Science Society of Japan, 41, 388–393.

[b]Sato, K. 1972b. Growth responses of rice plant to environmental conditions. II. The effects of air-temperatures on the organic and mineral composition of the plant parts. Proceedings of the Crop Science Society of Japan, 41, 394–401.

[b]Sato, K. 1974. Growth responses of rice plant to environmental conditions. IV. The effects of air- and soil-temperatures upon translocation and distribution of ^{14}C. Proceedings of the Crop Science Society of Japan, 43, 410–415.

[b]Shimazaki, Y., Satake, T. and Watanabe, K. 1963. Studies on the growth and nutrient absorption of the rice plant reared with cool water irrigation during its early growth stage. Research Bulletin of the Hokkaido National Agricultural Experiment Station, 80, 1–12.

[b]Shishido, Y. and Kumakura, H. 1994. Effects of root temperature on photosynthesis, transpiration, translocation and distribution of ^{14}C-photoassimilates and root respiration in tomato. Journal of the Japanese Society of Horticultural Science, 63, 81–89.

Sie, M., Dingkuhn, M., Wopereis, M.C.S. and Miezan, M.K. 1998. Rice crop duration and leaf appearance rate in a variable thermal environment. I. Development of an empirically based model. Field Crops Research, 57, 1–13.

Sinclair, T.R. and Amir, J. 1992. A model to assess nitrogen limitations on the growth and yield of spring wheat. Field Crops Research, 30, 63–78.

Sinclair, T.R. and Muchow, R.C. 1999. Radiation use efficiency. Advances in Agronomy, 65, 215–265.

Takami, S., Kabata, T. and van Bavel, C.H.M. 1990. Quantitative method for analysis of grain yield in rice. Agronomy Journal, 82, 1149–1153.

[b]Takamura, Y., Takeuchi, S. and Hasegawa, H. 1960. Studies on the effects of soil temperature upon the growth of crop plants. III. Soil temperature and leaf emergence of rice plant, 8: Relation of temperature of several parts of rice plant to the rate of leaf emergence. Proceedings of the Crop Science Society of Japan, 29, 195–198.

[b]Tanaka, M. 1962. Studies on the growth injuries of lowland rice caused by cool water irrigation and delay heading. Aomori Agricultural Experiment Station Report, 7, 1–108.

[b]Tsunoda, K. 1964. Studies on the effects of water-temperature on the growth and yield in rice plants. Bulletin of the National Institute of Agricultural Sciences, A11, 75–174.

[b]Wada, G. 1969. The effect of nitrogenous nutrition on the yield-determining process of rice plant. Bulletin of the National Institute of Agricultural Sciences, A16, 27–166.

[a]Wada, S. 1992. Cool Damage in Rice Plants. Tokyo, Youkenndo, 261 p.

---

[a] In Japanese.

[b] In Japanese, with English summary.

Temperature Constraints to Rice Production in Australia and Laos: A Shared Problem

T.C. Farrell[a,b,c]*, K.M. Fox[b,c], R.L. Williams[b,c], S. Fukai[a], R.F. Reinke[c] and L.G. Lewin[b,c]

Abstract

With the transition to dry-season rice production, Laos now faces many new challenges relating to extreme temperature problems. Temperatures are highly variable throughout Laos, because of variable altitudes. Provinces in northern Laos suffer from low temperatures during the rice crop's vegetative and reproductive stages. These problems are shared with temperate-climate rice-growing countries such as Australia, where temperature variation is seasonal. Provinces in southern Laos face problems relating to high temperatures during anthesis. With the establishment of the Cooperative Research Centre for Sustainable Rice Production, Australia now focuses on improving the level of cold tolerance in commercial varieties at establishment and during the reproductive stage. Cultivars with superior seedling vigour and cold tolerance have already been identified and incorporated into the Australian breeding program. Collaborative research between Australia and Laos on the management of extreme temperature variability to reduce yield loss will prove mutually beneficial to both countries.

Seasonal temperature variation is common throughout the world, at times causing severe food shortages. Extreme temperatures throughout the rice season dramatically reduce yield, changing key yield components. Cooperative research into the effect of temperature on rice can contribute to food security worldwide.

Important factors for grain yield potential are vegetative development (emergence to panicle initiation [PI]), reproductive development (panicle initiation to heading) and grain formation and ripening (Boerema 1974). Although the dynamics of rice production in Australia and Laos are at different extremes of the production and mechanization spectrum (Table 1), significant yield losses due to temperature variability are experienced in both countries.

Table 1. Estimates of rice production in Australia and Laos in 1998.

	Australia	Laos
Planting method	90% aerial sowing	100% transplanting
Rice area (ha)	139 902	650 000
Total annual rice production (tons)	1.32 million	1.67 million
Average yield (t ha^{-1})	9.42	2.7
Export (%)	85	<10
Percentage of cropped land (%)	0.76[a]	<80
Irrigated land (%)	100	8.3

[a] Calculated from ABARE's (2000) commodity report.

With the development of the Cooperative Research Centre for Sustainable Rice Production (Rice CRC) in Australia, a multifaceted approach to research on low temperature has begun, with

---

[a] School of Land and Food Sciences, University of Queensland, Brisbane, Qld., 4072, Australia
[b] Cooperative Research Centre for Sustainable Rice Production, Yanco Agricultural Institute, New South Wales, 2703, Australia
[c] New South Wales Agriculture, Yanco Agricultural Institute
*Corresponding author:
E-mail: tim.farrell@agric.nsw.gov.au

KEYWORDS: Australia, Cold tolerance, Laos, Low temperature, Rice

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

progress being made in the understanding of low temperature problems at the protein, cell, organ and plant levels. The collaborative project between Rice CRC and the ACIAR, *Increased Crop Production for Lowland Rice in Laos*, *Cambodia and Australia*, has initiated research towards solving the problems caused by extreme temperatures on rice production in Australia and Laos.

Rice Practices

Australia

Rice growing in Australia is confined to the Riverina region of New South Wales (NSW), centred at 35° south and 146° east. Altitude (averaging 120 m) throughout the region varies little. About 140 000 ha are sown each year, producing an average yield as high as 9.4 t ha^{-1}, with the highest yielding crops exceeding 13 t ha^{-1}. Although rice-growing areas in southern Riverina are 1° to 2°C cooler than in northern Riverina, temperatures usually vary little within a given season across the whole rice-growing area. Average rainfall during the growing season is 200 mm with the crop requiring full irrigation. The growing season is characterized by long days with high levels of solar radiation. Low temperatures during establishment and a cool grain-filling period restrict the length of the growing season, while low night temperatures during reproductive development can cause catastrophic yield loss.

The crop is planted in spring and, after summer growth, is harvested in autumn. Planting starts in late September, as soon as the risk of frost is negligible. Full-season and short-season cultivars are sown in early October and November, respectively, to ensure—as far as possible—that reproductive development coincides with the warmest night temperatures (late January–early February). Grain filling occurs in February–March when the cooler temperatures extend the duration of grain filling, producing grains of high quality. Rice crops are drained and harvested in March–April, before the first frosts and when grain moisture content is between 16% and 22%. More than 90% of Australian rice crops are sown aerially. Most of the nitrogen is applied before permanent flooding and, if necessary, top-dressed at PI. Average N application rates are 80–100 kg ha^{-1}.

Laos

The Lao People's Democratic Republic (Lao PDR) is located in the tropics, between 14° and 22° north and 100° and 108° east. The Lao rice area comprises 650 000 ha, producing an average yield of 2.7 t ha^{-1}, with the highest yields reaching 4 t ha^{-1}. Lao PDR is geographically divided into northern, central and southern regions, each having different temperature regimes as a result of variations in altitude and latitude. Laos has distinct wet and dry seasons. Historically, most rice production in Laos was produced during the wet season as upland and lowland crops. With the advent of irrigation, rice production in the dry season has increased from 13 600 ha in 1995 to 87 000 ha in 1999 (NAFRI 2000). The wet-season crop is transplanted to the field in June and harvested in October, whereas the dry-season crop is transplanted between November and January and harvested in May.

Of the rice produced in Laos in 1998, the rainfed lowlands accounted for 74%, the rainfed uplands for 13% and another 13% was irrigated (IRRI 1999). The long-term aim for Lao rice production is to reduce the area of rainfed upland rice and increase that of irrigated rice. Almost all rice in Laos is transplanted by hand and harvested by non-mechanized methods.

The impact of low temperature on Lao rice production relates specifically to the dry-season crop at both establishment and during the reproductive stage. As mentioned before, temperature variation is principally determined by altitude and latitude. For example, Champassak, a southern province (15° north), has an average altitude of 120 m, with high temperatures during flowering in April (Figure 1f) that sometimes limit dry-season yields. In contrast, Xieng Khouang has an average altitude of 1050 m and is located at 19.5° north. It suffers from low temperatures at establishment and during the microspore stage in the dry season (Figure 1d). Temperature patterns in all six provinces show that the average minimum temperatures slowly decrease from November to December throughout early establishment (Figure 1).

Low Temperatures during the Vegetative Stage

Background

The vegetative stage refers to the period from germination to PI and is characterized by active tillering, gradual increase in height, and leaf emergence at regular intervals. Germination starts when seed dormancy has been broken, the seed absorbs adequate water, and is exposed to a soil temperature ranging from about 10° to 40°C. Temperature has a profound influence on germination by affecting the activation stage and post-germination growth. There are clear varietal differences in seed germination at low temperatures (Yoshida 1981). Low temperatures can affect the rice plant's developmental processes; and impair photosynthesis, thus reducing growth and

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

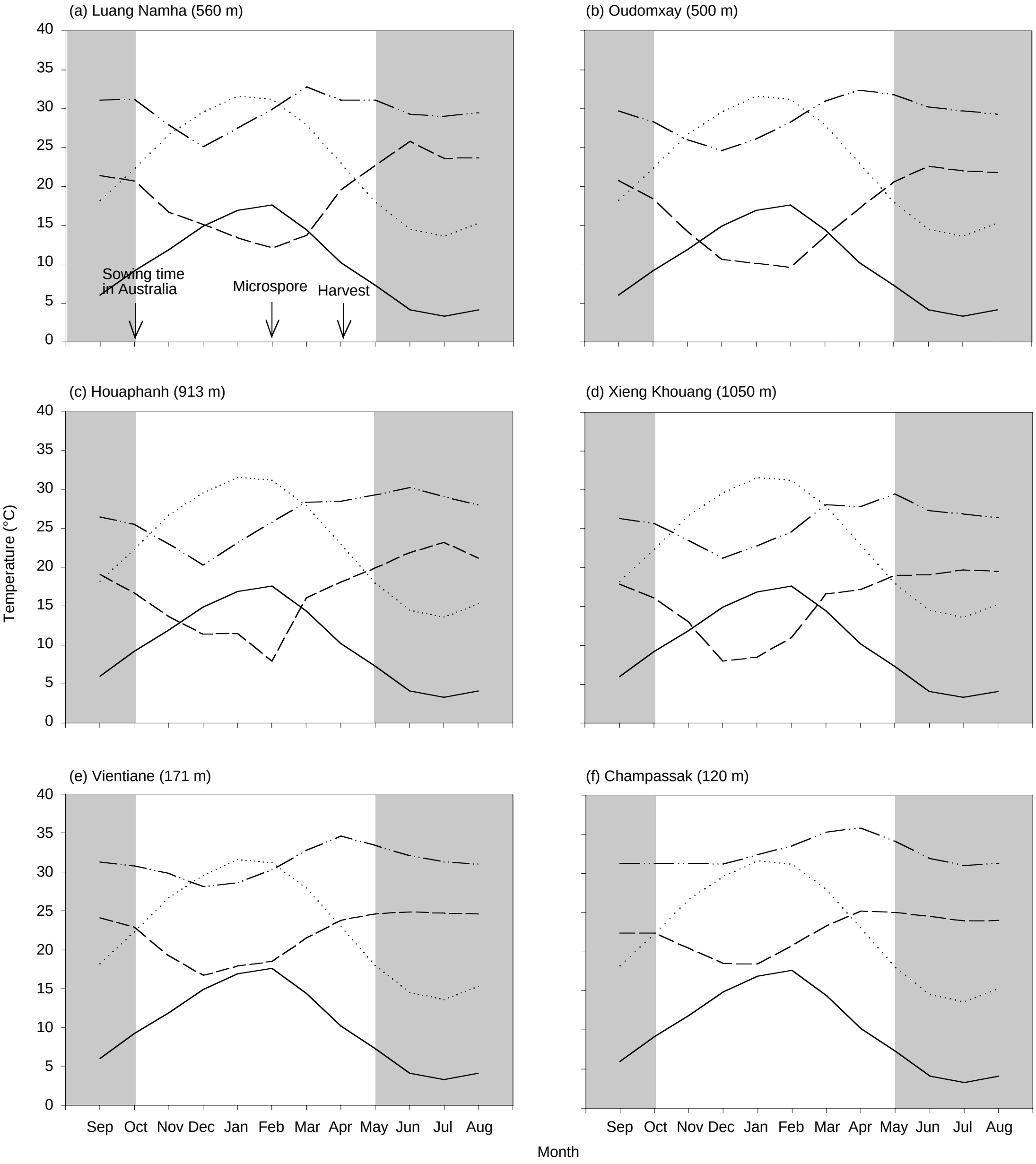


Figure 1. The long-term maximum and minimum temperatures of Yanco, Australia, compared with six provinces in Laos: (a) Luang Namtha, (b) Oudomxay, (c) Houaphanh and (d) Xieng Khouang, all in the northern region, (e) Vientiane, central region, and (f) Champassak, southern region. Values in parentheses refer to altitude. ☐ = Laos dry season; ▨ = Laos wet season; —··— = provincial maximum temperatures; — — = provincial minimum temperatures; ...... = Yanco (Australia) maximum temperatures; —— = Yanco minimum temperatures.

resulting in indirect yield loss because of less carbohydrate available for grain production (Smillie et al. 1988). Poor establishment and vegetative growth in rice, caused by low temperatures, are common problems in countries such as Australia and Laos.

Temperature variability

The average minimum temperature during establishment (November) in Yanco, New South Wales, Australia, is 12.3°C, with the variation being higher within, rather than across, years. For the corresponding period in Laos (December), the average minimum temperatures in Xieng Khouang and Champassak were 8.3° and 18.5°C, respectively.

Variation for temperature within and across years was calculated according to daily maximum and minimum temperature data. The coefficient of variation (CV) of temperature across years was calculated from the standard deviation of the mean temperature for each year divided by the mean temperature across all years. The CV of temperature within years was calculated as the mean of the CV of daily data for each year. All CVs are shown as percentages (Table 2).

Establishment of dry-season rice crops in provinces such as Xieng Khouang (where the minimum temperature is 8.3ºC) is difficult, because 10°C is probably the critical minimum temperature for the elongation of shoots and roots (Yoshida 1981). Temperature variability was higher within years than across years in all six provinces. In Laos, the distribution of low temperatures appears to be related to altitude, with rice in the Vientiane (171 m) and Champassak (120 m) provinces not being affected by low temperatures during establishment.

Seedling vigour

Seedling vigour is important for efficient crop production. Vegetative vigour—the rapid attainment of plant biomass—depends on the initial size of seedlings and the rate at which they grow. A controlled environment experiment was conducted at Yanco to explore differences in seedling vigour among 38 direct-sown cultivars from the International Rice Cold Tolerance Nursery (IRCTN). Seedlings were grown at 25°–15°C for 2 weeks before temperature treatments were imposed. Seedling size at 2 weeks was considered as the initial size. Temperature treatments comprised 7°/22°C, 10°/25°C and 13°/28°C (minimum and maximum temperatures, respectively), reflecting the range of conditions likely to occur during establishment in Australia and Laos.

There was a five-fold difference in average seedling biomass between the low and high temperature treatments. Cultivars exposed to the highest temperatures had the greatest biomass, averaging 600 mg per seedling. Average biomass of seedlings at the intermediate and low temperature treatments were significantly lower, at 290 mg and 120 mg, respectively. A selection of four cultivars, including those with the greatest and least response to temperature is shown in Figure 2.

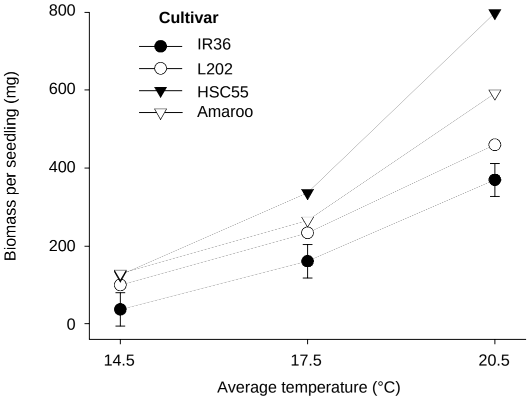


Figure 2. Effect of temperature on biomass per seedling, 41 days after sowing from a subset of rice cultivars displaying variation in temperature response. Vertical bars = standard error.

Table 2. Comparison of average minimum and maximum temperatures during 1 month of establishment at the Yanco Agricultural Institute, Australia, and six provinces in Laos.

Month	Site	Country	Min. °C	Across[a] CV%	Within[b] CV%	Max. °C
Nov	Yanco	Australia	12.3	10.0	32.4	26.6
Dec	Luang Namtha	Laos	15.0	8.2	16.9	24.6
Dec	Oudomxay	Laos	11.5	16.0	26.3	24.5
Dec	Houaphanh	Laos	11.1	11.9	28.4	20.8
Dec	Xieng Khouang	Laos	8.3	22.1	38.6	21.6
Dec	Vientiane	Laos	17.2	7.4	13.9	28.3
Dec	Champassak	Laos	18.5	—	—	31.2

[a] Coefficient of variation across years relative to the mean.
[b] Coefficient of variation within years relative to the mean.

The tropical cultivar IR36 had the smallest response to increasing temperature. Surprisingly, a temperate cultivar from California, L202, showed a modest response to temperature. HSC55, a cultivar from Hungary (a temperate-climate region) showed the greatest positive response to increasing temperature. There were significant differences between cultivars for each temperature treatment, with differences being greatest at the highest temperature. The NSW cultivars Amaroo (Figure 2), Jarrah, Millin and Illabong (not shown) performed similarly and were intermediate in their response to temperature. At the lowest temperature treatment, no cultivar had a higher biomass than Amaroo but, at higher temperatures, significant genotypic variation was seen. In Laos, temperature conditions during establishment resemble the 10°/25°C and 13°/28°C temperature treatments.

The potential benefits of incorporating early vigour cultivars such as HSC55 into commercial cultivars, include early leaf area display causing increased radiation capture, improved weed competitiveness and rapid biomass accumulation during the vegetative phases (Reinke, 2000).

Nitrogen uptake

The NSW rice industry considers that N uptake by the rice plant at PI is a key determinant of yield potential. Temperatures during establishment control the amount of N in the above-ground tissue of the rice plant at PI. Mean air temperature from November 1 to December 31 was calculated for 1989 to 1999 at the Yanco Agricultural Institute. For each year, the average N uptake for all ‘Amaroo’ crops sown in the first 7 days of October was calculated across all rice-growing areas.

A significant correlation (r^2 = 0.55) was found between average air temperature and N uptake at PI (Figure 3a). The average temperature in 1994 was 20°C and N uptake was 87 kg ha^{-1}. In 1995, the average temperature was 23°C and N uptake was 125 kg ha^{-1}. A significant correlation existed between N uptake and yield (r^2 = 0.45), which suggests that good early growth resulting in higher PI nitrogen uptake is an important factor contributing to higher yields (Figure 3b). A strong correlation between average temperature during establishment and grain yield (r^2 = 0.73) highlights the importance of early growth in contributing to Australia’s high yields (Figure 3c).

Low Temperatures during the Reproductive Stage

Background

Low temperatures during reproductive development (i.e. PI to maturity) comprise a major constraint to productivity for the NSW rice industry. Low temperatures during late January to early February disturb the normal development of pollen grains, causing spikelet sterility. The risk of yield reduction in a cool year is greatly enhanced by increased N status of the crop (Heenan 1984; Satake et al. 1987). Hayase et al. (1969) concluded that, in rice plants, the young microspore stage, which is related to male sterility, is the stage that is the most sensitive to low temperatures. Low temperatures during reproductive development reduce the number of engorged pollen grains and fertilized spikelets in rice (Ito 1971). Deep irrigation water (20 cm) during the reproductive period can help protect young panicles from low air temperatures by providing a buffer and increasing panicle temperature by as much as 7°C on a cool night (Williams and Angus 1994).

A recent greenhouse experiment at the University of Queensland found a significant positive correlation between the total number of engorged pollen grains produced in an anther and the number of pollen grains intercepted by the stigma (r^2 = 0.81). This correlation suggests that 600 engorged pollen grains per anther would result in more than 40 being intercepted on the stigma (Figure 4a). A significant negative correlation was found between the number of engorged pollen grains and spikelet sterility (r^2 = 0.59). The relationship suggests that 600 engorged pollen grains will result in less than 30% sterility (Figure 4b). These correlations indicate that a large number of engorged pollen grains per anther is key to successful fertilization.

Temperature variability

The critical temperature for inducing sterility varies among cultivars. The unpredictability of low temperature during the microspore stage of rice has caused severe yield losses throughout the world. Low temperatures throughout Japan in 1993 led to the opening up of Japanese markets to rice imports. An extended low temperature event in Australia in 1996 during the rice crop’s reproductive stage reduced yields across the rice industry by 25%. In Laos, the 1999–2000 season was the coolest since 1974, causing major shortfalls in rice production. Satake (1969) estimates that critical temperatures are 15° to 17°C in a tolerant cultivar and 17° to 19°C in a susceptible one.

Australian rice crops are exposed to damage from low temperatures in the reproductive stage from late January through early February. Long-term data show that this period is usually the warmest, with an average minimum temperature of 17°C.

In Laos, however, for dry-season rice crops, the time of reproductive development is more variable,

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

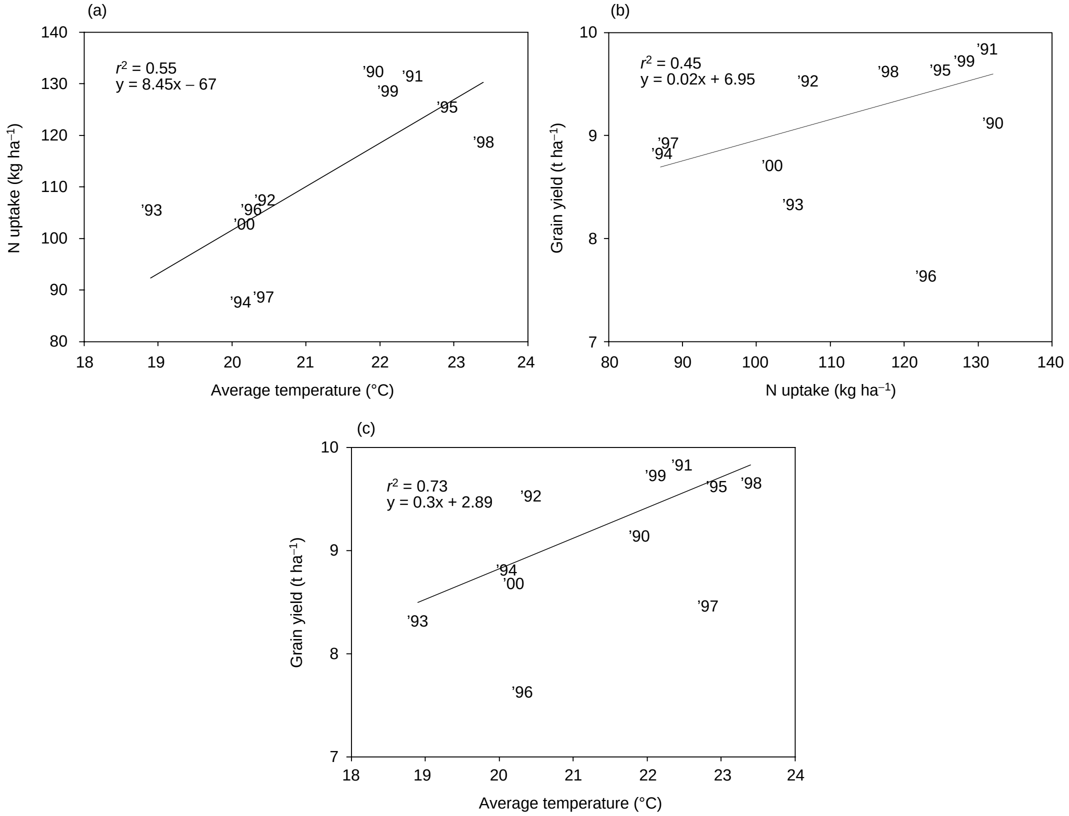


Figure 3. (a) Average temperature from November 1 to December 31 and nitrogen uptake during panicle initiation for 'Amaroo' rice crops sown during the first 7 days of October 1990 to 2000. (b) Nitrogen uptake plotted against grain yield for 'Amaroo' rice crops, 1989 to 2000. (c) Average temperature plotted against grain yield. The correlation of (b) and (c) does not include 1996, which experienced yield reduction due to low temperatures during the reproductive phase (late January–early February). Numbers with apostrophe refer to the year plotted.

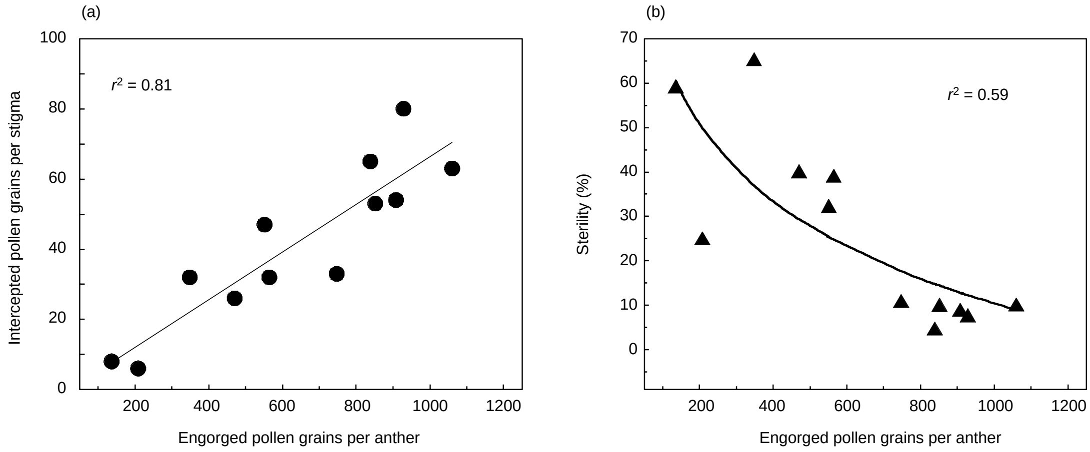


Figure 4. (a) Number of engorged pollen grains per anther regressed against intercepted pollen grains per stigma for rice cultivar Amaroo. (b) Number of engorged pollen grains per anther plotted against spikelet sterility (Gunawardena unpublished data).

occurring between early March and mid-April. The average minimum temperature across five Lao provinces increases by 3.5°C from early March to early April (Figure 5). For example, the average minimum temperature in Oudomxay, northern Laos, increases from 12°C in early March to 16.4°C in early April. Delaying reproductive development by sowing later may reduce the extent of low temperature damage in Laos.

Genotypic variability

Greenhouse trials

Two experiments, using 36 and 18 cultivars, respectively, on genotypic variation for low-temperature tolerance were recently conducted in temperature-controlled facilities at the Yanco Agricultural Institute. Three day/night temperature regimes (32°/25°C, 25°/15°C and 27°/13°C) were imposed on the cultivars from after PI to head emergence. A combined analysis identified seven international cultivars that consistently performed better than all the Australian cultivars. These were cultivars Liman and Pavlovsky (from Russia), Plovdiv 22 (Bulgaria), Akihikari and Haenuki (Japan), HSC55 (Hungary) and M103 (California, USA). Low temperatures reduced harvest index (grain/total biomass) of these tolerant cultivars by only 20%, compared with 50% for the major Australian cultivars.

Field trials

Field trials at the Yanco Agricultural Institute during the 1998–99 and 1999–2000 seasons aimed to confirm the tolerance of cultivars in the field. The 1998/99 season consisted of nine sowing dates from early October to late December, with each sowing date including a replicated trial of 30 genotypes. However, attempts to confirm cold tolerance in the field were thwarted by the occurrence of above-average temperatures. The 1999–2000 field trial comprised six sowing dates from 5 October to 30 December 1999. Deep (22 cm) and shallow (5 cm) water depth treatments were imposed throughout the critical

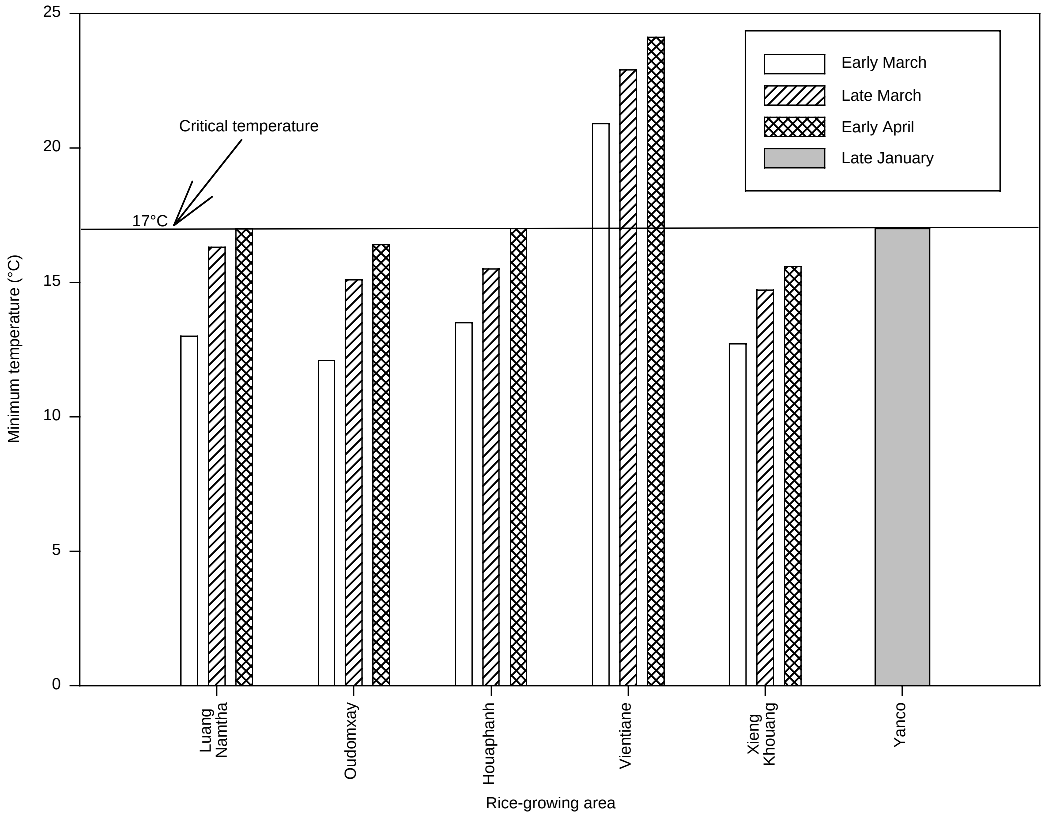


Figure 5. Temperature variability during the microspore period of the rice crop compared for Yanco, Australia, with the alternative growing periods in five Laos provinces. Champassak data were not available.

young microspore stage. Twenty-eight cultivars from different origins, with varying susceptibility to low temperatures, were replicated in each of the 12 bays.

Low night temperatures during the late December–early January and late January caused significant levels of sterility in most cultivars in the shallow water treatments. Cultivars Liman, M103 and Hitomebore (Japan) had low levels of sterility, despite experiencing low temperatures during critical stages in late January. Cultivars Sprint (Russia), Doongara (Australia) and Leng Kwang (China) had high levels of sterility in the shallow water treatments and appeared to be susceptible to mid-season low temperatures.

Screening for Low Temperature Tolerance during the Reproductive Stage

Background

With more than 100 000 rice cultivars worldwide, screening for low-temperature tolerance at establishment and during the microspore stage in rice has been targeted. Australia's researchers have successfully used temperature-controlled facilities and serial field trials, while Japan's researchers have developed field screening, using cool water from bores.

Genetic materials

The IRCTN carries a selection of cultivars from different origins evaluated at different sites for cold tolerance. Australia has sourced cold-tolerant cultivars a result of their performance in the IRCTN, reports in the literature or recommendations by international scientists. In 1995, 105 international cultivars from the 1991 and 1992 IRCTNs were introduced to Australia and grown in small plots at the Yanco Agricultural Institute. In recent temperature- controlled experiments, seven cultivars from this nursery were more cold tolerant than 'Millin', Australia's most cold-tolerant cultivar.

Australia has successfully exchanged cold-tolerant material, and continues to do so, with many countries such as Japan. Australia's plant physiologists and breeders are working closely together to improve the level of cold tolerance in commercial rice cultivars.

Deep cool water screening

Japanese experiment stations successfully carry out rapid screening of genotypes for cold tolerance during the reproductive stage of rice. Many other research stations have dedicated small experimental bays to screening of cold-tolerant cultivars. Rice is transplanted into these bays and cool bore water (19°C) is introduced after PI of the first cultivar until flowering of the last cultivar. Water depth is maintained at 20 cm for about 40 days. The rice breeder from the Miyagi Prefecture Agriculture Experiment Station, Furukawa, has successfully released cold-tolerant cultivars such as Jyoudeki, using the Station's deep cold water screening facility (Nagano 1998). The water temperature from a spearhead bore at Yanco, Australia, is about 20°C, which is about 5°C warmer than bore water in Japan and may not be suitable for cool water screening.

High Temperatures during Flowering

Temperature variability

When high temperatures occur during flowering, spikelet sterility can sometimes be seen on the windward side of Australian rice crops. Evaporative cooling can reduce canopy temperature by 7°C on hot windy days, protecting spikelets from high temperatures at anthesis. Historically, high-temperature-induced sterility has not been a major problem in South-East Asia because most rice is grown in the wet season. However, high temperatures and high humidity during flowering are now becoming constraints to rice production in the lowlands, particularly in southern Laos.

A recent report confirms that spikelet sterility under high temperature increases with humidity (Matsui et al. 1997). The average maximum temperatures during March and April in the Champassak province, is 35.3° and 35.8°C, respectively (Figure 1f). In the Sekong province, the average maximum temperature was greater than 35°C from January to May 1998.

The breeding program that produces cultivars for southern Laos should aim to improve heat tolerance and attempt to induce earlier flowering.

Mechanisms

The rice plant is most sensitive to high temperatures during flowering. Too much heat can impair pollen germination and reduce the number of pollen grains on the stigma, thus leading to spikelet sterility (Yoshida et al. 1981). IRRI (1979) confirmed that genotypic variation existed by identifying 13 of 291 selections that tolerated high temperature damage at flowering. High temperatures occurring within the hour after anthesis disturb such reproductive processes as anther dehiscence, pollen shedding, pollen-grain germination and pollen-tube elongation (Yoshida 1981). More than 10 germinated pollen grains on a stigma are needed for normal fertilization (Togari and Kashiwakura 1958, cited in Yoshida 1981). Yoshida (1981) suggested that high temperatures on the day of flowering caused spikelet sterility. Anthesis usually occurs between 1000 and

1200 h, with temperatures rising in the morning and exceeding the critical temperature (35°C) by 1000 h in hot areas. Therefore, early morning anthesis is highly desirable if high temperatures are to be avoided and sterility reduced (Yoshida 1981).

The flowers of *Oryza glaberrima*, an African cultivated rice species, open early in the morning (IRRI 1979), and this species has been a source of earliness for *Oryza sativa*. The 1-h earlier flower-opening time may have a significant effect in decreasing sterility, because air temperature rises at a rate of 3°–4°C h^{-1} in many tropical areas. In screening tolerant materials, 8-h treatments of 35° and 38°C were effective in selecting heat susceptible and tolerant lines, respectively (Yoshida 1981). Two methods are therefore possible to improve the heat tolerance of cultivars in Laos: increasing true tolerance through the use of cultivars that have improved pollen shedding and pollen germination, and encouraging earlier flowering time to avoid high day temperatures.

Conclusions

Although Australia and Laos have very different environments, the problems relating to the effect of extreme temperatures on rice production are shared. Altitude accounts for a large proportion of the temperature variability in Laos. In the northern and central regions, low temperature causes problems during establishment and the reproductive stage, whereas, in the southern lowlands, high temperatures during flowering causes damage.

Identifying and screening genotypes to minimize the impact of extreme temperatures at establishment, and during the reproductive and flowering stages must remain a major focus target of research efforts. Collaboration between international scientists on the common problem of temperature constraints to rice production can contribute to increased productivity and worldwide food security.

References

ABARE (Australian Bureau of Agricultural Resources and Economics). 2000. Australian commodities. Forecasts and Issues, 7(1). March Quarter.

Boerema, E.B. 1974. Climatic effects on growth and yield of rice in the Murrumbidgee Valley of New South Wales, Australia. Riso, 23(4), 385-397.

Hayase H., Satake T., Nishiyama I. and Ito N. 1969. Male sterility caused by cooling treatment at the meiotic stage in rice plants. II. The most sensitive stage to cooling and the fertilizing ability of pistils. Proceedings of the Crop Science Society of Japan, 38(4) 706-711.

Heenan, D.P. 1984. Low-temperature-induced floret sterility in the rice cultivars Calrose and Inga as influenced by nitrogen supply. Australian Journal of Experimental Agriculture and Animal Husbandry, 24(125), 255-259.

IRRI (International Rice Research Institute). 1979. Annual report for 1978. Manila, Philippines. 137 p.

IRRI (International Rice Research Institute). 1999. 1998 annual technical report. National rice research program and Lao-IRRI project. Manila, Philippines.

Ito, N. 1971. Male sterility caused by cooling treatment at the young microspore stage in rice plant. VIII. Free amino acids in anthers. Proceedings of Crop Science Society of Japan, 41, 32-37.

Matsui, T., Omasa, K. and Horie, T. 1997. High temperature induced spikelet sterility of japonica rice at flowering in relation to air temperature, humidity and wind velocity conditions. Japanese Journal of Crop Science, 66(3), 449-455.

National Agriculture and Forestry Research Institute (NAFRI). 1999. Research highlights. September, 2000.

Nagano, K. 1998. Development of new breeding techniques for cold tolerance and breeding of new rice cultivars with highly cold tolerance, Hitomebore and Jyoudeki. Proceedings of International Workshop on Breeding and Biotechnology for Environmental Stress in Rice. Sapporo, Japan.

Reinke, R.F. 2000. Genetic improvement of seedling vigour in temperate rice. PhD Thesis.

Satake, T. (1969). Research on cool injury of paddy rice plant in Japan. JARQ, 4(4), 5.

Satake, T., Lee S.Y., Koike S. and Kariya K. 1987. Male sterility caused by cooling treatments at the young microspore stage in rice plants. XXVII. Effect of water temperature and nitrogen application before the critical stage on the sterility induced by cooling at the critical stage. Japanese Journal of Crop Science, 56(3), 404-419.

Smillie, R.M., Hetherington, S.E., He, J. and Nott, R. 1988. Photoinhibition at chilling temperatures. Australian Journal of Plant Physiology, 15, 207-222.

Williams, R.L. and Angus J.F. 1994. Deep floodwater protects high-nitrogen rice crops from low-temperature damage. Australian Journal of Experimental Agriculture, 34, 927-932.

Yoshida, S., Satake T. and Mackill D.S. 1981. High-temperature stress in rice. IRRI Research Paper Series No. 67. International Rice Research Institute, Manila, Philippines, 15 p.

Yoshida, S. 1981. Fundamentals of Rice Crop Science. International Rice Research Institute (IRRI), Manila, Philippines, 81–82.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Response of Dry-Season Irrigated Rice to Sowing Time at Four Sites in Laos

V. Sihathep[1], Sipaseuth[2], C. Phothisane[2], Amphone Thammavong[3], Sengkeo[3], Sonekhone Phamixay[4], Manith Senthonghae[4], M. Chanphengsay[5], B. Linquist[6] and S. Fukai[7]*

Abstract

Experiments were conducted on dry-season irrigated rice at four sites: Vientiane Municipality and Provinces of Champassak, Xieng Khouang and Luang Namtha, Laos. The aims were to determine optimal sowing time and varietal requirements, and to identify temperature effects on growth and yield. Results indicated that optimal sowing time in southern and central Laos is December, when winter temperatures are appropriate for rice establishment. The experiments were conducted in the 1999–2000 season, which was particularly cool. Securing enough seedlings for transplanting was therefore key to obtaining high yields this season. In northern Laos, sowing in November improved establishment, compared with sowing in December, when the cold period began at the end of the month. Once the crop was successfully transplanted, low temperatures did not appear to severely limit yield in any of the regions studied. The experiments need to be repeated in at least one more year to obtain crop yield response to sowing time under more typical seasonal conditions. Historical records should be checked to identify the risk of occurrence of low temperatures that would limit production of dry-season rice in northern Laos.

RICE is the single most important crop in Laos. The area under dry-season irrigated rice is currently about 12% (87 030 ha) of the total rice area in Laos. This represents an increase of about 60%, compared with the area planted in the 1997–98 dry season (54 000 ha), and almost 500%, compared with the area planted in the 1992–93 dry season (13 000 ha). Such expansion reflects governmental policy to rapidly increase the level of national rice self-sufficiency while reducing the year-to-year variability of production caused by the impact of extreme climatic conditions.

Cultivation of dry-season rice is important for furthering the economic development of Laos. However, agronomic research has not kept pace with the expansion of irrigated areas. Some parts of Laos suffer heavy rice yield losses in the dry season, because of adverse weather conditions such as overly high or low temperatures (J.M. Schiller et al. 2001, this volume). Problems associated with low temperatures include low germination levels (Yoshida 1981; Nishiyama 1985), poor seedling establishment, delayed flowering and spikelet sterility (Hayase et al. 1969; Ito 1971; Gunawardena et al. 1999). High temperatures during flowering and grain filling (late March and April) can also cause yield losses in southern Laos.

In northern Laos, the common cropping pattern for dry-season irrigated rice is to sow in early November and transplant in late November to early December. In the south, where altitudes are lower and low temperatures are not such a problem, sowing is typically carried out in December and transplanting in January. However, sowing time often

---

[1] Rice Research Station, Champassak Province, Laos
[2] National Agriculture Research Centre, Vientiane, Laos
[3] Provincial Agricultural Service, Xieng Khouang Province, Laos
[4] Rice Experiment Station, Luang Namtha Province, Laos
[5] National Agriculture and Forestry Research Institute, Vientiane, Laos
[6] Lao–IRRI Project, Vientiane, Laos
[7] School of Land and Food Sciences, The University of Queensland, Brisbane, Qld., Australia
*Corresponding author: E-mail: s.fukai@mailbox.uq.edu.au

KEYWORDS: Irrigated rice, Cold tolerance, Laos

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

depends on the availability of irrigation water. To estimate optimal sowing time and harvesting, wet-season cropping patterns must also be considered. The wet and dry-season crops are commonly harvested in November and June, respectively. Early maturing, high-yielding varieties are required for dry-season irrigated conditions to ensure that the wet-season rice can be sown at an appropriate time. Optimal sowing times and varietal requirements differ throughout Laos because of temperature variability (J.M. Schiller, et al. 2001, this volume).

This study aims to establish appropriate sowing times for different phenological groups to improve dry-season rice yields. This research will contribute to the development of a double-cropping rice system, and will identify the impact of extreme temperatures at different stages on rice growth and yield in Lao provinces.

Materials and Methods

Field experiments were conducted at four sites in Laos, one in each of the Vientiane Municipality (central Laos, altitude 170 m), and the Provinces of Champassak (southern Laos, 168 m), Luang Namtha (northern Laos, 600 m) and Xieng Khouang (northern Laos, 1050 m). The 5-year average minimum temperatures during sowing time (November–December) are 21.5°, 23.0°, 19.4° and 18.5°C, respectively.

At each site, varieties from three phenological groups were evaluated. These were early (var. SK12), medium (var. RD10) and late flowering (var. TDK1) plus a local check. Check varieties were TSN1 (Vientiane), PN1 (Champassak), TDK3 (Luang Namtha) and Tiane (Xieng Khouang). The experimental design was a split plot with three replicates. Sowing times, that is, first sowing (S1), second sowing (S2), third sowing (S3) and forth sowing (S4), were assigned to main plots, and varieties to subplots. Plot size was 4 × 4 m. Seeds were soaked for about 2 days before they were sown into nursery beds.

Seeds were usually sown at 3-week intervals, although actual sowing dates varied to some extent at different sites (Table 1). Seedlings were transplanted 30 days after sowing. For RD10 at S1 in the Vientiane Municipality (VTN), not enough seeds were available and seedlings were transplanted only into one replicate. Transplanting of the S2 crop in Luang Namtha Province (LNT) was delayed for 15 days because the seedlings were too small at 30 days after sowing. Fertilizer (90 kg ha^{-1} of N and 60 of P_2O_5) was applied to the seedbed at 7 days after sowing. Six seedlings were transplanted at a spacing of 15 × 15 cm. After transplanting, fertilizer was again applied, at the rates of 90 kg ha^{-1} of N, 60 of P_2O_5 and 30 of K_2O. Nitrogen was applied in three equal splits: at transplanting, and 30 and 50 days after transplanting.

Table 1. Sowing times (S1–S4), and ranges of flowering times of dry-season irrigated rice varieties, of average maximum temperatures at flowering and of average minimum temperatures for 10–20 days before flowering at four sites in Laos.

Site[a] Sowing cycle	Sowing date	Dates of flowering time	Avg. maximum temperatures (°C) at flowering (± 5 days)	Avg. minimum temps. (°C) for 10–20 days before flowering
CPK				
S1	15 Nov 99	5 Mar–19 Mar	35.0–35.5	21.4–23.9
S2	6 Dec 99	13 Mar–27 Mar	34.2–36.0	21.3–25.1
S3	27 Dec 99	25 Mar–3 Apr	33.6–36.1	24.4–25.6
S4	17 Jan 00	15 Apr–26 Apr	32.1–36.4	24.9–25.9
VTN				
S1	15 Nov 99	10 Mar–27 Mar	34.7–36.2	19.1–20.7
S2	6 Dec 99	22 Mar–3 Apr	35.0–37.0	19.3–21.9
S3	27 Dec 99	31 Mar–26 Apr	32.1–36.2	20.3–22.6
S4	17 Jan 00	17 Apr–20 May	29.4–31.6	22.8–24.1
LNT				
S1	15 Nov 99	14 Apr–26 Apr	30.1–31.7	17.8–19.0
S2	6 Dec 99	5 May–18 May	26.9–31.5	20.0–20.8
S3	27 Dec 99	—	n.a.[b]	n.a.[b]
S4	21 Jan 00	22 May–31 May	27.6–31.2	20.7–21.6
XK				
S1	15 Nov 99	31 Mar–2 Apr	34.1–35.1	15.6–17.9
S2	6 Dec 99	—	n.a.[b]	n.a.[b]
S3	30 Dec 99	9 May–14 May	29.2–30.7	21.3–21.7
S4	10 Jan 00	28 May–5 June	n.a.[b]	20.4–22.1

[a] CPK = Champassak Province; VTN = Vientiane Municipality; LNT = Luang Namtha Province; XK = Xieng Khouang Province.

[b] n.a. = not available.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

To protect against rice bug damage in VTN and Champassak Province (CPK), Furadan (carbofuran) was applied 30 days after transplanting, and Sevin (carbaryl) was applied at flowering. In LNT and Xieng Khouang Province (XK), applying rodenticide at sowing, Sevin at flowering and Furadan at 3% at 30 to 45 days after transplanting is common practice. Despite these precautions, rice bug damage was a severe problem for the early maturing varieties in S1 in VTN (var. SK12) and CPK (var. PN1). In LNT, the crop planted at S4 was heavily attacked by rats, birds and rice bug and could not be harvested. Rats also damaged the S4 nursery in XK. Seedlings were therefore insufficient for all three replicates, the available seedlings being sufficient mostly for two replicates.

Dry weight and height of 200 seedlings were determined at transplanting, and tiller number was recorded 40–45 days after transplanting. Grain yield at 14% moisture content, panicle number per m^2, grains per panicle, 100-grain weight and the filled-grain percentage were recorded at maturity. The filled-grain percentage was estimated according to the 100-grain weights of filled and unfilled grain and the weights of filled grain and unfilled grain per m^2. Daily maximum and minimum temperatures for the experiment's duration were collected from meteorological stations, which were each located within 10 km of the trial site and at similar altitudes.

Results

Temperatures

Figure 1 shows the mean maximum and minimum temperatures for 10-day periods from November 1999 to May 2000 for the four sites. Temperature data for December in XK were not available, and were estimated from the regression of daily temperatures in XK against corresponding temperatures in LNT obtained in other months.

The 1999–00 season was extremely cold, particularly during late December, with low minimum temperatures in LNT (4°C), VTN (7°C) and CPK (14°C). In many places in Laos, the late-December temperatures were believed to be the lowest since 1974. In all study sites, temperatures were higher at the beginning of the dry season (November) and decreased to the lowest in the last 10 days of December. Minimum temperatures were low in January and February but increased gradually thereafter. Seasonal variation was higher for minimum temperatures than for maximum temperatures. The maximum temperature was lowest in December and increased gradually until April when it was around 35°C at all sites. The maximum temperature dropped slightly in May at the beginning of the wet season.

If a 10-day mean minimum temperature of below 15°C constitutes low temperature stress, then the crops at the CPK site experienced no low temperatures during establishment. However, in central VTN, the minimum temperature was close to threshold between December and mid-February, except in late December when the temperature dropped much lower. At the two northern sites, low temperatures extended from December to March.

Effects of low temperatures on germination and seedling growth

During late December, in LNT and XK, low temperatures affected germination, resulting in either no germination or seedling death for the S2 crop in XK. In LNT, germination problems occurred for the crops sown at S2, S3 and S4. Figure 2 shows the daily temperatures in LNT during the early part of the experiment. Daily minimum temperatures were about 15°C during most days in November and early December, before it dropped sharply to almost 0°C in the last 5 days of December. Minimum temperature was above 10°C after January 5.

Because of the extreme low temperatures, one variety (TDK3) did not germinate, and the number of seedlings for the other varieties was greatly reduced in S2. Consequently, only one replicate could be transplanted with the available seedlings. Seedling growth for the S2 crop in the nursery was also very slow, and transplanting was delayed for 15 days, compared with other sowings and sites. The S3 sowing, which corresponded with the lowest temperature period in late December, resulted in no germination. Germination of the S4 crop (sown 17 Jan) also failed, when the minimum temperature dropped below 10°C. The S4 crop was re-sown 4 days later (21 Jan), when the minimum temperature was higher than 10°C. The 17 Jan seeds might have germinated had they remained in the field longer.

Seedling weight and height

Dry weight and plant height of 200 seedlings were determined at transplanting. Mean seedling weight and height were regressed with mean air temperature during the nursery period (Figure 3). Strong relationships existed between temperature and seedling growth. Seedling height and weight data were not available from CPK.

At the LNT site, at S2, 45-day-old seedlings were used, while at all other sites and sowings, 30-day-old seedlings were used. Seedling weight and height for the S2 crop at the LNT site were adjusted for the difference in number of days from sowing to transplanting. Mean air temperature in VTN was higher than in the north, as reflected by improved seedling

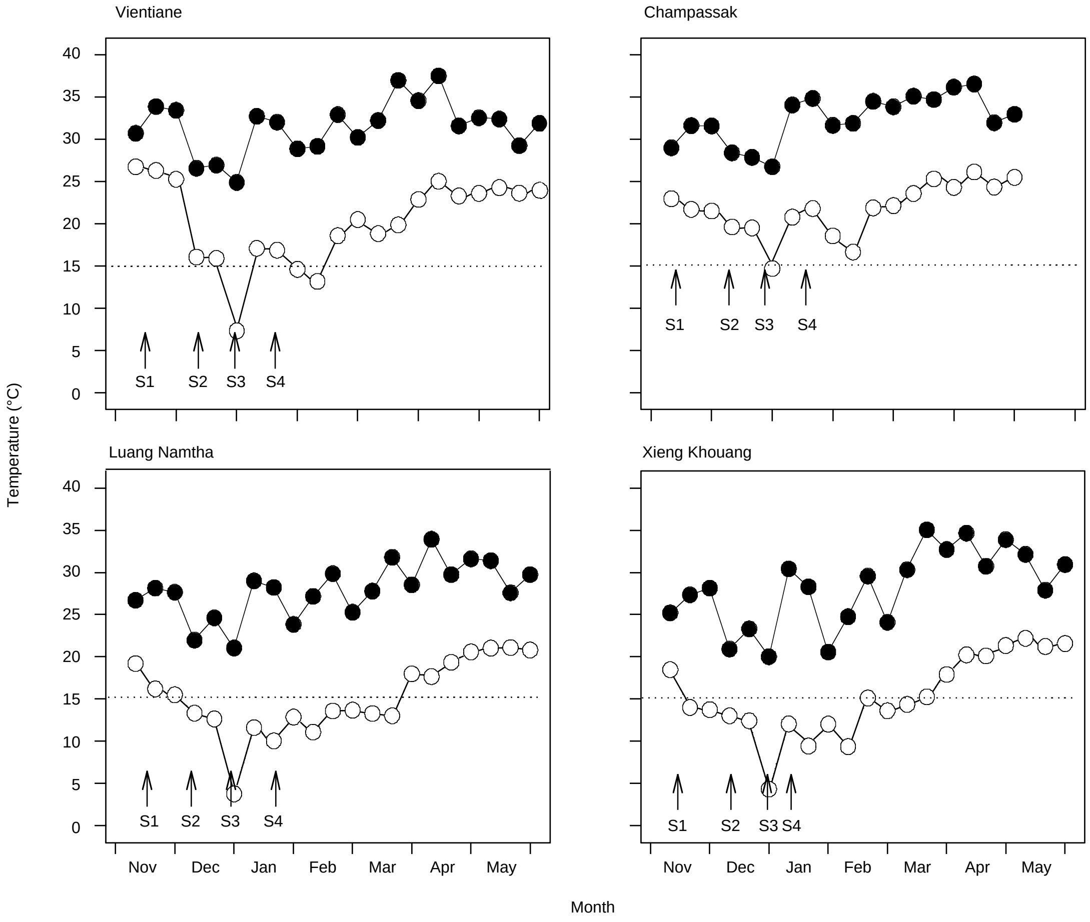


Figure 1. Maximum (-●-) and minimum (-○-) temperatures during November 1999 to May 2000 at sites in the Vientiane Municipality (VTN), and the Provinces of Champassak (CPK), Luang Namtha (LNT) and Xieng Khouang (XK), Laos. Sowing dates (S1–S4) for dry-season irrigated rice are shown. Dotted line indicates the critical temperature of 15°C for low temperature damage.

growth. Most sowings at the VTN site had higher seedling weights and heights than did those of the LNT and XK sites.

Flowering times and heat sum requirements

The flowering time of the four varieties differed according to site and sowing time (Table 1). The higher temperatures in CPK induced earlier flowering than in VTN, LNT or XK. Maximum temperatures at flowering were about 35°C at CPK and VTN, while it was cooler at LNT. The maximum temperature data in Table 1 indicated that high temperature problems were unlikely to occur in XK, except at S1. The crop flowered 14–24 days earlier than did the S1 crop at LNT, and it may have suffered male sterility problems.

The mean minimum temperature for 10–20 days before flowering is also shown in Table 1. The period was chosen because temperatures lower than 17°C at this growth stage can cause male sterility. Except for the S1 crop at the XK site, the mean minimum temperature exceeded 17°C.

Heat sum requirements from sowing to flowering were calculated by assuming the base temperature to be 10°C. Results showed that heat sum requirements for TDK1 and RD10 were similar and were greater than for SK12 in CPK and VTN, while the differences among varieties were much smaller in LNT and XK (Table 2). The estimated heat sum was slightly higher at the CPK site than at the other sites for RD10 and TDK1, possibly because the base temperature was lower than 10°C. The heat sum for the S1 crop in XK was consistently lower than that for other sowings. The reason for this is not known, but it should be noted that temperature records were not available for December at XK and, therefore, the heat sum was estimated, using a regression based on temperatures recorded at the LNT site.

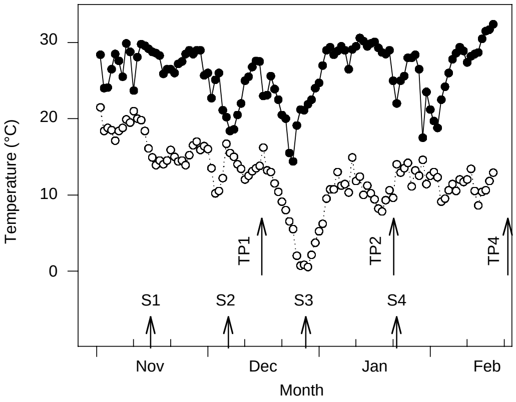


Figure 2. Maximum (-●-) and minimum (-○-) temperatures during November 1999 to February 2000 in Luang Namtha Province, Laos. Sowing dates (S1–S4) and transplanting dates (TP1, TP2 and TP4) for dry-season irrigated rice are also shown.

Grain yields

Grain yield varied greatly, depending on site and sowing time, while genotypic variation was relatively small in most cases. Figure 4 shows the effect of site and sowing time on mean yield across four varieties. Champassak Province and VTN showed similar responses to sowing date. Yields were lower at S1 and highest at S2, with a gradual decline towards S4. In LNT, the mean yield was over 2500 kg ha^{-1} for the first two sowings, but the S3 and S4 crops failed to yield. The S3 crop failed because of low temperatures, preventing germination, whereas the S4 crop failed because of heavy infestations of rats, birds and rice bug before harvest, because most of the S4 rice crops near the experimental site were harvested well before maturity of the S4 crop. Although the S2 crop produced a good yield, low temperatures reduced germination and no replicates could therefore be carried out. In XK, the S2 crop failed because of low temperatures at germination, whereas the mean yield of other sowings varied between 2500 and 3500 kg ha^{-1}. It should be pointed out that the S4 crop did not produce sufficient seedlings because of low temperatures at the nursery, and yield was produced only in two replicates.

The three highest yields were similar at 4500 kg ha^{-1}, being obtained by the S2 and S3 crops in CPK and the S2 crop in VTN. The mean yield of the three crops was calculated for each of the three common varieties to estimate the potential yield for

Table 2. Estimated heat sum accumulation for sowing to flowering of rice varieties TDK1, SK12, RD10 and local check varieties PN1 (Champassak Province), TSN1 (Vientiane Municipality), TDK3 (Luang Namtha Province) and Tiane (Xieng Khouang Province) at four sowing times (S1–S4), Laos.

Variety Location	Heat sum (°C-days)				
	S1	S2	S3	S4	Mean
SK12					
Champassak	1766	1592	1584	1650	1648
Vientiane	1582	1456	1425	1470	1483
Luang Namtha	1733	1655	—	1673	1687
Xieng Khouang	1370	—	1682	1930	1661
RD10					
Champassak	1964	1776	1954	1817	1878
Vientiane	1618	1583	1706	1874	1695
Luang Namtha	1577	1813	—	1560	1650
Xieng Khouang	1370	—	1698	1913	1660
TDK1					
Champassak	2044	1847	2039	1857	1947
Vientiane	1635	1612	1724	1892	1716
Luang Namtha	1604	1863	—	1706	1724
Xieng Khouang	1406	—	1745	1985	1712
PN1 (Champassak)	1865	1672	1766	1702	1751
TSN1 (Vientiane)	1899	1682	1924	2057	1891
TDK3 (Luang Namtha)	1546	—	—	1656	1601
Tiane (Xieng Khouang)	1334	—	1665	1842	1614

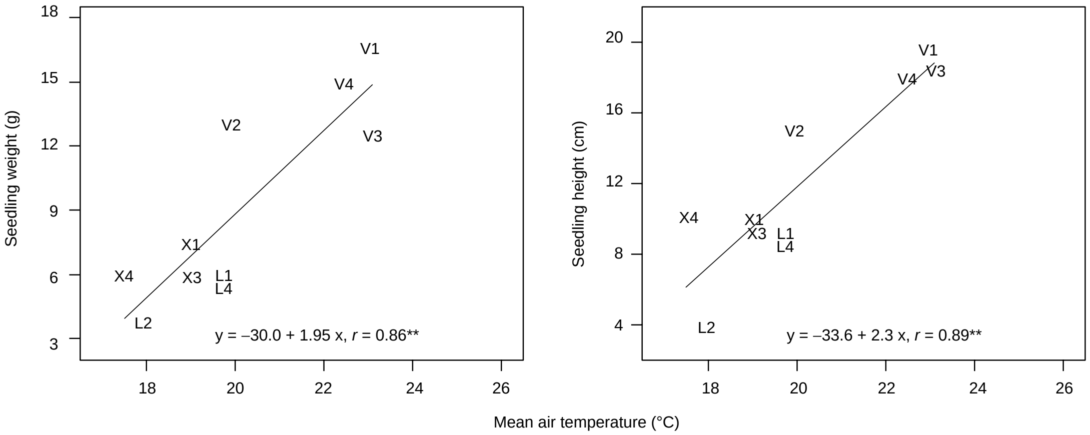


Figure 3. Relationships between mean air tempeature (°C) during the nursery stage and (a) seedling weight and (b) seedling height of dry-season irrigated rice at four sowing times in Vientiane Municipality (V), and the Provinces of Luang Namtha (L) and Xieng Khouang (X), Laos. The number after letter indicates sowing time.

the dry season. The mean yields were higher for TDK1 (4790 kg ha^{-1}) and RD10 (4800) than for SK12 (4190). These were then used to estimate yield loss percentage at other sowing times and sites for each variety (Table 3). The reduction was lower for SK12 than for other varieties in most combinations.

Table 3. Yield reduction in three, dry-season, irrigated rice varieties in relation to sowing time (S1–S4) at four sites, Laos. The S2 and S3 crops in Champassak Province and the S2 crop in Vientiane Municipality were used to estimate reduction percentage.

Site Variety	Yield reduction (%)			
	S1	S2	S3	S4
Champassak				
TDK1	50	0	0	17
SK12	50	0	0	4
RD10	50	0	0	9
Vientiane				
TDK1	31	0	20	37
SK12	28	0	7	12
RD10	66[a]	0	21	44
Luang Namtha				
TDK1	31	70[a]	100	100
SK12	24	38[a]	100	100
RD10	35	9[a]	100	100
Xieng Khouang				
TDK1	38	100	16	54[b]
SK12	30	100	11	37[b]
RD10	37	100	30	49[b]

[a] Only one replicate.
[b] Only two replicates.

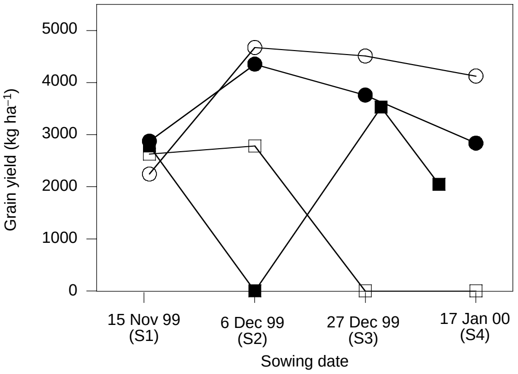


Figure 4. Association between grain yield of dry-season irrigated rice and sowing date at four sites: Vientiane Municipality (-●-) and the Champassak (-○-), Luang Namtha (-□-) and Xieng Khouang (-■-) Provinces, Laos.

Yield and yield components of the four varieties at the four sites are shown in Table 4. In CPK, the lower yields at S1, compared with those at S2 and S3, were related to the smaller number of grains per panicle with low percentages of filled grain in all varieties. In the later flowering TDK1 and RD10, tiller numbers of the S1 crop were higher than for the other sowings, whereas the panicle number was smaller in S1. This indicates the effect of adverse weather conditions during panicle development period in the S1 crop in CPK.

Table 4. Yield and yield components of four rice varieties sown four times (S1–S4) in (a) Champassak Province, (b) Vientiane Municipality, (c) Luang Namtha Province and (d) Xieng Khoung Province, Laos.

Sowing date	Variety	Yield (kg ha^{-1})	Tillers per m^2	Panicles per m^2	Grains per Panicle	Filled grain (%)	100-grain weight (g)
(a) Champassak Province							
15 Nov 99 (S1)	TDK1	2388 a	593 a	326 a	60 a	39.5 a	3.0 a
	SK12	2080 a	467 b	303 a	59 a	38.7 a	2.6 b
	RD10	2383 a	614 a	306 a	70 a	22.9 b	3.0 a
	PN1	2118 a	524 b	312 a	57 a	38.2 a	2.7 ab
6 Dec 99 (S2)	TDK1	5097 a	475 b	391 a	81 b	72.3 a	3.0 a
	SK12	4281 b	488 b	319 b	111 a	58.9 b	2.6 b
	RD10	4880 a	511 ab	331 ab	104 a	60.1 ab	2.9 a
	PN1	4428 b	556 a	345 ab	97 ab	70.0 a	2.8 ab
27 Dec 99 (S3)	TDK1	4598 a	526 a	343 a	84 a	65.0 ab	3.0 a
	SK12	4147 b	504 a	293 a	91 a	68.4 a	2.7 b
	RD10	4717 a	491 a	319 a	99 a	59.5 b	2.9 a
	PN1	4572 a	494 a	324 a	93 a	64.8 b	2.9 a
17 Jan 00 (S4)	TDK1	3971 b	510 a	293 a	100 a	58.6 b	3.0 a
	SK12	4010 b	483 a	281 a	100 a	62.5 a	2.7 b
	RD10	4367 a	516 a	324 a	87 a	58.3 b	3.0 a
	PN1	4153 ab	477 a	315 a	88 a	62.9 a	2.9 a
Sowing date	Variety	Yield (kg ha^{-1})	Tillers per m^2	Panicles per m^2	Grains per Panicle	Filled grain (%)	100-grain weight (g)
(b) Vientiane Municipality							
15 Nov 99 (S1)	TDK1	3277 a	519 a	306 a	111 a	55.5 b	2.8 a
	SK12	3000 a	424 a	274 ab	82 a	40.2 c	2.4 b
	RD10	1642^z	255^z	259^z	—	63.7^z	2.9^z
	TSN1	3106 a	287 b	201 b	80 b	63.2 a	2.7 a
6 Dec 99 (S2)	TDK1	4697 a	535 a	367 a	96 a	72.2 a	2.9 a
	SK12	4136 a	403 b	286 b	91 a	68.3 a	2.5 b
	RD10	4805 a	390 b	275 b	94 a	71.6 a	2.9 a
	TSN1	4387 a	362 b	278 b	91 a	67.4 b	2.5 b
27 Dec 99 (S3)	TDK1	3804 a	433 a	279 a	97 a	49.8 b	2.8 a
	SK12	3864 a	352 a	261 a	83 a	66.5 a	2.6 b
	RD10	3767 a	329 a	215 a	86 a	64.2 a	2.8 a
	TSN1	3600 a	352 a	199 a	86 a	63.2 a	2.4 c
17 Jan 00 (S4)	TDK1	3021 ab	523 a	265 ab	65 a	37.6 b	2.7 b
	SK12	3666 a	458 ab	282 a	85 a	71.2 a	2.6 c
	RD10	2643 bc	376 b	204 ab	68 a	46.7 b	2.9 a
	TSN1	2016 c	382 b	386 b	63 a	28.3 b	2.4 d

^{z} Only one replicate

The lower potential yield of SK12 in the S2 and S3 crops in CPK and the S2 crop in VTN was related to a smaller number of panicles per m^2. In VTN, the lower yields of the S1 crop, compared with those of the S2 crop, were related to reduced panicle density and low percentages of filled grain. Filled-grain percentages were particularly low for SK12 because of rice bug infestation. In the S4 crop, the yield of late-flowering varieties that flowered in May was lower than that of SK12, which flowered in mid-April. While maximum temperatures in April were higher than in May, late-flowering varieties had lower percentages of filled grain and were not suitable for VTN.

Variety TDK3 did not perform well at any sowings in LNT. In the S1 crop, the low yield of this variety was related to low panicle number per m^2, while in the S2 crop, it was a result of poor germination, possibly because of increased susceptibility

Table 4. (Continued)

Sowing date	Variety	Yield (kg ha^{-1})	Tillers per m^2	Panicles per m^2	Filled grain (%)	100-grain weight (g)
(c) Luang Namtha Province						
15 Nov 99 (S1)	TDK1	3307 a	409 a	255 a	78.3 a	3.0 a
	SK12	3146 a	341 a	120 b	59.9 b	2.8 a
	RD10	3108 a	328 a	147 b	57.8 b	2.8 a
	TDK3	942 b	337 a	70 c	37.2 c	2.9 a
6 Dec 99 (S2)	TDK1	1426[z]	248[z]	248[z]	80.2[z]	3.0[z]
	SK12	2562[z]	294[z]	295[z]	69.8[z]	2.9[z]
	RD10	4355[z]	286[z]	286[z]	76.1[z]	2.9[z]
	TDK3	—	—	—	—	—
21 Jan 00 (S4)	TDK1		432 a			
	SK12		261 b			
	RD10		250 b			
	TDK3		148 b			

Sowing date	Variety	Yield (kg ha^{-1})	Tillers per m^2	Panicles per m^2	Filled grain (%)	100-grain weight (g)
(d) Xieng Khoung Province						
15 Nov 99 (S1)	TDK1	2956 a	324 a	266 a	58.2 a	3.0 a
	SK12	2925 a	300 b	262 a	59.2 a	2.7 b
	RD10	2093 b	312 ab	263 a	53.1 b	2.9 a
	Tiane	3643 a	300 b	268 a	59.0 a	3.0 a
30 Dec 99 (S3)	TDK1	4018 a	372 a	319 a	57.6 a	2.8 a
	SK12	3704 a	324 b	294 b	58.5 a	2.7 b
	RD10	3332 a	325 b	303 a	58.3 a	2.8 a
	Tiane	3058 a	332 b	207 a	54.4 a	3.0 a
10 Jan 00 (S4)	TDK1	2192 a[y]	276 a[y]	226 a[y]	83.1 a[y]	3.0 a[y]
	SK12	2630 a[y]	228 b[y]	200 a[y]	68.1 b[y]	2.7 c[y]
	RD10	2432 a[y]	210 c[y]	194 b[y]	42.5 b[y]	2.9 b[y]
	Tiane	941 b[y]	216 bc[y]	201 a[y]	40.5 b[y]	3.1 a[y]

[z] Only one replicate.
[y] Only two replicates.

to cooler temperatures. In XK, the low yields of RD10 in the S1 crop and Tiane in the S3 crop were related to low percentages of filled grain.

Discussion

The four sites reported in these field trials experienced contrasting minimum and maximum temperatures during crop establishment and flowering. In CPK and VTN, minimum temperatures were higher than 15°C during most of the growth period. LNT and XK experienced extremely low temperatures (below 10°C) during crop establishment that affected germination and seedling vigour. M.-H. Lee (2001, in this volume) has also reported temperatures of below 10°C as causing germination failure in Korea. The S2 crop in XK and the S3 crop in LNT were affected by extremely low temperatures (below 5°C), either failing to germinate or the seedlings of all four varieties dying. The variety TDK3 did not germinate in the S2 crop in LNT, probably indicating higher susceptibility to low temperatures (between 10° and 15°C) than the other varieties, which could germinate. Nishiyama (1985, 1995, 1997) also reported varietal differences for germination under low temperatures. Systematic screening of varieties may therefore be needed to identify varieties for low temperature tolerance in these regions.

Poor crop establishment was the main cause of crop failure in XK and LNT. In addition to complete failure, in some cases, not enough seedlings were available to complete transplanting to the fields (e.g. the S2 and S4 crops in LNT and XK, respectively), thus reducing grain production further.

Data do not clarify whether extreme temperatures during rice growth in the main fields reduced yields. While temperatures at flowering were often high, no clear relationships between temperatures at flowering and filled-grain percentages could be seen. Yoshida (1981) and Yoshida et al. (1981) reported that high temperatures cause pollen abortion in rice grown under tropical conditions.

Further studies need to be conducted to confirm the impact of high temperatures on spikelet sterility and yield in central and southern Laos. The experimental results for the northern regions suggest that the effect of low temperatures during germination and establishment are more crucial for crop growth in northern Laos than low temperatures during the reproductive stage (T.C. Farrell, at al., 2001 in this volume). Low minimum temperatures of below 17°C at the critical panicle development stage were obtained only in the S1 crop in XK, but filled-grain percentages in the S1 crop were similar to those obtained in the S3 crop for which the minimum temperature during panicle development was higher than 20°C.

The 1999–00 dry season in which this experiment was conducted was extremely cool, particularly in late December. This experiment therefore needs to be repeated to confirm the results of the present experiment. Optimal times for sowing in northern Laos therefore cannot be recommended, using these data alone. The early and late sowings were damaged by pests, and the impact would probably have been reduced if larger rice areas had been used.

Further research should be carried out to identify optimal sowing times, taking more into account other biotic constraints (such as pest population buildup) prevailing in the low-temperature areas of northern Laos. For central and southern Laos, December sowing appears appropriate and yields close to 5000 kg ha^{-1} should be expected with appropriate varieties and crop management.

Acknowledgements

This project was funded by the Australian Centre for International Agricultural Research (ACIAR).

References

Gunawardena, T.A., Farrell, T.C., Fukai, S., Blamey, F.P.C. and Williams, R.L. 1999. Cold tolerance research in Australia—a snapshot in understanding cold induced yield reduction in rice varieties as exacerbated by high N status. Paper presented at the Proceedings of the 2nd International Temperate Rice Conference, Sacramento, CA, 13–17 June.

Hayase, H., Satake, T., Nishiyama, I. and Ito, N. 1969. Male sterility caused by cooling treatment at the meiotic stage in rice plants. II. The most sensitive stage to cooling and the fertilising ability of pistils. Proceedings of the Crop Science Society of Japan, 38: 4, 706.

Ito, N. 1971. Male sterility caused by cooling treatment at the young microspore stage in the rice plant. VIII. Free amino acids in anthers. Proceedings of the Crop Science Society of Japan, 41: 32.

Nishiyama, I. 1985. Physiology of Cool Weather Damage to Rice Plant. Sapporo, Japan, Hokkaido University Press.

Nishiyama, I. 1995. Damage due to extreme temperatures. In: Matsuo, T., Kumazawa, K., Ishii, R., Ishihara, K. and Hirata, H. ed. Science of the Rice Plant, vol. 2. Physiology. Food and Agricultural Policy Research Centre, Tokyo, 769–812.

Nishiyama, I. 1997. Cool weather damage of the rice plant. In: Asian paddy fields: their environmental, historical, cultural and economic aspects under various physical conditions. France, Scientific Committee on Problems of the Environment (SCOPE), International Council for Science (ICSU), 59–69.

Yoshida, S. 1981. Fundamentals of Rice Crop Science. Los Baños, Laguna, Philippines, International Rice Research Institute (IRRI), 81–82.

Yoshida, S., Satake, T. and Mackill, D.S. 1981. High-temperature stress in rice. Research Paper Series No. 67. Los Baños, Laguna, Philippines, International Rice Research Institute (IRRI), 15 p.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Finding Genetic Donors for Cold Tolerance in the INGER Gene Pool

Edwin L. Javier* and Ma. Concepción Toledo

Abstract

The International Network for Genetic Evaluation of Rice (INGER) is a collaborative effort between national agricultural research systems (NARS) and international agricultural research centres. Rice-breeding programs all over the world contribute elite breeding lines and varieties to INGER, who then organizes them into nurseries that are distributed freely to interested NARS for evaluation and use. A nursery may have 50 to more than 100 entries. Cold-tolerant genetic materials are entered in any of the International Rice Cold Tolerance Nursery (IRCTN), the International Rice Boro Observational Nursery (IRBON), and the International Rice Temperate Observational Nursery (IRTON). The IRCTN consists of japonica and indica genetic materials, which are used mainly as genetic donors. Testing sites differ according to low temperature regimes. IRBON carries mostly indica genetic materials with good yield potential and tolerance at the seedling and vegetative stages in their country of origin. IRTON carries temperate rice lines with good agronomic characteristics. Some of these lines are adapted to tropical conditions. Results of trials over a wide range of environments are analysed, and outstanding entries are stored in the IRRI Genebank. INGER data include the origins, pedigrees and grain characteristics of genetic materials and the results of trials across locations. Annual nursery reports are sent to collaborators and interested parties. Some INGER partners make seed requests based on results given in annual reports. INGER data are managed through the INGER Information System, which is integrated with the International Rice Information System, which handles genealogical, characterization and evaluation data on rice.

THE development and use of improved rice varieties has contributed substantially in improving rice production throughout the world. The International Network for Genetic Evaluation of Rice (INGER), formerly designated as the International Rice Testing Program (IRTP), has been a major player in the worldwide dissemination of improved cultivars and genetic donors since its establishment in 1975. This cooperative activity involving international agricultural research centres (IARCs) and national agricultural research systems (NARS) has the following objectives:

1. To facilitate the unrestricted, safe exchange of germplasm and information across geographical and political boundaries worldwide.
2. To broaden the genetic diversity and genetic base of rice varieties used by farmers.
3. To acquire, characterize and evaluate superior rice germplasm.
4. To assess and validate important traits of superior germplasm, including resistance to, or tolerance of, stresses and quality characteristics.
5. Characterize and evaluate G × E interactions for important traits so that rice improvement programs, particularly in the NARS, can capitalize on general and specific adaptation.
6. To enhance the capacity of NARS to use and improve rice germplasm.

More than 21 000 breeding lines and varieties of rice developed in countries around the world have been exchanged and evaluated through INGER over the years. More than 350 INGER genetic materials have been released as 530 varieties in 62 countries. Those countries that directly use INGER materials save 2–5 years of research time and resources per material. About 6000 INGER materials have been used as parents in more than 15 000 crosses generated worldwide by various NARS since 1975. They

---

International Rice Research Institute (IRRI), Makati City, Philippines
*Corresponding author: Edwin L. Javier
E-mail: e.javier@cgiar.org

KEYWORDS: Boro rice, Cold tolerance, Genetic donors, INGER

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

were used to diversify and improve locally adapted varieties. More than 1200 lines derived from these crosses have also been released.

This paper discusses the finding of genetic donors for cold tolerance in the INGER gene pool. It provides an overview of how INGER operates, describes the different nurseries with cold-tolerant germplasm, presents test entries with cold tolerance and good phenotypic acceptability over a wide range of environments, and describes information exchange through INGER.

Overview of INGER Operations

INGER members send their outstanding rice genetic materials, together with their pedigrees and salient characteristics, to the International Rice Research Institute (IRRI), usually in the form of small quantities of seed. Nominated entries are initially multiplied at IRRI's post-quarantine area at Los Baños, where the IRRI Seed Health Unit and the Philippine Plant Quarantine Office monitor them for disease incidence. Further seed multiplication at the IRRI Farm is done until the amounts required for the nurseries are obtained. A variety or line will take at least 2 years from being nominated to being included in a nursery.

Resulting seeds are thoroughly cleaned and checked. Seeds that are half-filled, discoloured, diseased and off-type are discarded. Only materials with at least 90% viability and that pass the seed health evaluation are included in the nurseries. For requests from NARS, the seeds are processed according to the phytosanitary requirements of the importing NARS, although INGER always ensures that it distributes seeds of the highest quality.

IRRI informs INGER members of the types of nurseries available each year. INGER members decide what nurseries to import and where to grow them. IRRI sends the nurseries, together with the Material Transfer Agreement for FAO-designated germplasm. After growing them, IRRI's collaborators send their data to IRRI for analysis and interpretation. Outstanding test entries are identified and stored in the IRRI Genebank. Results of analyses are sent back to the collaborators.

INGER Nurseries with Genetic Donors for Cold Tolerance

International Rice Cold Tolerance Nursery (IRCTN)

The first IRCTN was established in 1975, then distributed every year from 1975 to 1993 and every other year after 1993. Since 1975, about 3000 varieties and breeding lines have been tested. So far, requests for IRCTN have been received from 65 countries. A country may request for one or more sets of IRCTN in a given year. More than 170 000 seed packets (sum of number of requests × number of varieties) have been distributed worldwide.

Entries that are nominated for the IRCTN have cold tolerance at one or more growth stages in their countries of origin. However, they may or may not have good agronomic characteristics. Thus, they are used mainly as genetic donors for cold tolerance. Entries are classified as indica or japonica type according to the information provided by the collaborators or to isoenzyme analyses. They are evaluated against the international check varieties and the best local check at each trial site. The 1999 IRCTN carried 63 test entries, originating from 11 countries and IRRI. The indica international checks were China 1039 and K39-96-1-1-1-2 (both from India) and the japonica international checks were Barkat K78-13 (from India), Stejaree 45 (former USSR) and Tatsumi-mochi (Japan).

An IRCTN is a non-replicated field trial. Each entry is evaluated in 5-m long plots with 4 rows and 1 plant per hill at a spacing of 25 × 25 cm. Collaborators decide the fertilizer rates, pest control measures and other cultural practices to be followed. The standard screening procedure uses the usual irrigation water in the station. The temperature of the irrigation water is unknown or beyond the control of the collaborator. The standard screening procedure may be modified by irrigating the trial with cold water, the temperature of which is controlled by the collaborators. The modified screening procedure is used only at a very few sites. Plant data collected include cold tolerance at different stages of growth, seedling vigour, tillering ability, plant height, days to flowering, phenotypic acceptability, panicle exsertion and spikelet fertility. Daily air temperature is also recorded.

The analysis of varietal performance is made relative to the temperature regime during the trial's execution. The air temperature pattern is defined for each site by considering the monthly average minimum temperature relative to the growth stages of the rice crop. There are eight general temperature patterns, based on data received over the last 5 years:

1. Low temperatures throughout the growing season.
2. Low temperatures at the vegetative stage.
3. Low temperatures at the vegetative and flowering stages.
4. Low temperatures at the seedling/vegetative stage and at maturity.
5. Low temperatures at flowering and at maturity.
6. Low temperatures at flowering.
7. Low temperatures at maturity.
8. Moderate temperatures throughout the growing season (no cold stress).

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Table 1. Selected entries based on phenotypic acceptability, origin, varietal groups, and number of sites for each temperature pattern where selected entries showed cold tolerance in the 1993 IRCTN.[a]

Selected entry	Origin	Group	Number of sites with temperature pattern:[b]	
			4	5
CN839-102-8/2	India	Indica	2	1
CT6742-22-5-4-M-3-M	Chile	Indica	2	1
Milyang 93	South Korea	Japonica	2	1
Stejaree 45	ex-USSR	Japonica	2	1
Tomihikari	Japan	Japonica	2	1
'79004-TR4-4-2-1-1'	Turkey	Japonica	2	1

[a] IRCTN = International Rice Cold Tolerance Nursery.

[b] Temperature pattern 4 = 3°–17°C, low temperatures at the seedling/vegetative stage and at maturity; 5 = 8°–16°C, low temperatures at flowering and at maturity.

Source: INGER (1994).

Table 2. Selected test entries based on mean phenotypic acceptability across sites in the 1993, 1995 and 1997 IRCTN.[a]

Year	Entry	Origin[b]	Group
1993	Tella Hamsa	India	Indica
	Tomihikari	Japan	Japonica
	Suweon 349 (Jinmibyeo)	Korea	Japonica
	K39-2	India	Japonica
	Panda	Italy	Japonica
	Arongana 688	Madagascar	Japonica
1995	Jinling 78-102	China	Japonica
	Dalizhaoxai	China	Japonica
	Yunlen 1	China	Japonica
	Yunlen 8	China	Japonica
	Diangen 8	China	Japonica
	Gendiao 3	China	Japonica
	Gihobyeo-M2-6-1	Korea	Japonica
	Yunlen 16	China	Japonica
	Yunlen 18	China	Japonica
	Kungen 4	China	Japonica
1997	IR58565-2B-10-2-2	IRRI	Indica
	IR59469-2B-3-2	IRRI	Indica
	CT6742-20-20-1-M-M-M	Chile	Japonica
	Hexi 10	China	Japonica
	IR62445-2B-12-1-2	IRRI	Japonica
	IR63352-AC-202	IRRI	Japonica

[a] IRCTN = International Rice Cold Tolerance Nursery.

[b] IRRI = International Rice Research Institute.

Sources: INGER (1994, 1996, 1999b).

Low temperatures are below 18°C, whereas moderate temperatures are between 18° and 25°C. Sites falling within the same temperature pattern may also vary for other factors such as soils and biotic stresses. The top entries for each trait evaluated can differ among sites belonging to the same temperature pattern. Collaborators decide what materials they want to use in their breeding program.

At IRRI, top entries with wide adaptation are stored for some years. They are selected according to cold tolerance and phenotypic acceptability at maturity over a range of environments. In the 1993 IRCTN, six entries with good phenotypic acceptability ratings were selected according to results of the modified cold tolerance screening procedure used at three sites (Table 1). All came from different countries, with two—CN839-102-8/2 and CT6742-22-5-4-M-3-M—belonging to the indica rice group and the others to the japonica group.

Based on mean phenotypic acceptability across 12 sites, employing the standard procedure, and across 3 sites, using the modified method, six entries were identified as promising in the 1993 IRCTN (Table 2).

In the 1995 and 1997 IRCTN, all collaborators used the standard field screening procedure and scored the test entries for cold tolerance and phenotypic acceptability. In 1995, 19 test entries were selected for cold tolerance in at least 3 test sites (Table 3).

Table 3. Selected entries based on cold tolerance, origin, varietal groups, and number of sites for each temperature pattern where selected entries showed cold tolerance in the 1995 IRCTN.[a]

Selected entry	Origin	Group	Number of sites with temperature pattern:[b]			
			1	2	3	6
Chuxai	China	Indica	0	1	3	0
Dalizhaoxai	China	Japonica	1	0	3	0
Yunlen 13	China	Japonica	0	0	3	1
Yunlen 16	China	Japonica	0	0	3	1
Yunlen 17	China	Japonica	0	1	3	0
Banjaiman	China	Japonica	0	0	3	1
Diangen 8	China	Japonica	1	1	3	1
Gendiao 3	China	Japonica	0	1	3	0
Gihobyeo-M2-6-1	S. Korea	Japonica	0	0	3	0
K39-96-1-1-1-2	India	Indica	0	2	2	2
Yunlen 12	China	Japonica	2	0	2	0
K457-107-3-4-1-1-2	India	Indica	2	0	2	1
Yungen 79-635	China	Indica	0	0	2	1
Yungen 20	China	Indica	1	0	1	1
Yunlen 1	China	Indica	0	0	2	1
Yunlen 9	China	Indica	1	0	1	2
Yunlen 8	China	Indica	3	0	2	1
Yunlen 7	China	Indica	0	0	2	1
Yunlen 20	China	Indica	0	1	2	1

[a] IRCTN = International Rice Cold Tolerance Nursery.

[b] Temperature pattern 1 = 10°–17°C, low temperatures throughout the growing season; 2 = 10°–20°C, low temperatures at the vegetative stage; 3 = 2°–18°C, low temperatures at the vegetative and flowering stages; 6 = 11°–18°C, low temperatures at flowering.

Source: INGER (1996).

All entries originated from China, except three. Ten entries belonged to the indica group and nine to the japonica group. Based on mean phenotypic acceptability across 17 sites, the top 10 entries were identified. Seven entries were common in both categories (Table 2). There were three entries rated as tolerant of low temperatures at three sites (Table 4) and six entries with good phenotypic acceptability in 4 or 5 sites in 1997 (Table 2).

Table 4. Selected entries based on cold tolerance, origin and varietal groups, and number of sites for each temperature pattern where selected entries showed cold tolerance in the 1997 IRCTN.[a]

Selected entry	Origin	Group	Number of sites with temperature pattern[b]			
			1	3	4	5
K479-2-3	India	Indica	1	1	1	0
CT6748-CA-17	Chile	Japonica	0	0	1	2
PR26390-581CRF	Philippines	Japonica	0	0	1	2

[a] IRCTN = International Rice Cold Tolerance Nursery.
[b] Temperature pattern 1 = 6°–16°C, low temperatures throughout the growing season; 3 = 8°–16°C, low temperatures at the vegetative and flowering stages; 4 = 3°–17°C, low temperatures at the seedling/vegetative stage and at maturity; 5 = 3°–17°C, low temperatures at flowering and at maturity.
Source: INGER (1999b).

International Rice Boro Observational Nursery (IRBON)

Boro rice is a special type of rice that is traditionally cultivated in India and Bangladesh during winter. The total area grown to boro rice is about 5.5 million hectares and is increasing every year. This is attributed to the rice's high yield potential in a season considered to be almost risk free, provided that there is supplementary irrigation. Low temperatures from seedling to early vegetative stage is a major constraint to boro rice production.

IRBON started in 1993, with entries coming from six countries and IRRI. It started with India and Bangladesh as the only countries conducting the trial. Over the years, countries requesting for IRBON have increased. The Philippines, Vietnam, Myanmar, South Korea, North Korea, Nepal, Iran, Senegal and Namibia are now exploring the potential of boro rice. Around 7000 seed packets of nearly 350 materials have been distributed.

IRBON is a yield nursery. It is laid out, using an augmented design in Latin square with five blocks. Five check varieties are always entered in each block. The international checks are IR72 (early maturing), PSBRC 2 (intermediate-maturing) and IR42 (intermediate to late maturing). Collaborators provide early maturing and late-maturing varieties. Plot size is 5 × 1.2 m (7 rows) and hill spacing is 20 × 20 cm, with 2 seedlings per hill.

Plant data collected include percentage of germination in the seedbed, seedling vigour before transplanting, seedling vigour 15 days after transplanting, cold tolerance at vegetative stage, yield, phenotypic acceptability, plant height and days to flowering. The average minimum and maximum temperatures for each month of the growing season are also recorded.

In IRBON, the time of occurrence and duration of low air temperatures at seedling to early vegetative stages differ from site to site. Some genetic materials tolerant of low temperatures at one site may not be tolerant at other sites. In general, the mean monthly air temperatures range from 12°–18°C at the early vegetative stage. Test entries with wide adaptation in the 1996 and 1997 IRBON (INGER 1998, 1999a) are given in Table 5. The top cold-tolerant lines had good seedling vigour and seedling recovery. Although the top entries for high yield were different from those for cold tolerance, their levels of cold tolerance were also good.

International Rice Temperate Observational Nursery (IRTON)

This yield nursery is the newest, having been established in 2000. It has 88 genetically diverse entries, contributed by 14 countries, IRRI and the Centre de Cooperation Internationale en Recherche Agronomique pour le Developpement (CIRAD). IRTON has three international checks: IR50 (very early maturing), IR72 (early maturing) and PSBRC 2 (intermediate maturing). Collaborators enter their best early and intermediate-maturing local varieties. Field design is similar to that of IRBON.

One of IRTON's objectives is to identify temperate rice lines that are adapted to tropical conditions, thus IRTON is being conducted under both temperate and tropical conditions. Countries currently conducting IRTON are Bhutan, India, Sri Lanka, Nepal, Pakistan, Vietnam, Philippines, North Korea, South Korea, China, Egypt, Iran, Turkmenistan and Italy.

Information exchange

Every year, INGER sends collaborators and interested parties nursery reports containing information on the pedigrees of test entries, their origins and grain characteristics (analyses done at IRRI), and the results of trials across environments. Collaborators with limited resources for testing often make seed requests

Table 5. Selected entries in the 1996 and 1997 IRBON.[a]

Year	Criteria			
	Cold tolerance, seedling vigour		Yield	
	Entry	Origin[b]	Entry	Origin[b]
1996	CR544-1-7	India	IR56381-155-1-2-2	IRRI
	IR59471-2B-20-2-1	IRRI	IR61009-37-2-1-2	IRRI
	IR58614-B-B-2-2	IRRI	IR61009-47-3-1-1	IRRI
	IR56394-70-1-2-2	IRRI	IR25924-51-2-3	IRRI
	IR61355-3B-11-2	IRRI	IR57259-9-2-1-3	IRRI
	IR72	IRRI		
1997	Gautam	India	BR1711-7-2-4-2	Bangladesh
	IR57257-34-1-2-1	IRRI	IR57080-2B-12-2-2-1	IRRI
	Nanjing 14	China	IR61336-4B-14-3	IRRI
	OM 987-1	Vietnam	NR11	Vietnam
	PSBRC 4	IRRI	RP2439-1195-623	India
			Zhi 20-5	China

[a] IRBON = International Rice Boro Observational Nursery.
[b] IRRI = International Rice Research Institute.
Sources: INGER (1998, 1999a).

based on the information provided by the INGER annual reports.

The flow of genetic information relating to INGER materials is as important as the flow of germplasm. Advances in information technology and availability of powerful database management tools offer exciting new approaches for information exchange among INGER partners. INGER data are managed through the INGER Information System, which is integrated with the International Rice Information System (IRIS), a database system for handling genealogical, characterization and evaluation data on rice germplasm and variety improvement. The IRIS's genealogical management system can be used to quickly generate genetic information for a particular variety such as full or partial pedigree, ancestral landraces and their specific genetic contributions, cytoplasmic source and degree of relationship (coefficient of parentage) with other varieties. Parental selection, variety development, and varietal release will be strengthened with the use of a comprehensive information system on rice genotypes.

References

INGER. 1994. Final report of the eighteenth International Rice Cold Tolerance Screening Nursery (18th IRCTN), 1993. Manila, Philippines, International Rice Research Institute (IRRI), 41 p.

INGER. 1996. Final report of the nineteenth International Rice Cold Tolerance Nursery (19th IRCTN), 1995. Manila, Philippines, International Rice Research Institute (IRRI), 57 p.

INGER. 1998. Summary report of the third International Rice Boro Observational Nursery (3rd IRBON), 1996. In: Summary Report of the 1996 INGER Nurseries. Manila, Philippines, International Rice Research Institute (IRRI), 57–69.

INGER. 1999a. Final report of the fourth International Rice Boro Observational Nursery (4th IRBON), 1997. Manila, Philippines, International Rice Research Institute (IRRI), 27 p.

INGER. 1999b. Final report of the twentieth International Rice Cold Tolerance Screening Nursery (20th IRCTN), 1997. Manila, Philippines, International Rice Research Institute (IRRI), 43 p.

Improving the Efficiency and Sustainability of Fertilizer Use in Drought- and Submergence-Prone Rainfed Lowlands in South-East Asia

R.W. Bell[1,*], C. Ros[2] and V. Seng[2]

Abstract

In the rainfed lowlands of South-East Asia, rice yields are low and often respond weakly to fertilizers. Studies of soils in Cambodia and North-East Thailand suggest that a complex combination of factors restrict rice yield and nutrient uptake in response to loss of soil-water saturation. Two significant and closely linked constraints are variable rainfall and lack of soil nutrients. Intermittent flooding and drying of soils depresses availability of some nutrients, even when water supply is adequate. Moreover, extreme fluctuations in soil-water levels may impair root activity, further restricting nutrient uptake. The resulting inefficient uptake apparently leads to weak responses to fertilizer nitrogen and phosphorus. Developing management strategies for optimizing the mineral nutrition of rice in drought-prone rainfed lowlands, particularly in the presence of aluminium toxicity and potassium deficiency, thus depends on understanding the function of rice roots in nutrient uptake and their response to temporal and spatial variation in water content and soil properties. This need is particularly relevant for the adoption of direct sowing of rice, which results in a root system developing initially in aerobic conditions, then being exposed to flooded conditions and, during the growing season, returning to aerobic and, in extreme cases, to drought conditions. With the potential increase of fertilizer use in the future, and thus potential pollution of groundwater and eutrophication of water bodies, new management strategies also need to assess risks of such contamination and seek ways of preventing it.

RAINFED lowland rice is grown in a wide diversity of environments, most of which are located in South and South-East Asia (Wade et al. 1999). From the perspective of crop nutrition and rice productivity, the main distinguishing characteristics of the rainfed lowlands are lack of irrigation water and non-continuous flooding of soil during crop growth (Zeigler and Puckridge 1995). While rainfed lowland rice is usually grown in relatively level, bunded fields to retain surface water, the depth and duration of field flooding vary greatly from year to year, within a growing season and spatially over relatively short distances within a field. Rainfed lowland rice is often exposed to an extremely variable water regime during growth.

Yields in rainfed lowlands are typically half those in irrigated rice ecosystems (Wade et al. 1999). The amount and timing of rainfall is considered as the major constraint to rice productivity, followed by low soil fertility, as represented by a range of limiting factors, including salinity, alkalinity, Fe toxicity, sulfide toxicity, N, P, K, and Zn deficiencies, and organic and acid sulfate conditions. The lack of soil fertility is exacerbated by the effects of a changing soil-water regime on nutrient forms and their availability in the soil. Low rates of fertilizer or, as is often the case, no fertilizer, mean that many of these constraints continue limiting rice production in farmers' fields.

KEYWORDS: Fertilizer, Loss of soil water saturation, Nutrient availability, Deficiency, Nutrient uptake, Root function

---

[1] School of Environmental Science, Murdoch University, Western Australia

[2] Soil and Water Program, Cambodian Agricultural Research and Development Institute (CARDI), Phnom Penh, Cambodia

*Corresponding author:
E-mail: rbell@central.murdoch.edu.au

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Within the rainfed lowland ecosystem, several subecosystems have been recognized, based on the maximum depth of water accumulating in the fields. Within areas where water depth is <25 cm, a further subdivision is made according to the prevalence of drought and/or submergence during the growing season (Table 1). In each country of South and South-East Asia, most of the subecosystems are represented, but the mix differs so that the main issues for soil fertility management (and breeding) also differ in emphasis from country to country.

About 20% of rainfed lowland rice grows in favourable environments where only minor events of drought or submergence limit rice production. These areas are relatively more prevalent in Indonesia, Philippines, Vietnam, Laos and Myanmar. In contrast, more than half of the rainfed lowlands of India and Thailand occur in drought-prone environments. The drought-prone environments of North-East Thailand (and Cambodia and Laos) differ from those in India because, while the rainy period is long, rainfall has an overall bimodal distribution and, in any given season, is erratic in amount and distribution. In contrast, the drought-prone areas of north-east India are characterized by a short growing season with an end-of-season drought being common. In Cambodia, more than half of the rainfed lowlands are on lands that are susceptible to both drought and submergence, either in different years or possibly the same year. Submergence is a widespread constraint for rainfed lowland rice, particularly in Vietnam, Myanmar and Bangladesh. Medium to deep water levels are most prevalent in the rainfed lowlands of Myanmar, Indonesia, the Philippines and Bangladesh.

In this paper, we focus on the less favourable subecosystems of the rainfed lowlands in South-East Asia and hence emphasize the soil and environmental constraints to efficient and sustainable fertilizer use in Cambodia, Laos and Thailand. Generally, in these areas, only one rice crop is grown per year. A long dry season follows the rice harvest and soils remain dry for several months of the year, with limited plant growth occurring. In Thailand and Cambodia, an early monsoon season from May to June is followed by a short dry period in June–July before the main rainy season (Fukai et al. 1995). Transplanting is often delayed until there is sufficient rainfall at the start of the main rainy season for flooding of the soil to occur.

Soils

Nutrients

The soils of the rainfed lowlands of South-East Asia usually have low levels of nutrients, especially of N and P and, to a lesser extent, K and S. This is especially so in Cambodia (White et al. 1997; Pheav et al. 1996), Laos (Linquist et al. 1998) and North-East Thailand (Ragland and Boonpukdee 1987). Indeed, given the low rates of fertilizer applied by farmers, the relatively low rice yields in rainfed lowlands of each of these countries can be attributed largely to low soil fertility. In Cambodia, rainfed lowland rice will respond to N on virtually all soils, including even the old marine floodplain soils that receive annual depositions of alluvial sediment, and are inherently more fertile than other rainfed rice soils of Cambodia (Table 2). Similarly, all the soils, except the old marine floodplain soils, are low in P and yield responses to P application on rainfed rice are expected. Many of the soils are low in K, and responses to this nutrient have been reported, especially when the supply of N and P is improved by fertilizer application. Other deficiencies, including S,

Table 1. Relative occurrence (as percentage of total area) of the main rainfed lowland rice subecosystems in South and South-East Asia.

Country	Shallow (0–25 cm) and prone to:				Medium to deep (25–50 cm)	Total area ('000 ha)
	No water stress	Drought	Drought + submerg.	Submergence		
Indonesia	58	10	0	9	23	1 404
Philippines	51	16	4	9	20	1 510
Myanmar	41	10	0	26	23	2 990
Vietnam	38	19	0	32	11	1 744
Laos	33	33	33	0	0	277
Bangladesh	16	16	19	30	19	5 328
India	12	51	15	10	13	14 530
Cambodia	10	29	57	0	5	747
Thailand	9	52	24	12	3	6 039
Total	20	36	15	16	13	35 907

Source: Wade et al. (1999).

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Mg and B, have been diagnosed in pot experiments (Pheav et al. 1996), but only S deficiency has been demonstrated in the field (CIAP 1995).

Low soil pH is prevalent in lowland soils used for rainfed rice in Cambodia, but the consequence of this for rice production is still unclear. In their oxidized state, pH ($CaCl_2$) is as low as 3.9, and Al saturation 70% (Seng et al. 1996). However, flooding induces relatively rapid increases in soil pH to values in the range of 5.5 to 6.0 after 2–3 weeks (Seng et al. 1996, 1999). At these pH values, no KCl-extractable Al can be detected; hence, Al toxicity for rice in flooded soils can be ruled out (Seng 2000). However, as discussed below, the consequences of temporary loss of soil-water saturation for soluble Al levels in the soil and for rice nutrition and water uptake are still unclear.

Many of the same nutrient constraints for rainfed lowland rice production found in Cambodian soils are shared with soils of North-East Thailand. The often extremely sandy nature of the latter soils (clay contents of <5%; Kawaguchi and Kyuma 1977; Mitsuchi et al. 1986; Willett and Intrawech 1988) is attributed to ferrolysis, which leads to the destruction and leaching of clays. In their oxidized state, the sandy soils are acidic with a pH (H_2O) between 4.6 and 5.0. Despite low levels of N, P, K and S, response to inorganic fertilizer is poor (Ragland and Boonpukdee 1987; Pairoj et al. 1996). These conclusions are further supported by a recent international study by Wade et al. (1999), who found that yields of rainfed lowland rice at sites in North-East Thailand were generally lower than at other sites in Bangladesh, Indonesia, India and the Philippines. In addition, in Thai soils, responses to N–P–K or complete fertilizer were generally weaker than in other sites.

In Laos, 85% of rainfed lowland rice crops in the northern region and 100% of those in the central and southern regions responded to N–P–K fertilizer (Linquist et al. 1998). Nitrogen deficiency was the most prevalent, with 40%–50% of crops responding to N alone and another 30% when P also was applied. Some evidence suggests a S deficiency for rice in Laos, and leaf analysis suggest that Mg levels may also be too low for rice.

Physical properties

Soil physical properties have a significant bearing on soil-water storage and retention, nutrient storage and leaching, the timing and ease of cultivation of soils and root growth. Soils that have been under lowland rice cultivation for several years develop a compacted layer at a depth of 10–40 cm in their profile (Samson and Wade 1998). The layer aids in retaining rainwater but may also restrict root penetration. In North-East Thailand, Laos and Cambodia, at least half of the lowland rice soils are sandy, either throughout the profile or in the surface layers (White et al. 1997; Linquist et al. 1998). This, coupled with the shallow plough pan and the rice crop's shallow root system, limits water storage and retention in the root zone. Even the presence of a conventional plough pan on coarse sandy soils is not sufficient to retain water for long after the rain stops. Sharma (1992) reported that water stress is evident in rice on sandy soils from North-East Thailand within 1 week after the rains cease.

However, when a significant amount of water in the profile is stored below the plough pan, mechanical impedance in the compacted layer may restrict root access to the stored water. Ahmed et al. (1996) found that increasing root mass density in the 10–20 cm layer of rainfed lowland soils of north-west Bangladesh increased rice yields (Table 3). Deep cultivation to 20 cm or growing a deep-rooted crop like the legume *Sesbania aculeata* before rice both decreased penetration resistance in the 10–20 cm layer and increased rice yields by 0.5–1.0 t ha^{-1}.

Deep sandy soils in North-East Thailand and Cambodia pose particular problems with water retention that not even the conventional plough pan can

Table 2. Chemical properties of the main soils used for cultivating rainfed lowland rice, Cambodia.

Property	Deep sandy soils	Shallow sand lying over clays	Depression soils	Black soils of rainfed lowlands	Brown plain soils	Old marine and lacustrine floodplain soils
Percentage of shallow-water rainfed rice crop	13	30	13	5	15	21
pH (1:1 soil:water)	5.6	5.9	5.8	5.1	5.5	5.9
Olsen P (mg kg^{-1})	1.3	0.4	1.0	2.6	3.1	4.6
Total N (mg g^{-1})	0.5	0.3	0.6	1.1	0.9	1.0
CEC (cmol(+) kg^{-1})	1.8	1.3	6.3	6.7	18.2	13.5
Exch. K (cmol(+) kg^{-1})	0.02	0.03	0.07	0.06	0.16	0.19
Organic C (mg g^{-1})	4.7	2.9	6.6	10.9	8.8	9.1

Source: White et al. (1997).

overcome. The rapid percolation of water through these soils means that they can lose saturation quickly after rainfall ceases. Garrity and Vejpas (1986) showed that an impermeable plastic sheet installed at 40 cm deep in a sandy lowland soil at Ubon Ratchathani, North-East Thailand, prevented water percolation loss and increased rice yields. Subsoil compaction on the same soil type was also effective in reducing percolation losses of water by 88%, and decreased from 60 to 17 the number of days when loss of soil-water saturation occurred, thus increasing yields by 60%–90% (Sharma et al. 1995).

Table 3. Effect of tillage depth on penetration resistance of soils, root mass density and grain yield of rice in a rainfed lowland soil, north-west Bangladesh.

Parameter	Tillage depth			
	6–8 cm	12–15 cm	18–20 cm	6–8 cm with *Sesbania* as pre-rice crop
Penetration resistance (MPa)				
0–10 cm	1.25	1.00	0.75	0.6
10–20 cm	2.20	1.25	1.25	1.1
Root mass density (kg m^{-3} at flowering)				
0–10 cm	3.73	3.75	3.57	3.84
10–20 cm	0.07	0.15	0.19	0.18
Grain yield (t ha^{-1})				
	3.9	4.3	4.5	4.5

Source: Ahmed et al. (1996).

Hard-setting behaviour of sandy rainfed lowland rice soils of Cambodia and North-East Thailand is a significant factor limiting land preparation for transplanting. When dry, the soils hard set and therefore become difficult to cultivate with draught animals. Within a few hours after cultivation, the soils again achieve high soil strength as the sand and silt grains consolidate, making transplanting difficult. Generally, farmers cultivate only as much land as can be transplanted within the hours following. The consequences of the hard-setting behaviour of these sandy soils for root growth and activity are unknown.

Nutrient–water interactions

Fluctuating water regimes comprise the defining characteristic of rainfed lowlands. Loss of soil-water saturation may occur at any time from transplanting onwards and for periods of up to several weeks at a time. Generally, rainfed lowland rice soils will be saturated and flooded at transplanting because, if possible, farmers delay transplanting until there is sufficient water to facilitate transplanting, and to maximize plant survival. An example from Seng et al. (1996) illustrates the variability of the soil-water regime for a rainfed lowland rice crop. In the 6 weeks after transplanting, soils lost saturation at the surface during three periods, each of about 4–7 days (Figure 1) and coinciding with maximum tillering. Thereafter, for 6 weeks, rainfall was adequate to maintain a water level above the soil surface, but for the remainder of the growing season, including panicle initiation, the soil was again exposed to intermittent loss of soil-water saturation. Surprisingly, relatively few studies report on the depth of the perched water table during the growing season so that the effects of loss of soil-water saturation on nutrient availability are poorly defined when comparing experimental results among sites and seasons. Installation and monitoring of observation bores in experimental plots are relatively simple and may add value to many experiments on fertilizer response in the rainfed lowlands.

Flooding has mostly beneficial effects on the availability of nutrients and their uptake by rice (Ponnamperuma 1972). Flooding, by increasing pH and P availability and decreasing levels of soluble Al, particularly and significantly benefits growth and nutrient uptake of rice growing on sandy, acidic, low-fertility, rainfed lowland soils (Ponnamperuma 1972; Willett and Intrawech 1988).

Flooding also has possible negative consequences, including increased levels of Fe^{2+} in some soils, loss of $NO_3 - N$, sulfide toxicity, organic acid toxicity and Zn deficiency. Symptoms of iron toxicity have been reported in rice on some soils of Cambodia but the yield losses associated with this disorder were not quantified (White et al. 1997). Application of S-containing fertilizers to sandy soils in Cambodia and North-East Thailand have been reported to cause toxicity by sulfides forming under flooded conditions, especially when soils are also supplied with organic manures (Willett and Intrawech 1988; White et al. 1997). The management of N under flooded conditions is different from that on oxidized soils. Under flooded conditions, NO_3 is subject to losses by leaching, except if an impermeable hardpan exists, and by denitrification in the reduced layers of flooded soils. Thus, NO_3 present in soils at flooding may be lost, whereas $NH_4 - N$ supplied and incorporated into the flooded soil or released by mineralization of organic matter is relatively stable.

When flooded soils lose saturation, re-oxidation reverses the beneficial changes that occurred during flooding. Several studies have examined the effects of draining a previously flooded soil on nutrient forms and availability for upland crops grown after rice (Willett and Higgins 1980; Sah and Mikkelsen 1986).

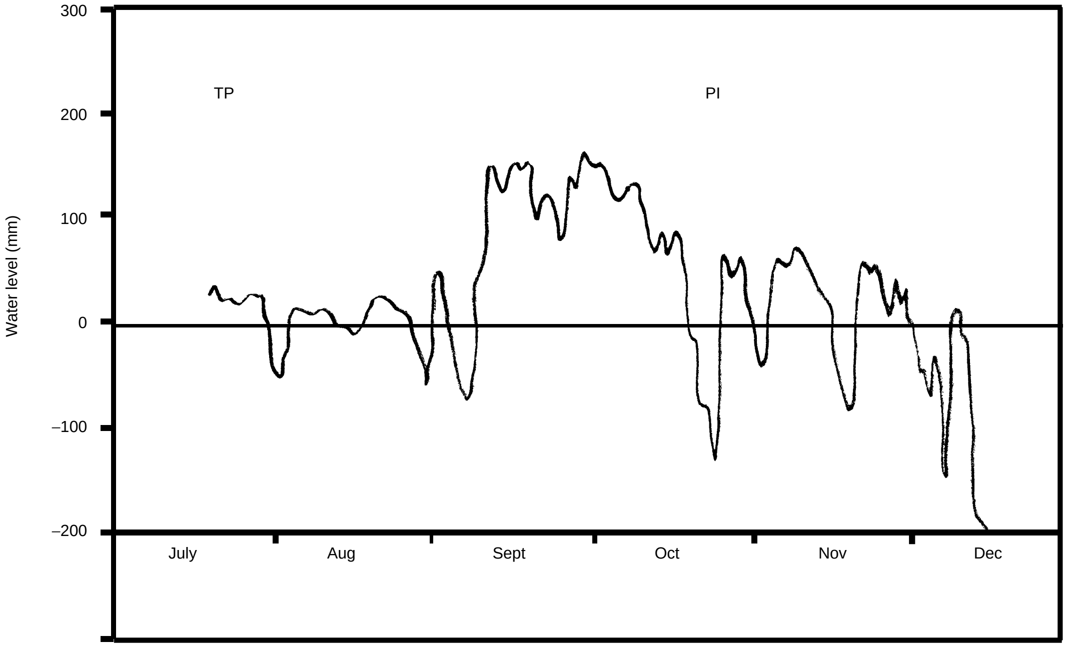


Figure 1. Perched water levels (mm) in relation to the soil surface (at 0) in a rainfed lowland rice field, south-eastern Cambodia. TP = transplanting; PI = panicle initiation. (After Seng et al 1996.)

On acid soils, pH drops and soluble Al re-appears. Oxidation of Fe^{2+} after drainage of flooded soil removes the risk of Fe toxicity, but generates amorphous Fe oxides that react with available forms of P to decrease P availability. Ammonium N oxidizes readily to NO_3. These changes in nutrient availability obviously are important considerations for nutrient supply to upland crops grown after rice. Typically, upland crops require more P after a flooded rice crop than after upland rice (Brandon and Mikkelson 1979). This fact has implications for the growing dry-season crops after rice, using stored soil water.

In the rainfed lowlands, the water regime is more complex and dynamic than the above cases where soils planted to irrigated rice are drained after harvest and planted to upland crops. Significant periods of loss of soil-water saturation occur intermittently throughout the growing season (e.g. Seng et al. 1996; Trebuil et al. 1998). The implications of the temporary periods of loss of soil-water saturation for nutrient availability are not fully understood, although growth may be depressed as nutrient availability decreases (Fukai et al. 1999). Laboratory studies show that intermittent flooding of soils results in a significant loss of soil N (Patrick and Wyatt 1964). Oxidation of NH_4 to NO_3 occurs during loss of soil-water saturation, and the NO_3 is then subject to leaching as the soil water drains below the root zone, and to denitrification once re-flooding of the soil occurs. In rainfed lowlands, where loss of soil-water saturation may occur on several occasions during the critical early growth stages, including tillering and panicle initiation (Figure 1), significant losses of N are expected to occur.

Seng et al. (1999) tested the effect of a 3-week period of loss of soil-water saturation on P uptake by rice in a pot experiment with two acid rainfed lowland soils from south-eastern Cambodia. They found that temporary loss of soil-water saturation led to decreased P uptake and shoot dry matter, whether with and without P fertilizer application. The decreases were attributed to the decreased availability of P during the period of loss of soil-water saturation. Subsequent field experiments on the same soil also suggested that the period of loss of soil-water saturation also depressed P uptake by rice (Seng 2000). However, Willett and Intrawech (1988) and Seng (2000) suggested that the increase in soluble Al following re-oxidation of the soil was a possible additional factor limiting P uptake during periods of loss of soil-water saturation.

Improving the Efficiency of Fertilizer Use

The weak responses of rainfed lowland rice to fertilizers, despite low soil fertility, suggest that the efficiency of fertilizer use can be increased, but taking into account not only soil factors limiting nutrient uptake but also plant factors.

Root biology

Rice roots can greatly modify their rhizosphere and in doing so, improve the availability of nutrients for uptake. However, optimal benefit from these root characteristics can only be captured if the roots are able to access the pools of water and nutrients available in the soil by appropriate root exploration. Limitations on root exploration are a function of both the genetics of a cultivar that determine the structure of the root system and its distribution in the soil, as well as soil physical and chemical factors that limit root growth. Developing management strategies to optimize mineral nutrition of rice in drought- and submergence-prone rainfed lowlands depends on understanding the function of rice roots in nutrient and water uptake and their response to temporal and spatial variation in water content and to soil physical and chemical properties.

Extreme fluctuations in soil-water levels may impair root activity, thus restricting nutrient uptake either temporarily or in the longer term. However, the function of the root system in nutrient uptake under changed water regimes is not well understood (Samson and Wade 1998). The dynamic nature of the soil-water regimes in rainfed lowlands may also mean that there is a distinct advantage in roots having a rapid and plastic response to changing water supply and redox potential.

Lowland rice has an unusually shallow root system. Generally, 70% or more of the roots are in the 0–10 cm layer, 90% in the 0–20 cm layer, and very few roots penetrate below 40 cm (Sharma et al. 1994; Figure 2). In contrast, upland rice can have rooting depths between 70 and 80 cm (Morita and Abe 1996). The shallow rooting behaviour of lowland rice is clearly controlled partly by genetics and partly by the soil's physical and chemical properties. Sharma et al. (1994) suggest that lowland rice cultivars show genotypic differences for root length density, although no differences were found among three cultivars for depth of maximum root penetration.

Sharma et al. (1994) also compared three cultivars, KDML 105, RD6 and IR46, at three sites representing high and low topographical positions, and clay and loamy sand textures. Measurable differences in root length density among the cultivars were most consistently found in the 10–30 cm layer. Cultivar differences in root length density were most obvious in the loamy sand and less so in the clay soil. Somewhat surprisingly, root density was greater in the 0–10 cm layer in the high fields, where the perched water table was below the soil surface for most of the season, than in the low fields where the soil surface was flooded. Unfortunately, the effects of root length density on nutrient uptake were not examined, although anoxic conditions can markedly alter nutrient availability in the rhizosphere.

To grow under anoxic conditions, rice roots carry O_2 to respiring tissues through longitudinal gas channels (known as aerenchyma) found in the cortex. Aerenchyma development and O_2 flux to root tips increase in response to anoxic conditions (Colmer et al. 1998). Oxygen may leak along the root axis, with excess leaking occurring from the older basal roots, thus limiting the amount of O_2 that can be delivered to the root tips. Hence, under flooded conditions, the depth of root growth may be limited by the amount of O_2 that can be delivered to the root tips. Cultivar selection for decreased O_2 leakage from basal roots under anoxic conditions may be advantageous.

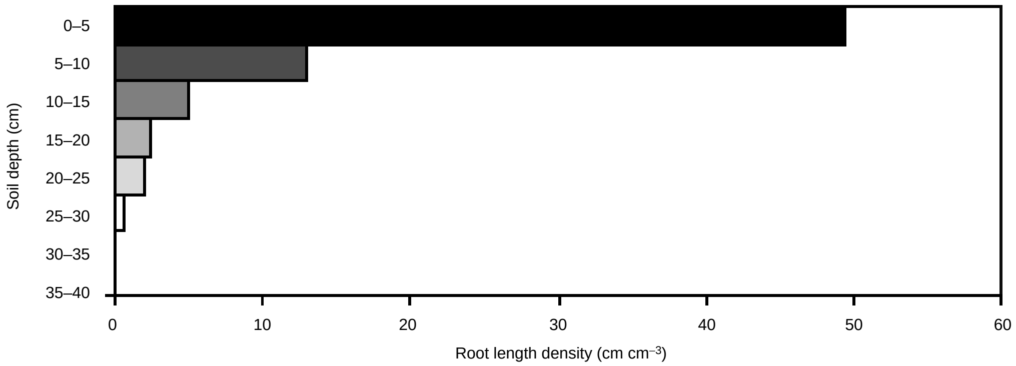


Figure 2. Decrease, with soil depth, in root length density of rice at heading, in a rainfed lowland soil. (After Samson and Wade 1998.)

Colmer et al. (1998) suggested that cultivars differ in the degree of aerenchyma development. They found two lowland cultivars that responded to stagnant anoxic solutions by decreasing O_2 leakage to negligible levels at 20–25 mm from root tips. In contrast, neither of the two upland cultivars showed any decline in O_2 leakage along the root axis in response to anoxic conditions. However, even if O_2 leakage in basal roots can be decreased, Kirk and Du (1997) showed that a significant proportion of O_2 leakage also occurred from fine lateral roots, and that these roots can proliferate from basal as well as apical parts of the root axis.

Kirk and Du (1997) also reported that P deficiency increased both root porosity and the rate of O_2 released per plant into the rhizosphere. Releasing O_2 into the rhizosphere is beneficial under anoxic conditions because it oxidizes Fe^{2+} and causes the soil pH of the rhizosphere to decline by 1 or 2 units. The excess uptake of cations relative to anions by rice under anoxic conditions also contributes to rhizosphere acidification. Collectively, these mechanisms increase P availability to rice because, in the acid rhizosphere, extractable-P levels increase. Rhizosphere acidification also appears to increase Zn uptake, but decreases uptake of $NH_4 - N$ and K (Kirk et al. 1994).

While root nutrient and water uptake processes under oxic or anoxic conditions is reasonably well understood, very little is known about how nutrient and water uptake by rice roots responds to a changing soil-water regime. In rainfed lowlands, roots may be exposed for most of the growing season to anoxic conditions, interspersed with periods of loss of soil-water saturation. Alternatively, the roots may be mostly exposed to oxic conditions with periods of anoxia. The transition from oxic to anoxic conditions appears to result in increased root porosity in only some cultivars (Colmer et al. 1998). Whether adaptive responses in root structure or physiology occur as conditions change from anoxic to oxic is unclear. Neither is it clear whether roots adapted to anoxic conditions effectively absorb nutrients and water when exposed to oxic conditions. Response to loss of soil-water saturation may require rapid initiation and growth of new roots adapted to these conditions. The dynamics of root response and the functional efficiency of roots for nutrient and water uptake under changing soil-water regimes require further research.

The problems of root adaptation to changing soil-water regimes are compounded in direct seeding. The roots of direct-seeded rice initially develop under oxidized conditions, are then exposed to anoxic conditions and, during the growing season, return to oxic conditions, which, in extreme cases, can mean drought. Fertilizer rates and methods of application developed for transplanted rice may have to be re-examined for direct-seeded rice. Detailed studies of root biology and physiology during the various transitions between oxic and anoxic soil conditions are needed to develop a rational basis for modifying existing fertilizer recommendations for direct-seeded rice crops.

Cultivars

Breeding for nutrient efficiency and adaptation to the variable growing environments of rainfed lowlands may be a cost-effective approach towards making a major impact on the productivity of drought- and submergence-prone rainfed lowlands, provided traits associated with efficiency in that environment can be identified. Ample evidence exists of variation in nutrient efficiency among rice germplasm in low-fertility rainfed lowlands in Laos and Thailand (Fukai et al. 1999). However, selection of germplasm for such conditions is difficult (Cooper et al. 1999), as is the management of water use and nutrient availability. Fortunately, nutrient efficiency appears to be expressed whether plants are grown with or without fertilizer application, thus simplifying the task of selecting because only one nutrient regime needs to be tested rather than two.

The results of field-screening studies for adaptation to low-fertility soils of the rainfed lowlands in Laos suggest that internal efficiency is a genetically determined trait that, overall, is consistent across environments (Fukai et al. 1999). Low nutrient concentration in the plant and higher nutrient allocation to grain were identified as potential selection criteria for nutrient-use efficiency.

Soil physical properties

Shallow rooting depth is a major constraint to productivity for rainfed lowland rice. Alleviating soil physical constraints to root penetration may therefore increase rice productivity by increasing access to stored water and nutrients in the deeper layers of the soil profile. If roots can penetrate the shallow plough pan, then rice crops can extract significant amounts of N from below 20 cm (Ventura and Watanabe 1984). Kundu and Ladha (1999) reported that deep cultivation increases rice yields. In Korea, increasing cultivation depth from 14 to 19 cm increased root depth from 27 to 36 cm and rice yield from 4.5 to 8.1 t ha^{-1}. Increasing cultivation depth from 15 to 40 cm on a soil with a hardpan at 15 cm increased both N uptake and grain yield (Kundu et al. 1996). The scope for increasing cultivation depth with draught animals is of course limited. In Cambodia, a pair of working animals can achieve a cultivation depth of 7–10 cm (Rickman et al. 1997). However, increasing availability of tractors for primary cultivation is making deeper cultivation possible on rainfed lowland soils with shallow hardpans. In 1996, for example, about 12% of primary cultivation in Cambodia was by tractor (Rickman et al. 1997).

In contrast to the above, studies at Ubon Ratchathani, North-East Thailand, suggested that subsoil compaction of deep sandy soils helps increase grain yield (Trebuil et al. 1998). Compaction in the 10–80 cm layer of soil was achieved by 10 passes with a 12-t vibrating roller. On such deep sandy soils, percolation is so rapid that the soil drains very quickly after rain. The primary benefit of compacting this deep sandy soil was to decrease saturated hydraulic conductivity from 38 to 12 cm day^{-1} and to increase the duration of surface flooding of soils from 1 to 9 weeks. However, even on these deep sandy soils, the importance of deep root penetration was still evident. Deep cultivation to 20 cm following compaction increased yields relative to shallow cultivation (7–10 cm) of the compacted profile.

However, apart from the practical consideration of how to achieve subsoil compaction at a reasonable cost to small farmers, the benefits were season dependent. In a season where water supply was adequate throughout, crops failed to respond to subsoil compaction + conventional fertilizer rates, requiring higher nutrient supply to benefit fully from the improved water retention (Trebuil et al. 1998). The decrease in percolation rates with subsoil compaction was insufficient to retain water in the soil profile after the rice harvest, hence providing no opportunity for growing a post-dry-season rice crop on the residual moisture.

Soil water–nutrient interactions

Nutrient losses from the root zone and decreases in availability of nutrients to rice roots are the two key processes that need to be managed if fertilizer-use efficiency is to be increased in rainfed lowlands.

Nitrogen

Considerable scope exists for decreasing N losses. Nitrate N that accumulates during the dry season may be substantially lost during early season rains, even before the rice is transplanted (Kundu and Ladha 1999). On deep sandy soils with high percolation rates, leaching losses are difficult to prevent with conventional practices. One strategy is to grow pre-rice crops in the early rainy season to capture $NO_3 - N$ and recycle it for the rice crop as organically bound N. The N mineralizes and is supplied as $NH_4 - N$ to the rice (George et al. 1994). Pulse crops like mung beans that mature in 65 days can be planted in May and harvested before the main rainy season in July–August. However, in many parts of Cambodia, crops grown during the early rainy season were unsuccessful because of temporary flooding of soils.

Sesbania, in contrast, tolerates waterlogging and, in 45–60 days, produces 1–18 t of aboveground fresh biomass per hectare (CIAP 1994). Incorporating sesbania into the soil before transplanting rice increased rice yield by 40% in on-farm trials in Cambodia (Nesbitt 1997). The benefits are usually attributed to improved N supply for rice from N_2 fixation by sesbania. However, the capture and recycling of accumulated soil $NO_3 - N$ may also be a significant benefit of growing sesbania during the early rainy season, because the amount of N_2 fixation is usually related to soil N supply. If the supply is high, then N_2 fixation is typically low and vice versa (George et al. 1994).

A second strategy, carried out in most of Cambodia, Laos and North-East Thailand, is to leave the soils fallow after the rice harvest. Animals usually graze the rice stubble during the dry season. In addition, volunteer weed and pasture plants may grow if residual soil water is sufficient, or in the early rainy season. P.F. White (pers. commun., 1999) noted that leguminous pasture species growing in the early rainy season increased in biomass, using residual P from fertilizer applied to rice. The N_2 fixed during the early wet season may therefore be a significant spin-off benefit to the farming system from P fertilizer application. Equally important may be the uptake by volunteer pasture species and weeds of NO_3 -N that accumulates in the soil during the dry season (George et al. 1994). Further research is needed to improve the management of the annual pasture-fallow period to increase nutrient availability to rice.

The third alternative for increasing the capture and recycling of $NO_3 - N$ accumulating in the soil after the dry season is to direct sowing rice during the early rainy season.

Phosphorus

If P uptake is restricted during growth, particularly at transplanting, loss of soil-water saturation may impair growth and final yield (De Datta et al. 1990; Seng et al. 1999; Seng 2000), although the relative sensitivity of yield to P deficiency at different stages of crop growth is poorly understood. Improved understanding would permit better tactical decisions on correction during the growing season. Options for minimizing the impact of periods of loss of soil-water saturation are either to use cultivars that are efficient in P uptake and use and presumably would be best able to cope with a temporary decline in P availability (Fukai et al. 1999); or to treat soil with straw (Seng et al. 1999). Straw keeps the redox potential lower during the period of soil-water

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

saturation loss, thus apparently decreasing the extent of Fe^{2+}oxidation and minimizing losses in P availability due to reaction with Fe oxides. Other forms of organic matter added to the soil at planting, including cow manure, or residues from pre-rice pulse crops or green manures like sesbania, can all help minimize losses of P during periods of soil-water saturation loss. The minimum amount of organic matter required to make a difference is not known, but Seng et al. (1999) had applied the equivalent of 5 t of straw per hectare.

Losses of P in leachate from lowland rice soils have not been adequately quantified, although Cho et al. (2000) estimate that 0.2 kg ha^{-1} of P are leached. On sandy soils, however, recent findings suggest higher rates of P leaching. Linquist et al. (2000) examined residual availability of P fertilizer on sandy lowland rice soils in Laos and found that 48% to 85% of the P was not used in the first crop, probably because of significant leaching of P through high percolation rates and low P sorption. Leaching of P has not usually been considered a significant issue for P nutrient management, but the prevalence of sandy lowland rice soils in North-East Thailand, Cambodia and Laos suggest that P leaching needs to be more thoroughly studied. The low residual effectiveness of P fertilizer due to P leaching suggests that annual P rates need to be matched with expected crop demand because any extra P would only exacerbate P losses. Alternatively, where available, rock phosphate could be used to minimize P leaching. In Cambodia, local rock phosphate is a potentially effective source of P for rainfed lowland rice (White et al. 1999) but, until the marketed product shows consistent quality, its use is not recommended (CIAP 1999).

Acidity

Aluminium toxicity has generally been ruled out as a significant limiting factor for rice under flooded conditions. However, several possible consequences of Al toxicity during temporary loss of soil-water saturation may warrant further attention to acid soils of rainfed lowlands (Willett and Intrawech 1988; Seng 2000). One consequence is to directly inhibit root elongation, thus limiting plants' capacity to access water stored deeper in the profile of a drying soil. A second consequence is, by limiting root extension, the uptake of nutrients, especially P, would also be limited. Finally, soluble Al may react with P, thus decreasing the availability of soil P for uptake by roots.

Nursery fertilizer use

In Cambodia, farmers in the rainfed lowlands often apply fertilizer and manures to the seedling nursery rather than to the main fields (Lando and Mak 1994; Ros et al. 1998). On the low-fertility soils of Cambodia, fertilizer applied to both nursery and main fields increased rice yield (Ros 1998; CIAP 1998). Fertilizer applied to the nursery increased seedling vigour, which generally increased subsequent rice yields by 5%–10%, regardless of whether the main field was treated with fertilizer or not. Cow manure at 3 t ha^{-1} and inorganic fertilizer at 50 kg N ha^{-1} and 22 kg P ha^{-1} were recommended for increasing seedling vigour (CIAP 1998).

Other low-cost strategies suggested by Ros et al. (1997, 2000) for increasing seedling vigour include seed coating with crushed rock phosphate and increasing seed P concentration in nursery-planted seed. The strategy adopted by Cambodian farmers of applying most of the fertilizer to the nursery was an efficient use of nutrients because applications to the main field could not replace the need for nursery fertilizer to produce vigorous seedlings.

Another P management strategy in the nursery phase, reported from India, is to dip seedlings in a P slurry before transplanting. This localizes P directly around roots and, in one study, improved P-use efficiency by 50% (Katyal 1978)

Managing the variability of a soil-water regime

Unevenness in the soil surface is a significant source of variability in a field's soil-water regime (CIAP 1997). Elevation differences between 7 and 33 cm are not uncommon in farmers' fields (CIAP 1997). These differences are sufficient to cause some parts of the field to experience intermittent loss of soil-water saturation during the growing season while other parts of the field are continuously flooded. Variation in surface elevation affects decisions on when to transplant, seedling survival after transplanting and weed control. In addition, such micro-variability aggravates the problem of efficiently managing nutrient supply and fertilizer applications to rainfed lowland rice. Laser levelling has been developed in Cambodia, leading to increases in rice yields between 400 and 1000 kg ha^{-1} in farmers' fields (CIAP 1996, 1997, 1998). While laser levelling may not be an option for poor lowland rice farmers, the research showed the benefits of level fields, suggesting the need for greater attention to manual levelling during land preparation.

Sustainability of Fertilizer Use

Cropping systems

Two major changes anticipated for the cropping systems found in rainfed lowland ecosystems will have a major bearing on the sustainability of fertilizer use. The first is the increasing adoption of direct sowing of rice across the rainfed lowland ecosystems as the reduced availability of labour makes transplanting a less attractive option. Direct-seeded rice is planted earlier, under essentially upland conditions, after the early rainy season. Subsequently, soils experience a variable soil-water regime, with periods of flooding interspersed with loss of soil-water saturation for intermittent intervals of variable duration. The variation in the soil-water regime under a direct-sowing system of crop establishment will require a re-examination of optimal methods and timing of fertilizer use, compared with establishment by transplanting. Secondly, the increased prevalence of dry-season cropping through direct sowing increases the intensity of crop production on these soils and, hence, the overall demand for nutrients and stored soil water. In areas other than rainfed lowlands, increased access to water for supplementary irrigation in the dry season permits the production of either a dry-season rice crop, or pulse or vegetable crops.

For rainfed lowland rice crops, the accumulation of nutrients, especially N, from the mineralization of organic matter during the long dry season represents a significant nutrient resource that needs to be managed. In areas such as Cambodia and North-East Thailand, where fields mostly lie fallow during the dry season, significant losses of $NO_3 - N$ may occur during the early rainy season, although no quantitative data exist on the likely rates. These soils are relatively low in organic matter, and mineralization may not be that high, compared with soils in Ilocos Norte (Philippines), where high rates of $NO_3 - N$ accumulate in the dry season. Furthermore, weeds often grow up during the early wet season before tillage, and are either grazed or incorporated during tillage. Hence, a significant proportion of $NO_3 - N$ may already be recycled in these rainfed lowland rice ecosystems. The same may be true for $SO_4 - S$ and K on sandy soils, but few data are available on this point.

In this environment, the most promising technologies for better using plant-available nutrients that accumulate during the dry season are planting a pre-rice crop or direct sowing rice early. In both cases, the aim is to encourage plant uptake of these nutrients to prevent their loss. In the case of a pre-rice crop, the mineralization of crop residues releases nutrients for rice at a time when the root system of the transplanted rice is capable of absorbing them. In the case of early direct-seeded rice, the nutrients absorbed are used directly for growth. In either case, appropriate adjustments in the rates of fertilizer applied at sowing and later will need to be worked out.

Nutrient budgets

Increasing concerns about the sustainability of the fertility status of rainfed lowland rice soils has prompted several studies on nutrient budgets. On a national scale, for example, Lefroy and Konboon (1998) estimated N–P–K budgets for Thailand and concluded that much more K was being exported from rice fields in harvested grain than was being replaced by fertilizer. In contrast, a positive balance was found for N and P, making the simple assumption that no other losses of nutrients occurred, except through harvested grain. Similarly, Lefroy and Konboon (1998) estimated nutrient budgets on regional and farm scales in North-East Thailand and concluded that N and P were, on the whole, positively balanced for rice production but that K was being depleted under the current cropping regime. Negative K balances were also reported for sandy soils in central Java (Indonesia; Wihardjaka et al. 1998). The removal of stubble from rice fields significantly depletes soil K. Few reports of S balances are available for rainfed lowlands. Low-S soils are relatively widespread in North-East Thailand, Cambodia and Laos and so depletion of soil S in harvested grain may significantly affect the productivity of rainfed lowland rice. However, S in rain may significantly offset losses through harvested grain (Lefroy and Hussain 1991).

The calculation of nutrient budgets as a tool for managing nutrient supply for rainfed lowland rice has considerable promise because of its relative simplicity, compared with alternative approaches such as soil and plant testing, and simulation modelling. However, Lefroy and Konboon (1998) pointed out that many of the assumptions underlying calculation of nutrient budgets need more rigorous support from field research.

Environmental consequences of fertilizer use

The application of fertilizer to rice has potential unintended consequences that are of increasing concern in many parts of the world (e.g. Mishama et al. 1999; Xing and Zhu 2000). Negative effects on the quality of surface and groundwater comprise the most common environmental impact (Shrestha and Ladha 1999). In rainfed lowlands with access to supplementary irrigation, dry-season cropping is becoming more common, especially where population density is high and increased output per unit area can be most readily achieved by dry-season cropping, using surplus labour (Pandey 1998). The environmental impact of these systems is under examination and may be a possible precursor of more widespread concern for agrochemical use in rainfed lowlands.

At present, fertilizer rates in rainfed lowlands are generally still low, leading Crosson (1995) to suggest that the negative environmental impact of fertilizer use on rice production is probably minimal. However, because nutrient deficiencies are prevalent and farmers are being advised to increase their fertilizer use and application rates, the possible future consequences of implementing these recommendations need to be considered. Villagers usually access stream water or shallow groundwater for domestic cleaning, cooking and drinking. Degraded quality of these water resources would be a matter of considerable concern for public health. In addition, artificial and natural wetlands in rainfed lowlands are often significant food resources for villagers. Loss of water quality in these wetlands likewise needs to be guarded against.

Because these problems generally do not exist yet in most rainfed lowland rice environments, now is an opportune time to set in place strategies to prevent it becoming a concern. Periodic monitoring of water quality and identifying areas in catchment basins that contribute most to nutrient enrichment of water bodies should be implemented.

Nitrogen accumulation in surface and groundwater has been reported as a consequence of fertilizer applications to irrigated-rice crops. Intensification of production in rainfed lowlands by growing dry-season vegetables, using supplementary irrigation, is also causing similar high losses of NO_3 -N through leaching into groundwater (Shrestra and Ladha 1999). In Ilocos Norte (Philippines), annual losses of up to 550 kg of N ha^{-1} were reported. In 50% of wells surveyed on farms practising the rice–sweet pepper rotation, nitrate concentrations exceeded the World Health Organization's (WHO) limits for drinking water. The high rates of N fertilizer use in these intensive production systems are driven by the high economic returns from dry-season vegetables and are not currently typical of the drought-prone and submergence-prone rainfed lowlands. However, even in Cambodia, installation of wells and pumps for dry-season cropping is spreading and may eventually lead to intensive production systems like those of Ilocos Norte.

In the irrigated-rice fields of central Korea, annual P losses in run-off were estimated to be 4.5 kg P ha^{-1} in water and 0.9 kg P ha^{-1} in sediments (Cho et al. 2000). Increasing P concentration in surface and groundwater also has potential environmental consequences. Most aquatic ecosystems are P limited, so that increases in P concentration in run-off water and groundwater can greatly increase the biological productivity of these systems. Eutrophied wetland systems may generate algal blooms that would harm fisheries by impeding movement of boats and killing fish—some algal species in blooms are potentially toxic.

Adoption of Improved Nutrient Management Strategies

Traditionally, rainfed lowland farmers use little fertilizer, probably to avert risks. Pandey (1998), for example, reported that rates of N–P–K fertilizer use across Asian countries correlate with percentages of rice crops irrigated. In Cambodia, farmers in irrigated areas have adopted modern methods of rice production to a much greater extent than those in rainfed lowlands. Surveys by Jahn et al. (1997) showed that only 1.2% of rainfed rice farmers grow IRRI varieties, representing only 0.9% of the rice-growing area. In terms of inorganic fertilizer use, only 27% of rainfed rice farmers use inorganic fertilizers, compared with 70% of dry-season rice farmers.

As discussed above, rainfed lowlands have several significant characteristics that distinguish them from irrigated rice-growing areas where significant gains in technology adoption and productivity have already been achieved. These are a high degree of spatial and temporal variability both in terms of soil type and water availability (Zeigler and Puckridge 1995); the soils often have poorer chemical and physical properties than soils in irrigated systems; and farmers in rainfed lowlands also have fewer resources for capital expenditure and limited access to credit than do farmers in irrigated systems (Zeigler and Puckridge 1995) and therefore their ability to invest in innovative technologies is limited. The range of options for improved management are consequently few; with a greater chance of crop failure. When crops fail, rainfed-rice farmers have fewer options to generate supplementary food or income. Risk avoidance, therefore, occupies a more important position in decision making for rainfed-rice farmers than it does for irrigated-rice farmers (Zeigler and Puckridge 1995). Once again, the range of technologies that rainfed lowland farmers are willing to adopt is further restricted.

Traditionally, fertilizer recommendations have been based on average responses for particular soils and ecosystems (Dobermann and White 1999). The high degree of spatial and temporal variation of soil conditions in the rainfed lowlands raises two questions: firstly, how useful are blanket recommendations and generalized advice on fertilizer and, secondly, how can site-specific nutrient management strategies be developed (Dobermann and White 1999). Current strategies need to be better targeted than were past strategies to specific environments that have relatively small recommendation domains (Pingali et al. 1998). Because many such recommendation domains exist in the variable rainfed lowlands, the cost of developing these strategies, using

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

normal empirical experimentation for each particular environment, is expensive and time consuming.

A major reason for this is the difficulty of identifying appropriate technologies that can feasibly be applied by a farmer, given his or her particular set of constraints and expectations. Predicting the magnitude of a response to management inputs for any given situation is therefore difficult unless prior knowledge exists for each individual circumstance. In an effort to solve this problem, emphasis in much of Asia is currently placed on improved characterization of the environment and development of mechanistic and empirical simulation models that will predict crop performance in a given environment (Zeigler and Puckridge 1995).

While simulation models can now make good predictions of crop yield (e.g. Alagarswamy and Virmani 1996), the process depends on data for calibrating the models. Such data are frequently not available in the many local environments of the rainfed lowlands because of limited research infrastructure and knowledge base. Indeed, even the simplest data sets, such as daily rainfall, that are needed for simulation models such as APSIM (McCown et al. 1996) are unavailable for many Cambodian environments. Furthermore, the crop simulation approach takes no account of the difficult-to-quantify farmer circumstances and other such constraints that significantly determine the adoption of improved technologies.

Management strategies, particularly for nutrient supply by fertilizer applications, must be flexible and capable of modification, depending on the progress of the season and/or the outcome of the previous season. Farmers need to maximize the advantage gained from a better-than-average season while also being able to minimize the risk and losses associated with a poor season. Farmers need to be able to make informed decisions about changing their strategies to suit the seasonal progress and other changed circumstances.

Farmer participatory research, which follows a bottom-up approach and aims at working with farmers to identify their problems and solutions, can give farmers the necessary knowledge to dynamically manage their system. Experience, nevertheless, has shown that this type of research has difficulty moving beyond the diagnostic and design stages and few practical solutions have been developed that can be applied outside the project area (Pillot 1988).

Improved management strategies must also accommodate the farmer's aims, which, because of economic circumstances or personal preferences, may favour management strategies or fertilizer types that do not necessarily maximize yields or economic returns. For example, some Cambodian farmers are reluctant to apply inorganic fertilizer to traditional varieties grown for their own consumption because they believe it degrades the flavour of cooked rice. Similarly, in areas of low population density, farmers with large farms (2–4 ha) place little emphasis on higher yield but stress yield stability and decreased labour requirements (Pandey 1998). Alternatively, farmers in remote locations may not be able to purchase fertilizer at the recommended times for application but need to know the likely benefits from application at other times in the growing season.

These factors have been well studied by social scientists and economists. And the modelling and integration of social, economic and biophysical data for specific systems has been possible, but again, application to the varied environment of the rainfed lowland rice-growing ecosystem has been difficult.

Finally and importantly, there is a need for a formal and organized mechanism whereby knowledge and experience about soil fertility and fertilizer response can be stored and shared at all levels within the agricultural sector. The system must allow for incremental improvements of the technologies as lessons are learnt, and for the entry of new technologies as they are developed. Drawing on this background, researchers are developing a model of rice farming in Cambodia that integrates information from a range of sources, including farmer experience (Bell et al. 2000). The model developed will predict the likely outcomes of given actions. Advisers can therefore use the model to identify the optimal technology for the particular circumstances of a farmer. By better targeting advice, the model will help facilitate the improved adoption of technology by farmers. The system will also facilitate the storage and transfer of farmers' knowledge between localities. Finally, the model's outputs can be represented spatially in a geographic information system. This will contribute to improved strategic planning on a provincial and district basis.

Conclusions

The rainfed lowlands comprise a complex environment for managing soil fertility. Contrary to previous views that drought was the major limiting factor for rice yield, recent research and simulation modelling suggest that nutrients and nutrient -water limitations are more significant. Breeding for nutrient efficiency and adaptation to these variable growing environments has been suggested as the most cost-effective approach towards making a major impact on the productivity of the drought- and submergence-prone rainfed lowlands. However, a deeper understanding of soil chemical changes due to the various transitions between oxic and anoxic conditions is needed to discover mechanisms of cultivar adaptation. Similarly, to better understand nutrient and water uptake by rice, an improved knowledge of root function, adaptation and turnover under the variable water regimes in rainfed lowlands is needed.

Rice production in rainfed lowlands stands at the threshold of major changes in nutrient management. Increased fertilizer use is expected. This has potential to generate benefits and harm. Elsewhere in the world, fertilizer practice has been developed to achieve high production but without considering the potential negative environmental consequences until too late. The opportunity exists to learn from these experiences by taking a more environmentally responsible approach to fertilizer use and nutrient management in the rainfed lowlands.

References

Ahmed, H.U., Ali, M.L., Kabir, M.A. and Miah, N.M. 1996. Varietal characteristics and soil management to reduce drought stress. In: Singh, V.P., Singh, R.K., Singh, B.B. and Zeigler, R.S. ed. Physiology of Stress Tolerance in Rice, Proceedings of the International Conference on Stress Physiology of Rice, 25 Feb–5 March 1994, Lucknow, India. Manila, Philippines, International Rice Research Institute (IRRI), 150–167.

Alagarswamy, G. and Virmani, S.M. 1996. Risk analysis of rainfed sorghum production at various levels of nitrogen fertiliser rate with the CERES sorghum crop simulation model. In: Ito, O., Johansen, C., Adu-Gyamfi, J.J., Katayama, K., Kumar Rao, J.V.D.K. and Rego, T.J. ed. Dynamics of Roots and Nitrogen Cropping Systems of the Semi-Arid Tropics. Tsukuba, Ibaraki, Japan, Japan International Research Centre for Agricultural Sciences, 603–615.

Bell, R.W., Ros, C., Cook, S. and White, P.F. 2000. A system to reduce risk in the adoption of new rice production technologies in Cambodia. In: IRRC 2000 Rice Research for Food Security and Poverty Alleviation, 31 March–3 April 2000, Abstracts. Los Baños, Philippines, International Rice Research Institute (IRRI), 210.

Brandon, A.M. and Mikkelsen, D.S. 1979. Phosphorus transformations in alternately flooded California soils. I. Cause of plant phosphorus deficiency in rice rotation crops and correction methods. Soil Science Society of America Journal, 43, 989–994.

CIAP (Cambodia–IRRI–Australia Project). 1994. Farming system and nutrient management. In: Annual Report 1993. Phnom Penh, Cambodia, 128–142.

CIAP (Cambodia–IRRI–Australia Project). 1995. Integrated nutrient management and farming systems. In: Annual Report 1994. Phnom Penh, Cambodia, 117–138.

CIAP (Cambodia–IRRI–Australia Project). 1997. Agricultural engineering. In: Annual Report 1996. Phnom Penh, Cambodia, 138–151.

CIAP (Cambodia–IRRI–Australia Project). 1998. Agricultural engineering. In: Annual Report 1997. Phnom Penh, Cambodia, 113–163.

CIAP (Cambodia–IRRI–Australia Project). 1999. Agricultural engineering. In: Annual Report 1998. Phnom Penh, Cambodia, 144–158.

Cho, J.Y., Han, K.H. and Choi, J.K. 2000. Balance of nitrogen and phosphorus in a paddy field of central Korea. Soil Science and Plant Nutrition, 46, 343–354.

Colmer, T.D., Gibberd, M.R., Wiengweera, A. and Tinh, T.K. 1998. The barrier to radial oxygen loss from roots of rice (*Oryza sativa* L.) is induced by growth in stagnant solution. Journal of Experimental Botany, 49, 1431–1436.

Cooper, M., Fukai, S. and Wade, L.J. 1999. How can breeding contribute to more productive and sustainable rainfed rice systems? Field Crops Research, 64, 199–209.

Crosson, P. 1995. Natural resource and environmental consequences of rice production. In: Fragile Lives in Fragile Ecosystems, Proceedings of the International Rice Research Conference, 13–17 Feb 1995. Los Baños, Philippines, International Rice Research Institute (IRRI), 83–100.

De Datta, S.K., Biswas, T.K. and Charoenchamrapcheep, C. 1990. Phosphorus requirements and management for lowland rice. In: Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania. Los Baños, Philippines, International Rice Research Institute (IRRI), 307–324.

Dobermann, A. and White, P.J. 1999. Strategies for nutrient management in irrigated and rainfed rice systems. Nutrient Cycling in Agroecosystems, 53, 1–18.

Fukai, S., Inthapanya, P., Blamey, F.P.C. and Khunthasavon, S. 1999. Genotypic variation in rice grown in low fertility soils and drought-prone, rainfed lowland environments. Field Crops Research 64, 121–130.

Fukai, S., Rajatsasereekul, S., Boonjung, H. and Skulkhu, E. 1995. Simulation modelling to quantify the effect of drought for rainfed lowland rice in Northeast Thailand. In: Fragile Lives in Fragile Ecosystems, Proceedings of the International Rice Research Conference, 13–17 Feb 1995. Los Baños, Philippines, International Rice Research Institute (IRRI), 657–674.

Garrity, D.P. and Vejpas, C. 1986. Percolation barriers increase and stabilise rainfed lowland rice yields on well-drained soil. In: Murty, V.V.N. and Koga, K. ed. Soil and Water Engineering for Paddy Management. Bangkok, Thailand, Asian Institute of Technology, 413–421.

George, T., Ladha, J.K., Garrity, D.P. and Buresh, R.J. 1994. Legumes as nitrate catch crops during dry-to-wet transition in lowland rice cropping systems. Soil Science Society America Journal, 86, 267–273.

Jahn, J.C., Pheng, S., Kiev, B. and Pol, C. 1997. Farmers' pest management practices in Cambodian lowland rice. In: Heong, K.L. ed. Management Practices of Rice Farmers in Asia. Manila, Philippines, International Rice Research Institute (IRRI).

Katyal, J.C. 1978. Management of phosphorus in lowland rice. Phosphorus in Agriculture, 73, 21–34.

Kawaguchi, K. and Kyuma, K. 1977. Paddy Soils in Tropical Asia: Their Material, Nature and Fertility. Honolulu, HI, The University of Hawaii Press.

Kirk, G.J.D. and Du, L.V. 1997. Changes in rice root architecture, porosity, and oxygen and proton release under phosphorus deficiency. New Phytologist, 135, 191–200.

Kirk, G.J.D., Solivas, J.L. and Begg, C.B.M. 1994. The rice root–soil interface. In: Kirk, G.J.D. ed. Rice Roots: Nutrients and Water Use. Manila, Philippines, International Rice Research Institute (IRRI), 1–10.

Kundu, D.K. and Ladha, J.K. 1999. Sustaining productivity of lowland rice soils: issues and options related to N availability. Nutrient Cycling in Agroecosystems, 53, 19–33.

Kundu, D.K., Ladha, J.K. and Lapitan de Guzman, E. 1996. Tillage depth influence on soil nitrogen distribution and availability in a rice lowland. Soil Science Society of America Journal, 60, 1153–1159.

Lando, R.P. and Mak, S. 1994. Rainfed Lowland Rice: A Baseline Study. Research Paper Series No. 152. Los Baños, Philippines, International Rice Research Institute (IRRI).

Lefroy, R.D.B. and Hussain, A. 1991. Sulfur in rainfall and its relevance to Malaysian agriculture. In: Khanaki, Y.M., Syed Omar, S.R. and Shamsuddin, J. ed. Developments in Soil Research in Malaysia. Kuala Lumpur, Malaysia, Malaysian Society of Soil Science, 14–22.

Lefroy, R.D.B. and Konboon, Y. 1998. Studying nutrient flows to assess sustainability and identify areas of nutrient depletion and imbalance: an example for rainfed rice systems in Northeast Thailand. In: Ladha, J.K., Wade, L.J., Dobermann, A., Reichardt, W., Kirk, G.J.D. and Piggin, C. ed. Rainfed Lowland Rice: Advances in Nutrient Management Research, Proceedings of the International Workshop on Nutrient Management Research in Rainfed Lowlands, 12–15 October 1998, Ubon Ratchatani, Thailand. Los Baños, Philippines, International Rice Research Institute (IRRI), 77–93.

Linquist, B., Sengxua, P. and Whitbread, A. 2000. Residual phosphate availability in lowland rice ecosystems of Laos. In: IRRC 2000 Rice Research for Food Security and Poverty Alleviation, 31 March–3 April 2000, Abstracts. Los Baños, Philippines, International Rice Research Institute (IRRI), 180.

Linquist, B., Sengxua, P., Whitbread, A., Schiller, J. and Lathvilayvong, P. 1998. Evaluating nutrient deficiencies and management strategies for lowland rice in Lao PDR. In: Ladha, J.K., Wade, L.J., Dobermann, A., Reichardt, W., Kirk, G.J.D., and Piggin, C. ed. Rainfed Lowland Rice: Advances in Nutrient Management Research, Proceedings of the International Workshop on Nutrient Management Research in Rainfed Lowlands, 12–15 October 1998, Ubon Ratchatani, Thailand. Los Baños, Philippines, International Rice Research Institute (IRRI), 59–73.

McCowan, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P. and Freebairn, D.M. 1996. APSIM: a novel software system for model development, model testing, and simulation in agricultural systems research. Agricultural Systems, 50, 255–271.

Mishama, S., Matsumoto, N. and Oda, K. 1999. Nitrogen flow associated with agricultural practices and environmental risk in Japan. Soil Science and Plant Nutrition, 45, 881–889.

Mitsuchi, M., Wichaidit, P. and Jeungnijnirund, S. 1986. Outline of Soils of the Northeast Plateau, Thailand. Their Characteristics and Constraints. Technical Paper No. 1. Khon Kaen, Thailand, Agricultural Development Research Centre in Northeast Khon Kaen Province, 79 p.

Morita, S. and Abe, J. 1996. Development of root systems in wheat and rice. In: Ito, O., Johansen, C., Adu-Gyamfi, J.J., Katayama, K., Kumar Rao, J.V.D.K. and Rego, T.J. ed. Dynamics of Roots and Nitrogen in Cropping Systems of the Semi-Arid Tropics. Tsukuba, Japan, Japan International Research Centre for Agricultural Sciences, 199–209.

Nesbitt, H.J. 1997. Rice Production in Cambodia. Manila, Philippines, International Rice Research Institute (IRRI), 106 p.

Pairoj, P., Kimura, K. and Takai, Y. 1996. Long-term effects of fertilization on paddy soil fertility for sustainable rice production. In: Attanandana, T., Kheoruenromne, I., Pongsakul, P. and Vearasilp, T. ed. Proceedings of International Conference on Maximising Sustainable Rice Yields through Improved Soil and Environmental Management, 7–11 November 1996. Bangkok, Thailand, Funny Publishing, 799–804.

Pandey, S. 1998. Nutrient management technologies for rainfed rice in tomorrow's Asia: economic and institutional considerations. In: Ladha, J.K., Wade, L.J., Dobermann, A., Reichardt, W., Kirk, G.J.D. and Piggin, C. ed. Rainfed Lowland Rice: Advances in Nutrient Management Research. Proceedings of the International Workshop on Nutrient Management Research in Rainfed Lowlands, 12–15 October 1998, Ubon Ratchatani, Thailand. Los Baños, Philippines, International Rice Research Institute (IRRI), 3–28.

Patrick, W.H., Jr. and Wyatt, R. 1964. Soil nitrogen loss as a result of alternate submergence and drying. Soil Science Society of America Proceedings, 28, 647–653.

Pheav, S., White, P.F. and Oberthur, T. 1996. Management constraints of the major rice-growing soils of Cambodia. In: Attanandana, T., Kheoruenromne, I., Pongsakul, P. and Vearasilp, T. ed. Proceedings of International Conference on Maximising Sustainable Rice Yields through Improved Soil and Environmental Management, 7–11 November 1996, Khon Kaen, Thailand. Bangkok, Thailand, Funny Publishing.

Pillot, D. 1988. Francophone and anglophone farming systems research: similarities and differences. In: Farming Systems Research and Development in Thailand. Haatyai, Thailand, Prince of Songkla University, 3–25.

Pingali, P.L., Hossain, M., Pandey, S. and Price, L.L. 1998. Economics of nutrient management in Asian rice systems: towards increasing knowledge intensity. Field Crops Research, 56, 157–176.

Ponnamperuma, F.N. 1972. The chemistry of submerged soils. Advances in Agronomy, 24, 29–96.

Ragland, J. and Boonpuckdee, L. 1987. Fertiliser responses in Northeast Thailand. 1. Literature review and rationale. Thai Journal of Soils and Fertilisers, 9, 65–79.

Rickman, J.F., Piseth, M. and Sothy, O. 1997. Farm mechanization. In: Nesbitt, H.J. ed. Rice Production in Cambodia. Phnom Penh, Cambodia, Cambodia–IRRI–Australia Project.

Ros, C. 1998. Nutrient Management of Rice Seedlings in the Rainfed Lowlands of Cambodia. PhD dissertation. School of Environmental Science, Murdoch University, Perth, WA, Australia.

Ros, C., Bell, R.W. and White, P.J. 1997. Effect of seed phosphorus and soil phosphorus applications on early growth of rice (*Oryza sativa* L.) cv. IR66. Soil Science and Plant Nutrition, 43, 499–509.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Ros, C., Bell, R.W. and White, P.F. 2000. Phosphorus seed coating and soaking for improving seedling growth of *Oryza sativa* (rice) cv. IR66. Seed Science and Technology, 28, 201–211.

Ros, C., White P.F. and Bell, R.W. 1998. Field survey on nursery and mainfield fertilizer management. Cambodian Journal of Agriculture, 1, 22–33.

Sah, R.N. and Mikkelsen, D.S. 1986. Transformations of inorganic phosphorus during the flooding and draining cycles of soil. Soil Science Society of America Journal, 50, 62–67.

Samson, B.K. and Wade, L.J. 1998. Soil physical constraints affecting root growth, water extraction, and nutrient uptake in rainfed lowland rice. In: Ladha, J.K., Wade, L.J., Dobermann, A., Reichardt, W., Kirk, G.J.D. and Piggin, C. ed. Rainfed Lowland Rice: Advances in Nutrient Management Research, Proceedings of the International Workshop on Nutrient Management Research in Rainfed Lowlands, 12–15 October 1998, Ubon Ratchathani, Thailand. Los Baños, Philippines, International Rice Research Institute (IRRI), 231–244.

Seng, V. 2000. Edaphic factors limiting lowland rainfed rice production in soils in southeast Cambodia. PhD dissertation. School of Environmental Science, Murdoch University, Perth, WA, Australia.

Seng, V., Bell, R.W., Nesbitt, H.J. and Willett, I.R. 1996. Response of rainfed rice to inorganic and organic fertilisers in southeast Cambodia. In: Attanandana, T., Kheoruenromne, I., Pongsakul, P. and Vearasilp, T. ed. Proceedings of International Conference on Maximising Sustainable Rice Yields through Improved Soil and Environmental Management, 7–11 November 1996. Bangkok, Thailand, Funny Publishing, 99–112.

Seng, V., Bell, R.W., Willett, I.R. and Nesbitt, H.J. 1999. Phosphorus nutrition of rice in relation to flooding and temporary loss of saturation in two lowland soils in south-east Cambodia. Plant and Soil, 207, 121–132.

Sharma, P.K. 1992. *In situ* water conservation in sandy soils for rainfed lowland rice. Rice Research Journal (Rice Research Institute, Bangkok), 1, 59–64.

Sharma, P.K., Ingram, K.T. and Harnpitchitvitaya, D. 1995. Subsoil compaction to improve water use efficiency and yields of rainfed lowland rice in coarse textured soils. Soil Tillage Research, 36, 33–44.

Sharma, P.K., Pantuwan, G., Ingram, K.T. and De Datta, S.K. 1994. Rainfed lowland rice roots: soil and hydrological effects. In: Kirk, G.J.D. ed. Rice Roots: Nutrient and Water Use. Manila, Philippines, International Rice Research Institute (IRRI), 55–66.

Shrestra, R.K. and Ladha, J.K. 1999. Nitrogen dynamics in intensive rainfed lowland rice-based cropping systems and strategies to improve efficiency. In: Ladha, J.K., Wade, L.J., Dobermann, A., Reichardt, W., Kirk, G.J.D. and Piggin, C. ed. Rainfed Lowland Rice: Advances in Nutrient Management Research. Proceedings of the International Workshop on Nutrient Management Research in Rainfed Lowlands, 12–15 October 1998, Ubon Ratchathani, Thailand. Los Baños, Philippines, International Rice Research Institute (IRRI), 95–108.

Trebuil, G., Harnpitchitvitaya, D., Tuong, T.P., Pantuwan, G. and Wade, L.J. 1998. Improved water conservation and nutrient–use efficiency via subsoil compaction and mineral fertilisation. In: Ladha, J.K., Wade, L.J., Dobermann, A., Reichardt, W., Kirk, G.J.D. and Piggin, C. ed. Rainfed lowland Rice: Advances in Nutrient Management Research, Proceedings of the International Workshop on Nutrient Management Research in Rainfed Lowlands, 12–15 October 1998, Ubon Ratchatani, Thailand. Los Baños, Philippines, International Rice Research Institute (IRRI), 3–28.

Ventura, W. and Watanabe, I. 1984. Dynamics of nitrogen availability in lowland rice soils: the role of soil below plow layer and effect of moisture regimes. Philippines Journal of Crop Science, 9, 812–821.

Wade, L.J., Fukai, S., Samson, B.K., Ali, A. and Mazid, M.A. 1999. Rainfed lowland rice: physical environment and cultivar requirements. Field Crops Research, 64, 3–12.

White, P.F., Oberthur, T. and Pheav, S. 1997. The Soils Used for Rice Production in Cambodia, A Manual for their Recognition and Management. Manila, Philippines, International Rice Research Institute (IRRI), 71 p.

White, P.F., Nesbitt, H.J., Ros, C., Seng, V. and Lor, B. 1999. Local rock phosphate deposits are a good source of phosphorus fertilizer for rice production in Cambodia. Soil Science and Plant Nutrition, 45, 51–63.

Wihardjaka, A., Kirk, G.J.D., Abdulrachman, S. and Marmaril, C.P. 1998. Potassium balances in rainfed lowland rice on a light-textured soil. In: Ladha, J.K., Wade, L.J., Dobermann, A., Reichardt, W., Kirk, G.J.D. and Piggin, C. ed. Rainfed lowland Rice: Advances in Nutrient Management Research, Proceedings of the International Workshop on Nutrient Management Research in Rainfed Lowlands, 12–15 October 1998, Ubon Ratchatani, Thailand. Los Baños, Philippines, International Rice Research Institute (IRRI), 127–137.

Willett, I.R. and Higgins, M.L. 1980. Phosphate sorption and extractable iron during irrigated rice-upland crop rotations. Australian Journal of Experimental Agriculture and Animal Husbandry, 20, 346–353.

Willett, I.R. and Intrawech, A. 1988. Preliminary Studies of Chemical Dynamics of Sandy Paddy Soils of Tung Kula Ronghai, Northeast Thailand. Divisional Report No. 95. Melbourne, Australia, CSIRO.

Xing, G.X. and Zhu, Z.L. 2000. An assessment of N loss from agricultural fields to the environment in China. Nutrient Cycling in Agroecosystems, 57, 67–73.

Zeigler, R.S. and Puckridge, D.W. 1995. Improving sustainable productivity in rice-based rainfed lowland systems of South and South-East Asia. GeoJournal, 35, 307–324.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Nutrient Requirements of Rainfed Lowland Rice in Cambodia

Vang Seng*, Chhay Ros[1], R.W. Bell[2], P.F. White[3] and Hin Sarith[1]

Abstract

In most rainfed lowlands of Cambodia, soils used for rice cultivation are low in available nitrogen (N), phosphorus (P) and potassium (K), and have low organic matter content and low cation-exchange capacity. Over the last 4 years, areas cultivated to rice have increased substantially from about 1.9 to 2.1 million hectares, of which rainfed lowlands comprise about 88%. The average rice yield increased from about 1.2 to 1.8 t ha^{-1}, even though nutrient deficiency remains a serious constraint for lowland rice production. The paper reviews current understanding of the nutrient requirements of rainfed lowland rice in Cambodia. Field and greenhouse trials have classified widespread N and P responses and, on sandy soils, K and sulfur responses. Recommended fertilizer rates (in kg ha^{-1}) for rice vary for the different nutrients: for N, from 20 to 120, for P, from 4 to 15, and for K, from 0 to 33. Recommendations are made for each soil type identified in the Cambodian Agronomic Soil Classification system. The need for further work on nutrient requirements of rice and other agricultural crops is also discussed.

THE total area cultivated to rice in Cambodia has substantially increased from about 1.9 million hectares in 1995 to 2.1 million ha in 1999 (MAFF 1999). Wet-season, rainfed lowland rice covers about 88% of the total rice area. Demand for fertilizers for rice cultivation has gradually increased. For example, in 1994, total consumption of fertilizers was 80 000 t, increasing to 87 000 t by 1995, indicating a 9% rise in demand (CNP and SCI 1996). The increase was primarily attributed to an increase in cultivated areas and higher application rates on improved rice varieties. Despite increased fertilizer demand and use of improved rice varieties, the national average rice yield was only 1.5 t ha^{-1} (Nesbitt 1997), which is still low, compared with 2–3 t ha^{-1} obtained by other rice-producing countries in South-East Asia (Pandey 1997). Most lowland soils of potential use for rice cultivation in Cambodia are low in available nitrogen (N), phosphorus (P), potassium (K), and have low organic matter contents and low cation-exchange capacity (CEC) (White et al. 1997a). Hence, nutrient deficiencies represent a major constraint to rice production at present.

Common problems of rainfed lowland rice cultivation in the diverse soil types of Cambodia include varied soil-water regimes, low nutrient availability and the interactions between these two factors (Fischer 1998; Wade et al. 1998). For example, the availability of N and P in soil varies strongly in relation to soil-water content (Kirk et al. 1990; De Datta 1995). This means that the complex problems in the rainfed lowlands cannot be solved without better understanding site-specific nutrient management. In response to this need, the Cambodian Agronomic Soil Classification (CASC) system was

KEYWORDS: Rainfed lowlands, Soil types, Fertilizer recommendations, Nutrient requirements, Nitrogen, Phosphorus, Potassium, Rice

---

[1] Soil and Water Research Program, Cambodian Agricultural Research and Development Institute (CARDI), Phnom Penh, Cambodia

[2] School of Environmental Sciences, Murdoch University, Perth, Western Australia

[3] Pulses Programme, Agriculture Western Australia, Perth, Western Australia

*Corresponding author: Soil and Water Research Program, Cambodian Agricultural Research and Development Institute (CARDI), Phnom Penh, Cambodia.
E-mail: VSENG@bigpond.com.kh

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

developed to provide better understanding of soil types. It forms the basis on which fertilizer rates and strategies for rainfed lowland rice production are recommended (White et al. 2000).

This paper reviews the work on nutrient research and management for rainfed lowland rice-based farming in Cambodia. Selected examples are presented to illustrate key elements of the integrated nutrient management strategy being developed in Cambodia. Some sections of this paper are summarized from White et al. (1998).

Soil Classification

The CASC system is used in soil and nutrient management in Cambodia to infer information about the soils' properties by using easily observable surrogate characters such as soil colour and texture, and stone contents, thus allowing management to be tailored accordingly. The CASC has also been used on a broad scale for applied agronomic research programs in Cambodia (principally on-farm trials) but, where possible, soil chemical analysis has been used in specific research experiments.

Discussion in this paper is based on the soil groups as described in the CASC system (White et al. 1997b). Chemical properties of the soil groups are given in Table 1, but where available, soil properties from specific experiments are also provided in the text.

Cambodian soils can be broadly divided into three groups: (1) the Prey Khmer and Prateah Lang groups, which are soils with potential for low to moderate yields (White et al. 1997b). These have low nutrient reserves, low levels of organic matter and low cation-exchange capacities. Maintaining an adequate supply of nutrients for high rice yields on these soils is difficult and farmers' experience is that response to fertilizer applications is variable. (2) The potential of the Bakan, Koktrap and Toul Samroung soils is considered as higher (White et al. 1997b). These soils have relatively low levels of nutrient reserves but have higher levels of organic matter, CEC and clay. These soils are therefore more robust, responding to fertilizers more readily. (3) On the high-potential Krakor soils, farmers can produce as much as 10 t ha^{-1} with dry-season rice and moderately high N fertilizer rates.

The decision to base much of the applied agronomic research and extension of fertility management in Cambodia on the CASC was made for both sound scientific and pragmatic reasons. The alternative would have been soil analysis and diagnosis, using chemical tests. However, for anything other than a limited research program, soil analysis and diagnosis are unworkable in the current Cambodian context. The country has no operating laboratory that can provide reliable soil analysis. Neither have soil tests been calibrated for the country's soils, environments and farming systems, and limited expertise exists for interpreting test results.

The CASC was established to improve soil and nutrient management by improving communication about soil resources and by providing a usable tool to help agronomists, extension agents and farmers make decisions. Surrogate characters often help in

Table 1. Chemical properties of major rice soils in Cambodia.

Soil type[a]	pH[b]	EC[c] (dS m^{-1})	Olsen P (mg kg^{-1})	Total N (g kg^{-1})	Organic C (g kg^{-1})	Exchangeable cation [cmol(+) kg^{-1}]				CEC[d] [cmol(+) kg^{-1}]
						K	Na	Ca	Mg	
Prey Khmer (Psamments)	5.6	0.03	1.3	0.5	4.7	0.02	0.04	0.38	0.12	1.8
Prateah Lang (Plinthustalfs)	*4.0*	0.07	0.4	0.3	2.9	0.03	0.13	0.84	0.25	1.3
Bakan (Alfisol/Ultisol)	5.8	0.05	1.0	0.6	6.6	0.07	0.26	2.33	0.68	6.3
Koktrap (Kandic Plinthaquualt)	*4.0*	0.06	2.6	1.1	10.9	0.06	0.1	0.42	0.16	6.7
Toul Samroung (Vertisol/Alfisol)	5.5	0.08	3.1	0.9	8.8	0.16	0.39	7.81	4.31	18.2
Krakor (Entisol/Inceptisol)	5.9	0.30	4.6	1.0	9.1	0.19	0.53	7.78	3.05	13.5

[a] Local name as classified by White et al. (1997b). Names in parentheses refer to the *Key to Soil Taxonomy* by the Soil Survey Staff (1994).

[b] 1:1, soil to water, except for values in italics, which were obtained from 1:5, soil to $CaCl_2$.

[c] EC = electrical conductivity; dS = decisiemen.

[d] CEC = cation-exchange capacity.

accurately predicting soil chemical properties. Indeed, elsewhere, farmers' soil classifications, which are similarly based on surrogate characters in the field, allow delicate management of those soils with which farmers have first-hand experience (Bellon and Taylor 1993). Their classifications are highly and positively correlated with laboratory chemical and physical indicators of soil quality (Sandor and Furbee 1996; Talawar 1996). A clear relationship has also been observed between land quality, as assessed by the farmer, and variety selection (Bellon and Taylor 1993).

Currently, more than 2000 copies of the Khmer-language version of the soil manual have been distributed and are used to identify soils for rice production. In 1999, seven training courses on integrated nutrient management and the use of soil manual were provided to more than 250 researchers and technical staff, extension workers and fertilizer dealers from various non-governmental and governmental organizations (CIAP 1999).

Local agronomists who use the CASC can separate soil variations sufficiently to classify a given soil and thus identify the interaction of soil type with fertilizer rates and varieties (White et al. 2000). With the CASC, agronomists can also adequately predict differences in grain yields of rice grown on the different soils in on-farm trials (CIAP 1998; White et al. 2000).

The CASC can be applied beyond Cambodia and, when combined with other management tools, is still relevant even where sophisticated soil analytical facilities are available. The philosophy, application and accuracy of the CASC are described by Doberman and White (1999), Oberthür et al. (2000a, b) and White et al. (2000).

Diagnosing Nutrient Disorders

Through nutrient omission and field trials on fertilizer response, the major deficiencies in Cambodian lowland soils for rice cultivation have been identified (Lor et al. 1996). Deficiencies of N, P, K and sulfur (S) were identified in pot experiments and confirmed in field trials. Many soils exhibit multiple deficiencies so that factorial field trials were needed to examine interactions between the elements. In pot experiments, responses to boron (B) and magnesium (Mg) were obtained in some soils, but have yet to be demonstrated in the field.

Responses to nitrogen, potassium and sulfur

Rice is highly variable in its response to fertilizer application, depending on soil type. In Koktrap soil, the highest yield was obtained when all nutrients (N, P, K and S) were applied together (Figure 1). When N, P or S were omitted the grain yield was decreased to 1–1.5 t ha^{-1}. On this site omitting K appeared to increase yield for reasons that are not clear (NPKS-3 and NPKS-4, Figure 1b). When the nutrients were applied singularly, only a small or sometimes negative response to fertilizer resulted, especially for N or K alone (Figures 1a, b), and rice leaves became bronzed. An adequate supply of N, P and S must therefore be maintained to realize the full benefits of fertilizer application on this soil.

On Prateah Lang soils, rice grain yield increased with K fertilizer application but the effect was additive to that of N and P fertilizer application (Table 2). That is, grain yield increased overall by 12% with the addition of K at 33 kg ha^{-1}, regardless of the N and P application rates.

Table 2. The effect of potassium (K) fertilizer on grain yield of the rice cultivar Santepheap 1 with various levels of nitrogen (N) and phosphorus (P) fertilizer applications.

N–P rate[a]	K rate (kg ha^{-1})	Grain yield (t ha^{-1})[b]				
		PK soil	PL soil	BK soil	KT soil	TS soil
0	0	1.5	2.3	2.6	1.0	3.5
1	0	1.7	3.0	3.6	1.4	3.3
2	0	1.5	3.1	3.8	1.6	4.4
0	33	1.6	2.5	3.0	1.0	3.5
1	33	1.8	3.3	4.0	1.5	3.3
2	33	1.5	3.6	4.2	1.9	4.1
F probabilities						
NP		0.116	<0.001	<0.001	0.018	0.481
K		0.444	0.008	0.006	0.038	0.833
NP × K		0.733	0.681	0.987	0.843	0.977

[a] Multiple of recommended fertilizer rate for each soil as shown in Table 3. [b] Soils: PK = Prey Khmer; PL = Prateah Lang; BK = Bakan; KT = Koktrap; TS = Toul Samroung.

Rice cultivated in Bakan and Koktrap soils, which generally contain relatively low levels of N, P and K (Table 1), also responded to additions of N, P and K fertilizers, similarly to rice in Prateah Lang soil (Table 2). In contrast, the response of rice to additions of N, P and K in Prey Khmer soil was low, probably because of climatic factors, since the Prey Khmer soil experienced a mid-season loss of soil-water saturation, followed by heavy rain (CIAP 1998), resulting in high losses of nutrients through run-off and leaching from the deep sandy textured profile and low-CEC soil.

Grain yields in heavy textured soils that were relatively rich in K did not respond to applied K. The exchangeable K level in the Toul Samroung soil [0.16 cmol(+) kg^{-1}] was higher than in other light-textured soil groups (Prey Khmer, Prateah Lang and

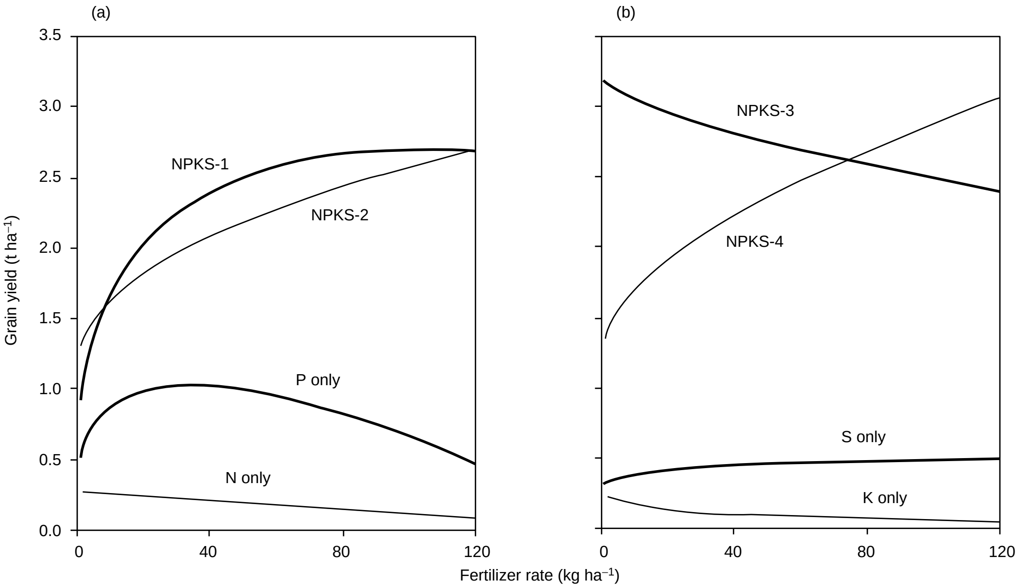


Figure 1. Rice grain yield after fertilizer application in a Koktrap soil (acid clay soil). Curves represent the predicted response based on the square root quadratic function fitted to experimental data. In the NPKS treatments, the rate of one element (i.e. in [a] N in NPKS-1, P in NPKS-2, and in [b] K in NPKS-3 and S in NPKS-4) was varied while all the other elements were kept constatnt. The combined rate of nutrients were NPKS-1 = 0–120N + 44P + 66K + 60S; NPKS-2 = 120N + 0–52P + 66K + 60S; NPKS-3 = 120N + 44P + 0–100K + 60S; NPKS-4 = 120N + 44P + 66K + 0–120S (from CIAP 1995).

Bakan), whose exchangeable K ranged from 0.02 to 0.07 cmol(+) kg^{-1} (Table 1).

With long-term use of N and P fertilizers to correct deficiencies of these elements, the soil reserves of K are likely to become depleted and K fertilizer may be needed in the future, even on the Toul Samroung soils.

Response to phosphorus

In Cambodia, more than three fifths of the soils used for rice production are deficient in P (Pheav et al. 1996), limiting rice yields over much of the country. Cambodia relies entirely on imported compound chemical fertilizers (e.g. di-ammonium phosphate or DAP, 16–20–0 and 15–15–15) for rice production. The expense obliges farmers to apply only small amounts of P for rice cultivation.

Local phosphate rock ores, which could supply much of the demand for P fertilizer, has only just been introduced into the local market, but with little support from research on the quantity and suitability of rock phosphate as a P fertilizer. However, previous research showed that high-grade rock phosphate was likely to be as effective as imported triple super phosphate (TSP) for rainfed lowland rice production in Cambodia, producing yields ranging from 1.5 to 2.5 t ha^{-1} when rock phosphate was applied at 5–10 kg P ha^{-1} (White et al. 1999). However, the response of rice to P fertilizer additions varies between soil types. Some soils (e.g. Koktrap and Prateah Lang) are acidic, with low available P and exchangeable Ca levels. They remain acidic, even after several weeks of flooding (White and Seng 1997). These factors favour rock phosphate dissolution, thus increasing the availability of P for rice (Hammond et al. 1986). In other soils (e.g. Prateah Lang), sulfur deficiency restricts the response of rice to P additions (Lor et al. 1996).

Low soil fertility, together with fluctuations in the soil-water regime during crop growth, causes rice to respond inconsistently to applied P fertilizers (White and Seng 1997). In acidic Koktrap clay soil and under flooded conditions, grain yield responds strongly to P addition alone, but the curve levels off after adding P at 20 kg ha^{-1} or more (Figure 1). In contrast, in the sandy Prateah Lang soil, grain yield did not respond to P additions alone, with yields of about 1.4 t ha^{-1} under flooded conditions (Figure 2). Loss of soil-water saturation decreased rice yield from 1.4 to 0.7 t ha^{-1}, but not because of water stress in rice plants. Instead, loss of soil-water saturation oxidizes the soil, enabling phosphates to react with iron oxides. This, in turn, reduces P availability and thus restricts P uptake by rice plants. Relationships between shoot dry-matter weights and plant P uptake remained close under different soil-water regimes with two soil types and under greenhouse conditions (Figure 3). The relationships suggested that changes in soil-water regimes, which affect soil redox potential, influenced rice growth by controlling P availability (Seng et al. 1999).

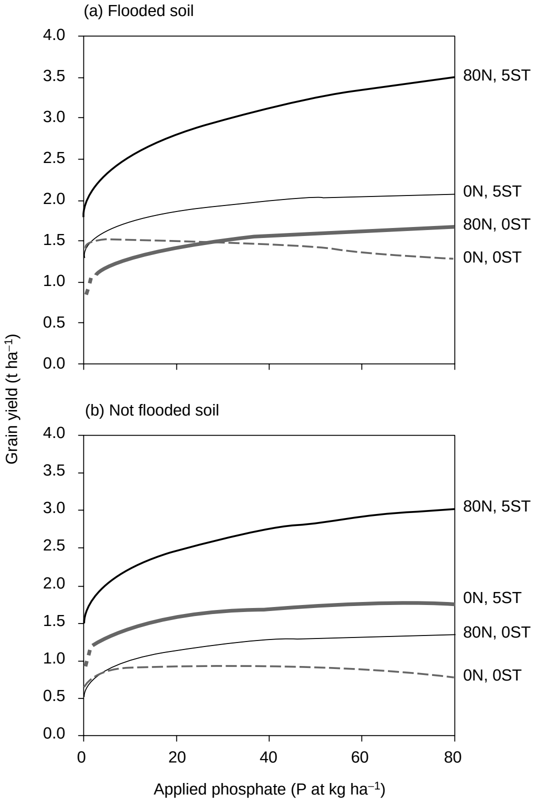


Figure 2. Modelled response of rice grain yield to P fertilizer application with combined nitrogen (N) and straw (ST) additions to (a) flooded and (b) non-flooded sandy Prateah Lang soils of south-east Cambodia. The levels of N added were in kg ha^{-1}, and of straw in t ha^{-1} (from Seng 2000).

Fertilizer Recommendations

Fertilizer application, together with the use of modern varieties, irrigation and other improved management practices, has been increasing food production in South-East Asia over the past 25 years. However, financial or crop losses and environmental damage may result if fertilizers are applied incorrectly. Careful consideration must be given to several factors when the rate and timing of fertilizer are being decided. Farmers implicitly consider some of these factors, such as risk associated with erratic rainfall, when deciding on fertilizer use.

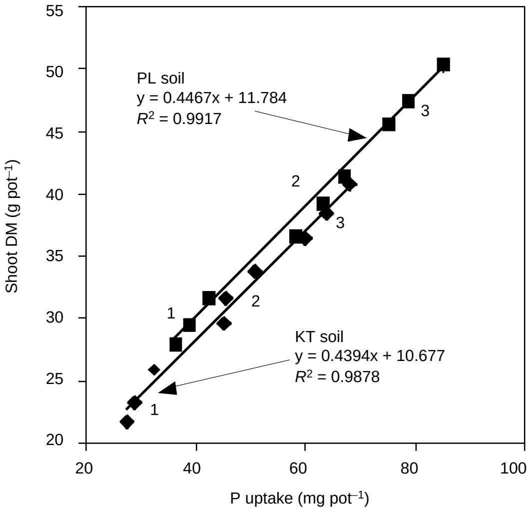


Figure 3. Relationships between shoot dry matter (shoot DM) and P uptake in rice grown in Koktrap (KT) and Prateah Lang (PL) soils under various soil-water conditions maintained in the greenhouse. Plotted values are means of three replicates. The numbers 1, 2 and 3 represent pots where the water regime was field capacity, and intermittently and continuously flooded soils, respectively (from Seng et al. 1999).

In Cambodia, current work is focused on the best use of fertilizer for particular soil types at the appropriate rates, according to the CASC (Table 3). These rates are also formulated from local knowledge and experience and from the results of fertilizer trials conducted by the Cambodia–IRRI–Australia Project during 1992–1997 (CIAP 1998).

On the Prey Khmer, Prateah Lang and Bakan soil types, fertilizers should be broadcast into soil that has been flooded for at least a week. Farmyard manure (FYM) and inorganic fertilizer applications are also recommended. If FYM is to be applied, inorganic fertilizers should be broadcast several days after the FYM is applied. Where possible, the field should be drained before transplanting and the initial fertilizer broadcast and thoroughly incorporated into the wet soil. Further fertilizer applications should also be broadcast into wet soil.

At present, however, few data exist to permit soil-specific predictions of the fertilizer requirements and response for rice production in Cambodia. Careful detailed research is still needed to determine how farmers would adjust recommended fertilizer rates and timing to take into account drought or submergence events.

No specific type of fertilizer or combination of fertilizers is currently recommended. Urea, DAP and KCl have been used as examples here, based simply on cost. Other fertilizers, combined to apply the same recommended rate of nutrients, would probably produce similar responses.

Table 3. Recommended rates of nutrients for rainfed rice on major soil types of Cambodia.

Soil type[a]	Recommended rate of nutrients (kg ha^{-1})		
	N	P	K
Prey Khmer (Psamments)	28	4	33
Prateah Lang (Plinthustalfs)	50	10	25
Bakan (Alfisol/Ultisol)	75	13	25
Koktrap (Kandic Plinthaquult)	73	15	25
Toul Samroung (Vertisol/Alfisol)	98	15	0
Krakor (Entisol/Inceptisol)	120	11	0

[a] Local names as classified by White et al. (1997b); names in parentheses refer to the *Key to Soil Taxonomy* by the Soil Survey Staff (1994).
Source: DOA (1999).

For the rice nursery, research in Cambodia has so far shown large benefits from applying fertilizers (Ros 1998). Farmers apply higher rates of fertilizer and manures to the seedling nursery than to the main fields (Ros et al. 1998). Such applications increase seedling vigour, which then increases subsequent rice yields by 5%–10%, regardless of whether the main fields were treated with fertilizers. Cow manure at 3.0 t ha^{-1} and inorganic fertilizer (N at 50 and P at 22 kg ha^{-1}) are recommended for increasing seedling vigour (CIAP 1998). Other low-cost strategies suggested by Ros et al. (2000) for increasing seedling vigour include coating seeds in rock P powder and selecting seeds with high P concentration for nursery planting.

The Cambodian farmers' strategy of applying more fertilizer to the nursery is an efficient use of nutrients because applications to seedlings already transplanted to the main fields do not adequately improve their vigour. Currently, manure and inorganic fertilizer are recommended for application to seedbeds in all soils, except the Kbal Po and Krakor groups (White et al. 1997b).

Recommended Work on Agricultural Soils in Cambodia

Variety × soil type interactions

Cultivar response to fertilizer varies between soil types, although, in unfertilized plots within each soil type, no significant differences in grain yield occur between farmer and recommended varieties (Figure 4). In the infertile sandy soils of the Prey Khmer group (Figure 4a), rice grain yields were lower than those obtained from the more fertile soils of the Prateah Lang or Bakan groups (Figures 4b, c). Adding fertilizer substantially increases grain yield of recommended varieties growing in the Prey Khmer (from 1.8 to 2.9 t ha^{-1}), Prateah Lang (2.5 to 3.0 t ha^{-1}) and Bakan (2.3 to 3.3 t ha^{-1}) soil groups. Under these conditions, farmer varieties on the Prey Khmer and Bakan soil groups show similar yields, but levels are much lower than those of the recommended varieties. In contrast, in the Prateah Lang soil group, grain yield of farmer varieties decreased by 0.2 t ha^{-1} when 1.5 times the recommended rate of fertilizer was applied. The greater response of recommended varieties to the recommended fertilizer rate, compared with farmer varieties, indicated that joint strategies of improved cultivars and nutrient management are needed to create significant impacts on crop yield.

Soils used for rice production in Cambodia vary largely in their physical and chemical properties. Not surprisingly, some rice varieties released by the Cambodia–IRRI–Australia Project (CIAP) are well adapted to some soils, but not to others, indicating that it is important to know how new varieties perform on different soils so that appropriate recommendations for varieties can be made.

Long-term nutrient management

Because farmers will continue to increase their inputs of inorganic fertilizers, and because the balance of nutrients entering and exiting Cambodian agricultural systems is unknown, long-term monitoring systems should be developed. Nutrient movement, particularly P and K nutrient retention in soils, and nutrient cycling through cropping, pasture or fallow rotations can therefore be monitored.

Simulation modelling shows that soil-specific fertilizer recommendations result in increased yields and more efficient fertilizer use than does the old recommended rate for all soils (N at 64 and P at 23 kg ha^{-1}). Yields increase by 0.2–0.5 t ha^{-1} when higher rates of fertilizer are applied to responsive soils and lower rates to unresponsive soils (Prey Khmer and Prateah Lang). Such rates result in savings of N at rates between 14 and 36 kg and of P at 7 and 16 kg ha^{-1} (Ros et al. in press). Further scope exists for developing site-specific nutrient management.

Improved management of the consequences of loss of soil-water saturation for rice growth may depend on the sensitivity of a given rice variety according to development stage. In the rainfed lowlands, loss of soil-water saturation can occur at any stage. Maximum tillering and panicle initiation, which are important for grain yield development in rice, may also be sensitive periods of loss of soil-water saturation (Fukai and Cooper 1996). Identifying critical stages for loss of soil-water saturation will help in the management of nutrients for rainfed lowland rice because it will indicate the growth phases when the crops most need irrigation to maintain soil saturation. Alternatively, preventing or minimizing yield losses to short periods of loss of soil-water saturation may be feasible with straw or organic-matter additions (Seng et al. 1999).

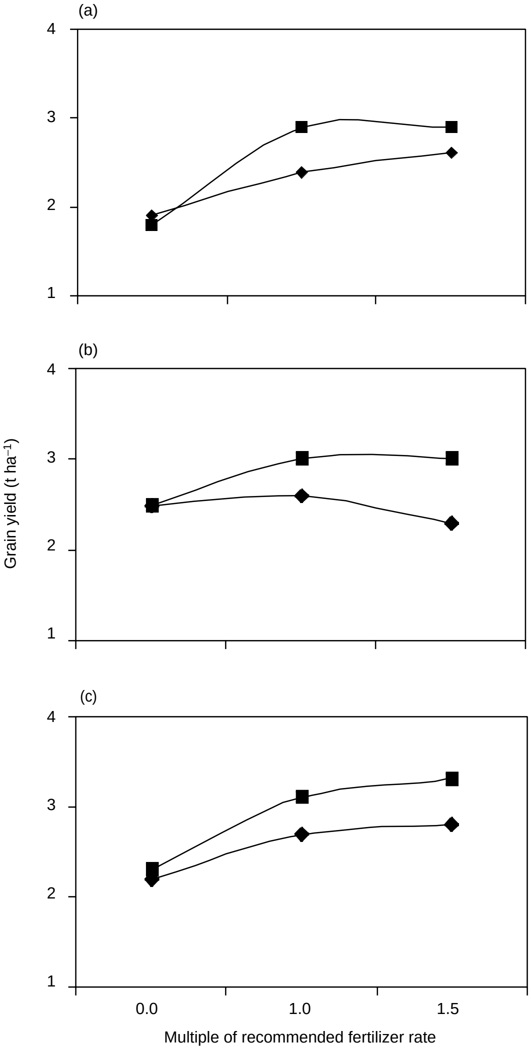


Figure 4. Grain yield response of farmer —◆— and recommended —■— rice varieties to fertilizer applications in rainfed lowland soils, Cambodia. Plotted data are means of (a) 3 sites in Prey Khmer soil, (b) 8 sites in Prateah Lang soil and (c) 18 sites in Bakan soil. The recommended fertilizer rates used are shown in Table 3 (from CIAP 1998).

Problem soils

In South-East Cambodia, thousands of hectares of soils are strongly acidic and many thousands of hectares of soils adjacent to coastal areas are also affected by sea salt, making rice cultivation risky. Research is needed to provide management recommendations for increasing the arable potential of these soils.

Rice bronzing

In Cambodia, rice bronzing occurs sporadically each year, especially on Koktrap, Prateah Lang and Bakan soil groups. Although loss of grain yields caused by this problem has not been confirmed, the disorder appears to be similar to that described for rice in Japan and Nigeria (Yamauchi 1989). In Cambodia, anecdotal evidence suggests that the problem is more prevalent and more severe with the increased use of inorganic N and P fertilizers, but no K fertilizer. Removal of rice-straw from the field limits the return of K in soils receiving none or low rates of applied K. Breeding for resistant cultivars may be the most effective strategy for the long-term alleviation of this disorder.

Soil classification for agricultural crops

The realization of Cambodia's agricultural potential is hampered by several inherent soil problems, compounded by limited soil information, not only for rice but also for other crops. Although a rice soil map is available and the current classification system for rice soils appears to be useful for other crops, further effort is needed to obtain soil information and maps of arable land that are both more complete and more sophisticated.

Acknowledgments

The authors are grateful to the Cambodia–IRRI–Australia Project (CIAP) and the Australian Agency for International Development (AusAID) for research funding.

References

Bellon, M.R. and Taylor, J.E. 1993. "Folk" soil taxonomy and the partial adoption of new seed varieties. Economic Development and Cultural Change, 41, 763–786.

CIAP (Cambodia–IRRI–Australia Project). 1995. Annual Research Report. Phnom Penh, Cambodia.

CIAP (Cambodia–IRRI–Australia Project). 1998. Annual Research Report. Phnom Penh, Cambodia.

CIAP (Cambodia–IRRI–Australia Project). 1999. Annual Research Report. Phnom Penh, Cambodia.

CNP (Center for National Policy) and SCI (Sparks Companies, Inc.). 1996. Fertilizer Procurement and Distribution in Cambodia: Issues and Options. Washington, DC.

De Datta, S.K. 1995. Nitrogen transformations in wetland rice ecosystems. Fertiliser Research, 42, 193–203.

DOA (Department of Agronomy), Ministry of Agriculture, Forestry and Fisheries. 1999. New fertilizer recommendation rates in rice production. Agricultural Note no. INM 99/01. Phnom Penh, Cambodia.

Fischer, K.S. 1998. Toward increasing nutrient-use efficiency in rice cropping systems: the next generation of technology. Field Crops Research, 56(1–2), 1–6.

Fukai, S. and Cooper, M. 1996. Stress physiology in relation to breeding for drought resistance: a case study of rice. In: Singh, V.P., Singh, R.K., Singh, B.B. and Zeigler, R.S. ed. Physiology of Stress Tolerance in Rice: Proceedings of the International Conference on Stress Physiology of Rice. Lucknow, India, International, Rice Research Institute, 123–149.

Hammond, L.L., Chien, S.H. and Mowunye, A.U. 1986. Agronomic value of unacidulated and partially acidulated phosphate rocks indigenous to the tropics. Advances in Agronomy 40, 89–140.

Kirk, G.J.D., Tian-ren, Y. and Choudhury, F.A. 1990. Phosphorus chemistry in relation to water regime. In: Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania. Manila, Philippines, International Rice Research Institute (IRRI), 211–223.

Lor, B., White, P.F. and Chan, P. 1996. Nutrient requirements for the growth of rice on Cambodian soils. In: Attanandana, T., Kheoruenromne, I., Pongsakul, P. and Verasilp, T. ed. Maximising Sustainable Rice Yields through Improved Soil and Environmental Management. Khon Kaen, Thailand, Ministry of Agriculture and Cooperatives, 45–56.

MAFF (Ministry of Agriculture, Forestry and Fisheries). 1999. Agricultural Statistics. Phnom Penh, Cambodia.

Nesbitt, H.J. ed. 1997. Rice Production in Cambodia. Manila, Philippines, International Rice Research Institute (IRRI).

Oberthür, T., Dobermann, A. and White, P. 2000a. The rice soils of Cambodia. II. Statistical discrimination of soil properties by the Cambodian Agronomic Soil Classification system. Soil Use and Management, 16, 20–26.

Oberthür, T., Ros C. and White, P.F. 2000b. Soil map of the main rice growing area of Cambodia. Phnom Penh, Cambodia, Cambodia–IRRI–Australia Project (CIAP).

Pandey, S. 1997. Rainfed lowland rice research: challenged and priority for the 21st century. In: Fukai, S., Cooper, M. and Salisbury, J. ed. Breeding Strategies for Rainfed Lowland Rice in Drought-Prone Environments; Proceedings of an International Workshop held at Ubon Ratchanthani, Thailand. Canberra, ACIAR Proceedings No. 77, 1–12.

Pheav, S., White, P.F. and Oberthür, T. 1996. Management constraints of the major rice growing soils of Cambodia. In: Attanandana, T., Kheoruenromne, I., Pongsakul, P. and Verasilp, T. ed. Maximising Sustainable Rice Yields through Improved Soil and Environmental Management. Khon Kaen, Thailand, Ministry of Agriculture and Cooperatives, 537–550.

Ros, C. 1998. Nutrient Management of Rice Seedlings in the Rainfed Lowlands of Cambodia. PhD dissertation. Perth, Western Australia, School of Environmental Science, Division of Science and Engineering, Murdoch University.

Ros, C., Bell, R.W. and White, P.F. 2000. Phosphorus seed coating and soaking for improving seedling growth of *Oryza sativa* (rice) cv. IR66. Seed Science and Technology, 28, 201–211.

Ros, C., Vang, S., Hin, S. and White, P. In press. Better soil management better impact: the Cambodian Agronomic Soil Classification. In: Proceedings of the International Conference on the Impact of Agricultural Research for Development in Southeast Asia. Phnom Penh, Cambodia, Cambodian Agricultural Research and Development Institute (CARDI).

Ros, C., White, P.F. and Bell, R.W. 1998. Field survey on nursery and mainfield fertilizer management. Cambodian Journal of Agriculture, 1, 22–33.

Sandor, J.A. and Furbee, L. 1996. Indigenous knowledge and classification of soils in the Andes of southern Peru. Soil Science Society of America Journal, 60, 1502–1512.

Seng, V. 2000. Edaphic Factors Limiting Rice Responses to Applied Inorganic Fertilizers in Rainfed Lowland Soils in Southeast Cambodia. PhD dissertation. Perth, Western Australia, School of Environmental Science, Division of Science and Engineering, Murdoch University.

Seng, V., Bell, R.W., Willett, I.R. and Nesbitt, H.J. 1999. Phosphorus nutrition of rice in relation to flooding and temporary loss of soil-water saturation in two lowland soils of Cambodia. Plant and Soil, 207, 121–132.

Soil Survey Staff, Soil Conservation Service, United States Department of Agriculture. 1994. Key to Soil Taxonomy, 6th ed. Washington, DC.

Talawar, S. 1996. Local soil classification and management practices: bibliographic review. Athens, GA, Laboratory of Agriculture and Natural Resources Anthropology, University of Georgia.

Wade, L.J., George, T., Ladha, J.K., Sign, U., Bhuiyan, S.I. and Pandey, S. 1998. Opportunities to manipulate nutrient-by-water interactions in rainfed lowland rice systems. Field Crops Research, 56(1–2), 93–112.

White, P.F. and Seng Vang. 1997. Response of rainfed lowland rice to P fertilizer application in Cambodia. In: Fukai, S., Cooper, M. and Salisbury, J. ed. Breeding Strategies for Rainfed Lowland Rice in Drought-Prone Environments; Proceedings of an International Workshop held at Ubon Ratchanthani, Thailand. Canberra, ACIAR Proceedings No. 77, 202–208.

White, P.F., Nesbit, H.J., Chhay Ros, Vang Seng and Bunna Lor. 1999. Local rock phosphate deposits are a good source of phosphorus fertilizer for rice production in Cambodia. Soil Science and Plant Nutrition, 45(1), 51–63.

White, P.F., Oberthur, T. and Pheav, S. 1997a. Soil and rice. In: Nesbitt, H.J. ed. Rice Production in Cambodia. Manila, Philippines, International Rice Research Institute (IRRI), 21–29.

White, P.F., Oberthur, T. and Pheav, S. 1997b. The Soils Used for Rice Production in Cambodia: A Manual for

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Their Identification and Management. Manila, Philippines, International Rice Research Institute (IRRI).

White, P.F., Dobermann, A., Oberthür, T. and Ros, C. 2000. The rice soils of Cambodia. I. Soil classification for agronomists using the Cambodian Agronomic Soil Classification system. Soil Use and Management, 16, 12–19.

White, P.F., Oberthür, T., Dobermann, A. and Ros, C. 1998. Simple soil classifications are important tools for improving fertility management of infertile rice soils of the rainfed lowlands. In: Ladha, J.K., Wade, L., Dobermann, A., Reichardt, W., Kirk, G.J.D. and Piggin, C. ed. Rainfed Lowland Rice: Advances in Nutrient Management Research, Proceedings of the International Workshop on Nutrient Research in Rainfed Lowlands held at Ubon Ratchanthani, Thailand, 12–15 Oct., 1998. Manila, Philippines, International Rice Research Institute (IRRI), 43–58.

Yamauchi, M. 1989. Rice bronzing in Nigeria caused by nutrient imbalances and its control by potassium sulfate application. Plant and Soil, 117, 275–286.

Nitrogen Management for the Rainfed Lowland Rice Systems of Laos

B. Linquist[1*] and P. Sengxua[2]

Abstract

Nitrogen (N) is the most limiting nutrient to rice in the rainfed lowlands of Laos. It is also required in higher quantities and is more susceptible to loss than are other nutrients and therefore efficient use of N is imperative for resource poor farmers. The current N recommendation for rainfed lowland rice is 60 kg N ha^{-1}, applied in three equal splits at transplanting, active tillering and panicle initiation. If problems due to floods, droughts and pests are eliminated, the agronomic efficiency of applied fertilizer N (AE), using this recommendation, is usually greater than 20 kg grain per kg N. The timing of N applications was evaluated in efforts to improve N-use efficiency and it was found that under conditions of sub-optimal N supply the timing of N is flexible. The first N application can be applied between 0 and 30 days after transplanting and the last N application between two weeks before and one week after panicle initiation. This is an advantage in the rainfed system where environmental or economic factors often results in farmers not being able to apply N on the "recommended" day. Increasing the percentage of N applied during active tillering and panicle initiation, when demand for N is high, increased AE, on average, by 9 kg per kg N, compared with applying N in equal splits. On-farm residues combined with inorganic fertilizers generally did not improve fertilizer-use efficiency in the first year of application. The yield benefit to rice following green manure (GM) incorporation was similar to that of urea-N applied at 30 to 60 kg N ha^{-1}. However, on coarse textured soils, GM crops required about three times more P than rice, making them unsuitable for this environment.

RICE is the single most important crop in Lao PDR, occupying a 60% share of the country's total agricultural production (UNDP 1998). About 70% of the total rice area (646 000 ha) is classified as rainfed lowland, of which more than 80% is in the south, growing primarily on six plains adjacent to the Mekong River. In the mountainous north, lowland rice production is confined to valleys. In this paper, southern Laos includes the provinces of Vientiane, Borikhamxay, Khammouane, Savannakhet, Saravane, Sekong, Attapeau and Champassak (south of 19° north), while the north refers to the remaining provinces located mainly north of the 19° latitude.

The annual rainfall pattern is weakly bimodal with a minor peak in May–June and a major peak in August–September (Fukai et al. 1998). However, annual rainfall is erratic with the possibility of drought and/or flooding in any given year. Rainfed lowland rice farmers are usually poor and most of the rice grown is consumed at home (Pandey and Sanamongkhoun 1998). Because of the riskiness of production in this environment and limited capital, fertilizer use is low, being the lowest in Asia (IRRI 1995), even though its use is increasing in the rainfed lowlands (Pandey and Sanamongkhoun 1998).

Nitrogen is required in higher quantities and is more susceptible to loss than other nutrients (Schnier 1995). These factors, combined with the lowland rice farmers' general poverty, make efficient use of N for crop production imperative. The Lao–IRRI Project has been working in collaboration with the Lao National Rice Research Program since 1991 to

KEYWORDS: Rainfed lowland rice, Fertilizer management, N use efficiency, N timing, Green manure, Laos

---

[1] Lao-IRRI Project, Vientiane, Laos
[2] National Agriculture and Forestry Research Institute, Vientiane, Laos
*Corresponding author: Bruce Linquist.
E-mail: b.linquist@cgiar. org

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

develop efficient nutrient management practices for rainfed lowland rice farmers.

This paper summarizes results from experiments that have focused on N-management strategies for the rainfed lowlands, including research on inorganic-N fertilizers, green manures and on-farm residues.

Nitrogen Deficiencies in Laos

Although Lao soils have not yet been fully classified, chemical and physical indicators of native soil fertility in the lowlands are known to differ between the two regions of Laos. Analyses (0–20 cm) indicate that 80% of the southern soils contain less than 2% organic matter, 68% are coarse textured (sands, loamy sands, and sandy loams) and 87% have a pH (H_2O) of less than 5.5 (Figure 1). In contrast, the northern lowland rice soils are more fertile: 66% of the soils contain more than 2% organic matter, 80% are loams or clay loams, and only 48% have a pH of less than 5.5.

Nitrogen is the most limiting nutrient for lowland rice, according to results from on-farm N–P–K omission trials conducted throughout Laos (Linquist et al. 1998). Nitrogen deficiencies were more common in southern (86% of sites evaluated) than in northern Laos (50% of the sites evaluated). When no N was applied, average yields across sites were significantly higher in the north (2.91 t ha^{-1}) than in the south (2.25 t ha^{-1}), reflecting the differences in soil fertility discussed in Figure 1.

A direct assessment of indigenous soil-N supply was not possible because of a lack of soil and plant N analyses, although soil indigenous-N fertility can be estimated from yield data in -N plots where P and K have been added. Under such conditions, N is the most limiting nutrient and yields would indicate soil N fertility level (Dobermann and Fairhurst 2000). For our analysis, 32 rainfed sites were available (11 in the north and 21 in the south). These both had -N yield data (P and K added) and soil organic matter (SOM) data. Regression analysis indicated a significant correlation existed between yield from -N plots and SOM (Figure 2), suggesting that the native-N supply was derived from mineralization of organic matter.

These data contrasted with those of Cassman et al. (1996b), who found no relationship between soil organic carbon and indigenous-N supply in intensive irrigated rice soils. They suggested that the reasons for the poor correlation were (1) inputs of N from other sources, (2) degree of congruence between soil-N supply and crop demand since N mineralization is sensitive to soil drying, fallow length, crop rotation and residue management and (3) differences in soil organic matter quality with intensive cropping under submerged soil, compared with rainfed lowland soils. In the extensive rainfed conditions of Laos, these factors are more uniform across locations than in intensive irrigated systems. For example, lowland rice receives no irrigation water that would provide additional sources of N; soil remains dry during the dry season; and straw, the primary residue in these systems, is either burned or grazed by the end of the dry season.

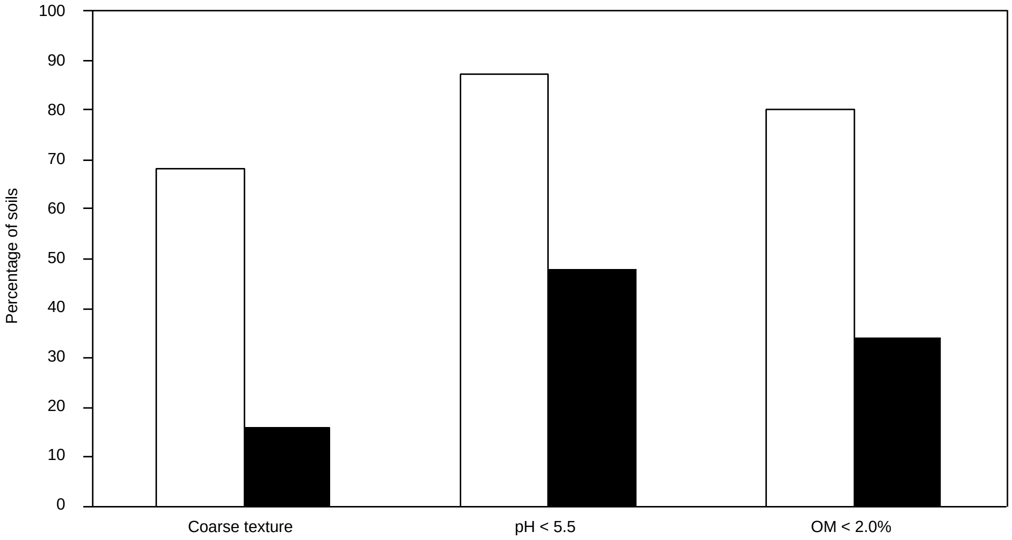


Figure 1. Comparison of soil texture, pH (H_2O) and organic matter contents (OM) of lowland rice soils (0–20 cm) in southern (☐) and northern (■) Laos. Coarse-textured soils include sands, loamy sands and sandy loams.

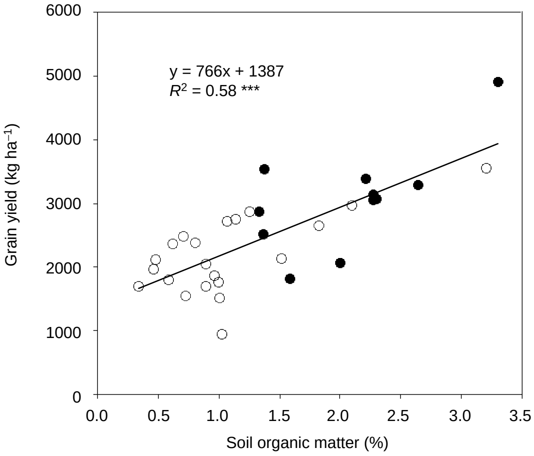


Figure 2. The relationship between soil organic matter and rice grain yields in minus N plots (which received P and K fertilizers). Values are means from 11 field experiments in northern (●) and 21 in southern (○) Laos. *** = significant at $P < 0.001$.

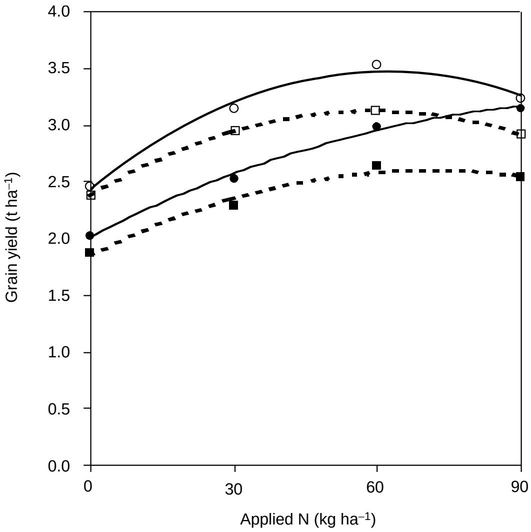


Figure 3. Responses of improved (circles) and traditional (squares) varieties to applied nitrogen (N), as averaged from five experiments in southern (solid) and four experiments in northern (open) Laos.

Nitrogen-Use Efficiency

The primary focus of N management research conducted in Laos has been to improve N-use efficiency. One of the many ways of estimating or calculating N-use efficiency is to use the agronomic efficiency (AE) index of N use, which is calculated as follows:

$$\text{AE (kg grain per kg N)} = \frac{\text{treatment yield (kg)} - \text{yield in control (kg)}}{\text{amount of N applied (kg)}} \qquad [1]$$

This incremental efficiency from applied N is proportional to the cost-benefit ratio from investment in N inputs (Cassman et al. 1996a).

The current N recommendation for improved varieties in the rainfed lowland environment is N at 60 kg ha^{-1}, applied in three equal splits at transplanting, active tillering (AT) and panicle initiation (PI). The N rate is based on N response experiments (Figure 3) and a realization of farmer risk. In both the northern and southern regions, response to N can be obtained with as much as 60 kg ha^{-1} (Figure 3). In the north, however, no response occurs with N rates higher than 60 kg ha^{-1}. The rainfed lowlands comprise a high-risk environment that is prone to drought, floods and pest damage. While higher yields may result from increased N inputs in the south, the additional cost of inputs needs to be evaluated against the risks of no additional response.

The AE of N applied at the recommended rate was estimated from 107 experiments conducted in Laos between 1991 and 1999 (32 in the north and 75 in the south). In all cases, improved varieties were used and P and K were applied at transplanting to ensure that these nutrients were not limiting. Sites that were adversely affected by drought, flood or insect damage were not removed from the analysis, so that a lack of response to N fertilizer at a site does not necessarily indicate that N was limiting. Rice yields in the absence of N averaged 2.9 t ha^{-1} in the north and 2.1 t ha^{-1} in the south, similar to the results from the N–P–K omission studies mentioned above.

These experiments show a significant N response ($P < 0.05$) at 77% of the sites. The average AE across all sites in response to N at 60 kg ha^{-1} was 14.9 kg kg^{-1} (Table 1), and ranged from 0 to 38 kg kg^{-1}. Pandey and Sanamongkhoun (1998) report that, if the AE is greater than 9 kg kg^{-1}, fertilizer use is economically attractive to farmers. As noted above, this data set includes all experiments, including those in which some of the crop was lost to biotic and abiotic stresses and, as such, the set reflects the risks inherent in this environment with fertilizer use. If crop failures are omitted from the analysis, AE is commonly in excess of 20 kg kg^{-1}, as will be seen in the following discussion.

Further analysis of this data set indicated no differences in the AE between northern (14.5 kg kg^{-1}) and southern (15.1 kg kg^{-1}) Laos (Table 1). Neither did soils differ in indigenous-N supply as estimated by using yield from the -N treatments (Dobermann and Farihurst 2000). Finally, an analysis of a subset of these data (those 31 sites for which data on significant responses to applied fertilizer N and soil data were available) indicated no relationship between the AE and either clay or organic matter content (data not shown). A prominent feature of Lao soils is that they are coarse textured (Figure 1) and, as such, tend to have higher percolation rates than finer textured soils. In such cases, N is more susceptible to leaching (Katyal et al. 1985) and denitrification (because of a higher probability of being subjected to wetting and drying cycles), and a lower AE would be expected. However, under the conditions in which the N was applied (three splits), differences in soil properties such as soil texture and organic matter or indigenous-N supply did not affect the AE. Probably, if all the N fertilizer were applied at one time only, such differences in soil properties would have a significant effect.

Table 1. Agronomic efficiency (AE = grain yield increase per unit of applied N) of rice production receiving nitrogen (N) at 60 kg ha^{-1} and averaged across 107 experiments conducted in Laos between 1991 and 1999.

Parameter	Sites (no.)	AE (kg grain per kg N)
Area		
Entire country	107	14.9
Northern region	32	14.5
Southern region	75	15.1
Yield under “-N” treatment (t ha^{-1})		
<1	5	13.8
1–2	43	15.4
2–3	36	14.1
>3	23	15.4

Improving Nitrogen-Use Efficiency

Effect of Cultivar

Until recently, 79% of the rainfed lowland rice area in southern Laos was planted to traditional rice varieties (Pandey and Sanamongkhoun 1998). However, the situation is changing rapidly, as an increasing number of improved varieties are being grown. Even so, many farmers still grow traditional varieties on a significant portion of their land. This may be because of preferences in taste or other grain qualities or to spread out risk and labour demands. Given the limited capital available to purchase N, the efficiency of N applied to traditional and improved varieties needs to be studied.

Nine studies were conducted during the 1995 and 1996 wet seasons at five sites in southern Laos and four in northern Laos to compare the response of traditional and improved varieties to fertilizer N. As seen in other studies, average yields in the south were lower than those in the north by about 0.5 t ha^{-1} (Figure 3). When no N was applied, yields of traditional varieties were similar to those of improved varieties. In all cases, yield response to N was positive until N was being applied at 60 kg ha^{-1}. Only in the south, with the use of improved varieties, was there a continued response to additional N inputs. Response to N also varied between traditional and improved varieties, with the improved varieties responding better. The AE of N use at rates of up to 60 kg ha^{-1} averaged 18.3 kg grain per kg N for improved varieties, compared with 15.0 kg grain per kg N for traditional varieties. Similar responses have been observed elsewhere and for different crops. However, these results suggest that, for resource-poor farmers to maximize N-use efficiency, limited N supplies should be applied to paddy fields with improved varieties rather than as a blanket application across all fields.

Nitrogen timing

Nitrogen is highly susceptible to loss. Matching supply of N with crop demand should increase N-use efficiency. To this end, the effect of applying the entire N recommendation at once or of applying it in splits was evaluated in 26 on-farm trials. Four treatments were used: (1) all N applied at transplanting, (2) N requirement split equally between transplanting and 50 days after transplanting (DAT), (3) N requirement split equally between transplanting, 35 DAT and 55 DAT, and (4) N requirement split equally between 20, 40 and 60 DAT. In all cases, improved varieties were used. Results indicated that applying N at the recommended rate in three or more splits was superior to one or two splits (Table 2), significantly increasing yields by about 0.37 t ha^{-1} (i.e. almost 12%) and improving the AE by 4.1 kg grain per kg N. These results are consistent with reports from Prasad and De Datta (1979) and De Datta et al. (1988), and form the basis for the broadly applied recommendation of splitting N requirements. Furthermore, for high-risk, low-input systems, splitting N requirements helps minimize risk in those cases where crops fail during vegetative growth. A large initial purchase of fertilizer is thus avoided.

The recommended times for N application are at transplanting, AT and PI. However, N application at these times is sometimes not possible because of temporary flooding, no standing water or no cash to purchase fertilizers. Those opportunities when N can be applied without loss in efficiency must therefore be established. Several experiments were conducted to discover the scope for adjusting the timing of the first and last N applications.

Table 2. Effect on rice grain yield when nitrogen (N) applications were split. In all cases, the rate of N at 60 kg ha^{-1} was applied and, when the application was split, the doses were equal. Grain yields are averages from 26 experiments conducted in Laos.

Treatment	At:[a]	Grain yield (kg ha^{-1})
One-time application	Transplanting	3130 c
2 splits	Transplanting + 50 DAT	3312 b
3 splits	Transplanting + 35 and 55 DAT	3496 a
4 splits	Transplanting + 20, 40 and 60 DAT	3405 ab

[a] DAT = days after transplanting.

Recommendations typically call for the first N application to be incorporated into the soil just before transplanting. This puts the fertilizer N into a reduced soil layer and minimizes loss through denitrification (Obcemea et al. 1984). Farmers have not generally adopted this practice, preferring to apply the first N application after crop establishment (Schnier 1995), a situation that is also observed in Laos. To determine whether such a recommendation was necessary, we compared the effect of incorporating N just before transplanting with applying N one day after transplanting, in six replicated experiments. Rice responded well to N at all sites, with yields increasing, on average, by 63% to applied N. However, no differences in rice yields were observed between the different methods of N incorporation (Table 3). The current farmer practice of applying N after crop establishment therefore seems reasonable.

Some researchers question the need for a basal application, arguing that transplanted rice suffers from physiological shock for 10 to 14 days after transplanting, resulting in low initial demand for N (Schneir et al. 1987). Fertilizer N applied at this time would not be readily taken up and would be prone to loss. Furthermore, N available from the mineralization of organic matter is greatest during crop establishment (Dei and Yamasaki 1979) and should be adequate to meet crop needs during the early growth stage, at least for soils with a high N status (Schnier 1995). However, Lao soils are inherently low in organic matter (Figure 1) and the need for early N application must be evaluated under these conditions.

The timing of the first N application was evaluated in Laos across 15 sites (each site being a single replicate). The first N application was applied either before transplanting, or 1, 10, 20 or 30 days afterwards. In all cases, N was applied at 60 kg ha^{-1} in three equal splits (20 kg ha^{-1} each) at the first application and 30 and 50 DAT. The exception was the treatment in which the first N application was applied at 30 DAT. In this treatment, N was applied in two equal splits (30 kg ha^{-1} each) at 30 and 50 DAT. In all cases, the popular improved variety, TDK1, was used.

Table 3. Comparison of rice yields after incorporating the first nitrogen (N) application with applying N after transplanting and not incorporating (based on the results of six replicated experiments conducted in Laos).

Treatment	Grain yield (kg ha^{-1})
No N	2451 b
N incorporated before transplanting	3880 a
N applied 1 day after transplanting	4120 a
Site	***
N treatment	***
Site × N	ns

*** = significant at $P < 0.001$.

Analysis across sites and treatments shows that yields increased by 1.39 t ha^{-1} in response to N, corresponding to an AE of 23 kg grain per kg N (Table 4), with no significant effect of timing of the first N application on rice yields. Furthermore, neither SOM nor soil texture affected these results. Either adequate N was available from N mineralization to provide N needs early during crop growth, even at low SOM, or the crop was able to compensate for temporary N deficiencies in early crop growth. The latter case seems more probable because the crops displayed visual N-deficiency symptoms during early growth when N was applied late. However, under conditions of suboptimal N supply, early season N deficiencies can be compensated for by applying N later.

The timing of the last N application should ideally be at PI. However, late-season drought often forces farmers to delay this application. To determine when the last N application is most efficiently used, seven replicated studies were conducted in the wet and dry seasons, and the last N applications were tried at 50, 65 and 80 DAT (in the dry-season experiments, we included a 40-DAT trial). During the wet season, N was applied at 60 kg ha^{-1}, while 90 kg ha^{-1} was applied during the dry season. In both cases, N was applied in three equal splits. Cultivar TDK1 was used in all studies. Panicle initiation for TDK1 is roughly 50 DAT, varying with location. To standardize timing across sites, we assumed PI to be 25 days before flowering (De Datta 1981). All application times were then made relative to PI rather than to transplanting time. To evaluate the data across sites, relative yield (relative to the highest yield at each site) was plotted against the time of the last N application (Figure 4). The data indicated that

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

delaying the last N application by more than a week after PI results in yield declines, but no negative effects appear when applying N up to 20 days before PI (although only two points support this). If conditions are favourable, farmers should therefore not wait until PI to apply N, but should apply it 2 weeks before. If conditions are unfavourable, application can wait until one week after PI, after which N-use efficiency declines.

Table 4. Effect on rice grain yields of timing of the first application of nitrogen (N) on soils differing in organic matter (OM) and clay contents. Data represent the increase in yields (kg ha^{-1}) relative to a control with no N.

Timing[a] of first N application	Increase in grain yield (kg ha^{-1})				
	All sites (n = 15)	Organic matter at:		Clay content at:	
		<0.8% (n = 6)	>1.0% (n = 9)	<12% (n = 4)	>15% (n = 11)
0[b]	1348	1450	1291	1610	1276
1	1353	1320	1376	1293	1375
10	1326	1308	1337	1519	1274
20	1395	1350	1425	1287	1434
30	1530	1452	1573	1406	1564
Significance:	ns	ns	ns	ns	ns

[a] Days after transplanting. [b] Applied and incorporated before transplanting.

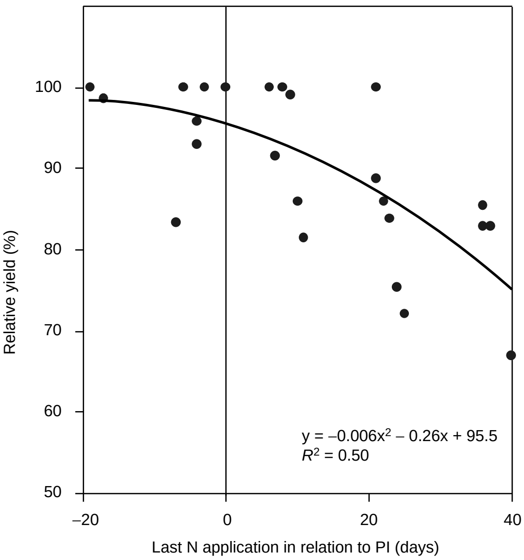


Figure 4. Relative yield (relative to the highest yield at each site) of the rice cultivar TDK1 in relation to the timing of the last application of nitrogen (N) fertilizer. Zero on the x axis = panicle initiation (PI).

Ratio of nitrogen in each split

Increasing N-use efficiency can be achieved by increasing the congruence between N supply and crop demand (Cassman et al. 1996a). As noted above, demand for N is low during early vegetative growth following transplanting, and N from the mineralization of organic matter may be enough to meet early crop demand. Furthermore, demand is high during AT and PI, suggesting that more N is required during this period. Therefore, a study was conducted to compare the effectiveness of N applied as three equal splits (the current recommendation) with a strategy whereby most of the N was applied at AT and PI. The replicated experiment was conducted at six sites during the 1998 and 1999 wet seasons. Nitrogen was either applied at 60 kg ha^{-1} in three equal splits at transplanting, AT and PI; or it was applied at a rate of 10, 25 and 25 kg ha^{-1} at transplanting, AT and PI, respectively.

Yields responded well to N in both treatments, increasing by 1.42 t ha^{-1}, on average, in response to the 60 kg ha^{-1} rate (average AE = 24 kg grain per kg N) (Table 5). When 83% of the N requirements was applied at AT or PI, yields were higher (0.53 t ha^{-1}) than when N was applied in equal splits. On average, the AE increased by about 9 kg grain per kg N (from 19.3 to 28.1 kg kg^{-1}). Examining the significant interaction between N treatment and site indicated that, at half of the sites, the response to applying a greater proportion of the N later during crop growth was greater than 0.4 t ha^{-1} while, at the remaining sites, yields were similar for the two N management strategies. Importantly, at no site was a negative impact found by applying a greater proportion of N later in the crop cycle.

Table 5. The effect on rice yields of applying nitrogen (N) in three equal splits at transplanting (TP), active tillering (AT) and panicle initiation (PI) versus applying a higher proportion of N during AT and PI. Data are the results of seven experiments conducted over two wet seasons in Laos.

N applied (kg ha^{-1}) at TP–AT–PI	Yield (kg ha^{-1})	Agronomic efficiency (kg grain per kg N)
0–0–0	2458 c	—
20–20–20	3615 b	19.3
10–25–25	4141 a	28.1
Significance		
Site	***	
N	***	
Site × N	***	

*** = significant at $P < 0.001$.

Effects of residue on fertilizer-use efficiency

Reports from across the border in Northeast Thailand indicate that, on some soils, rice did not respond to inorganic fertilizers without organic amendments also being applied (Ragland and Boonpuckdee 1988; Willett 1995). In a more recent study, Wade et al. (1999) found that response to inorganic fertilizers in Northeast Thailand was less than at other rainfed locations in India, Philippines, Indonesia and Bangladesh. In Laos, most farmers do not efficiently use on-farm residues such as manure, rice straw and rice husks (Linquist et al. 1999).

To evaluate whether organic amendments would improve fertilizer-use efficiency, two studies were conducted at each of two sites during the 1998 and 1999 wet seasons. At the three sites in the south (two in Saravane and one in Champassak), soils were low in organic C and N and available P and K, whereas the soil at the Vientiane site was generally more fertile (Table 6).

The objective of the 1998 study was to determine whether residues, used in combination with N, improved N-use efficiency. The experiment was conducted in Vientiane and Saravane (Khongsedon District) Provinces. The experimental design was a split plot, with the treatments “with and without N fertilizer” as the main plots and residue treatments (no residue control, manure at 2.6 and 5.2 t ha^{-1} and rice husks at 1.3 t ha^{-1}, dry weight basis) as subplots. Basal rates of P and K were applied to ensure that these nutrients were not limiting.

Table 6. Soil properties of the sites for experiments conducted in the 1998 and 1999 wet seasons, Laos, to determine whether residues improve nitrogen- and fertilizer-use efficiency.

Year and Site	Soil texture	Organic C (%)	Kjeldahl N (%)	Olsen P (mg kg^{-1})	Exch. K (cmol kg^{-1})
1998					
Vientiane	Loam	0.68	0.096	1.7	0.082
Saravane[a]	Silty loam	0.11	0.007	1.1	0.077
1999					
Champassak	Sandy loam	0.13	0.028	1.1	0.035
Saravane[b]	Silty loam	0.31	0.070	1.1	0.085

[a] Khongsedon District.

[b] Saravane District.

A similar study was conducted in 1999 in Champassak and Saravane (Saravane District) Provinces to evaluate the effect of residues on fertilizer-use efficiency (as opposed to N-use efficiency). The experiment was a split plot design, with the treatments “with and without fertilizer” (60, 13, 18 kg ha^{-1} of N, P and K, respectively) as the main plots, and residue treatments (manure, rice husks and straw, each at 2.0 t ha^{-1}, dry weight basis) and a control as subplots.

In the 1998 study, yields increased by 0.9 (AE = 15 kg kg^{-1}) and 1.4 t ha^{-1} (AE = 23 kg kg^{-1}) in Vientiane and Saravane, respectively, in response to fertilizer N alone (Figure 5). Yield increases from residues alone ranged from 12% to 35%, with the response to residues being greater in Vientiane than in Saravane. On average, yields for the two sites increased by 0.3, 0.4 and 0.7 t ha^{-1} in response to rice husks and 2.6 and 5.2 t ha^{-1} of FYM, respectively. In Vientiane, the interaction between residues and N was not significant, suggesting that the benefits of residues and N fertilizer were additive. However, in Saravane, a significant, but negative, interaction was found. In this case, if N fertilizer was already applied, then applying residues was of no benefit to grain yield.

In the 1999 study, applying fertilizer alone increased yields by 134% and 107% in Champassak and Saravane, respectively, while amendments of residues alone increased yields by about 50% at both sites (Figure 6). The greater response to fertilizer and residues in 1999, compared with 1998, is probably because the response was to a combination of N, P and K versus only N in 1998. In Champassak, a significant but negative interaction, similar to that observed in the 1998 Saravane study, was also observed. In the 1999 Saravane study, the interaction between fertilizer and residue treatments was positive. In this case, manure, applied with inorganic fertilizers, increased yields by 1.4 t ha^{-1}, suggesting a synergistic benefit from manure + inorganic fertilizer.

These studies demonstrate that commonly available on-farm residues applied alone and at realistic rates can result in yield increases of up to 50%. In our study, the yield responses to residues are generally higher than those reported from Northeast Thailand. Supapoj et al. (1998) found that amendments of rice straw (6.25 to 18 t ha^{-1}) and rice husks (3.13 t ha^{-1}) increased rice yields by 10% to 15% (0.3 t ha^{-1}, on average). In another study, Whitbread et al. (1999a) reported small but significant yield increases (8%–10%) in response to returning rice straw in two of the five years of their study. Finally, with the application of manure (6.25 t ha^{-1}), Wonprasaid et al. (1996) reported that yields increased by up to 0.9 t ha^{-1}.

Our studies further demonstrate that modest rates of inorganic fertilizer applied alone can result in yield increases of over 100%. These data contrast those of Willett (1995) and Ragland and Boonpuckdee (1988), who reported that, on some sandy soils in

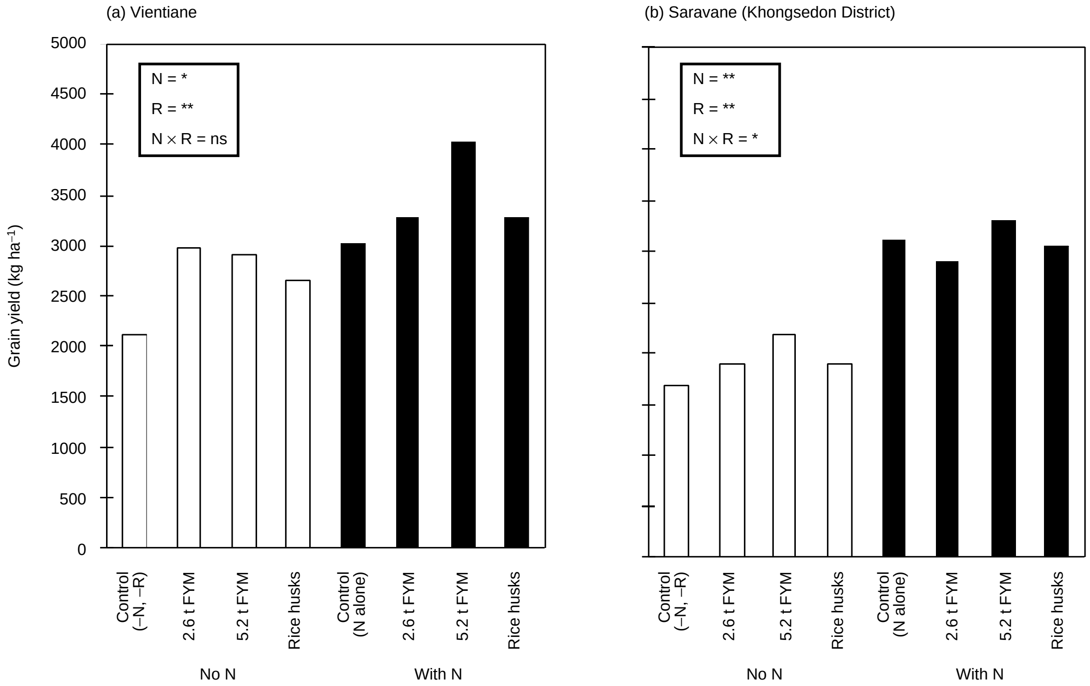


Figure 5. Rice grain yield response to the application of inorganic nitrogen (N at 60 kg ha^{-1}) and on-farm organic residue (R; rice husks at 1.3 t ha^{-1}, and farmyard manure [FYM] at 2.6 or 5.2 t ha^{-1}), Laos, 1998 wet season. * = significant at *P* = 0.05; ** = significant at *P* = 0.01.

Northeast Thailand, the rice crop did not respond to inorganic fertilizers without organic amendments also being applied. Furthermore, only in one case was a positive interaction between a combined residue and fertilizer application found (Saravane, manure + fertilizer, Figure 6b). In fact, at two sites, a significant negative interaction was found (Figures 5b and 6a), indicating that the immediate benefits of residues were lost when inorganic fertilizer was applied.

Reasons for this discrepancy may be, first, fertilizers have been used in Thailand longer than in Laos. The use of primarily N and P fertilizers over a long period, as in Thailand, may result in deficiencies of other nutrients (e.g. K or other micronutrients), which are available in organic amendments. Second, the soils evaluated in our study were coarse-textured loams and loams, whereas Thai soils were sandy with a lower capacity for nutrient retention and buffering. However, as Table 4 and the above discussions suggest, if N is applied as a split application, it is used relatively efficiently, regardless of soil texture.

These data indicate only the immediate effect of residues on rice yields. Long-term benefits of repeated residue applications are likely to be more significant. A strategy of applying only N and P over time results in deficiencies of other nutrients not available in these fertilizers (Dobermann et al. 1998). Long-term benefits of repeated residue applications may therefore result in positive interactions if SOM increases and the benefits from other nutrients besides N and P are realized. However, because increasing SOM in cultivated soils, especially sandy soils, is difficult, it should not be assumed that adding organic matter will always increase SOM. Even so, applying available on-farm residues is a recommendable strategy for enhancing the sustainability of these systems, even though direct evidence of their benefits is, at present, lacking.

Green manure

Green manure (GM) technology has often been proposed as a means of alleviating N deficiencies in low-input cropping systems and as a way of improving N conservation within the cropping system by capturing N that accumulates during the dry and early wet seasons (George et al. 1994). Several experiments have been conducted to evaluate GM in central and southern Laos. These are reported elsewhere by Chanphengsay et al. (1999) and Whitbread et al. (1999b), but a summary of some of their work and that of others is presented here.

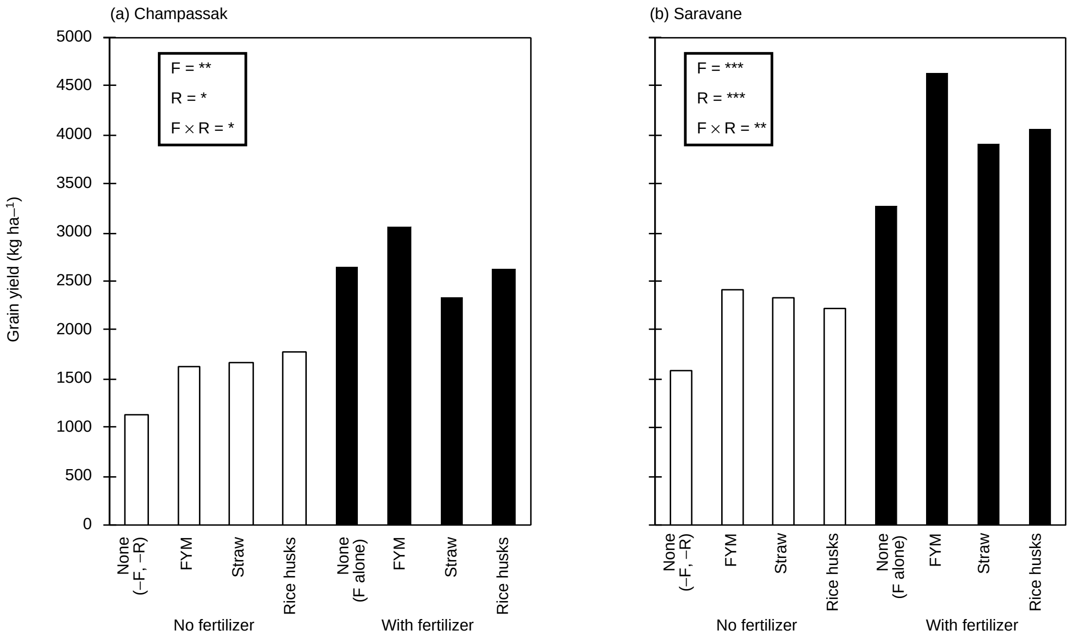


Figure 6. Rice grain yield response to on-farm residues (R; 2 t ha^{-1}, dry weight basis), with and without inorganic fertilizer (F), Laos, 1999 wet season. The inorganic fertilizer was applied at a rate of 60-30-20 kg ha^{-1} of N, P_2O_5 and K_2O, respectively. * = significant at $P = 0.05$; ** = significant at $P = 0.01$.

A 7-year study was conducted in Vientiane to evaluate the potential of various stem-nodulating legumes and grain legumes. The stem-nodulating legumes (*Sesbania rostrata*, *S. aculeata* and *Aeschynomene afraspera*) performed consistently well over the years. The grain legumes evaluated did not tolerate saturated soils but performed as well as the stem-nodulating legumes when soils remained unsaturated. The aboveground biomass of the stem-nodulating legumes averaged 2.6 t ha^{-1} and contained N at 60 to 80 kg ha^{-1}. Becker et al. (1990) reported biomass yields of *S. rostrata* exceeding 8 t ha^{-1} and N contents of over 150 kg ha^{-1}. In Laos, however, early season drought often limits yields.

In most studies, the increase in rice yields in response to GM was equivalent to N supplied as urea at 30 to 60 kg ha^{-1}. Improved response to GM may be possible by combining straw with the GM. Becker et al. (1994) reported that doing this slowed N mineralization, reducing N losses and improving N-use efficiency. In Laos, we evaluated the effect of adding straw to *S. rostrate* and *A. afraspera* during GM incorporation on rice yields and N-recovery efficiency (NRE = increase in N uptake per unit of N applied). Nitrogen from GM (GM-N) provided the equivalent of 30 to 60 kg ha^{-1} of N as urea, which was not enough to meet rice requirements, as evidenced by the significant increase in yield when N was applied at 90 kg ha^{-1} (Table 7).

Table 7. Response of rice to inorganic and organic nitrogen (N) sources. Organic sources were *Sesbania rostrata* (S.r.), *Aeschynomene aferaspera* (A.a.) and rice straw.[a]

Treatment[b]	GM yield	Total N added	Rice yield	N uptake	NRE[c] (%)
		kg ha^{-1}			
0 N		0	1749 e	17.9 c	
30 N		30	2854 bc	30.0 bc	40.4
60 N		60	3074 b	37.6 ab	32.9
90 N		90	3664 a	51.6 a	37.4
S.r.	1916 a	35.6	3093 b	34.3 bc	46.0
S.r. + straw	1916 a	42.7	3017 b	37.0 b	44.6
A.a.	1626 a	34.6	2351 cd	27.8 bc	28.6
A.a. + straw	1626 a	41.7	3029 b	38.7 ab	49.9
Straw		7.1	2197 de	26.6 bc	123.1

[a] Within columns, means followed by the same letter do not differ significantly at the 0.05 probability level.
[b] Straw was added at a rate of 1335 kg ha^{-1} to all straw treatments.
[c] NRE = nitrogen recovery efficiency, which is the increase in N uptake per unit of N applied.

The NRE for urea-N averaged 37%. Nitrogen inputs for both GM crops were similar and averaged

35 kg ha^{-1}. Without straw, the NRE of *S. rostrata*-N was 46%, compared with only 29% for *A. afraspera*-N. Adding 1.5 t ha^{-1} of rice straw to *A. afraspera*, the biomass before incorporation increased rice yields by about 0.7 t ha^{-1} and the NRE from 29% to 50% (Table 7). But this was not observed for *S. rostrata*. The difference in the effect of straw on the two GMs is most likely a result of *S. rostrata* having a higher C:N ratio than does *A. afraspera* (Becker et al. 1990). In this study, N concentration (1.86%) in the *S. rostrata* biomass was lower than in *A. afraspera* (2.13%), which suggests a higher C:N ratio. Furthermore, C:N ratios were probably higher than normal for both GMs in this study because they were grown for 75 days, rather than for the recommended 60 days.

Optimal GM growth and biological N_2 fixation is dependent on an adequate P supply. The aboveground dry weight of *S. rostrata* averages less than 0.5 t ha^{-1} without P fertilizer on coarse-textured soils (Whitbread et al. 1999). Data from four experiments conducted on coarse-textured soils indicate that P at 20 kg ha^{-1} is required to optimize *S. rostrata* yields on these soils (Figure 7). On similar soils, rice P requirements were only 6.5 kg ha^{-1} (Figure 7), based on results from a different set of four P-rate experiments conducted in the same region as the *S. rostrata* studies. The higher P requirements of GMs, relative to rice, is also reported by Ventura and Ladha (1997), and may be caused by P being less available under aerobic conditions, which are more common during the GM growth period (start of wet season), than under anaerobic conditions, which prevail during most of the rice-growing season (Mahapatra and Patrick 1969; Willett 1986). Legumes, in any case, tend to have higher P requirements than do other crops because of the energy requirements for biological N_2 fixation. Given the high P requirements of GMs, relative to rice on these soils, GMs may not be economically attractive to resource-poor farmers.

Apart from the high P requirements, farmers cite other constraints for not adopting GMs, including high labour demand during peak periods such as transplanting; difficulties in land preparation before the heavy rains (especially for farmers who use buffalo); and difficulties in purchasing or producing seed. These constraints are consistent with Pandey and Sanamongkhoun's hypothesis (1998) that technologies that increase labour requirements are unlikely to be accepted in places like Laos. Furthermore, in southern Laos, fertilizers are readily available. While the widespread adoption of GM technology in southern Laos is doubtful, it may have a role in the rainfed lowland systems of northern Laos where fertilizers are less accessible and P deficiencies are not as prevalent.

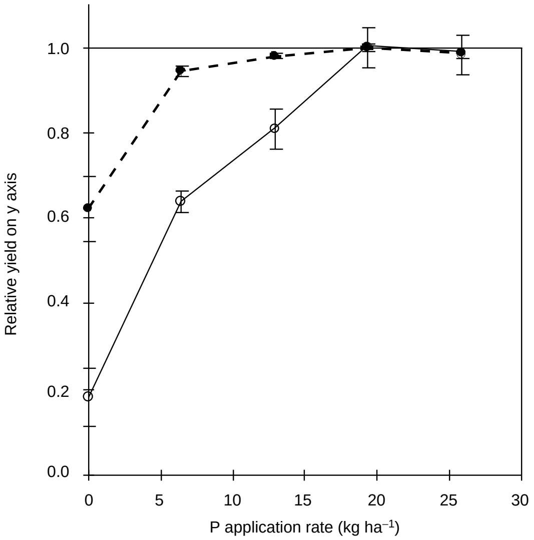


Figure 7. Relative yield (relative to maximum yield) of the legume *Sesbania rostrata* (○) and rice (●) in response to phosphorus (P) on coarse-textured soils, Laos. Data represent means of four experiments. Error bars represent one standard deviation.

Conclusions

Despite the relative efficiency of applied N when drought, floods and pests do not lower yields, scope still remains for improving N-use efficiency at the farm level. First, limited N resources should be applied to improved varieties, which are more responsive to inputs. Second, timing N supply with the crop's demand for N should be improved to ensure a greater proportion of N during the vegetative stage when N demand is greatest. Third, while applying organic amendments does not improve inorganic fertilizer use efficiency in the short term, recycling of crop residues should, in the long-term, improve N-use efficiency, as nutrients removed in these residues become limiting and weaken response to N. Finally, under suboptimal N conditions, considerable flexibility exists for varying the timing of N application around transplanting and PI without decreasing N-use efficiency or yield. While response to pre-rice GMs is relatively good, the relatively high P requirements of the latter make the technology less attractive to farmers.

References

Becker, M., Ladha, J.K. and Ottow, J.C.G. 1990. Growth and N_2-fixation of two stem-nodulating legumes and their effects as green manure on lowland rice. Soil Biology and Biochemistry, 22, 1109–1119.

Becker, M., Ladha, J.K., Simpson, I.C. and Ottow, J.C.G. 1994. Parameters affecting residue nitrogen mineralization in flooded soils. Soil Science Society of America Journal, 58, 1666–1671.

Cassman, K.G., Gines, G.C., Dizon, M.A., Samson, M.I. and Alcantara, J.M. 1996a. Nitrogen-use efficiency in tropical lowland rice systems: contributions from indigenous and applied nitrogen. Field Crops Research, 47, 1–12.

Cassman, K.G., Dobermann, A., Sta. Cruz, P.C., Gines, G.C., Samson, M.I., Descalsota, J.P., Alcantara, J.M., Dizon, M.A. and Olk, D.C. 1996b. Soil organic matter and the indigenous nitrogen supply of intensive irrigated rice systems in the tropics. Plant and Soil, 182, 267–278.

Chanphengsay, M., Whitbread, A., Schiller, J., Blair, G., Linquist, B.A., Lathvilayvong, P. and Sengxua, P. 1999. Soil fertility decline in Lao PDR and the potential of pre-rice green manures to improve the sustainability of rice production systems. In: Whitbread, A.M. and Blair, G.J. ed. Integrated nutrient management in farming systems in Southeast Asia and Australia. Vientiane, Laos, ACIAR Proceedings No. 93.

De Datta, S.K. 1981. Principles and Practices of Rice Production. John Wiley, New York.

De Datta, S.K., Buresh, R.J., Samson, M.I. and Wang, K.-R. 1988. Nitrogen use efficiency and nitrogen-15 balances in broadcast flooded and transplanted rice. Soil Science Society of America Journal, 52, 849–855.

Dei, Y. and Yamasaki, S. 1979. Effect of water and crop management on the nitrogen-supplying capacity of paddy soils. In: Nitrogen and Rice. Los Baños, Philippines, International Rice Research Institute (IRRI), 451–463.

Dobermann, A. and Fairhurst, T. 2000. Rice: Nutrient Disorders and Nutrient Management. Singapore, Potash & Phosphate Institute (PPI), Potash & Phosphate Institute of Canada (PPIC), and International Rice Research Institute (IRRI), 191 p.

Dobermann, A., Cassman K.G., Mamaril, C.P. and Sheehy, J.E. 1998. Management of phosphorus, potassium and sulfur in intensive, irrigated lowland rice. Field Crops Research, 56, 113–138.

Fukai, S., Sittisuang P. and Chanphengsay, M. 1998. Increasing production of rainfed lowland rice in drought prone environments: A case study in Thailand and Laos. Plant Production Science, 1, 75–82.

George, T., Ladha, J.K., Garrity, D.P. and Buresh, R.J. 1994. Legumes as nitrate catch crops during the dry-to-wet transition in lowland rice cropping systems. Agronomy Journal, 86, 267–273.

IRRI (International Rice Research Institute). 1995. World Rice Statistics, 1993–1994. Los Baños, Philippines.

Katyal, J.C., Singh, B., Vlek, P.L.G. and Craswell, E.T. 1985. Fate and efficiency of nitrogen fertilizers applied to wetland rice. II. Punjab, India. Fertilizer Research, 6, 279–290.

Linquist, B.A., Sengxua, P., Whitbread, A., Schiller, J. and Lathvilayvong, P. 1998. Evaluating nutrient deficiencies and management strategies for lowland rice in Lao PDR. In: Ladha, J.K., Wade, L.J., Dobermann, A., Reichardt, W., Kirk, G.J.D. and Piggin, C. ed. Rainfed Lowland Rice: Advances in Nutrient Management Research; Proceedings of the International Workshop on Nutrient Research in Rainfed Lowlands, 12–15 Oct. 1998, Ubon Ratchatathani, Thailand. International Rice Research Institute. p 59-73.

Linquist, B.A., Sengxua, P., Whitbread, A. and Changpengsay. 1999. The potential of on-farm residues for improving rainfed lowland rice productivity. In: Whitbread, A.M. and Blair, G.J. ed. Integrated Nutrient Management in Farming Systems in Southeast Asia and Australia. Vientiane, Laos, ACIAR Proceedings No. 93.

Mahapatra, I.C. and Patrick, Jr., W.H. 1969. Inorganic phosphate transformation in waterlogged soils. Soil Science, 107, 281–288.

Obcemea, W.N., De Datta, S.K. and Broadbent, F.E. 1984. Movement and distribution of fertilizer nitrogen as affected by depth of placement in wetland rice. Fertilizer Research, 5, 125–148.

Pandy, S. and Sanamongkhoun, M. 1998. Rainfed Lowland Rice in Laos: A Socio-Economic Benchmark Study. Los Baños, Philippines, International Rice Research Institute (IRRI).

Prasad, R. and De Datta, S.K. 1979. Increasing fertilizer nitrogen efficiency in wetland rice. In: Nitrogen and Rice. Los Baños, Philippines, International Rice Research Institute (IRRI), 465–484.

Ragland, J. and Boonpuckdee, L. 1988. Fertilizer responses in NE Thailand. 3. Nitrogen use and soil acidity. Thai Journal of Soils Fertility, 10, 67–76.

Schnier, H.F. 1995. Significance of timing and method of N fertilizer application for the N-use efficiency in flooded tropical rice. Fertilizer Research, 42, 129–138.

Schnier, H.F., De Datta, S.K. and Mengel, K. 1987. Dynamics of ^{15}N labelled ammonium sulfate in various inorganic and organic soil fractions of wetland rice soils. Biology and Fertility of Soils, 4, 171–177.

Supapoj, N., Naklang, K. and Konboon, Y. 1998. Using organic material to improve soil productivity in ranfed lowland rice in Northeast Thailand. In: Ladha, J.K., Wade, L.J., Dobermann, A., Reichardt, W., Kirk, G.J.D. and Piggin, C. ed. Rainfed Lowland Rice: Advances in Nutrient Management Research; Proceedings of the International Workshop on Nutrient Research in Rainfed Lowlands, 12–15 Oct. 1998, Ubon Ratchathani, Thailand. International Rice Research Institute. p 161–168.

UNDP (United Nations Development Programme). 1998. Development Cooperation Report 1997—Lao People's Democratic Republic. Vientiane, Laos 159 p.

Ventura, W. and Ladha, J.K. 1997. Sesbania phosphorus requirements when used as a biofertilizer for long-term rice cultivation. Soil Science Society of America Journal, 61, 1240–1244.

Wade, L.J., Amarante, S.T., Olea, A., Harnpichtvitaya, D., Naklang, K., Wihardjaka, A., Senegar, S.S., Mazid, M.A., Songh, G. and McLaren, C.G. 1999. Nutrient requirements in rainfed lowland rice. Field Crops Research, 64, 91–107.

Whitbread, A., Blair, G.J., Naklang, K., Lefroy, R., Wonprasaid, S., Konboon, Y. and Suriya-Arunroj, D. 1999a. The management of rice straw, fertilizers and leaf litters in rice cropping systems in Northeast Thailand.

2. Rice yields and nutrient balances. Plant and Soil, 209, 29–36.

Whitbread, A.M., Chanphengsay, M., Linquist, B.A., Sengxua, P., Blair, G.J., Vongsouthi, S. and Phengsounanna, V. 1999b. *Sesbania rostrata* as a green manure and phosphorus management for lowland rice production in Lao P.D.R. In: Whitbread, A.M. and Blair, G.J. ed. Integrated Nutrient Management in Farming Systems in Southeast Asia and Australia. Vientiane, Laos, ACIAR Proceedings No. 93.

Willett, I.R. 1986. Phosphorus dynamics in relation to redox processes in flooded soils. In: Transactions of the 13th Congress of the International Society of Soil Science, vol. 6. Hamburg, International Society of Soil Science, 748–755.

Willett, I.R. 1995. Role of organic matter in controlling chemical properties and fertility of sandy soils used for lowland rice in Northeast Thailand. In: Lefroy, R.D.B., Blair, G.J. and Craswell, E.T. ed. Soil organic matter management for sustainable agriculture: 24–26 August 1994. Ubon, Thailand, ACIAR Proceedings No. 56, 163 p.

Wonprasaid, S., Khunthasuvon, S., Sittisuang, P. and Fukai, S. 1996. Performance of contrasting rice cultivars selected for rainfed lowland conditions in relation to soil fertility and water availability. Field Crops Research, 47, 267–275.

Genotypic Performance of Rainfed Lowland Rice under Different Fertilizer Conditions in Laos

P. Inthapanya[1], Sipaseuth[1], P. Siyavong[2], V. Sihathep[3], M. Chanphengsay[4], S. Fukai[5*] and J. Basnayake[5]

Abstract

Low soil fertility is a major constraint to increasing rice productivity under rainfed lowland conditions in Laos. Even though farmers generally apply low fertilizer rates to rainfed lowland rice, the Lao breeding program selects genotypes under higher, although moderate, rates (60 N, 30 P_2O_5 and 20 K_2O kg ha^{-1}). A combined analysis of results from a series of fertilizer experiments conducted over 3 years at three locations revealed that the interactions of genotype-by-location (G × L), genotype-by-fertilizer (G × F) and genotype-by-location-by-fertilizer (G × L × F) had significant effects on grain yield. However, variance components for genotype and the G × L interaction were larger than those for the G × F and G × L × F interactions. Because the G × F interaction had a small effect, the ranking of lines across non-fertilized and fertilized conditions was consistent over the 3 years. Early selection of better performing lines under the program's current fertilizer application rates in a multi-locational testing program could produce better cultivars for the generally poor soils of Laos. The percentages of N and P in seeds were also found to be negatively associated with grain yield among the lines studied. Nitrogen and P use efficiencies (g dry matter g^{-1} nutrient) in lines were consistent across varying fertilizer conditions. Selecting lines for low seed N concentration and high N and P use efficiencies can therefore comprise an alternative approach for selecting high-yielding cultivars for Laos.

THE soils in which most rainfed lowland rice in Laos is cultivated are inherently of low fertility. Systemic studies, conducted since 1991, suggest that low soil fertility is a major constraint to rice production in rainfed lowlands (Lathvilayvong et al. 1997; Linquist et al. 1999). Nitrogen and phosphorus are the most important nutrients that limit grain yields in most areas of Laos. Lathvilayvong et al. (1997) suggest that an initial application of P at 6.5–19 kg ha^{-1} is needed for high grain yield in most areas. Current fertilizer recommendations in Laos range from 60 to 90 kg ha^{-1} for N and from 13 to 19 kg ha^{-1} for P (Linquist et al. 1999).

Breeding programs for rainfed lowland rice usually use higher rates of fertilizer application than is commonly used by Lao farmers. For example, the Lao breeding and selection program uses the rates of 60, 13 and 16 kg ha^{-1} for N, P and K, respectively. The program also uses grain yield to select advanced materials, and use of the appropriate fertilizer rate may be critical in this phase of breeding. Most work on responses to fertilizer by rainfed lowland rice cultivars used only a few cultivars, making it difficult to judge the impact of the genotype-by-fertilizer (G × F) interaction on the efficiency of a breeding program in developing new cultivars suitable for different soil fertility conditions (Romyen et al. 1998).

The varying ability of genotypes to use nutrients may cause variation in grain yield among genotypes under different soil fertility conditions. It is important to identify whether the nutrient use efficiencies

---

[1] National Agriculture Research Center, Vientiane, Laos
[2] Agriculture and Forestry Office, Savannakhet, Laos
[3] Agriculture and Forestry Office, Champassak, Laos
[4] National Agriculture and Forestry Research Institute, Vientiane, Laos
[5] The University of Queensland, Brisbane, Qld., Australia
*Corresponding author:
E-mail: s.fukai@mailbox. uq.edu.au

KEYWORDS: Fertilizer, Genotype-by-fertilizer interaction, Nutrient use efficiency, Rainfed lowland rice

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

(g dry matter g^{-1} nutrient) of those genotypes are consistent across different growing conditions. This information would help in the understanding of the adaptation mechanisms of different genotypes for different fertilizer environments. Morphological and physiological differences in those cultivars can be studied to identify the traits that have high association with nutrient use efficiency.

This work aimed to:

1. Quantify the magnitude of the G × F interaction for grain yield of rainfed lowland rice, using a large number of genotypes that are typical of the Lao breeding program. This should help identify the appropriate level of fertilizer to be used by the breeding program to maximize its efficiency in developing new cultivars.
2. Investigate the importance of nutrient uptake and nutrient use efficiency in determining the variation for grain yield under different fertility conditions.
3. Investigate the effects of N and P on the grain yield of different genotypes in three locations.

Because detailed results of the experiments conducted in 1996 and 1997 are described in Inthapanya et al. (2000a and 2000b), this paper only summarizes the results for those years, and reports on the main features of the 1998 experiments.

Materials and Methods

Three sets of rainfed lowland rice experiments were conducted on farm fields in the Vientiane, Savannakhet and Champassak Provinces of Laos in 1996, 1997 and 1998. The chemical and physical properties of the soils at the three locations are presented in Table 1. First, two experiments in 1996 and 1997 were conducted, using 72 and 60 genotypes, respectively, under fertilized and non-fertilized conditions. For the 1996 experiments, the set of 72 genotypes comprised 20 lines selected from a cross between RD6 and IR46331-PMI-32-2-1-1, 32 lines from a cross between RD6 and IR49801-UBN-7-B-1-4-1, 11 promising lines from Laos, 7 promising lines and improved cultivars from Thailand and 2 traditional Thai and Lao cultivars. Chemical fertilizer was applied at the rate of 60, 13 and 16 kg ha^{-1} of N, P and K, respectively. The N was applied in two split-levels at planting and 50 days after transplanting.

For the 1997 experiment, 13 high-yielding genotypes were selected from the 1996 population and 47 promising lines were taken from the Lao selection program. Most genotypes were of the glutinous grain type. In 1998, a set of 12 lines was taken for further study of their yield response to four levels of N and P fertilizers. The levels were zero fertilizer, N only (at 60 kg ha^{-1}), P only (at 13 kg ha^{-1}) and NPK (at 60 N + 13 P + 16 K kg ha^{-1}).

Table 1. Chemical and physical properties of soils at three locations in the Vientiane (V), Savannakhet (S) and Champassak (C) Provinces, Laos.

Soil property	V	S	C
Soil property			
pH (H_2O)	5.3	5.4	5.5
Organic matter (%)	0.5	0.4	0.5
Total N (%)	—	—	0.04
Available phosphorus (µg g^{-1}) (Bray 2)	7.5	9.3	17.0
Available potassium (µg K_2O g^{-1})	24.0	44.0	108.0
Soil texture			
Sand (%)	66.1	86.2	67.4
Silt (%)	29.2	9.3	27.2
Clay (%)	4.5	4.6	5.3

Source: Inthapanya et al. (2000a).

Plot sizes differed across the 3 years. In 1996, two rows of 3-m plots were used with two replicates, whereas, in 1997, five rows of 3-m plots were used with two replicates. Plot size for 1998 experiments was 1.25 × 3 m (five rows) with three replicates. Seeds were sown in June and transplanted in July in most of the experiments.

Free water levels, both above and below the ground, were measured, using 50 × 10 cm PVC pipes inserted 40 cm deep into the field. Date of flowering was recorded when 75% of the panicles had emerged, and plots were harvested as they matured. Plant height was recorded a few days before harvesting. Grain yield was determined after harvest for the whole plot in 1996, the middle three rows in 1997 and the whole plot in 1998. Moisture content was measured and grain yield adjusted to 14% moisture content.

In the 1997 experiment, a subset of 16 genotypes was used to estimate the N, P and K concentration in seeds and straw separately. Samples were also collected from 12 genotypes in four fertilizer treatments for nutrient analysis in 1998. The N, P and K analyses were conducted as described by Inthapanya et al. (2000b). Nutrient contents in grain and straw were estimated from the tissue nutrient concentration and respective dry weight of seeds and straw.

Each experiment was statistically analysed separately to identify the genotype, fertilizer and their interactions in each environment. Combined analyses were conducted across three locations for 3 years. The variance component for each source of variation was estimated for these experiments.

Nutrient use efficiencies (NUE) were estimated for seed, straw and total plant for each of N, P and K, using the grain and total dry matter (TDM) at

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

harvest. Nitrogen-use efficiencies for the plant (N_iUEp) and grain (N_iUEg) are defined as:

$$N_iUEp = TDM / N\ plant$$
$$N_iUEg = Yield / N\ plant$$

where,

N plant = N content of plant

Similarly, P use efficiency for plant and grain (PUEp and PUEg, respectively) and K use efficiency for plant and grain (KUEp and KUEg, respectively) was estimated.

Results

Variance components in G × F interaction analysis

Results of analyses of variance, variance components and proportion of variance components for grain yield in 1996, 1997 and 1998 are shown in Table 2. In 1996, when yield was particularly low at Vientiane, the location (L) variance was large, accounting for more than 60% of the total variance. The fertilizer variance (F) was the second largest (17.9%), and L × F the third. Genotype (G) effect was significant ($P < 0.05$), and the G variance component (1.1%) was greater than the G × F component. Other two-way interactions and the three-way interaction were also significant. The sum of variances involving genotypes (G, G × L, G × F and G × L × F) was 6.8% and the G × L component was the largest (2.7%) among the four variances. The sum of genotypic variances that did not involve fertilizer (G and G × L) was greater than that involving fertilizer (G × F and G × L × F).

In 1997, the L variance was smaller than the F variance. Similar to 1996, however, the effects of components G, G × L, G × F and G × L × F were all significant, and the G variance was greater than the G × F variance. The sum of four variances that involved genotypes (11.9%) and also the G variance itself were greater in 1997 than in 1996, but as for 1996, the sum of variances for G and G × L was greater than that involving fertilizer.

As in 1997, the L variance was smaller than the F variance in 1998. The effect of G × F interaction was not significant, while the effects of G, G × L and G × L × F were significant. The G and G × L variances had similar effects and were greater than the G × F variance. The sum of four variances that involved genotypes (19.4%) and also the G variance itself were greater in 1997 than in 1996. In all 3 years, results were consistent in that the sum of variances for G and G × L was greater than those involving fertilizer.

Combined year analyses for the 13 common genotypes in 1996 and 1997 showed that the G variance (1.3%) was greater than the G × F variance (0.8%) (data not shown). Among the interaction components involving genotypes, the G × year interaction variance (1.1%) was the largest, followed by the G × L and G × F variances.

Table 2. *F*-ratios and significance of each source of variation, estimated variance components with their approximate standard errors and proportion of variance component from the combined analysis of variance for grain yield (kg ha^{-1}) in genotype-by-fertilizer interaction experiments conducted with rainfed lowland rice genotypes at three locations in Laos in 1996, 1997 and 1998.

Year Source of variation	*F*-ratio and the level of significance	Variance component × 10^4	Proportion of variance component (%)
1996			
Location (L)	529.78 **	73.8 ± 7.9	61.5
Fertilizer (F)	838.27 **	21.6 ± 3.5	17.9
L × F	101.33 **	8.7 ± 0.9	7.3
Genotype (G)	1.76 *	1.3 ± 0.7	1.1
G × L	2.00 *	3.3 ± 0.8	2.7
G × F	1.33 *	0.7 ± 0.5	0.6
G × L × F	1.76 *	2.8 ± 0.8	2.4
1997[a]			
Location (L)	13.46 **	13.5 ± 1.6	16.1
Fertilizer (F)	65.37 **	36.3 ± 53.8	43.1
L × F	2.95 ns	3.4 ± 5.2	4.0
Genotype (G)	7.47 **	5.4 ± 1.5	6.5
G × L	1.48 *	1.5 ± 0.7	1.8
G × F	1.83 *	1.7 ± 0.8	2.1
G × L × F	1.26 *	1.3 ± 0.8	1.5
1998			
Location (L)	52.19 **	8.0 ± 8.9	26.4
Fertilizer (F)	16.54 **	14.2 ± 12.4	47.0
L × F	4.82 **	2.1 ± 1.6	6.9
Genotype (G)	3.26 **	2.4 ± 1.6	8.2
G × L	3.72 **	2.4 ± 1.0	8.1
G × F	1.08 ns	0.1 ± 0.3	0.2
G × L × F	1.34 *	0.9 ± 0.6	2.9

[a] Data for year 1997 were taken from Inthapanya et al. (2000a).

* = $P < 0.05$; ** = $P < 0.01$; ns = not significant.

Grain yield in different experiments

Mean grain yields of all genotypes with or without fertilizer application at three locations in 3 years are shown in Table 3. In all nine experiments (3 years × 3 locations), there was a positive effect of fertilizer application, although the effect was not significant in Vientiane in 1997 when analysed as a single experiment. The low yield at this location in 1996 was the result of a nutrient disorder. Yield was lower at the Savannakhet location than in Champassak over the 3 years because of early season drought in 1996 and late drought in 1997 and 1998.

Table 3. Average grain yield (kg ha^{-1}) of rice lines grown at three locations in the Vientiane (V), Savannakhet (S) and Champassak (C) Provinces, Laos, under non-fertilized (NF) and fertilized (F) conditions, 1996, 1997 and 1998.

Province	Year								
	1996			1997			1998		
	NF	F	Mean	NF	F	Mean	NF	F	Mean
V	488	823	655	1405	1957	1681	1119	1937	1528
S	1205	1811	1508	1217	2091	1619	1348	2061	1705
C	1845	3008	2426	1774	2966	2370	1445	2664	2055
Mean	1179	1880	1530	1465	2314	1890	1304	2206	1755
LSD 5% (location)			426			420			436
LSD 5% (fertilizer)			427			421			441

When grain yields at the three locations were combined for the 1996 experiment, the coefficient of determination for yield of genotypes between the two fertilizer conditions was 0.54 (Figure 1a). However, in 1997, the coefficient was lower (0.45) where a significant G × F interaction was obtained (Figure 1b). Some high-yielding genotypes differed in their responses to fertilizer application: genotypes with a mean yield between 1600 and 1900 kg ha^{-1} under non-fertilized conditions, had yields that varied greatly between 2200 and 3300 kg ha^{-1} when fertilizer was applied.

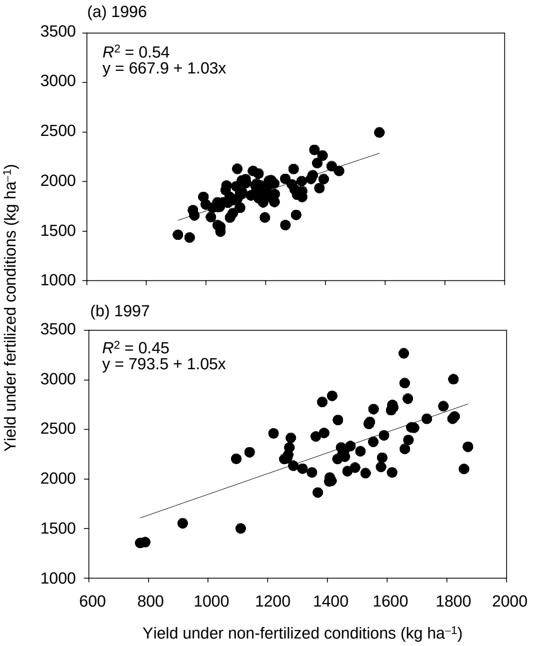


Figure 1. Yield performance of rainfed lowland rice in (a) 1996, with 72 lines, and (b) 1997, with 60 lines, under non-fertilized and fertilized conditions in Laos. Each point represents the mean across three locations (after Inthapanya et al. 2000a).

The 10 highest yielding lines obtained from the three locations and two fertilizer levels for 1996 and 1997 are shown in Table 4. Some of these lines (e.g. TDK1 and IR57514-PMI-5-B-1-2) were often in the top 10 lines for each of the six experiments. All high-yielding entries in 1996 were examined in 1997. Line IR68102-TDK-B-B-31-3 produced the highest yield (2462 kg ha^{-1}), out-yielding TDK1 (2414 kg ha^{-1}) in 1997. Other high-yielding lines were IR68105-TDK-B-B-6-1 (2330 kg ha^{-1}) and IRUBN-4-TDK-1-2-1. In 1997, ranking was often similar between the non-fertilized and fertilized conditions at each location, whereas differences in ranking were larger in 1996. In the same year, ranking in Vientiane differed from that of other locations, because of a problem with nutrient disorder, possibly Fe toxicity in the soil.

Nutrient content and nutrient use efficiency

A subset of 16 lines was used to analyse the total N, P and K content in seeds and straw in the 1997 experiment. Results of combined analyses of variance for the three locations for total N and P contents and nutrient use efficiency in grain (NUEg) and plant (NUEp) for N and P are shown in Table 5 (Inthapanya et al. 2000b). A highly significant effect of genotype (G) was obtained for total contents of N and P. However, the G × F interaction effect was significant only for N content.

Genotypic variation in grain yield for a given total N or P content was found. Thus, the ratios of grain yield and total dry matter to total N and P contents (N_iUEg, N_iUEp, PUEg and PUEp) differed significantly among genotypes (Table 5). While no significant interactions of G × F were found for these attributes, G × L × F interaction was significant for PUEg and PUEp. While high-yielding lines such as

Table 4. Ranking by yield of 10 rainfed lowland rice genotypes that produced the highest mean yields for all experiments in three Lao provinces under non-fertilized (NF) and fertilized (F) conditions in 1996 and 1997.

Year Line	Province						Grain yield (kg ha^{-1})
	Vientiane		Savannakhet		Champassak		
	NF	F	NF	F	NF	F	
1996							
IR57514-PMI-5-B-1-2	4	17	5	5	1	1	2187
NSG19	37	26	48	3	9	2	1901
IR64345-TDK-148-9-2	14	24	2	21	25	6	1837
TDK1	57	62	6	1	10	8	1827
IR66368-CPA-32-P1-3R	3	5	9	2	13	47	1823
IR64906-TDK-249-10-11	18	37	18	50	12	4	1744
IR66369-CPA-51-P1-3R	9	8	34	11	23	14	1741
IR64906-TDK-15-B-1-1	2	11	38	20	8	33	1734
IR66369-CPA-39-P1-3R	30	45	12	8	11	23	1719
IR68104-CPS-6-1-2	55	54	49	57	5	5	1687
1997							
IR68102-TDK-B-B-31-3	7	2	21	1	12	1	2462
TDK1	6	11	11	2	3	4	2414
IR68105-TDK-B-B-6-1	2	27	8	7	15	2	2330
IRUBN-4-TDK-1-2-1	10	13	12	5	29	3	2313
IR66488-TDK-25-1-1-1	4	17	10	8	45	5	2240
IR57514-PMI-5-B-1-2	3	38	3	9	17	6	2228
IR57514-SRN-299-2-1-1	12	23	17	20	1	9	2213
IR68102-TDK-B-B-28-1	38	8	6	11	19	13	2183
Dok-mai	26	14	9	26	6	16	2170
IR68105-TDK-B-B-27-1	8	10	14	19	44	11	2153

Source: Inthapanya et al. (2000a).

Table 5. Degrees of freedom (DF), *F*-ratio and the level of significance for total N and P content and N and P use efficiencies (NiUE and PUE, respectively) of grain (g) and plant (p) of 16 rainfed lowland rice lines for the combined analysis of variance across three locations in Laos.

Source of variation	DF	Total N content	Total P content	N_iUEg	N_iUEp	PUEg	PUEp
Location (L)	2, 6	12.38 **	9.19 **	8.01 **	14.15 **	26.70 **	9.97 **
Fertilizer (F)	1, 6	28.76 **	16.79 **	8.97 **	3.47 ns	16.01 **	7.44 **
L × F	2, 6	5.88 *	3.83 ns	2.63 ns	2.79 ns	8.17 **	8.23 **
Genotype (G)	15, 30	4.35 **	3.25 **	5.98 **	3.07 **	3.85 **	2.25 *
G × L	30, 30	1.37 ns	1.00 ns	1.96 *	1.15 ns	1.20 ns	1.12 ns
G × F	15, 30	2.29 *	1.34 ns	1.06 ns	1.66 ns	2.00 ns	1.00 ns
G × L × F	30, 192	1.00 ns	1.27 ns	1.01 ns	1.19 ns	2.12 **	2.24 **

Source: Inthapanya et al. (2000b).

IR68102-TDK-B-B-31-3, TDK1, IRUBN-4-TDK-1-2-1, IR57514-PMI-5-B-1-2 and IR57514-SRN-299-2-1-1 generally had high N_iUEg and PUEg, they did not have high N_iUEp and PUEp, except for PUEp in TDK1. These high-yielding lines generally had low grain N concentration.

The effect of fertilizer application on nutrient concentration was generally small, except for P concentration in straw. The N concentration in grain was 2–3 times greater than in straw, while the ratio was higher for P (data not shown). In contrast, K concentration in straw was much higher than in grain. Nitrogren concentration in grain was negatively related to N_iUEg at the Savannakhet and Champassak locations (Figure 2). At Vientiane, N_iUEg was generally high, even in genotypes with high N concentration in grain.

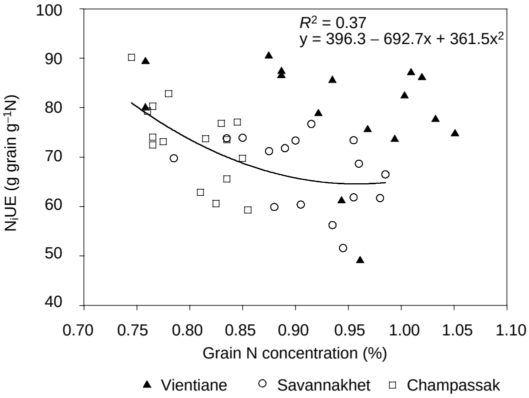


Figure 2. Relationship between grain nitrogen concentration and nitrogen-use efficiency (N_iUE) in grain for 16 rainfed lowland rice lines grown across fertilized and non-fertilized conditions at three locations in Laos. Note that only the Savannakhet and Champassak data were used for the regression (after Inthapanya et al. 2000b).

Because a significant G × L × F interaction for PUEg existed, the relationship of grain yield with total P content at each location and fertilizer level was examined for each line. Results for six contrasting lines in 1997 are shown in Figure 3 (Inthapanya et al. 2000b). The linear regression shown for each line has a positive intercept, indicating PUEg generally decreases with increase in P content in the plant. The slope of the line connecting each location/fertilizer point and the origin is the PUEg.

In Vientiane, some lines had low PUEg under fertilized conditions while others did not, causing the G × L × F interaction for PUEg. TDK1 had high PUEg, except in Vientiane under fertilized conditions (+F). PUEg was also lower in Vientiane +F for IR57514-PMI-5-B-1-2, but other lines did not have such decreased levels of PUEg in Vientiane +F. Lines IR66368-CPA-11-P1-3R-0, IR66369-CPA-63-P1-3R-0 and IR58821/IR52561/CA-11 had consistently high, medium and low PUEg, respectively. Line IR68102-TDK-B-B-31-3 had lower PUEg than TDK 1, but total P content was higher for the same treatment.

Genotype response to nitrogen and phosphorus applications

Mean grain yield, total dry matter, harvest index and total N, P and K content under four nutrient treatments at the three locations in 1998 are shown in Table 6. In all locations, grain yield increased with applications of N and P. The effect of N was greater than that of P in Vientiane and Champassak, whereas the effect of N and P were similar in Savannakhet. Applications of N, P and K, however, resulted in the

Table 6. Mean yield, total dry matter (TDM), harvest index and total N, P and K contents of rainfed lowland rice under four nutrient treatments in the Champassak, Savannakhet and Vientiane Provinces, Laos, 1998.

Location Treatment	Yield (kg ha^{-1})	TDM (kg ha^{-1})	Harvest index	Total N (kg ha^{-1})	Total P (kg ha^{-1})	Total K (kg ha^{-1})
Vientiane						
Nil	1119 d*	4094 d	0.27	20.5 b	2.49 c	3.57 c
+N	1754 b	6268 b	0.28	34.3 a	2.54 c	5.83 a
+P	1386 c	5523 c	0.25	24.6 b	3.37 b	4.71 b
+NPK	1937 a	7062 a	0.27	36.1 a	4.12 a	5.85 a
Mean	**1549**	**5737**	0.27	28.9	3.13	4.99
LSD 5%	142	529	ns	5.09	0.61	0.70
Savannakhet						
Nil	1348 c	2791 c	0.48 a	14.81 c	2.10 c	2.87 c
+N	1662 b	3965 b	0.42 bc	21.66 b	2.29 c	4.23 b
+P	1737 b	3901 b	0.44 b	20.82 b	3.87 b	4.00 b
+NPK	2061 a	5092 a	0.41 c	28.25 a	4.88 a	5.50 a
Mean	**1702**	**3937**	0.44	21.38	3.28	4.15
LSD 5%	204	528	0.02	3.21	0.68	0.67
Champassak						
Nil	1445 d	3847 d	0.38 b	21.17 d	2.73 c	1.03 d
+N	2429 b	6406 b	0.38 b	35.62 b	4.24 b	2.32 a
+P	1966 c	4881 c	0.40 a	27.47 c	4.23 b	1.65 c
+NPK	2664 a	6973 a	0.38 b	40.09 a	5.80 a	1.94 b
Mean	**2126**	**5527**	0.38	31.09	4.25	1.73
LSD 5%	125	378	0.01	2.48	0.51	0.26

*Values followed by the same letter are not significantly different at the 5% probability level.

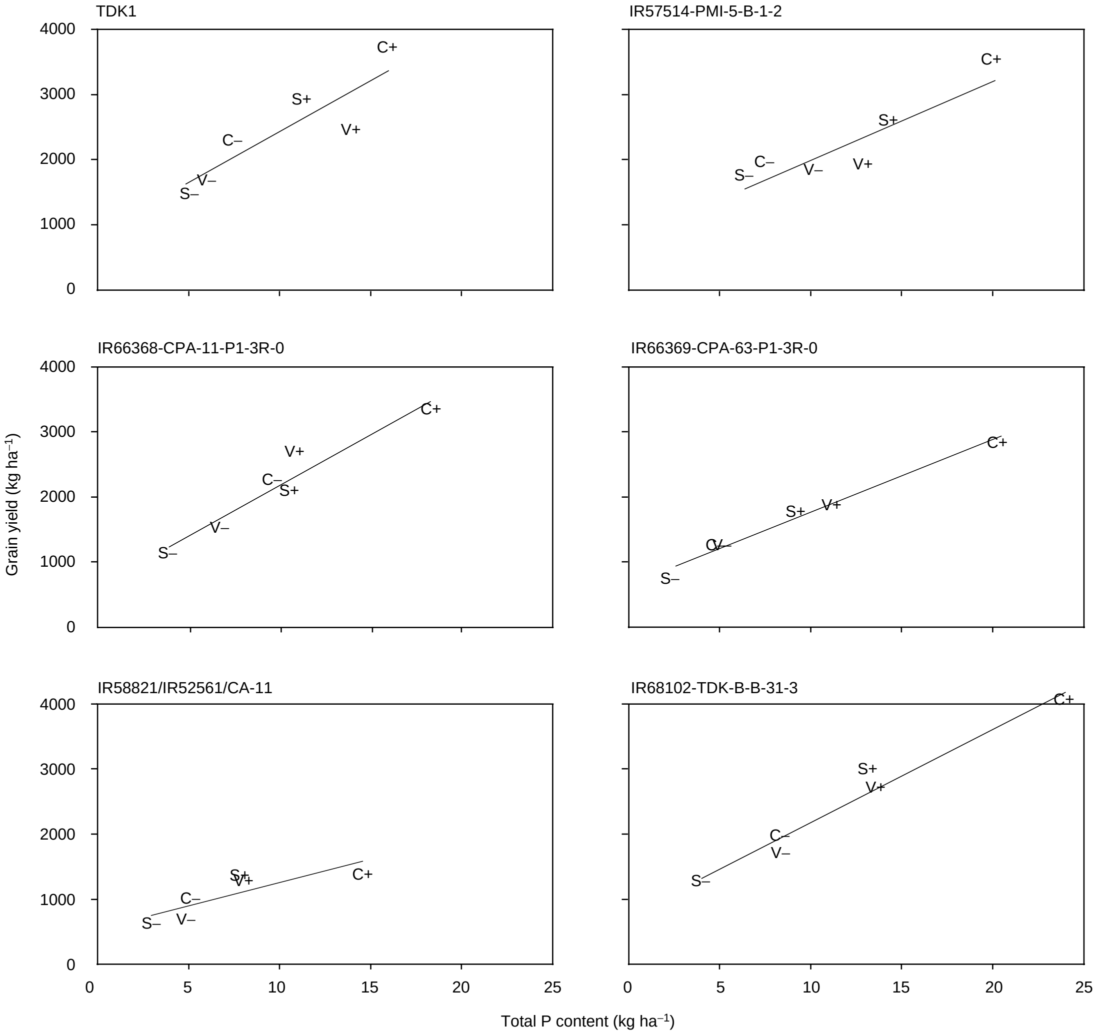


Figure 3. Relationship between grain yield and total P content for six rainfed lowland rice lines grown under non-fertilized and fertilized conditions at three locations in Laos, 1997. V = Vientiane; S = Savannakhet; C = Champassak; + = fertilized conditions; – = non-fertilized conditions. (After Inthapanya et al. 2000b.)

highest yield ($P < 0.05$) at all locations. Total N content followed the same pattern as grain yield. However, total P content responded more to P application and less to N application, except in Champassak, where N application promoted P uptake.

Grain yield and total dry matter were strongly related to total N, P and K content (Figure 4). The R^2 for total N, P and K content were higher for total dry matter than grain yield. Generally, grain yield and total dry matter were more strongly associated with total N content than with total P and K contents.

Discussion

The G × F interaction was often significant with a small contribution to the total variation for grain yield in each experiment in 1996 and 1997. However, the combined analysis showed that the variance component of G was greater than the G × F variance component. The sum of the G and G × L variance components was greater than that of the G × F and G × L × F components. This was particularly obvious in 1997 when adverse soil effects in Vientiane was not as severe as in 1996. Thus, in

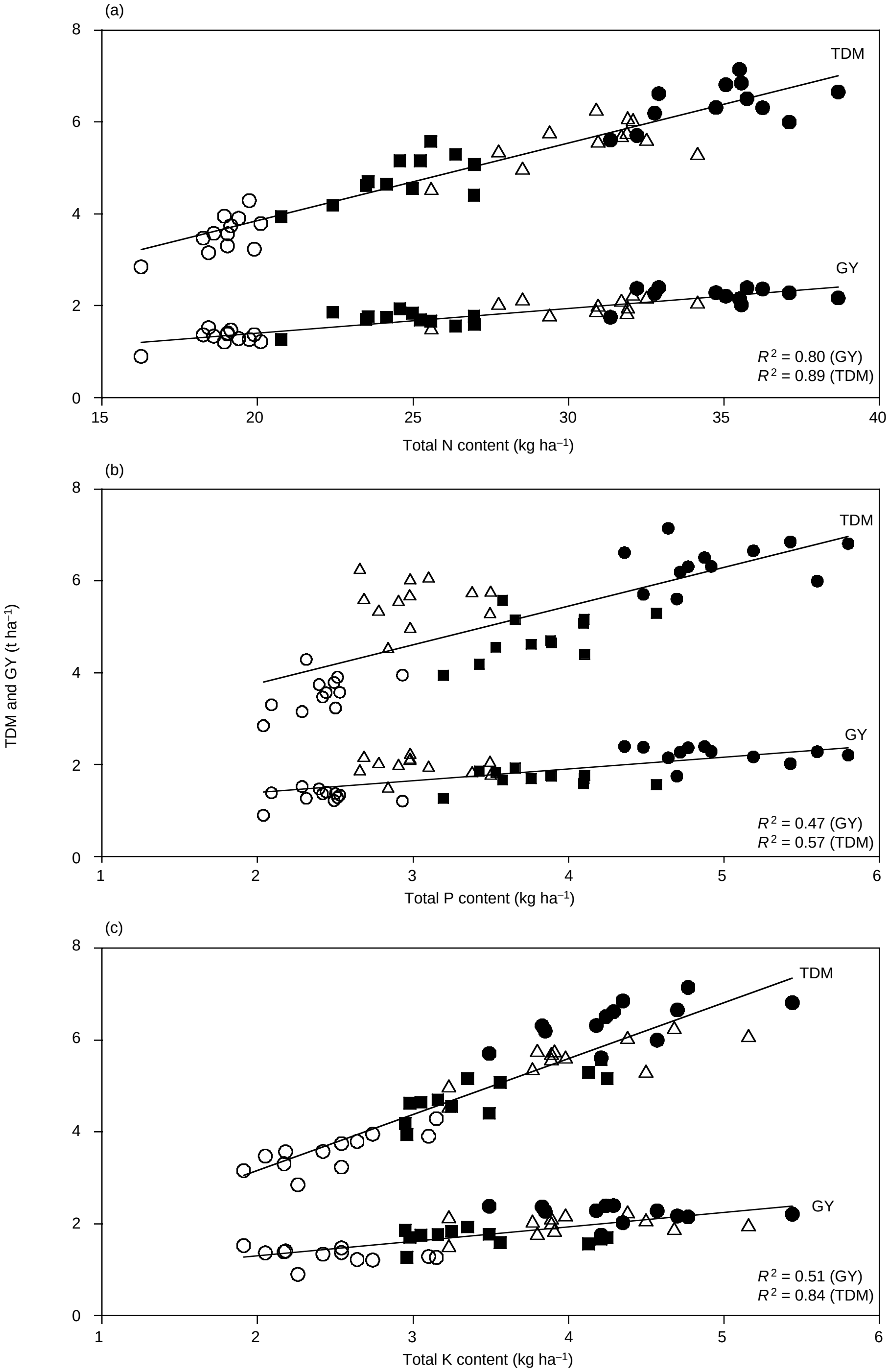


Figure 4. Relationships between total N, P and K contents and grain yield (GY) and total dry matter (TDM) in rainfed lowland rice at three locations, Laos, under treatments of no fertilizer (○); with P at 13 kg ha^{-1} (■); with N at 60 kg ha^{-1} (△); with NPK at 60, 13, 16 kg ha^{-1} (●), 1998.

1997, the G variance was about the same as the sum of the all interaction variances.

The rather large G variance component may be attributed to the fact that a similar type of drought pattern developed in all locations in 1997, prejudicing late-maturing lines. These findings corroborated those for similar situations in Thailand (Rajatasereekul et al. 1997). Moreover, this effect was similar under both fertilized and non-fertilized conditions. Growing conditions at the three locations were more variable in 1996 when early season drought developed in Savannakhet and Vientiane but not in Champassak, and adverse soil conditions caused a large yield reduction only at Vientiane.

A series of experiments in Thailand also showed a large G × L variance, compared with G variance (Fukai and Cooper 1998). The results of the combined analysis for the 13 entries in 1996 and 1997 showed that G × year variance component was greater than the G × F variance component. The largest interaction variance component involving genotype was G × L in 1996 and 1998.

These results suggest that the genotypic interaction involving fertilizer does not exert a very strong influence on the overall genotypic performance and, hence, would not significantly affect the selection of genotypes in a breeding program. The results of the 1996 experiments suggest that, judging from the higher proportion of genetic variation to total phenotypic variation (Inthapanya et al. 2000a), selection under fertilized conditions would be better than under non-fertilized conditions, although this proportion was similar between the two conditions in 1997. Coefficient of variation was often smaller under fertilized conditions (Inthapanya et al. 2000a), providing more opportunity to differentiate genotype performance statistically. It should also be stated that fertilizer use has increased rapidly in recent years in at least two provinces of Laos (Pandey and Sanamongkhoun 1998). This trend is likely to continue in the near future. The breeding program should therefore apply fertilizer rather than not apply it.

The Lao breeding program is rather small and the use of two fertilizer levels is not justified. The current rate of 60–30–20 kg ha^{-1} for N, P_2O_5 and K_2O, respectively, used by the program may be considered moderate as rice yield often responds to even higher N rates in Laos. It should be stated, however, that some genotypes did relatively well under non-fertilized conditions, suggesting that on-farm trials, conducted just before new cultivars are released, should be carried out under the fertilizer conditions of the targeted environments. In any case, the breeding program should not always be conducted in areas of high soil fertility, and the selection program should avoid relying heavily on those research stations whose soils are more fertile than those of the average farm.

The selection of locations appears important, particularly considering the rather large G × L variance obtained for all 3 years. If advanced genotypes consistently perform well in one location and not in other locations, those genotypes may be considered for release only to that area where they performed well. However, the location should be representative of farmers' fields in terms of soil fertility and drought occurrence.

These conclusions are similar to those obtained from our earlier work where 35 cultivars and advanced lines mostly from Thailand were compared at two locations in the Vientiane and Champassak Provinces for 3 years (Inthapanya et al. 1997).

Tirol-Padre et al. (1996) suggest that nutrient use efficiency for grain (N_iUEg and PUEg), which did not show any significant G × F interaction effect, may be more consistent across environments than total nutrient content, and may be a more useful character in developing new cultivars adapted to low soil fertility. In Vientiane, the different behaviour of PUEg with fertilizer was probably caused by nutrient toxicity problems observed in the field.

The analysis presented here indicates that N_iUEg was negatively associated with N concentration in grains. This contrasts with the results of Tirol-Padre et al. (1996) who found larger genotypic variation in stem rather than in grain N concentration, and suggested the importance of low stem N concentration for yield under low soil fertility conditions. Sahu et al. (1998), at Raipur, India, reported a significant variation for yield among five lines at low N application rates (30 and 60 kg ha^{-1}), and that this variation was due to variation in total N content at the low N rates usually applied in lowland conditions.

Similarly, in the present experiments, genotypic variation for yield response to applied fertilizer was closely related to the variation for total N content response. However, the ability to take up N appears to be affected by soil conditions and water availability (Fukai et al. 1999) and, in the present experiments, a significant G × F interaction was observed for total N content at maturity. Poor correlation was also observed between years for total N content and grain yield in the 2-year study by Tirol-Padre et al. (1996), confirming the results of our 3-year fertilizer experiments. Selecting lines with consistently high N contents across different soil N environments would therefore be difficult, a view supported by Ladha et al. (1998). However, low percentages of seed N and higher N and P use efficiencies could be an alternative approach for selecting lines for rainfed lowland environments.

The results at the Vientiane and Champassak locations suggested that N fertilizer could potentially increase grain yield more than would the P fertilizer treatment. Yield response to P fertilizer was similar to the response to N fertilizer in Savannakhet. The P effects observed in this experiment were similar to the results reported by Lathvilayvon et al. (1997), where P application could increase grain yield under rainfed lowland conditions. However, the highest grain yield was produced with the NPK fertilizer treatment. Nitrogen was the most important nutrient for yield, with 80% of variation in yield among lines being accounted for by the total N content in the plant.

Conclusions

For grain yield, the G × F interaction effect was smaller than the effects of genotype and the G × Y and G × L interactions. This indicates that current fertilizer levels (60 N, 13 P and 16 K kg ha^{-1}) could be used in the early testing programs for cultivar selection. However, because the G × L interaction effect was strong for grain yield, the use of more environments in multi-locational trials would be advantageous in selecting lines for higher yield.

References

Fukai, S. and Cooper, M. 1998. Plant breeding strategies for rainfed lowland rice in Northeast Thailand. In: World Food Security and Crop Production Technologies for Tomorrow. Special issue of Japanese Journal of Crop Science, 67, 256–257.

Fukai, S., Inthapanya, P., Blamey, F.P.C. and Khunthasuvon, S. 1999. Genotypic variation in rice grown in low fertile soils and drought-prone, rainfed lowland environments. Field Crops Research, 64, 121–130.

Inthapanya, P., Sipaseuth, Sihathep, V., Chanphengsay, M. and Fukai, S. 1997. Drought problems and genotype requirements for rainfed lowland rice in Lao PDR. In: Fukai, S., Cooper, M. and Salisbury, J. ed. Breeding Strategies for Rainfed Lowland Rice in Drought-Prone Environments, Proceedings of an International Workshop held at Ubon Ratchathani, Thailand, 5–8 November 1996. Canberra, ACIAR Proceedings No. 77, 74–81.

Inthapanya, P., Sipaseuth, Sihavong. P., Sihathep, V., Chanhphengsay, M., Fukai, S. and Basnayake, J. 2000a. Genotypic performance under fertilized and non-fertilized conditions in rainfed lowland rice. Field Crops Research, 65, 1–14.

Inthapanya, P., Sipaseuth, Sihavong. P., Sihathep, V., Chanhphengsay, M., Fukai, S. and Basnayake, J. 2000b. Genotypic differences in nutrient uptake and utilisation for grain yield production of rainfed lowland rice under fertilized and non-fertilized conditions. Field Crops Research, 65, 57–68.

Ladha, J.K., Kirk, G.J.D., Bennett, S., Peng, S., Reddy, C.K., Reddy, P.M. and Singh, U. 1998. Opportunities for increased nitrogen-use efficiency from improved lowland rice germplasm. Field Crops Research, 56, 41–72.

Lathvilayvong, P., Schiller, J.M. and Phommasack, T. 1997. Soil limitation for rainfed lowland rice in Lao PDR. In: Fukai, S., Cooper, M. and Salisbury, J. ed. Breeding Strategies for Rainfed Lowland Rice in Drought-Prone Environments, Proceedings of an International Workshop held at Ubon Ratchathani, Thailand, 5–8 November, 1996. Canberra, ACIAR Proceedings No. 77, 192–201.

Linquist, B., Sengxua, P., Whitbred, A., Schiller, J.M. and Lathvilayvong, P. 1999. Evaluation of nutrient deficiencies and management strategies for lowland rice in Laos. In: Proceedings of an International Workshop on Nutrient Research in Rainfed Lowlands, 12–15 October 1998, Ubon Ratchathani, Thailand.

Pandey, S. and Sanmongkoun, M. 1998. Rainfed lowland rice in Laos: a socio-economic benchmark study. Social Sciences Division, International Rice Research Institute (IRRI), Los Baños, Philippines.

Rajatasereekul, S., Sriwisut, S., Porn-uraisanit, P., Mitchell, J.M. and Fukai, S. 1997. Phenology requirement for rainfed lowland rice in Thailand and Lao PDR. In: Fukai, S., Cooper, M. and Salisbury, J. ed. Breeding Strategies for Rainfed Lowland Rice in Drought-Prone Environments, Proceedings of an International Workshop held at Ubon Ratchathani, Thailand, 5–8 November, 1996. Canberra, ACIAR Proceedings No. 77, 97–104.

Romyen, P., Hanviriyapant, P., Rajatasereekul, S., Khunthasuvon, S., Fukai, S., Basnayake, J. and Skulkhu, E. 1998. Lowland rice improvement in Northern and Northeast Thailand, 2. Genotype differences. Field Crops Research, 59, 109–119.

Sahu, R.K., Tirol-Padre, A., Ladha, J.K., Singh, U., Baghel, S.S. and Srivastava, M.N. 1998. Screening genotypes for nitrogen use efficiency on a nitrogen deficient soil. Oryza, 34, 350–357.

Tirol-Padre, A., Ladha, J.K., Singh, U., Laureles, E., Punzalan, G. and Akita, S. 1996. Yield performance of rice genotypes at suboptimal levels of soil N as affected by N uptake and utilization efficiency. Field Crops Research, 46, 127–143.

Microbiological Interventions in Acid Sandy Rice Soils

Wolfgang Reichardt[1*], Suntree Meepetch[2], Olivyn Angeles[1] and Sawaeng Ruaysoongnern[3]

Abstract

Declining fertility of rainfed lowland soils in drought-prone North-East Thailand poses a challenge for microbiological intervention. Results from a series of field and phytotron experiments on Ubon, acid, sandy soil led to the development of a conceptual model of a microbe-driven turnover of labile organic-matter pools. The model provides a yardstick for assessing the short-term effects of soil-amelioration practices. Organic amendments and liming enhance both soil organic nutrient pools and the remineralization potential of soil microbial biomasses. Functional profiles in the microbial turnover of C and N sources were severely reduced during single-cropping seasons. Organic amendments were more effective than liming in recovering these functions, whereas liming was more effective in stimulating the production of soil microbial biomass and suppressing soluble phenols. Mutual positive responses to both liming and organic amendments (rice-straw compost) suggested that a sustainable improvement of microbe-mediated soil fertility might be best achieved by combining the two treatments. Functional diversity profiles in bulk soil for rainfed lowland rice were much narrower than in the rhizosphere. A selective, stable and even variety-specific composition of microbiota in association with rice roots indicated a potential for microbiological intervention. In particular, the finding that metabolically different, ammonium-oxidizing, bacterial suppliers of nitrate associate with different drought-tolerant rice varieties suggests promising clues for improving N-use efficiencies in rice-cropping systems found in drought- and flood-prone rainfed lowlands.

RAINFED lowland rice farming in North-East Thailand accounts for about 40% of the nation's total rice production. However, it faces the challenge of sustaining and increasing yields on drought-prone, sandy soils with extremely low cation-exchange capacity (CEC) and organic-matter contents. Acidification is progressing with the continued chemical degradation of deforested Acrisol-type soils (Noble et al. 2000). The fertility of these soils is steadily declining, or even accelerated by current socioeconomic trends that favour off-farm work for rural populations. Because the major soil problems are associated with drought, acidity, low CEC, low organic-matter content and slowed-down nutrient cycling, possible remedies would include improved supplies and more efficient use of water and nutrients by the rice crop.

In principle, such approaches to recover, sustain, or improve soil fertility can be either soil or plant mediated. Because of the key role played by biocatalytic processes in nutrient cycling, soil microbiota provide promising targets in both soil and plant-directed fertility management. Hence, soil microbiota management is indispensable for reversing, in a sustainable way, trends of declining soil quality, but its practice implies a detailed knowledge of microbe-driven key mechanisms and their interconnections in nutrient cycling that has yet to be developed. For the time being, simple deterministic models of soil-nutrient supply can be built on emerging soil biochemical clues. As producer and converter of labile soil-organic-nutrient pools, the soil microbial biomass varies under the influence of stabilizing and destabilizing environmental factors (Anderson and

KEYWORDS: Degraded soil, Rainfed rice, Nutrients, Fertility, Microbiota, Soil organic matter, Drought

---

[1] International Rice Research Institute (IRRI), Los Baños, Philippines
[2] Ubon Rice Research Centre, Ubon Ratchathani, Thailand
[3] Khon Kaen University, Khon Kaen, Thailand
*Corresponding author: W.Reichardt@CGIAR.ORG

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Domsch 1980; Wardle and Parkinson 1990; Wardle 1998; Reichardt et al. 2000). Conceptual nitrogen (N) sink and source models, based on these observations (Duxbury and Nkambule 1994), may help explain soil-N-supplying capacity in terms of N release functions linked to the reduction of labile organic-N pools.

The biocatalytic capacity controlling these processes in soils is ultimately reflected by the functional diversity of soil microbial communities, which diversity is only now being studied (Zak et al. 1994). While these assays are often useful, yet far from being comprehensive, they can be seen as promising indicators of sustainability in soil nutrient cycling, including N dynamics (Reichardt et al. 2000).

In addition to microbiological intervention in soils, the microbe-driven nutrient supply functions on root surfaces can also be exploited. Microflora in the immediate vicinity of nutrient-uptake sites have the potential to alleviate abiotic stresses in the rice plant, or to modulate and finetune its nutrient-uptake efficiency. Certain microbial associations with roots of drought- and flood-affected rice plants have proved to be variety specific (Briones and Reichardt 2000). This suggests a potential for microbial biofertilizers in the future.

Materials and Methods

Single-season field experiments conducted in rainfed lowlands on extremely nutrient-deficient, acid (pH 4.1–4.5), sandy soils with low organic-matter content (0.028% N and 0.377% C). The experiments were conducted at the Ubon Rice Research Centre (URRC), Ubon Ratchathani, Thailand, during three cropping seasons from 1997–1998. On a 40 × 80 m field, 3 × 5 m subplots (with three replicates and a randomized block design) were planted to the rice variety KDML105. Treatments were untreated controls, additions of organic fertilizer based on chicken manure, rice-straw compost at 15 t ha^{-1}, a mixture of rice straw and farmyard manure (FYM) at 15 t ha^{-1}, mineral fertilizer, ash of rice straw at 15 t ha^{-1} and lime additions at 1.2 t ha^{-1}.

The same soil, rice variety and treatments as in the field were also used in phytotron experiments at the International Rice Research Institute (IRRI) in 1.5 L pots at 25^{o}–30^{o}C and 13/11 h light/dark regime at10^{2} µE m^{-2} s^{-1}.

Analyses of the soil organic phase included:

Total soil protein (Herbert et al. 1971);

Total soluble phenols (Box 1983);

Phospholipid-based soil microbial biomass (PL-biomass; Tunlid and White 1992);

Production rates of heterotrophic soil microbial biomass based on incorporating ^{3}H thymidine into DNA (Christensen and Christensen 1995);

Diversity of microbial functions in sole C source utilization, using the commercial BIOLOG assay kit (Zak et al. 1994; Reichardt et al. 2000).

Results and Discussion

Interventions through soil management practices

Underlying our experimental attempts to identify microbe-mediated mechanisms was the idea of the soil microbial biomass and other labile soil-organic-matter constituents acting as a kind of nutrient pump (Figure 1). Based on a few soil biochemical parameters that can be used in routine soil-quality monitoring, labile organic-matter pools, consisting of microbial biomass and extracellular protein, are permanently tapped by the indigenous nitrogen supply (INS) and refilled by soil organic-matter production. Nitrogen release is largely driven by phenol-suppressible, respiratory, organic-matter degradation. This remineralization is linked to aerobic and anaerobic processes, and is measured as ‘respiratory electron system activity’ or ‘ETS activity’. In their function as ‘N pumps’, labile N pools are permanently replenished by inputs of energy (solar radiation, organic crop residues) and fertilizers. They are further modified by soil and crop management practices, which affect the functional profiles and diversity of soil microbiota (Reichardt et al. 2000).

Managing the long-term fertility of sandy, nutrient-poor, rice soils in drought-prone areas requires a detailed knowledge of differential effects on nutrient immobilization on the one hand and nutrient release on the other. Sustainable management will depend on the time frame of these effects. While improving the soil organic phase by means of straw reincorporation takes about 4 years to show detectable effects on yields and yield stability, soil fertility determinants of the N-pump model can be assessed in much shorter intervals. These short-term effects have been investigated in both field experiments at Ubon Ratchathani and phytotron experiments, using soil from these fields, at IRRI, with some illustrated below.

Short-term effects of soil management

Protein

In a phytotron experiment with the rice variety KDML105, protein pools were initially boosted by mineral fertilizer, organic fertilizer (chicken manure) or liming but afterwards declined during the vegetative part of the crop’s growth cycle (Figure 2). Liming contributed to the strongest decline in soil protein concentrations. To conclude, both organic amendments and liming caused soil protein pools to

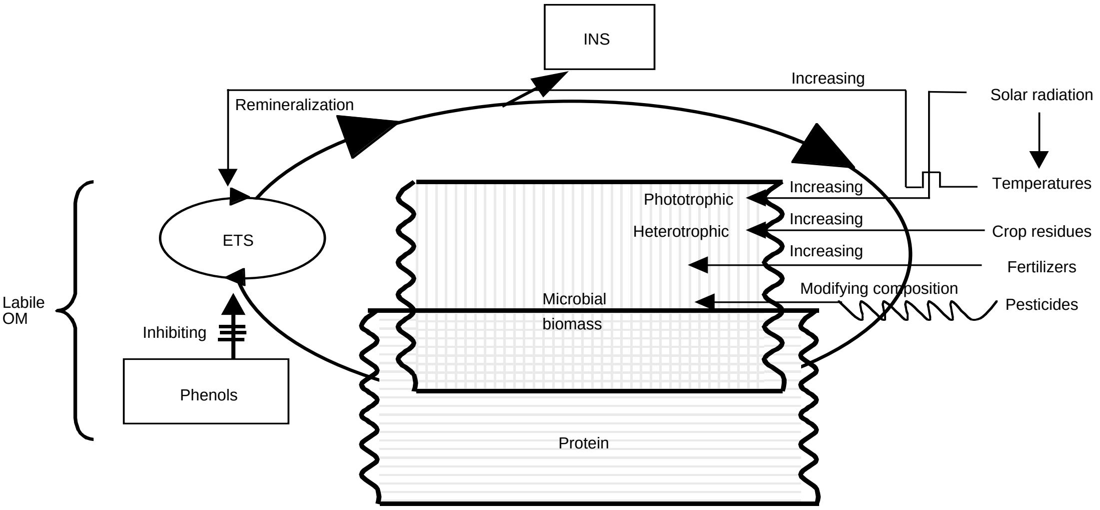


Figure 1. Conceptual model of labile soil-organic-matter functioning as a nutrient pump driving indigenous soil nutrient supply in rice soils. ETS = respiratory electron system activity; INS = indigenous nitrogen supply; OM = organic matter.

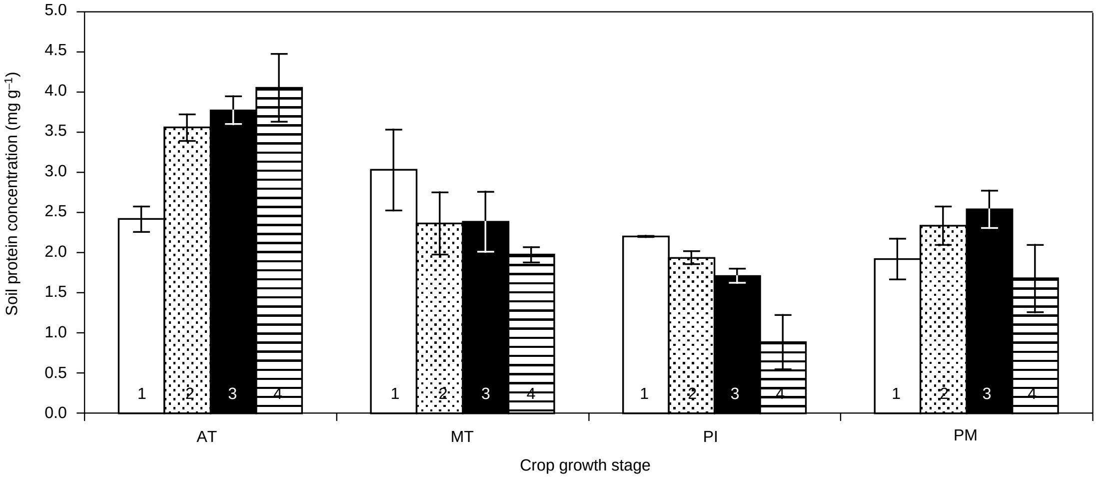


Figure 2. The rice variety KDML 105 in a phytotron experiment with Ubon soil. Samples of total soil protein concentrations were taken at key crop growth stages: AT = 25 days after transplanting (DAT); MT = maximum tillering (43 DAT); PI = panicle initiation (64 DAT); PM = physiological maturity (136 DAT). Treatments were 1 = control; 2 = mineral fertilizer; 3 = organic manure; 4 = liming. Error bars indicate SD (n = 4).

fluctuate at greater amplitudes, suggesting an intensification of nutrient-pump functions, either by energy input as organic matter or by improving growth conditions for less acidophilic soil microbiota.

Phospholipid-based soil microbial biomass

Similar effects of soil-amelioration practices on soil organic-nutrient pools were also indicated for PL-biomass in the field (Figure 3). These and other data from field and phytotron experiments confirm the plasticity of soil microbial biomass pools under changing environmental conditions (Reichardt et al. 2000).

Microbial biomass production

Gross productivity of heterotrophic bacterial biomass in the soil as measured by tritiated thymidine uptake was strongly enhanced by liming, whereas organic amendments failed to show such increases (Figure 4). Closed-system artefacts may have contributed to a general increase in bacterial production rates. The initial boost caused by raising the pH reflects an immediate response of soil microbial communities to improved growth conditions. This also confirms the stimulatory effects of liming observed in earlier field experiments at Ubon (Reichardt et al. 1998).

'Respiratory electron system' activity

'Respiratory electron system' activities reflected mainly short-term responses. Organic amendments and, to a lesser extent, liming raised the remineralization capacity, as indicated by ETS assays, significantly above those of sole mineral fertilizer treatments (Figure 5). Because respiratory activities are based on energy supply and organic substrate, organic amendments prove the most sustainable in maintaining elevated activity levels.

Phenols

Soluble phenolic compounds in the soil are known to inhibit ETS activities (Reichardt et al. 2000). Elevated phenol concentrations in untreated plots in the field experiment at Ubon were reduced most effectively by liming during the initial stages of crop growth (Figure 6). Hence, the positive response of ETS activities to liming could have resulted from reduced phenol levels at an elevated pH. A link between organic amendments and accumulation of phenolic compounds can therefore be expected (Tsutsuki and Ponnamperuma 1987).

Indicators of functional microbial diversity in soil

Microbial communities in intensively cropped, irrigated, rice soils may not necessarily show major shifts in their functional diversity (Reichardt et al.

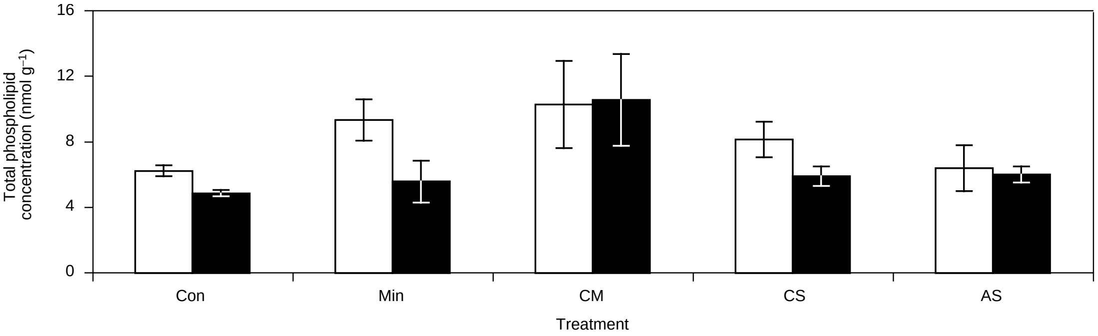


Figure 3. Rainfed lowland field experiment at Ubon, Thailand. Change in soil microbial biomass as total phospholipid concentration between crop growth stages of transplanting (white) and panicle initiation (black) for the following treatments: Con = control; Min = mineral fertilizer; CM = chicken manure; CS = rice-straw compost; AS = ash of rice straw. Error bars indicate SD (n = 4).

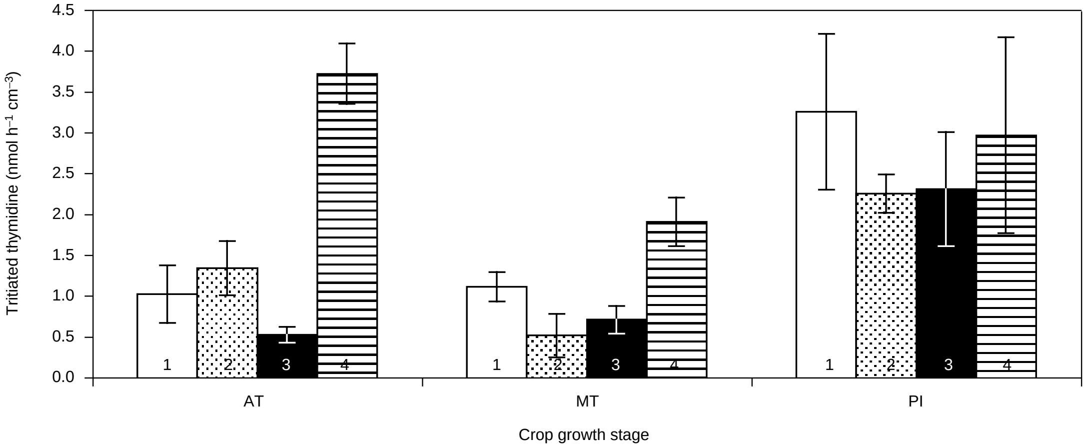


Figure 4. Phytotron experiment with Ubon soil, planted to the rice variety KDML 105. Gross heterotrophic bacterial biomass production was measured as short-term uptake of tritiated thymidine at key crop growth stages: AT = 25 days after transplanting (DAT); MT = maximum tillering (43 DAT); PI = panicle initiation (64 DAT). Treatments were 1 = control; 2 = mineral fertilizer; 3 = organic manure; 4 = liming. Error bars indicate SD (n = 4).

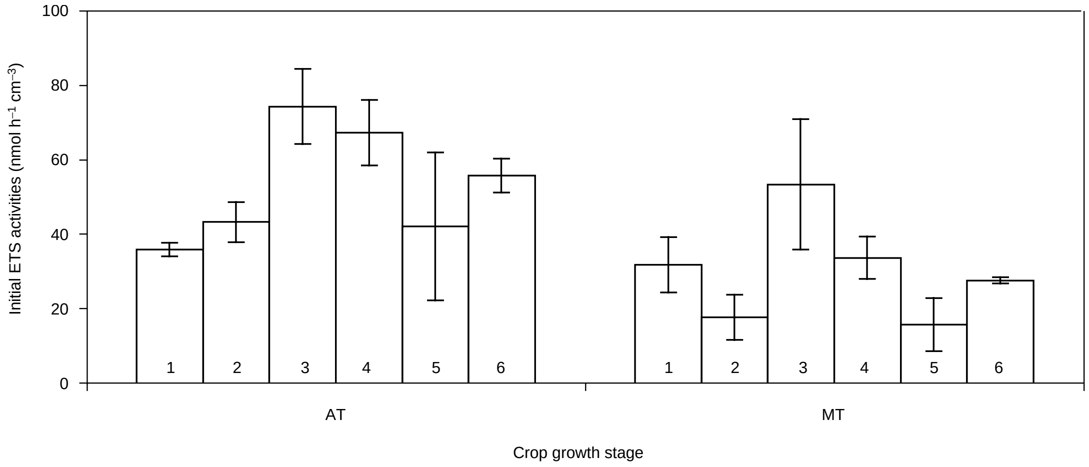


Figure 5. Field experiment with the rice variety KDML 105 at Ubon, Thailand, in 2000. Initial ETS activities at transplanting (AT) and maximum tillering (MT), with the following treatments: 1 = control; 2 = mineral fertilizer; 3 = chicken manure; 4 = rice-straw compost; 5 = ash of rice straw; 6 = liming. Error bars indicate SD (n = 4).

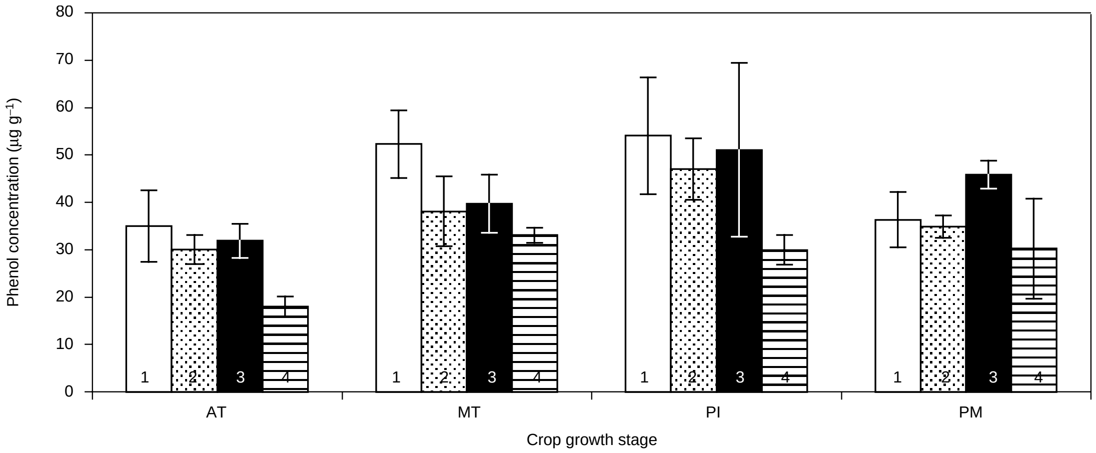
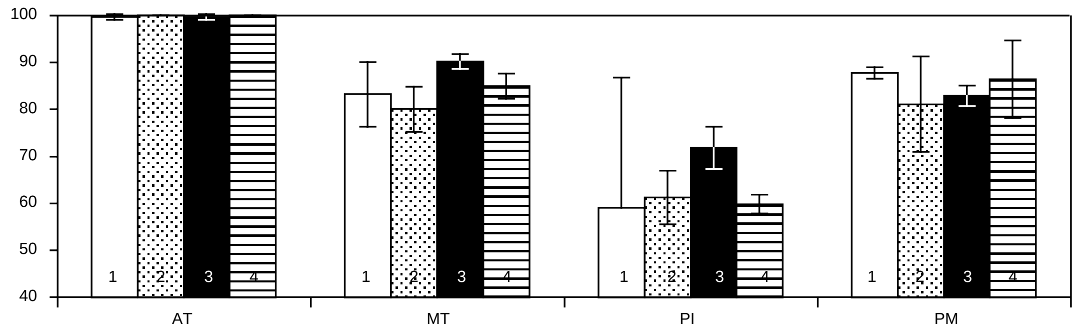


Figure 6. Concentrations of soil phenolic compounds in a phytotron experiment with Ubon soil, planted to the rice cultivar KDML 105, at key crop growth stages: AT = 25 days after transplanting (DAT); MT = maximum tillering (43 DAT); PI = panicle initiation (64 DAT); PM = physiological maturity (136 DAT). Treatments were: 1 = control; 2 = mineral fertilizer; 3 = organic manure; 4 = liming. Error bars indicate SD (n = 4).

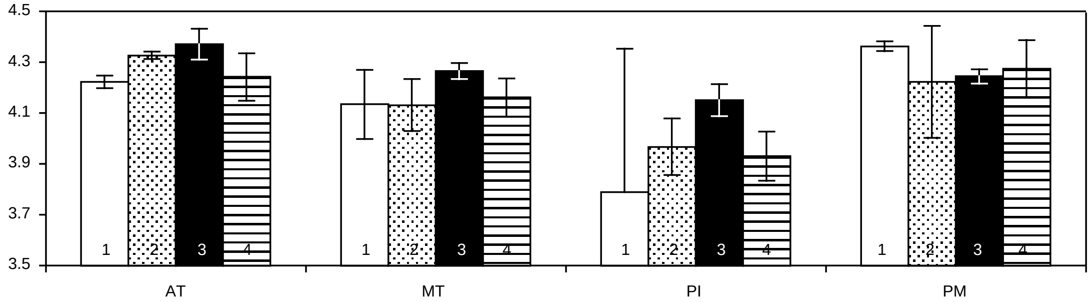
2000). However, BIOLOG assays of the infertile, acid, sandy, Ubon soils, show that biocatalytic functions decline steeply as the crop grows (Reichardt et al. 1998). Single organic amendments, for example, rice straw at 15 t ha^{-1} per cropping season proved insufficient to reverse this trend of declining functional diversity.

A subsequent phytotron experiment with Ubon soil was designed to compare the relative effects of organic manure, liming and mineral fertilizer on soil microbial diversity indices (Figure 7). Most probably because of closed-system effects, functional richness and Shannon diversity indices were roughly halved at the panicle initiation stage, but recovered partially at harvest. Nevertheless, the contribution of organic matter amendments to functional diversity during the vegetative growth phase proved significantly higher than for liming. Increasing substrate evenness at advanced growth stages (Figure 7) means enhanced equitability of activities across all used substrates (Zak et al. 1994). This reflects the common trend that lower activity plateaus are reached as the crop grows.

(a) Richness (%)



(b) Shannon diversity index



(c) Evenness

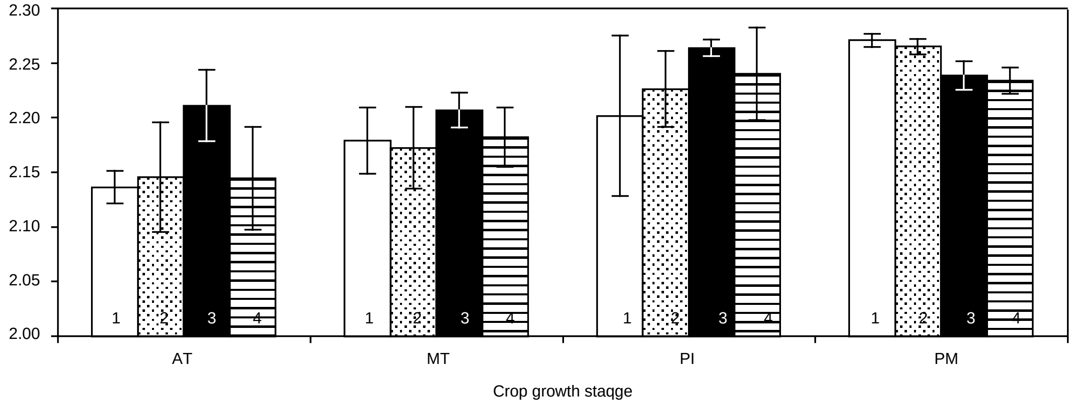


Figure 7. Phytotron experiment with Ubon soil planted to the rice variety KDML 105. Functional diversity patterns of soil microbial community at key crop growth stages: AT = 25 days after transplanting (DAT); MT = maximum tillering (43 DAT); PI = panicle initiation (64 DAT); PM = physiological maturity (136 DAT). Treatments were: 1 = control; 2 = mineral fertilizer; 3 = organic manure; 4 = liming. Error bars indicate SD (n = 4).

As far as trends sustained during the entire cropping season can be derived from three annual field trials at Ubon and two supplementary phytotron experiments, these have been summarized in Table 1. Organic amendments, as well as liming, can improve soil fertility by enhancing the build-up of labile organic-nutrient pools and their remineralization capacity. Liming has the additional advantage of reducing the concentrations of soluble phenols that suppress respiratory remineralization processes, while organic amendments proved superior in sustaining functional diversity. Hence, a combination of both liming and repeated organic amendments would appear optimal for reaching the goal of sustainable, microbe-mediated, soil fertility in these soils.

Table 1. Relative trends of sustained positive and negative responses of soil biochemical parameters to soil-amelioration practices in acid, sandy, Ubon soil from several field and phytotron experiments.

Effect of treatment on:	Organic amendments[a]	Liming
Soil protein	+	–
Microbial biomass	+	n.d.[b]
Microbial biomass production rate	+	+
ETS activity	+	–
Phenolic compounds	+	–
Functional diversity (BIOLOG)	+	–

[a] farmyard manure, rice straw compost.

[b] n.d. = insufficient data.

References

Anderson, J.P.E. and Domsch, K.H. 1980. Quantities of plant nutrients in the microbial biomass of selected soil. Soil Science, 130, 211–216.

Box, J.D. 1983. Investigation of the Folin-Ciocalteau phenol reagent for the determination of polyphenolic substances in natural waters. Water Research, 17, 511–525.

Briones, A.M. and Reichardt, W. 2000. Ammonium oxidation in the rhizosphere of drought-tolerant RL varieties: potential for microbial interventions to improve N use efficiencies. In: Thematic Workshop on: Improving Tolerance to Abiotic Stresses in Rainfed Lowland Rice. Los Baños, Philippines, International Rice Research Institute (IRRI), Abstract.

Christensen, H. and Christensen. S. 1995. [^{3}H] Thymidine incorporation technique to determine soil bacterial growth rate. In: Alef, K. and Nannipieri, P. ed. Methods in Applied Soil Microbiology and Biochemistry. London, Academic Press, 258–270.

Duxbury, J.M. and Nkambule, S.V. 1994. Assessment and significance of biologically active soil organic nitrogen. In: Doran, J.W., Coleman, D.C., Bezdicek, D.F. and Stewart, B.A. ed. Defining Soil Quality for Sustainable Environments. Soil Science Society of America (SSSA) Special Publication 35, 125–145.

Herbert, D., Phipps, P.J. and Strange, R.E. 1971. Chemical analysis of microbial cells. Determination of protein: The Folin Ciocalteu reagent. In: Norris, J.R., and Ribbons, D.W. ed. Methods of Microbiology, vol. 5B, 249–252.

Noble, A.D., Gillman, G.P. and Ruaysoongnern, S. 2000. A cation exchange index for assessing degradation of acid soil by further acidification under permanent agriculture in the tropics. European Journal of Soil Science, 51, 233–243.

Reichardt, W., Meepetch, S., Briones, A.M., Ruaysoongnern, S. and Naklang, K. 1998. Microbial biomass, its assessment, functions and management in drought-prone, nutrient-poor, rainfed lowland soils. In: Ladha, J.K., Wade, L., Dobermann, A., Reichardt, W., Kirk, G.J.D. and Piggin, C. ed. Rainfed Lowland Rice: Advances in Nutrient Management Research. Manila, Philippines, International Rice Research Institute (IRRI), 141–159.

Reichardt, W., Inubushi, K. and Tiedje, J. 2000. Microbial processes in C and N dynamics. In: Kirk, G.J.D. and Olk, D.C. ed. Carbon and Nitrogen Dynamics in Flooded Soils. Makati City, Philippines, International Rice Research Institute (IRRI), 101–146.

Tunlid, A. and White, D.C. 1992. Biochemical analysis of biomass, community structure, nutritional status and metabolic activity of microbial communities in soil. Soil Biochemistry, 7, 229–262.

Tsutsuki, K. and Ponnamperuma, F.N. 1987. Behavior of anaerobic decomposition products in submerged soils. Effects of organic material amendment, soil properties, and temperature. Soil Science Plant Nutrition, 33, 13–33.

Wardle, D.A. and Parkinson, D. 1990. Interactions between microclimatic variables and the soil microbial biomass. Biology and Fertility of Soils, 9, 273–280.

Wardle, D.A. 1998. Controls of temporal variability of the soil microbial biomass: a global scale synthesis. Soil Biology and Biochemistry, 30, 1627–1637.

Zak, C.J., Willig, M.R., Moorhead, D.L. and Wildman, H.G. 1994. Functional diversity of microbial communities: a quantitative approach. Soil Biology and Biochemistry, 26, 1101–1108.

Grain Yields and Nitrogen Contents of Rice and Secondary Crops Grown in *Sorjan* and Flat-Bed Rotation Systems in Indonesia

A. Clough[ab,*], S. Partohardjono[c] and S. Fukai[a]

Abstract

The *sorjan* farming system comprises a series of narrow, raised beds (ridges) and furrows used to simultaneously grow upland and lowland crops, respectively, thereby increasing crop diversity and decreasing risk of crop failure. We compared this system with two conventional flat-bed rotation systems in terms of grain production, nitrogen uptake and economic returns in a trial held in Lampung, Indonesia. We planted rice (*Oryza sativa* L.; wet and dry season) in *sorjan* furrows and in a flat-bed lowland rotation system; maize (*Zea mays* L.; wet) and soybean (*Glycine max* L.; dry) on *sorjan* ridges, and rice (wet) and maize (dry) in a flat-bed upland rotation system. Nitrogen treatments were 0, 40, 80 and 160 kg ha^{-1}, with both flat-bed rotation systems receiving an additional treatment of 120 kg ha^{-1}. Over the two seasons, average rice grain yield was higher for the *sorjan* system (3.35 t ha^{-1}) than for the flat-bed lowland (2.94), although, in the wet season, it was slightly higher for the flat-bed lowland. Yields for maize and soybean were low, primarily because water supply to the *sorjan* ridges was excessive and inadequate, respectively. Maize in the flat-bed upland yielded little because of uneven in-season rainfall distribution. Over the two seasons, the average N content of the above-ground biomass (N_{agb}) of rice was higher in the *sorjan* furrows than in either flat-bed rotation system. Maize grown on *sorjan* ridges responded to N fertilizer by increasing N_{agb}, whereas N_{agb} in soybean remained unchanged. Averaging across the two seasons, flat-bed lowland was more profitable than the *sorjan* system by about 13%, probably because the *sorjan* ridge crops had low market value and low yields. High-value cash crops should therefore be tried.

The *sorjan* farming system is a form of intensive intercropping used in several South-East Asian countries such as the Philippines and Indonesia (De Datta 1981). The benefits of using the *sorjan* system over the flat-bed lowland rotation system in semiarid regions of Indonesia have been reviewed by van Cooten and Borrell (1999). Mawardi (1997) fully described the system's design in Indonesia.

Briefly, the *sorjan* system is a series of alternate raised beds (ridges) and furrows that create a striped pattern across the field (Figure 1). The ridges and furrows vary in width from about 2 to 8 m, depending on the amount of floodwater expected in the area. Ridges are created in a lowland field by excavating the topsoil, placing it to one side of the field, building the ridges with subsoil, then replacing the topsoil over the entire area. The height of ridges used for growing annual crops range from 0.45 to 0.75 m.

Because upland and lowland crops are grown at the same time, the major advantages of a *sorjan* farming system over a flat-bed lowland rotation system are greater opportunity for crop diversification, lower risk

KEYWORDS: Raised beds, Red-yellow Podsol, *Sorjan* farming system

---

[a] School of Land and Food Sciences, The University of Queensland, St Lucia, Qld., 4072, Australia
[b] Current address: Department of Natural Resources and Environment, 402-406 Mair St, Ballarat, Vic., 3350, Australia
[c] Central Research Institute for Food Crops, Jalan Merdeka 147, Bogor 16111, Indonesia
*Corresponding author: angela.clough@nre.vic.gov.au

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

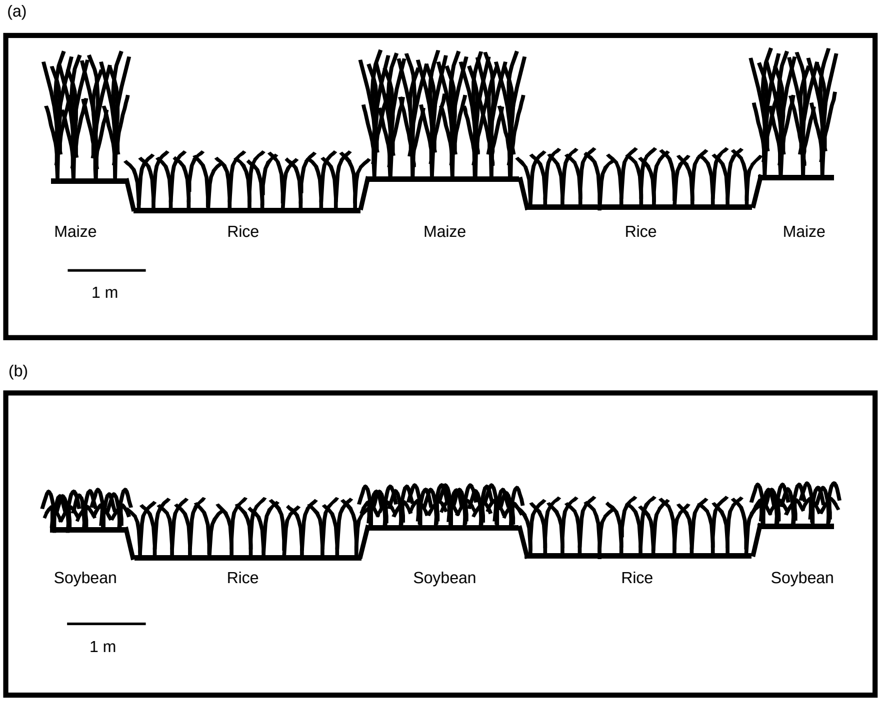


Figure 1. Diagrammatic representation of the *sorjan* farming system in cross-section at Taman Bogo Experiment Farm, Sumatra, during (a) the wet seasn and (b) dry season.

of total crop failure and increased farm income (Domingo and Hagerman 1982). Crop diversification means farmers can grow staple food such as lowland rice along with high-value cash crops such as chilli, garlic or onion (*Allium cepa* L.) or with alternative food crops such as maize, soybean, cowpea (*Vigna unguiculata* L.) or mung bean (*Vigna radiata* L.) (Mawardi 1997). Risk of total crop failure is reduced because, in seasons with heavy rainfall, crops on the ridges have good drainage, whereas, in seasons of low rainfall, water collects in the furrows thus decreasing the risk of drought to lowland rice (Mawardi 1997).

Most research into *sorjan* systems has focused on the economic inputs and returns given that, initially, more labour is required than in a flat-bed rotation system but potential returns are higher. The general conclusion is that, once established, the *sorjan* system is more profitable than the flat-bed lowland rotation system (Domingo and Hagerman 1982). Research focused on quantifying the nutritional or water management advantages of the *sorjan* system are very limited with few studies comparing crops grown in a *sorjan* system with crops grown in flat-bed lowland or upland rotation systems. Most studies that quantified the advantages of growing crops on raised beds have compared various irrigation or fertilizer regimes within a raised-bed system rather than comparing with a flat-bed system (Troedson et al. 1989; Borrell et al. 1998; Molle et al. 1999). The purpose of this study was to quantify the advantages or disadvantages of using a *sorjan* system versus flat-bed rotation systems as practised in Sumatra, Indonesia, in terms of seasonal and cumulative grain yields, nitrogen uptake and economic returns.

Materials and Methods

Location and site characteristics

A *sorjan* system, a flat-bed lowland rotation system and a flat-bed upland rotation system were trialled at Taman Bogo Experiment Farm in central Lampung Province, Sumatra, Indonesia (5° 05′ south, 105° 30′ east). The experiment's area (50 × 125 m) was composed of two upland areas and four lowland bays. Before the trial, the rainfed upland areas were under volunteer pasture and the irrigated lowland bays were used to grow certified seed for distribution.

The soil has been classified as a red-yellow Podsol (Miyake et al. 1984) and is also known as a silty clay loam Ultisol (Ismunadji et al. 1991). Previous soil analysis showed that the site had a high, active Fe concentration (138 mg kg^{-1}). A red-brown oily scum on stagnant water on the soil surface indicated iron was present at toxic concentrations near the soil surface (Benckiser et al. 1982). Visual inspection of the soil at 15 cm deep revealed iron colouration. In the 0 to 20 cm layer, initial organic carbon content and extractable K (determined by 25% HCl extraction) ranged from 0.7% to 0.9% and 57 to 78 mg K kg^{-1}, respectively, in the lowland bays and was 1.2% and 100 mg K kg^{-1}, respectively, in the upland area used for the flat-bed upland rotation system. Soil pH (H_2O) ranged from 4.2 to 4.8 across the trial site. Other soil properties (0–100 cm depth) for the upland area and the lowland bays before the trial began are given in Table 1. All soil samples were analysed at the Centre for Soil and Agroclimate Research (CSAR) in Bogor, West Java.

Table 1. Soil characteristics in the 0 to 100 cm layer of the ridges in the *sorjan* farming system, lowland and upland areas at Taman Bogo Experiment Farm, Sumatra, November 1998.

Depth cm	Clay[a] %	Sand[a] %	Total N[b] %	Extractable P[c] mg kg^{-1}	Bulk density Mg m^{-3}
Ridge					
0–20	37	40	0.12	163	1.28
20–40	31	42	0.11	216	1.35
40–60	26	50	0.10	189	1.36
60–80	38	35	0.05	48	1.52
80–100	59	22	0.04	26	1.30
Lowland					
0–20	32	43	0.10	154	1.46
20–40	39	37	0.06	40	1.56
40–60	47	31	0.06	31	1.23
60–80	26	53	0.03	35	1.51
80–100	44	39	0.04	26	1.41
Upland					
0–20	46	39	0.11	57	1.42
20–40	57	30	0.08	40	1.53
40–60	58	29	0.06	40	1.33
60–80	50	28	0.06	44	1.38
80–100	51	32	0.03	44	1.27

[a] Soil texture (%) determined by the pipette method.
[b] Total N (%) by Keldahl digestion.
[c] Extractable P (mg kg^{-1}) by extraction in 25% HCl.

Constructing the *sorjan* system

The *sorjan* system was built in a 12 × 50 m lowland bay, adjacent to a small upland area. Ridges were manually built by transferring topsoil (0–15 cm layer) from the adjacent upland area to the lowland bay. The authors recognize that this is not the technique normally used by farmers and described by Mawardi (1997). However, time was limited and the construction method used was seen as the next best option, especially given the site had high iron concentrations at a depth of only 0.15 m. Ridges were 0.45 m high and 2 m wide and the furrows were 3 m wide. This arrangement yielded two ridges and two furrows plus one border ridge on the edge of the upland area.

Treatments

The trial was conducted during a wet season and the following dry season between November 1998 and June 1999. Rainfall (Figure 2) was recorded at Taman Bogo Experiment Farm throughout the trial. The total amount of rainfall in the wet season was 1334 mm for lowland rice, 1358 mm for maize and 1363 mm for upland rice. In the dry season, the total amount of rainfall was 410 mm for lowland rice, 394 mm for soybean and 445 mm for maize.

The three systems included in the trial represented cropping systems practised in Lampung and West Java. Crops grown in the trial were upland rice (cultivar Cirata), lowland rice (cv IR64), maize (cv Bisma) and uninoculated soybean (cv Wilis). Cropping periods are given in Figure 2. Lowland rice was transplanted by hand at 25 × 25 cm intervals. Upland crops were sown by dibbling at 25 × 25 cm intervals for rice, 75 × 25 cm intervals for maize and 25 × 10 cm intervals for soybean.

In the wet season, the two flat-bed rotation systems were arranged as a randomized complete block design with 5 N treatments (0, 40, 80, 120 and 160 kg N ha^{-1}) in three replicates. In the dry season, the 5 N rates were re-applied to the same plots. In the flat-bed lowland rotation system, plot sizes were about 40 m^2. All plots in the flat-bed lowland rotation system were separated by small bunds. Plots in the flat-bed upland rotation system were 56 m^2.

The *sorjan* area was divided into plots 8 × 2 m on the ridges and 8 × 3 m in the furrows. Four N treatments (0, 40, 80 and 160 kg N ha^{-1}) were arranged in blocks with three replicates. In the wet season, each N treatment was applied in a strip across the ridges and furrows because N can leach from the ridges into the furrows during the trial. Small bunds were built between the N treatments in the furrows to prevent movement of N. In the dry season, plots in the furrows received the same N treatment as in the wet season. N treatments were not applied to soybean grown on the ridges.

Agronomy

The *sorjan* ridges and the flat-bed upland rotation system were rainfed in both seasons. The *sorjan* furrows and the flat-bed lowland rotation system were fully irrigated in the wet season. In the dry

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

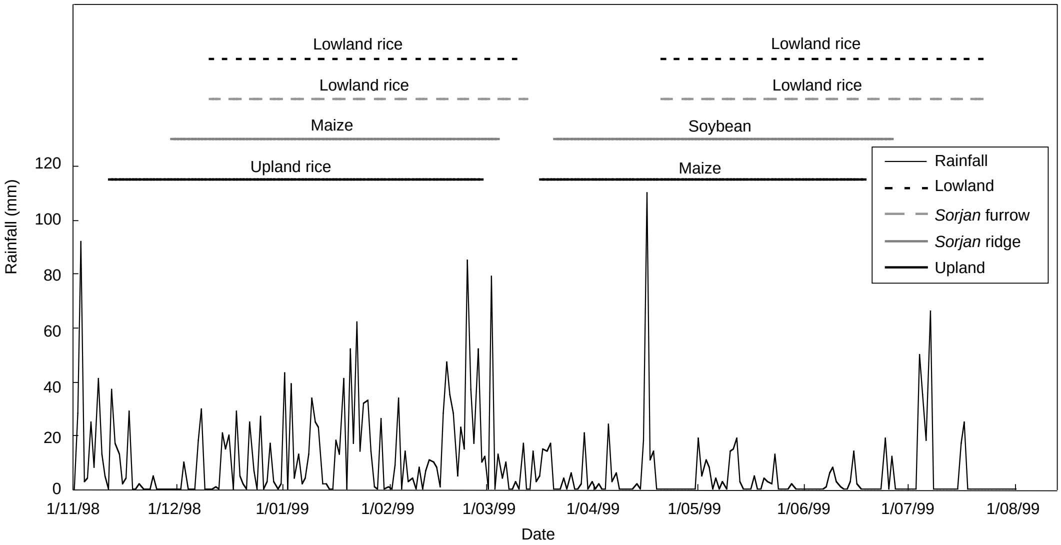


Figure 2. Daily rainfall (mm) from 1 November 1998 to 1 August 1999 at Taman Bogo Experiment Farm, Sumatra. The growing season for each crop in the three systems are indicted by the bars at the top of the figure.

season, however, irrigation in the district was limited because of low rainfall upstream, and the *sorjan* furrows and flat-bed lowland rotation system were only partially irrigated. In the two seasons, irrigation water was applied to equal depths for both the flat-bed lowland rotation system and *sorjan* furrows.

Phosphorus (80 kg SP36–P ha^{-1}) and potassium (60 kg KCl–K ha^{-1}) were manually broadcast and incorporated into the topsoil for all crops in the wet season. Potassium was applied at the same rate and using the same method as in the dry season. For lowland rice, urea-N was broadcast onto drained fields to minimize volatilization, and in equal quantities at transplanting, 14 days after transplanting and at panicle initiation. In the flat-bed upland rotation system and *sorjan* ridges, all the urea-N was applied at sowing. The fertilizer types used in the trial were commonly used in the area and the application techniques used were those recommended to farmers by local extension officers.

Plastic rat barriers were placed around the perimeter of the trial area to minimize rat damage to rice plants. Weeding was by hand. After sub-sampling plots to obtain crop data, plots were entirely hand-harvested at the end of each season. Straw was removed from the fields in lowland areas and left in each plot in upland areas as practised by local farmers.

Crop data at harvest

Straw yields (after drying at 70°C) (data not presented) and grain yields (at 14% moisture) were determined by harvesting a small area (1 × 2 m) within each plot. Yields from all systems were expressed relative to the cropping area. That is, yields from the *sorjan* system were expressed relative to the amount of area used to grow the crop, not the total area of the *sorjan* system. Grain from all plots and both seasons was dried, ground and passed through 0.5-mm mesh sieve for nutrient analysis. Grain harvested in both seasons was analysed for N, P, K, Mg and Fe concentrations. Grain from the dry seasons was also analysed for Cu and Zn concentrations. Straw was only analysed for N and P. After the wet season, plant material from each plot was analysed for N and P. Each treatment was analysed for all nutrients in the 0 and 160 kg N ha^{-1} treatments. In the other treatments, one analysis was conducted for each nutrient. Nitrogen and phosphorus analyses were conducted on each replicate for all treatments in both seasons.

Statistical analysis

Effects of N treatment on grain yield, N concentration and total N_{agb} were assessed, using the general linear model (GLM) procedure of SAS version 6.12 (SAS Institute 1996). When grain yields significantly increased with N application rates, the results were used to determine how much fertilizer N was required to achieve 90% of the maximum grain yield. The required fertilizer N rate was calculated using the quadratic equation derived from the relevant data set.

Total N_{agb} was calculated as the total N content of harvested grain and straw (kg N ha^{-1}).

The GLM procedure was also used to compare grain yields from rice grown in the three systems in the same season. Comparisons were made, using replicates within each system as the error term. Comparisons between the flat-bed rotation systems and the *sorjan* system only included the common N rates: 0, 40, 80 and 160 kg N ha^{-1}. All differences were deemed significant at $P < 0.05$.

Results

Water availability

In the wet season, water was not limiting for lowland rice because irrigation water was fully available. For upland rice, the amount of rain that fell during the wet season was adequate at more than 1000 mm (De Datta 1981) and there were no extended periods of drought (Figure 2). The longest period with limited rainfall was 13 days (days 9 to 22) where only 5 mm fell. Previous water-stress trials (Lilley and Fukai 1994; Prasertsak and Fukai 1997) indicated that this 13-day period was too short to reduce plant growth, even at the highest rate of N application. In the dry season, while the amount of irrigation water supplied to the *sorjan* furrows and the flat-bed lowland rotation system was the same, supply was limited and rainfall was below the minimal amount needed by rice (according to De Datta 1981) at less than 500 mm.

Non-treatment nutrients in grain produced in the *sorjan* and flat-bed rotation systems

Grain analysis showed that concentrations of non-treatment nutrients (Table 2) did not vary with cropping system or N application rate. Iron concentrations ranged from high to toxic in lowland rice grain produced in the wet season and within tolerance limits for rice produced in the dry season. Phosphorus concentrations were adequate in rice and soybean, and marginal in maize. Potassium was deficient in all rice and maize grains grown on *sorjan* ridges in the wet season. Zinc was present in adequate concentrations in rice and soybean grains.

Grain yield response to N in the wet season

In the *sorjan* furrows, rice grain yields increased from 3.04 t ha^{-1} at zero N to 3.68 t ha^{-1} at 160 kg N ha^{-1}. However, this increase was not statistically significant ($P = 0.415$) (Figure 3). Average grain yields in *sorjan* furrows were 3.39 t ha^{-1}. In the flat-bed lowland rotation system, grain yields significantly increased ($P < 0.001$) from 2.33 t ha^{-1} at zero N to 4.12 t ha^{-1} at 160 kg N ha^{-1}. The amount of N fertilizer required to attain 90% maximum grain yield was 71 kg N ha^{-1}. In the flat-bed upland rotation system, grain yield significantly increased from 2.36 t ha^{-1} at zero N to 3.53 t ha^{-1} at 160 kg N ha^{-1}. The amount of N fertilizer required to attain 90% maximum grain yield was 75 kg N ha^{-1}. There was no significant difference between grain yields from *sorjan* furrows and the flat-bed lowland rotation system ($P = 0.995$) or the flat-bed upland rotation system ($P = 0.138$). Comparing grain yields between rotation systems showed that lowland rice yielded significantly more than upland rice ($P = 0.036$) with 3.49 t ha^{-1} and 3.07 t ha^{-1}, respectively.

Nitrogen applied to maize grown on the *sorjan* ridges produced a significant increase in grain yield. Yields rose from 1.10 t ha^{-1} at zero N to 3.11 t ha^{-1} at 160 kg N ha^{-1} ($P < 0.001$) (Figure 3).

Table 2. Concentrations of non-treatment nutrients[a] in rice, maize and soybean grain produced under different farming systems: the *sorjan* system, the flat-bed lowland rotation system and the flat-bed upland rotation system at Taman Bogo Experiment Farm, Sumatra.

Nutrient	Sorjan		Rotation	
	Furrow	Ridge	Lowland	Upland
Wet season crop	Rice	Maize	Rice	Rice
P (%)	0.26	0.32‖	0.24	0.18
K (%)	0.16†	0.31§	0.16†	0.16†
Mg (%)	0.08	0.10	0.08	0.06
Fe (mg kg^{-1})	113‖	154	159	156
Dry season crop	Rice	Soybean	Rice	Maize
P (%)	0.25	0.79‖	0.23	0.27§
K (%)	0.28‡	2.14‖	0.23†	0.36‖
Mg (%)	0.05	0.18	0.10	0.11
Fe (mg kg^{-1})	91‖	91	89‖	101
Cu (mg kg^{-1})	15	31	30	54
Zn (mg kg^{-1})	39‖	67‖	22‖	34

[a] Nutrients below critical limits (according to Reuter and Robinson 1997) are marked as follows:
Unmarked values = critical limits unknown.
† = less than 60% of critical limits.
‡ = 60%–80% of critical limits.
§ = 80%–95% of critical limits.
‖ = sufficient and non-toxic.

Grain yield response to N in the dry season

In the *sorjan* furrows, rice grain yields significantly increased ($P = 0.038$) from 2.94 t ha^{-1} at zero N to 3.60 t ha^{-1} at 80 kg N ha^{-1} (Figure 4). The amount of N required to achieve 90% maximum grain yield was 25 kg N ha^{-1}. In the flat-bed lowland rotation system, rice grain yields were not affected by N fertilizer rates ($P = 0.25$). Average rice grain yield was much higher ($P = 0.004$) in *sorjan* furrows than in

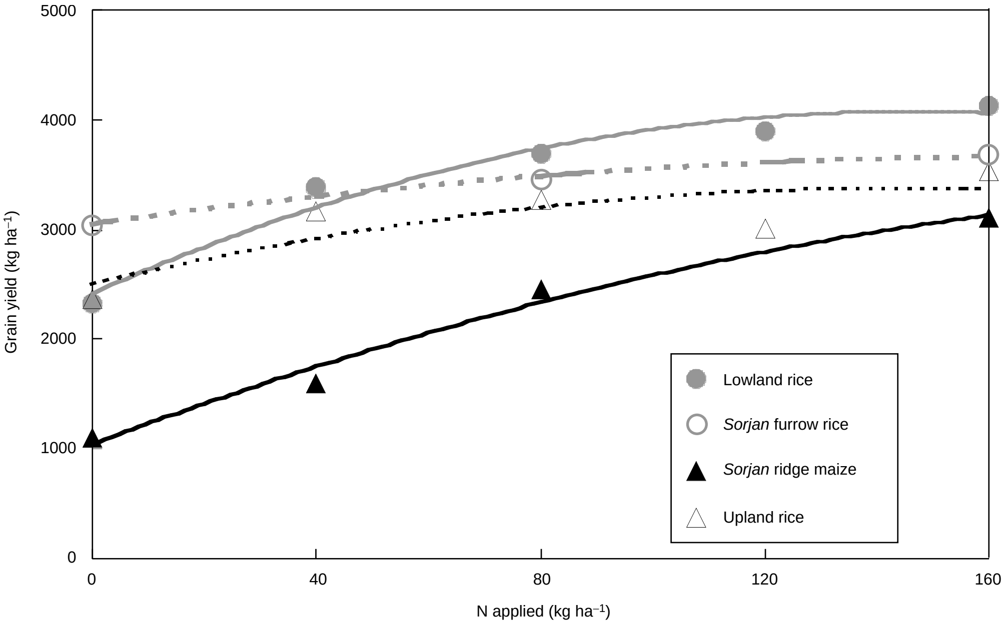


Figure 3. Nitrogen response curves attained for lowland rice and maize grown in the *sorjan* farming system; lowland rice grown in the flat-bed lowland rotation system; and upland rice grown in the flat-bed upland rotation system, wet season, Taman Bogo Experiment Farm, Sumatra.

flat-bed lowland rotation system (3.31 t ha^{-1} and 2.39 t ha^{-1}, respectively).

Soybean grain yields from *sorjan* ridges were not affected by the N rates applied to maize in the previous season ($P = 0.20$) (Figure 4). The average soybean grain yield over all previous N treatments was 928 kg ha^{-1}. Maize grown in the flat-bed upland rotation system yielded very poorly with only 15 of the 30 plots producing any more than 150 kg ha^{-1} of grain. The average maize grain yield was 540 kg ha^{-1} and yields varied between plots (cv = 103%). Consequently, there was no significant response to N fertilizer (Figure 4). This result for maize produced in the dry season is vastly different from the grain yields and N response obtained for maize grown on *sorjan* ridges during the wet season.

Concentrations of N in grain during the wet season

Nitrogen concentration in rice grain significantly increased with N fertilization rate for lowland rice grown in the *sorjan* furrows ($P = 0.011$) and for upland rice ($P = 0.032$), that is, N concentrations were 3.0% and 0.97%, respectively, at zero N application, but 3.14% and 1.27%, respectively, at 160 kg N ha^{-1}. Grain N concentration also increased in rice grown in the flat-bed lowland rotation system ($P = 0.047$) from 1.63% at zero N application to 2.32% at 120 kg N ha^{-1}. In maize grown in the *sorjan* ridges, N concentration increased from 2.96% at zero N application to 3.58% at 160 kg N ha^{-1} ($P = 0.007$).

Concentrations of N in grain during the dry season

For lowland rice grown in *sorjan* furrows, with increased N applications, N concentrations in grain increased significantly ($P = 0.034$) from 1.37% to 1.82%, and for lowland rice grown in the flat-bed lowland rotation system, increases ($P = 0.042$) were from 1.18% at zero N to 1.51% at 160 kg N ha^{-1}. In soybean grown on *sorjan* ridges, N concentrations in grain were unaffected, averaging 7.15% (cv = 6.7%) across wet season treatments at zero N and 160 kg N ha^{-1}. Nitrogen concentrations in maize grain were unaffected by N rates, averaging 2.11%, although concentrations were relatively low, compared with concentrations recorded for maize grown on *sorjan* ridges during the wet season.

Total N content in above-ground biomass during the wet season

Nitrogen uptake by the three rice crops and maize grown on *sorjan* ridges significantly increased with N

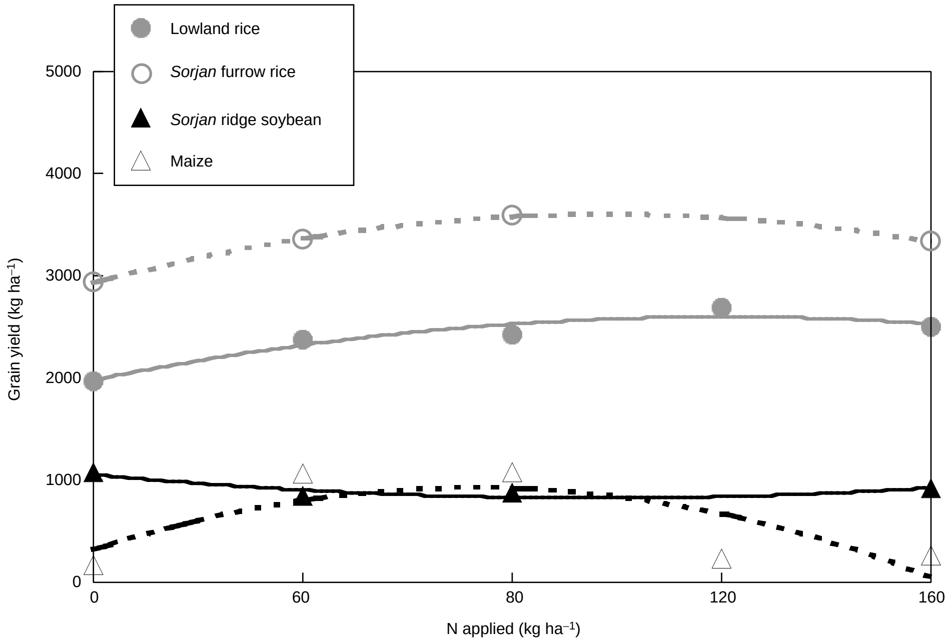


Figure 4. Nitrogen response curves attained for lowland rice and soybean grown in the *sorjan* farming system; lowland rice grown in the flat-bed lowland rotation system; and maize grown in the flat-bed upland rotation system. Fertilizer N available to soybean was residual from N applied to the previous crop. Dry season, Taman Bogo Experiment Farm, Sumatra.

rate (Table 3a). A significant difference in N_{agb} was found between rice grown in *sorjan* furrows and rice grown in the flat-bed upland rotation system ($P = 0.002$). However, no differences were found between rice grown in *sorjan* furrows and rice grown in the flat-bed lowland rotation system ($P = 0.081$). For the flat-bed rotation systems, N_{agb} values for rice from the flat-bed lowland rotation system were higher, but not significantly ($P = 0.206$), than those for upland rice. Average N_{agb} values were 130 kg ha^{-1}, 100 kg ha^{-1} and 73 kg ha^{-1} for *sorjan* furrows, flat-bed lowland rotation and flat-bed upland rotation systems, respectively.

Total N content in above-ground biomass in the dry season

Total N content in above-ground biomass in rice and soybean is given in Table 3b. Comparing N_{agb} values for the two rice crops, rice grown in *sorjan* furrows contained significantly more N, averaging 87 kg N ha^{-1}, than did rice grown in flat-bed lowland rotation system, which accumulated an average of 57 kg N ha^{-1} ($P < 0.001$).

Table 3a. Nitrogen contents of above-ground biomass (N content [kg ha^{-1}] of harvested grain and straw) at harvests of rice and maize grown under different farming systems: the *sorjan* system, the flat-bed lowland rotation system and the flat-bed upland rotation system, wet season, Taman Bogo Experiment Farm, Sumatra.[a]

N treatment kg N ha^{-1}	Sorjan		Rotation	
	Furrow (Rice)	Ridge (Maize)	Lowland (Rice)	Upland (Rice)
0	114 a	50 a	59 a	51 a
40	124 ab	76 b	105 b	71 ab
80	132 ab	106 c	93	85 b
120	—	—	129 c	71 ab
160	151 b	145 d	112 bc	87 b

[a] Common letters in a column indicate means that are not significantly different at $P = 0.05$.

Total N content in the above-ground biomass of soybean grown on *sorjan* ridges was unaffected by previous N applications ($P = 0.803$), averaging 115 kg N ha^{-1}. Maize straw was not analysed for N concentration therefore no N_{agb} results are presented.

Table 3b. Nitrogen contents of above-ground biomass (N content [kg ha^{-1}] of harvested grain and straw) at harvests of rice and soybean grown under the *sorjan* farming system versus the flat-bed lowland rotation system, dry season, Taman Bogo Experiment Farm, Sumatra.[a]

N treatment kg N ha^{-1}	Sorjan		Rotation (Lowland rice)
	Furrow (Rice)	Ridge (Soybean[b])	
0	67 a	112 a	41 a
40	87 b	112 a	56 b
80	89 bc	116 a	56 b
120	—	—	66 c
160	105 c	118 a	68 c

[a] Common letters in a column indicate means that are not significantly different at $P = 0.05$.

[b] Fertilizer N source for soybean was from residual N only.

Comparative profitability of the different cropping systems

Sorjan is an expensive system to establish, compared with flat-bed lowland rotation systems. However, because establishment costs are incurred only once and can be recovered over several cropping seasons, these costs for each system were not included when determining the systems' profitability over the only two seasons recorded at Taman Bogo.

Returns to farmers were based on two factors: first, the 90% maximum grain yields attained in one hectare of each system over the two seasons; and, second, the cost of fertilizers and sale price of produce in Lampung in June 1999. The applied fertilizer rates were assumed to be the N rates required to achieve 90% maximum grain yields in each system (Table 4), plus 60 kg K ha^{-1}. Urea and KCl was sold to farmers for Rp1000 kg^{-1} and Rp1700 kg^{-1}, respectively (Fauzi, lowland rice farmer in south Lampung, pers. comm.,2000). Rice, maize and soybean were sold by farmers for Rp1000 kg^{-1}, Rp800 kg^{-1} and Rp1500 kg^{-1}, respectively (A. Kasno, Centre for Soil and Agroclimate Research, pers. comm., 2000). Using these values, the *sorjan* system gave a lower economic return (crop sale price minus fertilizer cost) than the flat-bed lowland rotation system at Rp5.17 M and Rp5.91 M, respectively. That is, profit from the flat-bed lowland rotation system was about 13% higher than that from the *sorjan* system.

Discussion

Effect of water availability and response to applied N

The *sorjan* system is designed to buffer crops against the effects of flooding and drought (Mawardi 1997). Water availability is therefore particularly relevant to comparisons between the *sorjan* system and the flat-bed rotation systems. The non-limiting water conditions in the wet season enables rice grown in the flat-bed rotation systems to respond to applied N. The failure of rice grown in the *sorjan* system to respond to N under the same water conditions was due to the crop's relatively high grain yields without N.

Although rainfall during the wet season was suitable for rice, the amount was in excess for maize. Total water use by maize within a growing season is

Table 4. The amount of N (kg ha^{-1}) required for each crop to attain 90% maximum grain yields (kg ha^{-1}) under different farming systems—the *sorjan* system, the flat-bed lowland rotation system and the flat-bed upland rotation system—during a wet season and following dry season, Taman Bogo Experiment Farm, Sumatra.

Grain yields and N requirements	Sorjan			Rotation	
	Furrow	Ridge	Area weighed average[a]	Lowland	Upland
Wet season crop	Rice	Maize	Rice/maize	Rice	Rice
Grain yield[b]	3384	2799	3150	3710	3180
N requirement[c]	0	121	48	71	75
Dry season crop	Rice	Soybean	Rice/soybean	Rice	Maize
Grain yield[b]	3240	928	2315	2390	540
N requirement[c]	25	0	15	0	0
Both seasons					
Total grain weight	6624	3727	5465	6100	3720

[a] 0.6 ha as furrows and 0.4 ha as ridges.

[b] 90% maximum grain yield.

[c] Amount of N fertilizer required to give 90% maximum grain yields.

reportedly between 602 and 693 mm (Moentono and Fagi 1992). Despite the high rainfall, maize grown on *sorjan* ridges did respond to N by increasing grain yields. This supports the concept that one advantage of a raised-bed system over the flat-bed lowland rotation system is that excess water drains from the ridges into the furrows, hence reducing the risk of waterlogging in the upland crops (Molle et al. 1999). Although growing maize on the *sorjan* ridges may have prevented total crop failure, grain yields were still low, compared with yields attained in previous trials held in Lampung, with flat-bed, upland, rotation systems, where maize was grown with as much as 907 mm of in-season rainfall (Manuelpillai et al. 1982). In those upland trials, maize grain yields ranged between 4.7 and 6.5 t ha^{-1} with applications of 70–80 kg N ha^{-1}, 50–60 kg P ha^{-1} and 100–120 kg K ha^{-1}.

The lack of water in the flat-bed lowland rotation system during the dry season was reflected in the relatively low rice grain yields, compared with rice grown in *sorjan* furrows, and in the lack of response to applied N. In *sorjan* furrows, rice grain yields were higher and more responsive to N, presumably because more water was available through drainage from the ridges into the furrows.

Flooding at the start of the dry season, followed by only 193 mm for the remainder of the season, restricted maize grain yields, overall plant growth and the crop's response to N. Grain yields from soybean grown on *sorjan* ridges were also low, compared with the average yields previously recorded for flat-bed lowland rotation trials with soybean (cv Wilis) at Taman Bogo Experiment Farm (1.48 t ha^{-1} at zero N [Simanungkalit et al. 1995] and 1.89 t ha^{-1} at 25 kg N ha^{-1} [Simanungkalit et al. 1998]). As with the dry-season maize crop in the flat-bed upland rotation system, low soybean grain yields were likely a result of insufficient water. Soybean requires between 508 and 762 mm of water per season (Carter and Hartwig 1963). The soybean crop grown at Taman Bogo had received only 394 mm of rain. Total crop failure was probably prevented by some irrigation and rain water seeping laterally into the ridges from the furrows. A previous study with raised-bed systems noted lateral seepage as being highly significant for the water balance, although the amount of water movement was not measured (Molle et al. 1999). The soybean's lack of response to residual N may have been due to a combination of low rainfall and the presence of N-fixing rhizobia. The bacteria's presence had been demonstrated in previous rhizobium trials with the same soybean cultivar at Taman Bogo Experiment Farm (Simanungkalit et al. 1998).

Effect of non-treatment elements

Given the results of the grain nutrient analysis, only rice had either excess or insufficient non-treatment elements. Low K concentrations in the grain were probably caused by too low an application rate of K. Although the amount of K fertilizer applied was higher than used in previous flat-bed lowland rotation rice trials held at Taman Bogo Experiment Farm (Miyake et al. 1984; Ismunadji et al. 1991), the rate was still low, compared with the rates of 100–125 kg K ha^{-1} recommended for lowland rice in Java (Partohardjono et al. 1977). A side effect of low K was a high accumulation of Fe in the grain, as shown in previous flat-bed lowland rotation trials with the same rice cultivar at Taman Bogo Experiment Farm (Ismunadji et al. 1991). Low K and high Fe concentrations limited rice grain yields to levels similar to those attained in other flat-bed lowland rotation rice trials held at Taman Bogo Experiment Farm (Miyake et al. 1984; Ismunadji et al. 1991) and were even lower than yields attained with the same rice cultivar in Java (Miyake et al. 1984).

Comparing cropping systems for N concentrations in rice

Rice grown in the *sorjan* system had higher N concentrations in grain and higher N_{agb} values in both seasons than did rice grown in the flat-bed lowland rotation system. The higher N_{agb} values for rice grown in the *sorjan* furrows could not be attributed to the total initial amount of soil N in the 0 to 60 cm layer (Table 1) because this amount was similar to that in the flat-bed lowland rotation system.

In the dry season, when water supply was limited, rice grown in the *sorjan* system responded to N by increasing grain yield, unlike the rice grown in the flat-bed lowland rotation system or maize grown in the flat-bed upland rotation system. Greater responsiveness to N and higher total N_{agb} was possibly due to more water being available to crops grown in the *sorjan* system than in the flat-bed rotation systems. The additional water would have come from water draining from the ridges to the furrows. In the wet season, however, water was adequate in all systems and therefore could not have caused differences in total N_{agb}.

Agronomic comparisons between cropping systems

Comparisons between the *sorjan* system and both flat-bed rotation systems support Mawardi's (1997) general observation that the *sorjan* system is advantageous to small landholders because of its increased crop diversity.

Higher rice grain yields in the *sorjan* furrows in the dry season lead to the *sorjan* system producing more rice per hectare over two seasons than the flat-bed lowland rotation system. However, in the *sorjan* system, 60% of the area was available for lowland rice and 40% of the area was sown to upland crops. Therefore, although the average rice grain yield over two seasons was higher in the *sorjan* system than the flat-bed lowland rotation system, the amount of rice grain produced was lower in one hectare of the *sorjan* system than in one hectare of the flat-bed lowland rotation system (Table 4). In terms of weight, this shortfall in rice grain was not fully compensated by the amount of maize and soybean grain harvested from the ridges. The overall lower grain production from the *sorjan* system was primarily because maize and soybean grain yields were relative low (Manuelpillai et al. 1982; Simanungkalit et al. 1995) because of excess and insufficient water, respectively.

These results contradict Mawardi's (1997) suggestions that the *sorjan* system is more productive than the flat-bed lowland rotation system because of higher crop yield per unit area per year.

Economic comparison between cropping systems

Returns from the 1998–1999 systems at Taman Bogo were similar to returns (crop sale price minus fertilizer and seed costs) based on farmer surveys conducted in 1983 and 1993, and 1995–1996 prices (Mawardi 1997). The crops grown in Mawardi's (1997) trials were rice in a flat-bed lowland rotation system; and rice, maize and peanut (*Arachis hypogaea* L.) in a *sorjan* system. The comparison showed that, for one hectare, profits in the flat-bed lowland rotation system were about 29% higher than in the *sorjan* system when establishment costs were disregarded. The farm surveys also accounted for the inputs used for land preparation in established systems, transplanting, crop maintenance and harvesting. These additional costs were about 36% higher for the flat-bed lowland rotation system than for the *sorjan* system (Mawardi 1997). However, even when these additional costs were included in calculations to give net profits for the systems, the flat-bed lowland rotation system was still about 22% more profitable than the *sorjan* system over two seasons in the studies by Mawardi (1997).

Despite low economic returns with the *sorjan* system relative to the flat-bed lowland rotation system, this trial at Taman Bogo does not discredit the *sorjan* system as an economically viable farming option. Rather, the 1998–1999 trial highlights the need to manage the system for profitability by including at least one high-value cash crop every year and possibly by building narrower ridges. Economic data presented by Mawardi (1997) for chilli grown on *sorjan* ridges in the third season can be used as an example for including a high-value cash crop. If maize grown on the *sorjan* ridges in the second season had been substituted with chilli, the *sorjan* system would have been about 58% more profitable than the flat-bed lowland rotation system.

Conclusions

The overall conclusion of this comparative study in conjunction with previous *sorjan* system and raised-bed field trials (Domingo and Hagerman 1982; Mawardi 1997; Borrell et al. 1998) is that the *sorjan* system is an agronomically and economically viable alternative to flat-bed rotation systems in lowlands. The risk of crop failure and low yields appear to be minimized by reducing the potential for flooding and drought, although quantitative work needs to be done in this area. The *sorjan* system was also able to carry a broader diversity of crops than flat-bed upland or lowland rotation systems. In addition, the *sorjan* system had higher N_{agb} values than did the two flat-bed rotation systems, regardless of the N application rate.

However, two important points of qualification should be made to this endorsement: first, higher yields are only achieved on the ridges and in the furrows in seasons with surplus and insufficient rainfall or irrigation, respectively. In seasons with adequate rainfall or irrigation, equivalent or higher grain yields can be achieved in the less labour-intensive, flat-bed, lowland rotation system. Thus, the *sorjan* system is best suited to regions that have erratic climatic conditions and limited irrigation infrastructure. Second, farmers must take advantage of the opportunity for crop diversification, because economic viability can only be achieved by growing high-value crops at least once per year.

Acknowledgments

The Australian Research Council (ARC), in partnership with Pivot Ltd, financially supported this research. The authors wish to thank Mr Ruchiat from the Central Research Institute of Food Crops for managing the trials. The staff at the Centre for Soil and Agroclimate Research, Bogor, West Java, conducted the soil and plant analyses.

References

Benckiser, G., Ottow, J.C.G., Santiago, S. and Watanabe, I. 1982. Physico-chemical characterization of iron toxic soils in some Asian countries. IRRI Research Paper Series, 85, 11.

Borrell, A.K., Kelly, R.M. and van Cooten, D.E. 1998. Improving management of rice in semi-arid eastern Indonesia: responses to irrigation, plant type and nitrogen. Australian Journal of Experimental Agriculture 38, 261–271.

Carter, J.L. and Hartwig, E.E. 1963. The management of soybeans. In: Norman, A.J. ed. The Soybean. New York, Academic Press, 161–226.

De Datta, S. 1981. Principles and Practices of Rice Production, New York. John Wiley & Sons, 618p.

Domingo, A.A. and Hagerman, H.H. 1982. *Sorjan* cropping system trial in irrigated wet land conditions. Philippines Journal of Crop Science 7, 154–161.

Ismunadji, M., Ardjasa, W.S. and von Uexkull, H.R. 1991. Increasing productivity of iron toxic soils of Indonesia. In: Deturck, P. and Ponnamperuma, F.N. ed. Rice Production on Acid Soils of the Tropics. Kandy, Sri Lanka, Institute of Fundamental Studies, 213–217.

Lilley, J.M. and Fukai, S. 1994. Effect of timing and severity of water deficit on four diverse rice cultivars, III. Phenological development, crop growth and grain yield. Field Crops Research 37, 225–234.

Manuelpillai, R.G., Sudjadi, M., Supartini, M. and Silva, J.A. 1982. Influence of P applications on maize yields in the typic Paleudults in South Sumatra. Tropical Agriculture (Trinidad) 59, 173–178.

Mawardi, M. 1997. *Sorjan*: an adaptive and productive farming method in a markedly different water condition. Indonesian Journal of Tropical Agriculture 8, 64–70.

Miyake, M., Ismunadji, M., Zulkarnaini, I. and Roechan, 1984. Phosphate response of rice in Indonesian paddy fields. Technical Bulletin of Tropical Agriculture Reseach Center 17, 1–78.

Moentono, M.D. and Fagi, A.M. 1992. Water requirement for maize production. Indonesian Agriculture Research and Development Journal 14, 33–40.

Molle, F., Sutthi, C., Keawkulaya, J. and Korpraditskul, R. 1999. Water management in raised bed systems: a case study from the Chao Phraya delta, Thailand. Agricultural Water Management 39, 1–17.

Partohardjono, S., Ismunadji, M. and Soepardi, G. 1977. Penentuan areal padi sawah di Jawa yang memerlukan pupuk K. Peranan penelitian dalam pembangunan pertanian 2, 309–316.

Prasertsak, A. and Fukai, S. 1997. Nitrogen availability and water stress interaction on rice growth and yield. Field Crops Research 52, 249–260.

Reuter, D.J. and Robinson, J.B. ed. 1997. Plant Analysis: an interpretation manual. Collingwood, Australia. CSIRO Publishing. 572 p.

SAS Institute. 1996. The SAS System Release 6.12. Cary, NC, USA, SAS Institute Inc.

Simanungkalit, R.D.M., Hutagalung, T., Hastuti, R.D., Pratiwi, E. and Roughley, R.J. 1998. Effectiveness of *Bradyrhizobium japonicum* strains selected for acid tolerance to increase yields of soybean grown in acid soils in Indonesia. Indonesian Journal of Crop Science 13, 32–40.

Simanungkalit, R.D.M., Indrasumunar, A., Hastuti, R.D., Pratiwi, E. and Roughley, R.J. 1995. Soybean response on nodulation to starter nitrogen and inoculation with *Bradyrhizobium japonicum*. Indonesian Journal of Crop Science 10, 25–32.

Troedson, R.J., Lawn, R.J., Byth, D.E. and Wilson, G.L. 1989. Response of field-grown soybean to saturated soil culture, 1. Patterns of biomass and nitrogen accumulation. Field Crops Research 21, 171–187.

van Cooten, D.E. and Borrell, A.K. 1999. Enhancing food security in semi-arid eastern Indonesia through permanent raised-bed cropping: a review. Australian Journal of Experimental Agriculture 39, 1035–1046.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

New Rice-Breeding Methods for the Rainfed Lowlands of North and Northeast Thailand

Boonrat Jongdee

Abstract

The rainfed lowlands comprise a major rice ecosystem in Thailand, occupying about 5.7 million hectares of the country's total rice land of 9.2 million ha. Most of these lowlands are found in the north and northeast, and can be classified as shallow-favourable and shallow-drought-prone. Grain yield is generally low, partly because current cultivars have low potential grain yield and lack resistance to biotic and abiotic stresses. Attempts to develop rice cultivars for the rainfed lowlands by the current breeding program have been successful, with two cultivars being recently released. However, identifying lines for release took a long time and, while they performed well across targeted environments, their yield improvement has been minor. One outcome of the ACIAR project on "Plant-Breeding Strategies for Rainfed Lowland Rice in Northeast Thailand and Laos" was the identification of areas for potential improvement in the current breeding program. A new breeding program was begun in the 2000 wet season. Its two major objectives were to improve resistance in existing cultivars, and to increase potential grain yield in new cultivars. The selection scheme was changed to emphasize inter-station selection and on-farm trials. Marker-assisted selection for drought and blast resistance is being developed and will be incorporated into the new breeding program.

A MAJOR food crop, rice is widely grown in Thailand, covering a total area of about 9.2 million hectares. Of the four rice ecosystems—uplands, rainfed lowlands, irrigated lowlands and deepwater—the rainfed lowlands comprise a major, occupying 5.7 million ha and accounting for 62% of the country's total rice-growing area (AIS 1997). The rainfed lowlands are found mainly in the northeast, comprising 4.3 million ha of the region's total rice land of 5.1 million ha. Another 1.4 million ha (of 2.0 million ha) are found in the north. Under rainfed lowland conditions, grain yield is generally low and varies across years and locations, ranging between 1.5 and 2.2 t ha^{-1}, compared with irrigated lowland rice in the central region, where the average grain yield is more than 4.0 t ha^{-1}.

The lower grain yields under rainfed lowland conditions result partly from the susceptibility of the major cultivars to biotic and abiotic stresses and partly from these cultivars' lower yield potential. They are also tall, traditional types that frequently lodge under high soil fertility and high input conditions. In north and northeast Thailand, the improved traditional cultivars KDML105, RD6 and RD15—all photoperiod sensitive—are the most popular, occupying almost 80% of the total rice land. Their popularity stems from their superior eating quality, higher market prices, good adaptation to low soil fertility and low inputs and intermediate resistance to drought and soil salinity.

Even so, these cultivars generally have similar phenological development and low potential grain yield, and lack resistance to blast, a fungal disease that commonly occurs in any growth stage. When it occurs between flowering and grain filling, this disease severely reduces yield. These popular cultivars are also late maturing, flowering in late October, except for RD15, which flowers a week earlier than the other two cultivars. Thus, grain yield is at risk of being reduced by drought (Table 1).

Phrae Rice Research Centre, Phrae, Thailand.
E-mail: rrcpre@phrae.ksc.co.th

KEYWORDS: Thai breeding program, Rainfed lowland rice

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Table 1. Mean monthly rainfall during 1991–1995 in selected provinces, north and northeast Thailand.

Province	Monthly rainfall (mm)						
	May	June	July	Aug.	Sept.	Oct.	Nov.
North							
Chiengrai	141	192	183	261	188	55	15
Phrae	168	113	162	224	147	47	24
Nan	60	132	111	256	104	87	18
Northeast							
Ubon	207	219	204	278	247	64	5
Roi-Et	133	180	144	246	216	56	17
Nong-Kai	184	263	289	300	197	24	0
Udon Thani	160	273	208	278	275	63	15

To minimize risks, and stabilize and increase production for the rainfed lowlands, cultivars need to be developed that have diverse flowering dates, higher grain yield potential and resistance to drought and important insect pests and diseases. They should also be well adapted to each target area of the rainfed lowlands. This paper describes the current breeding program, and the changes that the program is undergoing to improve the efficiency of its rice-breeding program for the rainfed lowlands of north and northeast Thailand.

Production Constraints and Breeding Objectives

The rainfed lowlands in north and northeast Thailand can be classified as shallow-favourable and shallow-drought-prone for rice cultivation (IRRI 1984). Drought is therefore a major cause of fluctuation in grain yield (Fukai et al. 1998). Rainfall has a bimodal distribution, with the monsoon season usually beginning in May and ending around mid- to late October (Table 1). Drought may develop at any time during the growing season. Early season drought occurs in most areas, affecting timely transplanting of seedlings and the growth of direct-seeded rice. Late-season drought develops at the end of monsoons in most years in the north-east, particularly if paddy rice is planted in high toposequence positions and the soil percolation rate is high. Somrith (1997) reported that sandy and saline soils are scattered throughout northeast Thailand, totalling about 1.0 and 2.8 million ha, respectively.

Leaf and neck blast are the most important diseases. In 1992, in northern Thailand, neck blast damaged rice yields in almost 70% of the area, particularly where cvs. KDML105 and RD6 were planted. However, cultivars that had flowered earlier than these two cultivars, such as RD10, and were also susceptible to blast, escaped severe damage. Mekwantanakarn et al. (1999) reported that 51 pathotypes of the rice blast fungus can be found in the north, northeast and central regions, with 12 being commonly found in the north and north-east.

Of the insect pests, the stem borer has often been reported to cause yield loss in the northeast, while the gall midge is a problem in the north and some northeast areas.

High grain quality is the first objective of the Thai rice-breeding program. Thai farmers and consumers alike require long-grain rice with good eating quality. Other traits for improvement in rainfed lowland rice cultivars for northern and northeast Thailand include intermediate to high grain yield; resistance to drought, major insect pests and diseases; appropriate flowering dates; and good adaptation to different environments.

Current Breeding Program

The breeding program for rainfed lowland rice for north and northeast Thailand comprises three phases: intra-station, inter-station and on-farm (Figure 1). The intra-station phase includes hybridization, pedigree selection and intra-station yield trials in which selection is made independently at each location. Selection is based on flowering time, grain size, plant height and plant type, except in the yield trial F_7 when selection is based on grain yield.

In the inter-station phase, lines that had performed well within each research station (i.e. in the intra-station trials) are evaluated against each other across research stations. Selection is based on average grain yield across research stations and on chemical grain quality. Three research stations participate in north Thailand and six in the northeast.

For on-farm trials, only four to six lines with different flowering times are tested in farm fields, mostly in farmer fields with shallow-favourable conditions, even though these are not representative of

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

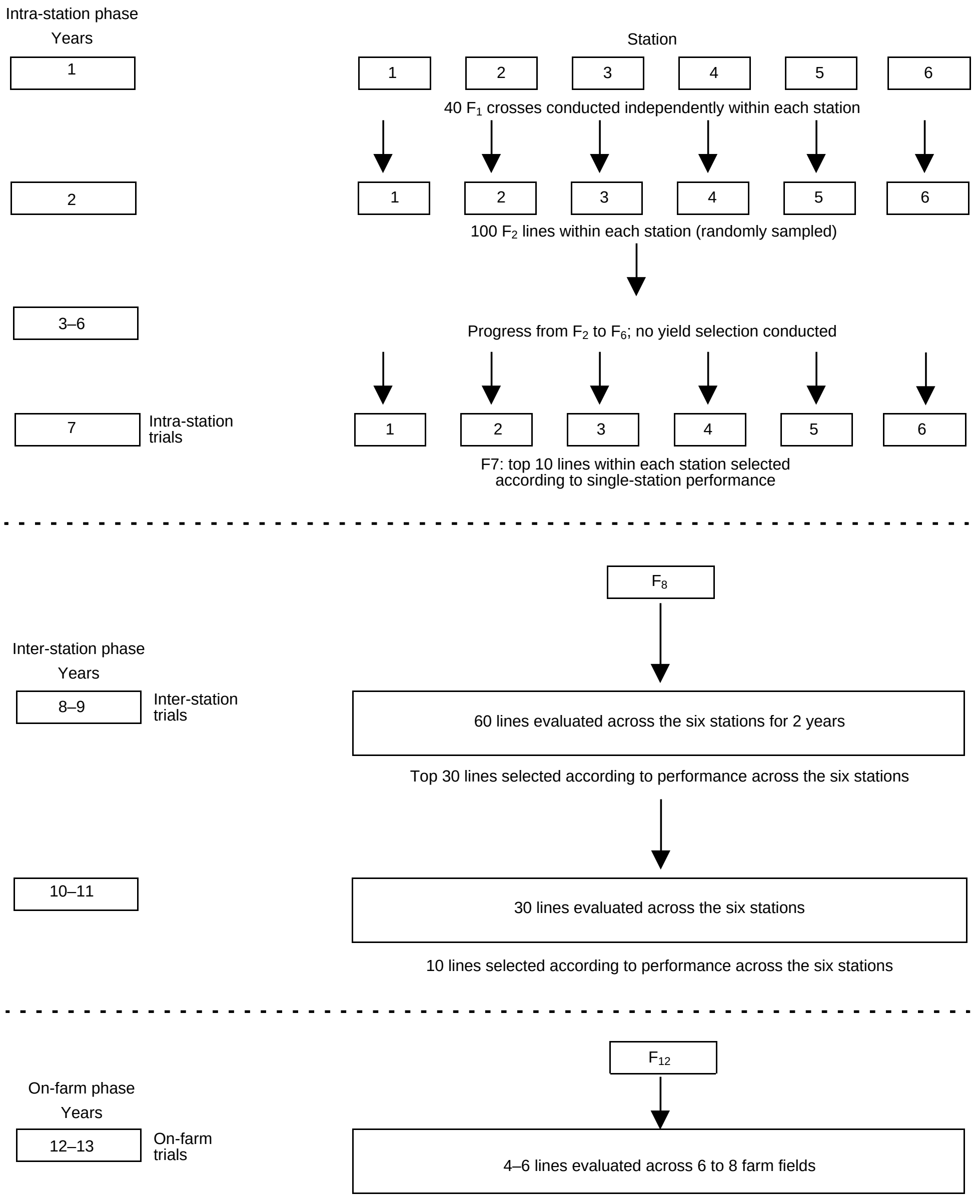


Figure 1. Current rice-breeding strategy for the rainfed lowlands of north and northeast Thailand (after Cooper et al. 1999).

all farmer fields. This strategy differs with the suggestion by Inthapanya et al. (2000) that farmer fields that represent soil fertility and drought occurrence should be selected.

This breeding strategy was somewhat successful, that is, of a total of nine that were released during 1997 to 2000, two were for the rainfed lowlands (Table 2). However, an average of 14 years were needed to successfully breed them. Selection during the intra-station phase was about 6 to 7 years, whereas selection during the inter-station and on-farm trial phases together varied from 6 to 10 years, depending on the consistency of line performance across locations. Cooper et al. (1999) commented that, under rainfed lowland conditions, yield variation was largely influenced by the genotype by location by year interaction (G × L × Y). Thus, identifying lines with good adaptation across targeted environments was difficult within a short time. Furthermore, because of the large G × E interaction for grain yield under rainfed lowland conditions, the use of only grain yield as a selection criterion may not be effective. However, factors influencing grain yield such as flowering time and the drought period likely to develop at each location should be considered when assessing genotypic variation in grain yield (Fukai and Cooper 1995).

Only a few parents have been used in the crossing program. Because eating quality is the most important trait for Thai rice, cvs. KDML105 and RD15 are mostly used as parents for the non-glutinous type, while cvs. RD6 and Niaw Sanpathong are often used for developing the glutinous type. Cooper et al. (1999) reported that developing high-yielding progenies was difficult when using KDML105 and RD6 as parents, even if these cultivars were crossed with high-yielding lines. The authors also showed that progeny of crosses based on non-traditional Thai rices tended to show higher grain yield than do those of KDML105 and RD6 across eight locations in northeast Thailand. Thus, grain yield in rainfed lowland rice can be improved.

Despite grain quality being of first priority, it is assessed in later generations, during the yield trial phase, that is, after F_6 or F_7. Many lines with high grain yield and good adaptation to targeted environments are discarded because of low grain quality, such as high amylose content, high chalkiness and poor eating quality.

Recommendations of the ACIAR Project

In view of the slow progress in developing rainfed lowland cultivars, the rice-breeding program for north and northeast Thailand was revised, using the results of the ACIAR project. Points discussed included production constraints in the target areas, objectives of the breeding program, parental lines used in the crossing program, selection strategies, and collaboration among breeders and scientists from other disciplines.

The ACIAR project on “Plant-Breeding Strategies for Rainfed Lowland Rice in North-East Thailand and Laos” was conducted during 1996–1999. The main objective was to develop breeding strategies that would increase the efficiency of rice improvement programs for these two countries. Based on the project’s outcomes, several areas of the current breeding program were identified as having potential for improvement. Overall efficiency could be improved by incorporating all or some of the following six elements.

1. *Coordination of early generation activities across stations.* The current coordination of crossing and early generation selection is poor across stations. Parental materials for crossing should be discussed and coordinated among the breeders of the different stations. Selection of segregating materials is based on grain size, flowering time, plant height and plant type, which are all traits of high heritability. Thus, selection activities for years 1 to 4 could be conducted at only a few stations.
2. *Rapid generation advance*. The main reason for using rapid generation advance (RGA) is that new cultivars can be released in a shorter time. At present, only one generation is produced per year, even though the rate could be increased by assessing photoperiod-insensitive types in the dry season. Rapid generation advance could also be used to maintain a higher level of genetic variability for later generations. The single-seed

Table 2. Rice cultivars released by the Thailand Rice Research Institute between 1997 and 2000.

Cultivar	Endosperm type[a]	Year of cross	Year of release	Growing area[b]	Photoperiod sensitivity[c]
Hawm Supan Buri 2	NG	1989	1997	I	Ins
Niaw Ubon 2	G	1983	1997	R	Ins
Niaw Phrae 1	G	1975	1999	I	Ins
Hawm Khlong Luang 1	NG	1983	1999	I	Ins
Sakon Nakhon 1	G	1982	2000	R	S
Sanpathong1	G	1984	2000	I	Ins
Surin 1	NG	1989	2000	I	Ins
Hawm Pathum Thani 1	NG	1990	2000	I	Ins
Phitsanulok 2	NG	1991	2000	I	Ins

[a] NG = non-glutinous; G = glutinous.
[b] I = irrigated; R = rainfed.
[c] Ins = Insensitive; S = sensitive.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

descent method could be used in those cases where a simply inherited character is to be added to existing cultivars.

3. *Introduction of early generation inter-station yield trials*. We analysed results from multiple environment trials (METs), conducted at eight locations in 1996 and 1997 with 1070 and 463 lines, respectively, from seven ACIAR populations. The yield results from the METs showed that the variance component for G × E interaction was six times larger than that for genotype. In contrast, the G × E variance component for flowering time and height were smaller than that for genotype. With the large effect of G × E interaction for yield, selection based on individual intra-station yield trials would not be successful in developing cultivars that are widely adapted to the region. However, selection for appropriate flowering time and height can be done by individual stations.

   Early generation inter-station yield testing would ensure that most progeny lines are evaluated across locations for their yield potential. At present, many lines are discarded without being tested for yield. Inter-station yield trials would greatly increase the chance that widely adapted lines are selected—a necessary requirement for improving the breeding program's efficiency in view of the large G × E interaction for yield. Lines specifically adapted to regions can also be selected when they are identified.

   The use of F_4 bulks would ensure that many lines can be tested for yield and, based on the F_4 bulk yield results, F_6 and F_7 rows can be selected. The modified F_4 bulk strategy has been successful in the Queensland wheat-breeding program, where large G × E interactions were observed (Cooper et al. 1996). However, these F_4 bulk methods require more resources to yield test numerous lines. Alternatively, F_6 or F_7 can be tested for yield in inter-station trials without using F_4 bulk, but this method is less effective as a large number of lines would be lost by this stage.

   In the breeding program for rainfed lowland rice, selection is usually conducted under a higher rate of fertilizer application than is farmer's practice. There were doubts as to whether the higher rate of fertilizer used by the breeding program was appropriate for producing cultivars adapted to the low soil fertility normal under farm conditions. The results of 3 years of experiments, conducted by the ACIAR project, where genotypes were compared under fertilizer and non-fertilizer conditions, suggested that selection under moderate fertilizer conditions is more effective than that under no fertilizer conditions. Combined analysis showed significant genotypic variation (G) and that the interactions genotype by location (G × L), genotype by fertilizer (G × F) and genotype by location by fertilizer (G × L × F) were also significant. However, variance components for G and G × L were larger than for G × F and G × L × F, indicating that genotypic ranking of lines between fertilizer and no-fertilizer conditions would be relatively consistent. In addition, Inthapanya et al. (2000) reported that the magnitude of genotypic variation in grain yield under fertilizer application was larger than that under no fertilizer, thus, selection would be more effective.

4. *Use of the Chum Phae Research Station for drought screening*. Drought screening facilities have been developed at the Chum Phae Rice Research Station, a location where rainfall is consistently low, compared with most other locations in northeast Thailand. Large numbers of lines can be screened against late-season drought, thereby increasing the chance of selecting resistant materials.

   Mechanisms for resistance against late-season drought were identified. A key mechanism was the maintenance of high leaf water potential during drought at flowering. A study at The University of Queensland showed that maintenance of leaf water potential was a consistent trait across vegetative and flowering stages, and across different environments. Under drought at flowering, reduced grain yield is due to reduced numbers of filled grain or increased spikelet sterility. The latter is negatively related to genotypic variation in the maintenance of leaf water potential (Jongdee et al. 1998). Maintenance of high leaf water potential thus minimizes the effect of drought on spikelet sterility, leading to higher grain yield. Results from other studies in Thailand showed that delayed flowering, green leaf area retention, panicle water potential and drought response index can be also used as selection criteria for drought resistance at flowering.

   For field screening, two growing conditions—irrigated and rainfed—are required. If most tested lines are photoperiod insensitive or only weakly sensitive, sowing should be delayed to ensure that less rain falls during the intended drought screening period. Under irrigated conditions, potential grain yield, harvest index, height and total biomass at anthesis and at flowering should be determined. Under rainfed conditions, standing water should be drained before anthesis and measurements made for drought resistance, including grain yield, spikelet sterility, delayed flowering, drought score and leaf or panicle water potential. This type of drought screening can be included as routine procedure in breeding programs, with all materials at around F_5 and F_6 being subjected to drought screening for two seasons.

5. *Early testing of grain quality*. Because grain quality is an important trait, early generation testing will increase the chance that advanced lines will have all the necessary grain quality characteristics.
6. *Increased emphasis on on-farm trials.* Under the current system, most breeding activities are conducted on research stations where growing conditions do not represent farmer fields. Increasing on-farm trials will increase the chance of selecting lines that will perform well under farmer field conditions. One possibility is to use two types of on-farm trials: one for testing 20 lines, using small plots (6 rows per plot); and the other for testing 6–8 lines on larger plots (16 rows per plot). A fertilizer trial would also be included in these on-farm trials.

The New Breeding Program

The new, and more efficient, rice-breeding program for the rainfed lowlands of northern and northeastern Thailand was the outcome of a workshop held by Thai scientists to consider the ACIAR project's recommendations. The new program, which began in 2000, combines the north and northeast programs. At the workshop, the Thai scientists agreed that rainfed lowland rice cultivars should have:

- Long grains, with good eating quality similar to cvs. KDML105 and RD6
- Flowering times appropriate for targeted environments
- Resistance to at least late-season drought and to leaf and neck blast diseases
- Moderate to high grain yield

The program's two major strategies for germplasm development are:

1. *Improve resistance in existing cultivars*. Popular cultivars such as KDML105, RD6, RD15, PTT1 and Sanpathong1 will be improved for drought and blast resistance while maintaining their superior eating and grain qualities. A backcrossing strategy will be used for this program. Grain yield may become more stable by adding those resistance traits, although potential grain yield may not be improved.
2. *Improve potential grain yield*. This long-term strategy will first improve potential grain yield, then ensure high grain quality.

In the new selection scheme, the time of the intra-station phase is reduced but the inter-station phase is increased (Figure 2). The intra-station phase includes hybridization, generation advance from F_2 to F_5 or F_6 and seed increase (F_6 or F_7) for yield testing in F_7 or F_8. During seed increase, lines that have desirable flowering time, height and grain size will be selected, and tested for grain yield in the next stage. The time of this phase will be 3 to 4 years, with only three research centres—Phrae, Ubon Rachathani and Sakon Nakorn—taking responsibility for these activities.

The inter-station yield trials will be conducted at nine research stations across north and northeast Thailand for 3 years, that is, 1 year for the observation yield nursery, with small plots due to limited seed availability, and 2 years for inter-station yield trials. Materials may be grouped according to flowering time, that is, into early, intermediate and late-maturing in each trial, when large numbers of lines will fall into their respective groups. Such grouping is significant because of management difficulties such as time of fertilizer application and bird control, and for eliminating the effects of different flowering times in determining grain yield. Resistance to drought and blast, and also some chemical grain quality traits are tested during this stage. Field drought screening will be conducted at the Chum Phae Research Station in the northeast and at the Phare Research Centre in the north.

The first of two stages of on-farm trials involves as many as 20 lines on small plots (6–8 rows per plot). The second stage will have a few lines on large plots (16 rows per plot). Three different farmer paddy conditions will be selected for testing the different flowering groups, that is, high (for early maturing), middle (intermediate) and low-lying (late) fields. Farmers are invited to participate in this selection stage.

The economic benefits of the modified breeding program, whereby the length of the rice-breeding cycle for the rainfed lowlands of northeast Thailand would be reduced, was evaluated by Pandey and Rajatasereekul (1999). They found that a large financial and positive impact on the Thai rice economy would occur if the breeding program could be shortened. Should the current breeding period be shortened by 2 years, the economic benefit would be about US$18 million over the variety's useful life. Obviously, the economic benefit would be further enhanced if the yield level of new cultivars were also increased.

Use of Molecular Markers

Marker-assisted selection (MAS) is a new tool suggested for the breeding program. Recently, rapid progress has been made in molecular marker studies,

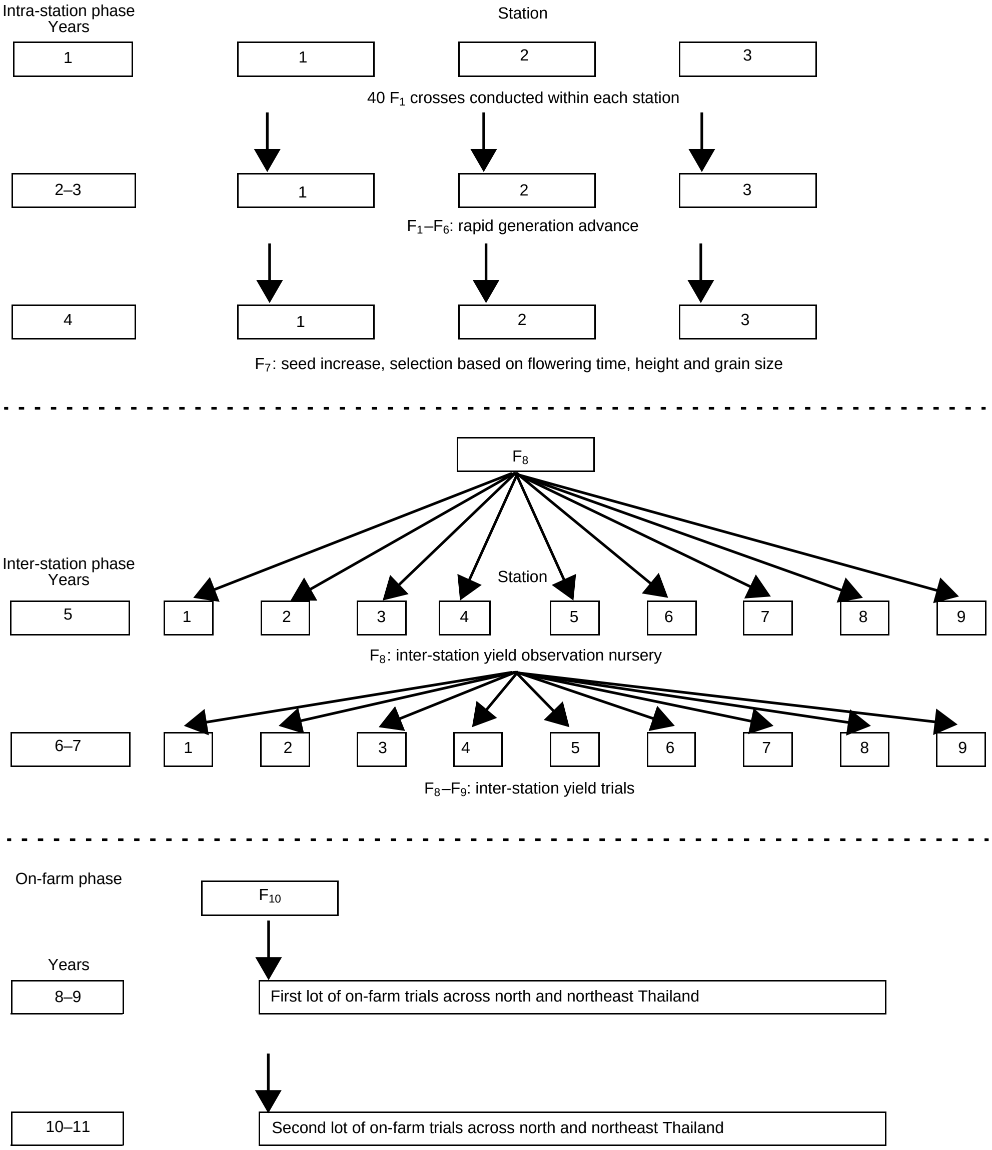


Figure 2. The selection strategy used by the new rice-breeding program for the rainfed lowlands of north and northeast Thailand.

and MAS is being incorporated in some breeding programs. The use of MAS would probably be more effective than selection based on phenotype alone (Lande and Thompson 1990; Kristin et al. 1997) for traits that have low heritability, are costly to research and time consuming for mass selection (Mackill et al. 1999).

The new breeding program is planning to incorporate MAS for traits (e.g. chemical grain quality and resistance to blast and drought) that must be screened at early generations when the numbers of lines are large.

At present, the Thailand Rice Research Institute, in collaboration with the National Centre for Genetic Engineering and Biotechnology (BIOTEC–Thailand), is conducting a project on the "Application of Molecular Breeding for Improving Drought Tolerance in Rainfed Lowland Rice", supported by the

Rockefeller Foundation. This project aims to identify quantitative trait loci (QTLs) and develop a MAS scheme for traits related to yield performance under water deficit at flowering, such as leaf water potential, spikelet sterility, delay in flowering, drought response index and osmotic adjustment.

Another project, which is being conducted at the Ubon Rice Research Centre, is to develop MAS for blast resistance for rainfed lowland rice in north and northeast Thailand. For chemical grain quality, markers for some traits such as amylose content have already been developed by BIOTEC–Thailand.

Conclusions

The current breeding program for rainfed lowland rice in north and northeast Thailand has been somewhat effective in developing new cultivars. However, the program takes a long time to produce new cultivars and the genetic progress in grain yield is limited. This is partly due to the selection strategy, which extensively uses intra-station selection, and the choice of parents in the crossing program.

In the new breeding program, several areas have been changed such as shorter periods for the intra-station phase and more emphasis on on-farm trials. Grain quality needs to be maintained at the same levels as those of existing cultivars but resistance to stresses and potential grain yield need to be improved. Marker-assisted selection—a new selection approach—for some traits such as drought and blast resistance is being developed and will be incorporated into the breeding program.

References

AIS (Agricultural Information Subdivision), Department of Agricultural Extension. 1997. Agricultural Statistics in Thailand. 112 p.

Cooper, M., Brennan, P.S. and Sheppard, J.A. 1996. A strategy for yield improvement of wheat which accommodates large genotype by environment interaction. In: Cooper, M. and Hammer, G.L. ed. Plant Adaptation and Crop Improvement. CAB International, International Rice Research Institute (IRRI) and International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), 487–511.

Cooper, M., Rajatasereekul, S., Somrith, B., Sriwisut, S., Immark, S., Boonwite, C., Suwanwongse, A., Ruangsook, S., Hanviriyapant, P., Romyen, P., Pon-Uraisanit, P., Skulkhu, S., Fukai, S., Basnayake, J. and Podlich, D.W. 1999. Rainfed lowland rice breeding strategies for northeast Thailand II. Comparison of intrastation and interstation selections. Field Crops Research, 64, 153–176.

Fukai, S. and Cooper, M. 1995. Development of drought-resistance cultivars using physio-morphlogical traits in rice. Field Crops Research, 40, 67–86.

Fukai, S., Sitisuang, P. and Chanphengsay, M. 1998. Increasing production of rainfed lowland rice in drought prone environments. Plant Production Science, 1, 75–82.

Inthapanya, P., Sipaseuth, Sihavong, P., Sihathep, V., Chanhphengsay, M., Fukai, S. and Basanayak, J. 2000. Genotypic performance under fertilizer and no-fertilizer conditions in rainfed lowland rice. Field Crops Research, 65, 1–14.

IRRI (International Rice Research Institute). 1984. Terminology for Rice-Growing Environments. Los Baños, Philippines.

Jongdee, B., Fukai, S. and Cooper, M. 1998. Genotypic variation in grain yield of rice under water limited conditions. In: Michalk, D.L. and Pratley, J.E. ed. Proceedings of the 9th Australian Agronomy Conference held at Wagga Wagga, NSW, Australia, 20–23 July. Australian Society of Agronomy, 403–406.

Schneider, K.A., Brother, M.E and Kelly, J.D. Kristin, A.S., Mary, E. and James, D.K. 1997. Marker-assisted selection to improve drought resistance in common bean. Crop Science, 37, 51–60.

Lande, R. and Thompson, R. 1990. Efficiency of marker-assisted selection in the improvement of quantitative traits. Genetics, 124, 743–756.

Mackill, D.J., Nguyen, H.T. and Zhang, J. 1999. Use of molecular markers in plant improvement programs for rainfed lowland rice. Field Crops Research, 64, 177–185.

Mekwantanakarn, P., Khumma, S. and Phromraksa, T. 1999. Characteristics of *Pyricularia grisea (Magnaporthe grisea)* populations in Thailand using molecular marker and pathotype. Paper presented at the International Program on Rice Biotechnology, 20–24 September 1999, Phuket, Thailand.

Pandey, S. and Rajatasereekul, S. 1999. Economics of plant breeding: The value of shorter breeding cycles for rice in Northeast Thailand. Field Crops Research, 64, 187–197.

Somrith, B. 1997. Cultivars improvement for rainfed lowland rice in Thailand. In: Breeding Strategies for Rainfed Lowland Rice in Drought-Prone Environments, Proceedings of an International Workshop held at Ubon Ratchatani, Thailand, 5–8 November 1996. Canberra, ACIAR Proceedings No. 77, 36–42.

Rice Improvement Methods for Laos

Chanthakhone Boualaphanh*, Phoumy Inthaphanya and Sengpaseuth Ratsabandit

Abstract

The Lao variety improvement program started in 1975 with the main objective of broadening the country's rice variety spectrum. Since then, the program has been upgraded through collaborative projects with IRRI and ACIAR, who provided technical and financial support. The result was a systematic variety improvement program for rainfed upland and lowland rice-production systems. Since 1991, the breeding program concentrated mainly on five areas: (1) variety introduction; (2) local germplasm collection, conservation, evaluation and use; (3) crossing and selection; (4) multi-locational testing; and (5) seed production. Nine varieties were eventually released for rainfed and irrigated lowlands in different agroclimatic regions. Another 18 new varieties are being recommended for different rice ecosystems. Recently, a screening program to develop rainfed lowland cultivars for water-limited conditions was set up. The variety improvement program's future emphases include quality improvement for the export market, improved non-glutinous varieties for rainfed and irrigated lowlands and improved cultivars for low-temperature areas in northern Laos.

AGRICULTURE is the largest economic sector in Laos, accounting for about 52% of the country's total gross domestic product and employing 80% of its labour force (Schiller et al., this volume). Rice is the single most important crop in the country and is cultivated in both wet and dry seasons. In the wet season, it is grown in different agroecosystems, ranging from rainfed uplands to rainfed lowlands. Dry-season rice may receive full or supplementary irrigation.

In 1995–1997, the total annual rice production varied between 1.41 and 1.66 million tons. With most of the planted area under rainfed conditions, annual rice production is highly influenced by climatic variability. Serious flooding caused crop losses in the rainfed lowlands during both 1995 and 1996. The total 1997 production was about 1.66 million tons, being higher than in either 1995 or 1996. During 1998–1999, the total rice production increased from 1.6 million tons to the highest recorded level of 2.1 million tons. Such improvement resulted in the country achieving self-sufficiency in rice in 1999. That is, during the last two decades, total rice production in Laos has increased almost by 100%. Most of the increase came from the rainfed lowlands (a two-fold increase from 705 000 t to 1 502 000 t), despite the production of dry-season irrigated rice increasing by almost eight times, from 41 000 t in 1990 to 354 000 t in 1999.

This success is partly a result of the development of new rice varieties, themselves an outcome of improved breeding strategies adopted by the plant-breeding program of the Lao National Agricultural Research Centre (NARC). During the last decade, the plant improvement program was upgraded by adapting new breeding strategies in conjunction with varietal introduction from other South-East Asian countries. The rice variety spectrum was expanded with the release of new varieties during this period. However, the number of improved varieties is limited and they are not necessarily suitable for each of the different rice ecosystems found in Laos. Demand is increasing for new varieties that can adapt to different environmental

---

National Agricultural Research Centre (NARC), Ministry of Agriculture and Forestry, Vientiane, Laos
*Corresponding author: E-mail: cboua@hotmail.com

KEYWORDS: Variety introduction, Germplasm collection, Multi-location test

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

conditions, including drought, poor soil fertility, low temperatures and floods. Another serious challenge that Lao breeders must face today is to improve rice grain quality. With the importance of varieties being recognized nationally, the main priority for national rice research is to further improve the Lao rice-breeding program.

Rice Production Environments of Laos

The rice-growing area in 1999 was 717 577 hectares. In the 1997/98 dry season, only 12% (87 030 ha) of the rice area was irrigated. The rainfed lowlands accounted for 66% of the rice area and 71% of rice production, while the rainfed uplands accounted for 22% of area and 12% of rice production.

The area for wet-season rice is divided into rainfed uplands and rainfed lowlands (Table 1).

Table 1. Rice-growing regions, conditions and area, Laos, 1999.

Region	Wet-season lowlands (ha)	Dry-season irrigated areas (ha)	Wet-season uplands (ha)
Northern	73 034	7 925	113 358
Central	271 422	55 710	26 904
Southern	132 720	23 395	13 109
Total area (ha)	477 176	87 030	153 371
Percentage	66	12	22

About 271 400 ha of wet-season lowlands are in central Laos. The wet-season lowlands in southern and northern Laos comprise about 132 700 ha and 73 000 ha, respectively. Most of upland rice area (73%) is in northern Laos, where low temperatures cause problems. Irrigated rice production is relatively small, but is expanding rapidly. Most irrigated lands are in central Laos, followed by southern and northern Laos.

In the rainfed lowland rice ecosystems of Laos, farmers have been cultivating traditional varieties for many years. These varieties provide grain for farmers and useful genetic materials for breeders. Germplasm collection and use are therefore major activities in the current plant improvement program.

For cultivar development, the Lao breeding program has targeted the rainfed lowland ecosystem. However, as rice production expands in Laos, varietal development for the irrigated rice ecosystem is also given high priority.

Constraints to Rice Production

Several factors limit rice productivity in Laos. Among the more severe constraints are droughts, floods, poor soil fertility, weed, pests and diseases, and limited adaptation of varieties for different agroecological zones.

Annual rainfall in most provinces in the Mekong River Valley ranges from 1500 to 2200 mm. However, in some northern provinces, the total annual rainfall drops to 1200–1300 mm. The rainfall pattern can vary from year to year, causing wide fluctuations in rice production. In most years, grain yields are lost to drought and floods in at least part of the country. About 15% of the Mekong River Valley is regarded as flood prone. Two types of drought are recognized for the wet-season rice crop: early season drought, which usually occurs between mid-June and mid-July as the monsoons change from south-east to south-west; and late-season drought, which usually occurs when the regular monsoons end early. Fukai and Cooper (1995), and Jongdee et al. (1997) have demonstrated that late-season drought alone can reduce grain yield by an average of 30% in northern and northeast Thailand.

In most of the rainfed lowlands of the central and southern agricultural areas, soils are highly weathered, with an inherently low fertility. Classified mostly as Alisols, Acrisols and Gleysols, the soils have low levels of N, P and, sometimes, K (Linquist et al. 1999; Inthapanya et al. 2000a, b). Low organic matter contents and low cation-exchange capacity are also common. Because of their high sand and low clay contents, the soils have a low water-holding capacity. Iron toxicity is thought to be common to most soils.

Limited availability of improved varieties for each rice ecosystem is another constraint to increasing production. About 30 different traditional varieties are growing in the rainfed lowland ecosystem. Most are low yielding, glutinous and photoperiod sensitive. Given the magnitude of variation in rice ecosystems in Laos, the current variety spectrum is insufficient to overcome abiotic and biotic constraints.

Weed competition is another constraint in most rice production environments. Sound agronomic practices, combined with chemical weed control, can help minimize weed competition. However, selecting varieties with capacity to compete strongly with weeds will remain as a long-term solution for the weed problem.

Pest and disease damage is another biotic constraint for lowland and upland rice production systems in Laos. While several diseases occur—leaf and neck blast, bacterial leaf blight and brown spot—they are generally not economically important. Economically more significant are insect pests, the most prominent of which are gall midge, stem borer, rice bug and brown plant hopper (BPH). The rice bug is an increasingly important economic pest in some areas, particularly in the central agricultural region (Inthavong 1999), where it is causing substantial yield losses in the provinces of the Mekong River Valley. The BPH occasionally causes severe damage, particularly in the central region.

Objectives of the Breeding Program

Main objective: to broaden the spectrum of rice varieties in Laos

The main aim of the rice-breeding program is to provide farmers with a range of varieties with increased yield potential and broad adaptability to Lao conditions even though it recognizes that fertilizer inputs will be necessary to help increase yields. However, input levels can be expected to be moderate, the actual inputs changing with prices. Maximizing nutrient-use efficiency in new varieties is a high priority for Laotian breeders. Most rainfed lowland rice varieties in Laos are adapted to local environments, including for time to flowering, drought recovery and cooking and eating qualities. Some of these varieties are resistant to common pests and diseases in those regions. However, grain yield production is low and, sometimes, these varieties show low yield response to N, P and K fertiliser application.

Specific objectives

Specific objectives for variety development in the near future are as follows (Inthapanya et al. 1995):

1. *Intermediate-to-late maturing varieties that are photoperiod-insensitive*. The main emphasis is to provide more photoperiod-insensitive varieties for the intermediate-to-late (125–140 days) maturing groups. However, photoperiod-sensitive varieties with flowering in mid-October or later will also be developed.

   Depending on their time to flowering, varieties are divided into three maturity groups: early, intermediate and late. Early varieties are those that flower before mid-October (photoperiod-sensitive varieties) or mature in fewer than 120 days (photoperiod-insensitive varieties). Intermediate-maturing varieties flower between mid-October and mid-November, or mature in less than 150 days, whereas late varieties flower after this period. Normally, early varieties are grown near villages where water levels are shallow and where crops can be irrigated if rain is insufficient. The intermediate-maturing varieties are often grown in middle-field terraces and the late-maturing varieties in the lowest terraces where water depths are deeper and available for longer periods.
2. *Grain with glutinous endosperm and acceptable quality.* Because most Laotians demand glutinous rice types, the program is developing new varieties with grains that have glutinous endosperm and acceptable grain characteristics and eating qualities. In response to increasing demand from the northern region, non-glutinous rice varieties are also being developed.
3. *High potential yield.* The program aims to increase the yield potential of both photoperiod-sensitive and photoperiod-insensitive rice varieties for all three production ecosystems in central, southern and northern Laos.
4. *Yield stability under drought.* Because of the unpredictable nature of droughts and floods, Laos can suffer wide fluctuations in its national rice production. The current program attempts to develop varieties with high yield stability for drought-prone areas and has recently begun screening genotypes for water-limited environments, in collaboration with a new ACIAR project.
5. *Resistance to or tolerance of major pests and diseases.* Although pests and diseases do not constitute serious threats to rice production in Laos, breeders are continuing to develop resistant germplasm for the region's most common diseases, including blast and bacterial leaf blight, and pests. Gall midge is often reported as a serious pest for both traditional and improved varieties cultivated under rainfed lowland ecosystems. Another pest, considered as a potentially serious threat in the future, is the rice bug.
6. *Improving plant type characteristics*. Generally, the program aims to develop cultivars of a semi-dwarf to intermediate plant type and with long grains. Laotian farmers are increasingly demanding long panicles and semi-dwarf plant types. However, these traits must be accompanied by good milling and good eating qualities.

Components of the breeding program

The program's components are as follows:

1. *Variety introduction, and collection of local germplasm and its evaluation, conservation and use.* Variety introduction started in 1991 and large numbers of varieties have now been introduced from IRRI, Philippines, Thailand, Vietnam and other South-East Asian countries. Collection of local germplasm started in 1995, with funding

from the Swiss Agency for Development and Cooperation (SDC) through the Lao–IRRI Project. Most rice-growing areas in Laos were explored between 1995 and 2000, and 13 193 samples of traditional cultivars were collected. Using passport data, all samples were classified according to ecosystem, endosperm type and time to maturity (Table 2). The numbers of samples collected were, for the northern region, 5919 (44.9%); central, 4623 (35.0%); and southern, 2651 (20.1%).

Table 2. The numbers of provinces and districts where traditional Laotian rice cultivars were collected, and the number of samples, 1995 and 1999.

Year	Provinces (no.)	Districts (no.)	Samples (no.)	Proportion (%)
1995	9	51	2 146	16.3
1996	18	80	4 223	32.0
1997	17	94	3 846	29.2
1998	17	69	2 392	18.1
1999	12	21	586	4.4
Total	18	136	13 193	100.0

The percentage of the collected population that was early maturing was 25.4%; intermediate-maturing, 47.1%; and late-maturing, 27.5% (Table 3). These samples were sent to IRRI, Philippines, for safe storage and most have been tested for various quality and agronomic attributes. The superior lines for specific traits will be used as parental sources in the crossing program.

Table 3. Classification according to time to maturity of the 13 193 samples of rice germplasm collected from different production environments of Laos.

Maturity group	Production environment		Total	Proportion (%)
	Lowlands	Uplands		
Early	1263	2084	3 347	25.4
Intermediate	3068	3145	6 213	47.1
Late	1494	2139	3 633	27.5
Total	5825	7368	13 193	100.0

2. *Crossing and selection program.* Most crosses are conducted at the NARC, Vientiane. Greenhouse facilities are used to make bi-parental and multiple crosses. Parental lines are selected according to the breeding program's objectives. Some crosses are imported from IRRI and the Thailand–IRRI breeding program.

This component has two sub-components. These are:

a. *Mass selection and pure line selection.* Mass selection and pure line selection methods are used to select the better traditional varieties for high adaptability to different rice ecosystems in Laos. This also allows the development of new breeding lines with superior traits than the existing parental lines (Table 4). Using this approach, the breeding program has released eight superior lines: Nang Nuan, Hom Nang Nuan, Mak-yom, Muang-nga, Ta-khet, Mak-hing, Dok-mai and Lay-keaw (Table 5).

Table 4. Traditional rice varieties used in the Lao crossing program and the number of lines available at the F6 selection stage.

Parentage	F_6
Muang-nga/IR253-100	50 lines
Muang-nga/TDK1	30 lines
Mak-hing/TDK1	70 lines
Ikhao/TDK1	30 lines
Mak-yom/TDK1	30 lines
Ta-khet/Hom Poo Phan	Early stage
Do-yuan//TDK1	Early stage

b. *Crossing and selection program* (Figure 1). The parents used by the crossing program are from local varieties, IRRI lines, Thailand–IRRI lines, and traditional and improved Thai lines. More than 100 crosses have been made in the Lao breeding program since 1995. These crosses derived mainly from parental lines from Lao local varieties (Mak-yom, Muang-nga, Ta-khet, Mak-hing, Ikhao, Do-yuan [Table 4] and Khao-kham), Lao improved varieties (TDK1, TDK2, TDK3, TDK4, NTN1 and SK12), Thai varieties (RD10, RD23, RD6, NSG19, Hom Poo Phan and KDML105), IRRI lines (IR43506-UBN-520-2-1-1, IR253-100, IR68, IR36 and IR8), Vietnam lines (CR 203 and B1014) and Philippine lines (PSBRC1 and PSBRC 10).

The methods used for these crosses are single crossing and three-way crossing. Bulk and modified bulk selection methods are normally used in the F_2–F_4 generations. Pedigree breeding methods are occasionally used in F_2–F_4 generations for particular crosses. However, this method is widely used for late generation selection (F_5–F_6).

3. *Variety testing program.* The varietal testing program is divided between the rainfed lowland, rainfed upland and irrigated ecosystems. After F_6,

Table 5. Rice varieties released and recommended by the Lao Varietal Recommendation Committee between 1991 and 2000.

GID number[a]	Variety name	Parentage	Year of:		
			Release	Introduction	Collection
568156	TDK1	SPT77149/IR13423-10-2-3	1993	1989	
168467	TDK2	IR2061-214-3-14-8/DR1	1993		
568123	TDK3		1997		
568095	TDK4	SPT149-429-3/IR21848-65-3-2	1998	1987	
—	PN1	UBN6721-13-5-6/IR19660-73-4-2	1993	1989	
—	PN2	IR262/Niaw Sanpatong	1995	1991	
568094	TSN1	NSPT/IR21015-80-3-3-1-2	1998	1993	
—	NTN1	NSPT/KKN7409-SRN-01//IR19431-72-2	1998	1993	
568782	SK12	RD10/B1014	2000	1993	
26612	RD6			1985	
409491	RD8			1985	
675435	RD10			1978	
253473	Hang-yi 71			1995	
675434	IR253-100			1969	
—	RD23			1994	
1709	KDML105			1975	
652376	IR66			1994	
—	Nam Sa Gui 19			1993	
275741	CR203	BG34-8/IR2071-625-1		1983	
—	Nang Nuan				1991
—	Hom Nang Nuan				1992
317766	Mak-yom				1975, 1992
—	Muang-nga				1988, 1991
—	Ta-khet				1991
597637	Mak-hing				1984, 1991
—	Dok-mai				1985, 1995
—	Lay-keaw				1991

[a] GID = Genetic identification.

the superior lines are subjected to several testing programs (Figure 2): observational yield trials (OYT), preliminary yield trials (PYT), replicated yield trials (RYT), multi-locational trials (MLT) and, for those superior lines that successfully pass, demonstration trials. The testing procedures, plot size and number of observations differ for each stage, varying according to objectives.

a. *Observational yield trials (OYT)*. In OYT, a simple design with 1 replicate is used. About 200 lines are tested at the NARC in plots of two rows. For some introductions, plots of four rows are used. The lines tested are from the Lao Breeding Program, IRRI and Thailand–IRRI. They are tested for plot yield and general performance for at least two seasons at Vientiane and other centres.
b. *Preliminary yield trials (PYT)*. In PYT, a randomized complete block (RCB) design, with two replicates, is conducted to test less than 100 lines at three or four sites and repeated over at least two cropping seasons. Mainly grain yield and quality are checked.
c. *Replicated yield trials (RYT)*. In RYT, generally, 10–20 lines, with one or two check varieties, are grown, using the RCB design with four replicates. The RYT are conducted at different stations with six to seven sites around the country and repeated over two seasons. Grain yield and quality traits are assessed.
d. *Multi-locational trials (MLT)*. Multi-locational trials are conducted on farm, using six to eight lines (including one or two popular local check varieties) in a RCB design with four replicates. The experiments are conducted at one or two sites per province and repeated over two seasons. Combined statistical analyses are conducted to quantify the components of genotype by environment interaction, and to identify location-specific and widely adapted varieties.
e. *Demonstration plots*. The demonstration experiments are conducted on farm. Three or four promising lines are compared with a popular variety in the targeted region. These lines are planted in a large area (about 100 m^2) and yields under normal growing conditions estimated.

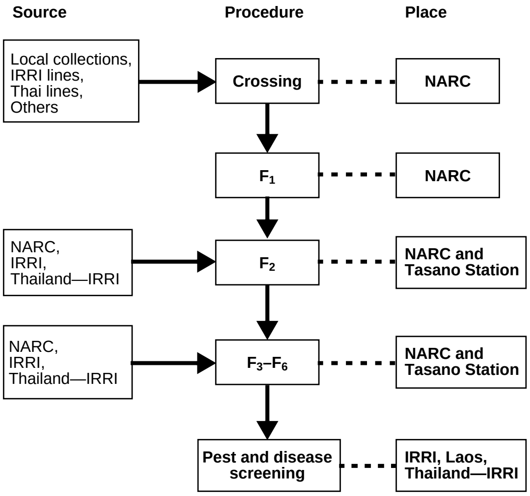


Figure 1. The crossing and selection subcomponent of the Lao rice breeding program.

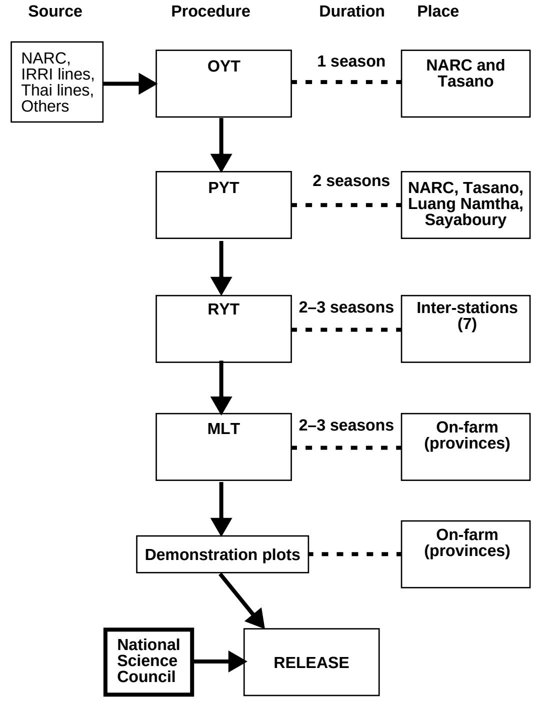


Figure 2. Line-testing stages and variety recommendations in Laos.

Plot size, planting density and fertilizer rate. Plot size varies widely according to the stage. For the PYTs, plot size is about 1 × 5 m, whereas for the RYTs, it is 1.5–2.0 × 5 m. Plot size for the MLTs is 2–3 × 5 m, with the actual size depending mainly on seed availability. Spacing is 20 × 20 cm. One border row is removed from both sides for the PYTs and RYTs at yield measurement. Two border rows from both sides are left unharvested for the MLTs. One seedling will be transplanted per hill in the OYTs, while 2–3 seedlings are transplanted in the other trials. The normal fertilizer rate, that is, 60–30–20 kg ha^{-1}, is applied for all trials.

Achievements of the rice-breeding program

So far the breeding program has released 9 varieties and recommended 18 varieties from introductions derived mostly from Thai and traditional Lao varieties (Table 5; Schiller et al. 1999).

Seed production

Breeder seed

In “breeder seed” production, 300 to 500 panicles from the superior lines are planted in rows. Seedlings are transplanted (one per hill) at a 20 × 20 cm spacing. Each row receives the same nutrient and water treatments and is closely checked for uniformity. Off-types are removed and seed from the remaining plants are bulked for use in foundation seed production.

Foundation seed production

Seed is collected from plants that had developed from bulked breeder seed. Seedlings are transplanted, one per hill, and uniformity is, again, closely checked for. Off-types are, again, discarded and the harvest of the remaining plants is bulked to produce registered seed for use in the next season.

Registered seed/stock seed production

Laos has recently started production of registered seed. For this seed type, foundation seed is planted in rows and carefully maintained with high fertilizer inputs and weeding. Seed certification standards are strictly followed in this stage. Plants are regularly checked and all off-types removed from the bulk population.

Future Expansion of the Rice Variety Improvement Program for Lowland Environments

The variety improvement program will, in the future, emphasize the following:

- Development of improved glutinous aromatic rice for both local and export markets.

- Because they are becoming popular among Lao consumers in the northern region, non-glutinous varieties must also be developed for both rainfed lowland and irrigated environments.
- Development of varieties adapted to low temperatures for the rainfed lowland (wet season) and irrigated (dry season) environments in northern Laos.
- Development of varieties with resistance to blast, bacterial leaf blight, brown plant hopper, green leafhopper and gall midge.
- Identification and selection of varieties with greater yield stability during drought.
- Development of varieties that are better suited for flood-prone areas. Collaborative work with the University of California—Davis has already begun.

Acknowledgments

For their help and considerable information, we gratefully acknowledge the assistance of Drs. John Schiller and Hatsadong in the preparation of this paper. We are also most thankful to the SDC and ACIAR Project, who funded the breeding program, and to the Lao–IRRI Project, who provided the breeding program with valuable logistic support and facilities.

References

Fukai, S. and Cooper, M. 1995. Development of drought-resistant cultivars using physio-morphological traits in rice. Field Crops Research, 40, 67–86.

Inthaphanya, P., Schiller, J.M., Sarkarung, S., Kupkanchanakul, T. and Viravanh, P. 1995. Rice production in Laos. Paper prepared for the International Rice Research Conference, IRRI, Philippines, 13–19 February 1995.

Inthapanya, P., Sipaseuth, Sihavong, P., Sihathep, V., Chanhphengsay, M., Fukai, S. and Basnayak, J. 2000a. Genotypic differences in nutrient uptake and utilisation for grain yield production of rainfed lowland rice under fertilized and non-fertilized conditions. Field Crops Research, 65, 57–68.

Inthapanya, P., Sipaseuth, Sihavong, P., Sihathep, V., Chanhphengsay, M., Fukai, S., Basnayak, J. 2000b. Genotypic performance under fertilized and non-fertilized conditions in rainfed lowland rice. Field Crops Research, 65, 1–14.

Inthavong, S. 1999. Ecological studies and yield loss assessment of rice gall midge, *Orseolia oryzae* (Wood-Mason) in rainfed lowland rice ecosystems of Laos. M.Sc. thesis. Los Baños, Philippines, University of the Philippines.

Jongdee, S., Mitchell, J.H. and Fukai, S. 1997. Modeling approach for estimation of rice yield reduction due to drought in Thailand. In: Fukai, S., Cooper, M. and Salisbury, J. ed. Breeding Strategies for Rainfed Lowland Rice in Drought-Prone Environments; Proceedings of an International Workshop held at Ubon Ratchathani, Thailand, 5–8 November 1996. ACIAR Proceedings No. 77, 65–73.

Linquist, B., Sengxua, P., Whitbred, A., Schiller, J. and Lathvilayvong, P. 1999. Evaluation of nutrient deficiencies and management strategies for lowland rice in Laos. In: Proceedings of the International Workshop on Nutrient Research in Rainfed Lowlands, 12–15 October 1998, Ubon Ratchathani, Thailand.

Schiller, J.M., Inthaphanya, P., Manivong, V. and Hatsadong. 1999. Rice Variety Recommendations for the Lowland Environments of Lao PDR, Lao–IRRI Project. In: Breeding Work on the Rice Plant. Shin-ichi Ono ed.

Rice-Breeding Methods for Cambodia

Men Sarom*, Ouk Makara, Hun Yadana, Sakhan Sophany and Pith Khon Hel

Abstract

Coping with a rapid annual population growth rate of 2.4%, Cambodia has achieved enormous success since 1995 in providing enough food for its 11.4 million people. Part of this success is undoubtedly a result of new breeding methods adopted by the Plant-Breeding Program of the Cambodian Agricultural Research and Development Institute. Four components comprise the program: germplasm collection and conservation, varietal development, varietal testing and seed production. Since 1990, the program has released 34 improved varieties with high yield potential and acceptable grain quality for the country's different rice agroecosystems: deep water, rainfed lowlands, rainfed uplands and dry-season ecosystems.

THE Cambodian economy relies heavily on agriculture, which employs nearly 80% of the labour force and contributes as much as 43% of the gross domestic product (Song 2000). Rice is the most important crop and is cultivated in both wet and dry seasons. In the wet season, it is grown in different agroecosystems, ranging from rainfed uplands, where there is no standing water in the fields, to rainfed lowlands and deep water where water can be 4–5 m deep. Dry-season rice may receive either full or supplementary irrigation, or be planted or transplanted as floodwaters recede, receiving little or no irrigation. 'Recession rice' is commonly practised in areas around lakes or where deepwater/floating rice has been grown.

No single variety can be adapted to all these agroecosystems, nor even to all the subsystems within a given agroecosystem. Even if this were possible, it would be inadvisable, as pest and disease outbreaks would probably increase as a result of the crop's uniform genetic background. Breeding efforts are therefore focused on developing varieties for specific agroecosystems, with numerous releases having been achieved within the last 10 years.

By the above achievements a general increase from 2.6 to 3.6 million tons in total rice production between 1989 and 1999 has been observed. The average rice yield also increased from 1.3 t ha^{-1} in 1989 to about 1.8 t ha^{-1} in 1999. These increases are commensurate with an increase in the rice research effort. Chaudhary and Papademetriou (1999) reported that, during 1987 to 1997, the country's rice production growth rate was as high as 4.4%, compared with 1.8% for Asia overall. For the first time since 1970, Cambodia achieved self-sufficiency in rice in 1995—an achievement that contributed significantly to the national economy.

Such success is partly attributed to the release of 34 improved rice varieties from the Plant-Breeding Program of the Cambodian Agricultural Research and Development Institute (CARDI). The structure and approach adopted by the Program were important to that contribution. This paper discusses how CARDI's Plant-Breeding Program helped reduce poverty in Cambodia.

Rice Production Environments

Rice has been grown in Cambodia for centuries. It is the country's most important commodity crop and staple food. Cambodia has a monsoon climate, with

---

Cambodian Agricultural Research and Development Institute (CARDI), Phnom Penh, Cambodia
*Corresponding author: E-mail: msarom@bigpond.com.kh

KEYWORDS: Plant breeding, Rice, Cambodia, Production constraint, Program components, Breeding objectives, Seed, Variety recommendation

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

two main seasons—the wet and dry—in which rice is cultivated. Currently, wet-season rice accounts for more than 88% of the rice area, and dry-season rice for 12%. Wet-season rice depends heavily on rainfall between May and October, whereas dry-season rice is cultivated under either full or supplementary irrigation or in receding floodwaters.

Depending on rainfall, flooding pattern and topography, wet-season rice can be categorized further into rainfed upland, rainfed lowland and deepwater (Figure 1). Rainfed lowland rice accounts for about 93% of the total production area of wet-season rice, followed by 5% in deep water and 2% in rainfed uplands (Table 1). In Cambodia, rainfed lowland rice can be found in all provinces but its production is concentrated mainly in the central plain around the Great Lake (Tonle Sap) and on the lower streams of the Mekong and Bassac Rivers (Figure 2). Average annual rainfall in the region ranges between 1200 and 2000 mm. Deepwater rice is also cultivated in the same areas as the rainfed lowland rice but is concentrated more on the edges of lakes where water is deeper than in higher fields (Figure 1). Rainfed upland rice is grown in small pockets, mainly in hilly regions in northern and north-eastern Cambodia where annual rainfall is higher than in the central plain.

Rainfed lowland rice, as the major group of rice produced in the country, has contributed significantly to the growth of the Cambodian economy. In this rice ecosystem, farmers have cultivated thousands of varieties for hundreds of years. Exposed to environmental pressures such as flooding, drought, adverse soils and insect pests throughout their history of cultivation, these traditional varieties provide not only valuable grain for farmers, but also highly valuable genetic stocks for plant breeders.

Depending on their time to flowering, the traditional varieties have been categorized into three groups for maturity, namely early, intermediate and late. Early varieties are those that are photoperiod sensitive and flower before mid-October, or are photoperiod insensitive but mature in fewer than 120 days. Intermediate-maturing varieties are those that flower between mid-October and mid-November, or mature in fewer than 150 days, whereas late-maturing varieties flower beyond this time.

Because of the variations in their time to flowering, varieties from different groups are grown at different water levels in the fields. Normally, early varieties are grown near villages where water levels are shallow and where the crop can be given supplementary irrigation if rain is insufficient. The intermediate-maturing varieties are often grown on middle field terraces, and the late-maturing varieties are grown in the lowest part of the fields where water is likely to be deeper and where submergence may

Table 1. Area cultivated to rice and its distribution by agroecosystem (1998 statistics), Cambodia.

Agroecosystem	Area (ha)	Total cultivated	Proportion (%)	
			Total wet season	Total rainfed lowland
Total cultivated	**2 103 783**	**100**	—	—
Wet-season rice	**1 860 000**	**88**	**100**	—
Rainfed upland	43 318	—	2	—
Rainfed lowland	1 731 961	—	93	100
Early	*347 869*	—	—	*20*
Intermediate	*761 032*	—	—	*44*
Late	*623 060*	—	—	*36*
Deepwater/floating	84 721	—	5	—
Dry-season rice	**243 783**	**12**	—	—

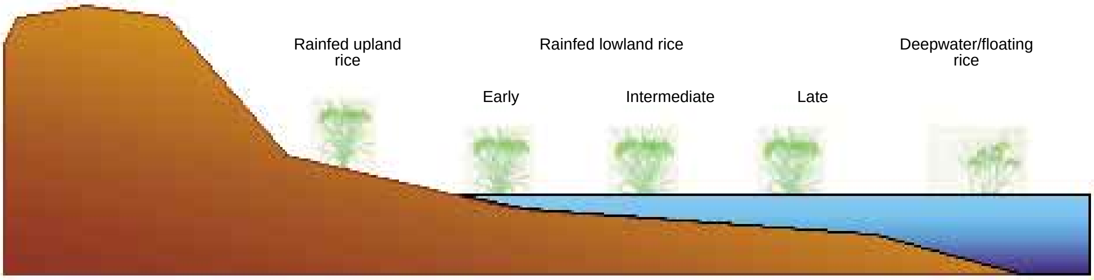


Figure 1. Wet-season rice ecosystems in Cambodia.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

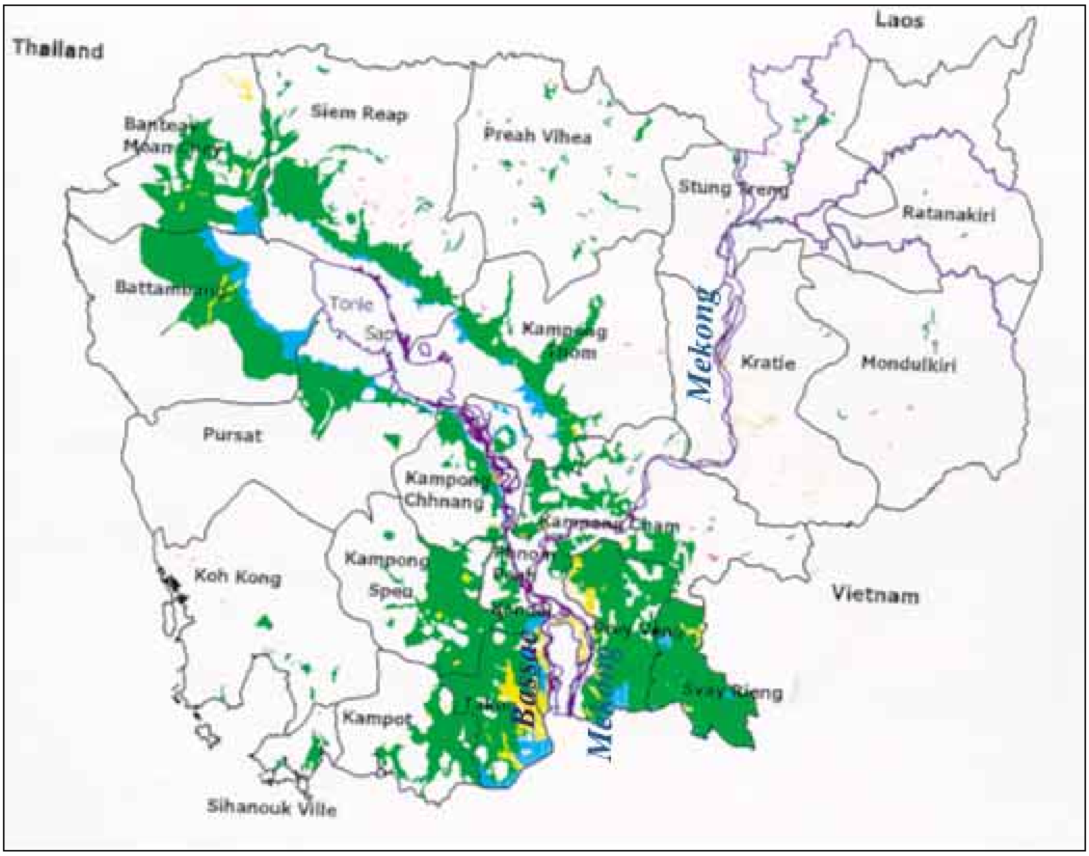


Figure 2. Rice-production regions (shaded areas) in Cambodia.

occur frequently. Nevertheless, rain shortfalls can cause drought for all three groups. The proportion of early, intermediate and late varieties is about 20%, 44% and 36%, respectively. Early varieties are also cultivated in the dry season with full or partial irrigation or under flood recession conditions.

Most rainfed lowland rice varieties have traits, such as time to flowering, that are adapted to local environments. They also satisfy taste preferences of the local people. Although only a few varieties are resistant to drought, a large proportion of these can recover once drought is over (Sahai et al. 1992). The highly variable levels of recovery indicate that levels of drought resistance are also variable.

Rice Production Constraints

In 1999, the average rice yield in Cambodia was 1.8 t ha^{-1}, the second lowest in Asia after Bhutan (Chaudhary and Papademetriou 1999). Several factors limit the possibility of further increasing rice productivity in Cambodia, including:

1. *Lack of rain*. As discussed earlier, about 90% of rice is produced in the wet season and, in most cases, rain is the only source of water available to the crop. From year to year, season to season and location to location, rainfall is variable in its amount and distribution, so much so, it can substantially affect the productivity of rainfed lowland rice. Floods may occur with excessive rain or droughts with shortages of rain. Floods and droughts commonly occur, one after the other, several times in a year. Rain irregularities at the beginning of the wet season may delay planting, induce weed growth and encourage a build-up of insect pest populations. These will reduce yield, especially if drought develops at flowering. In 1999, because of drought in May and June, thousands of hectares of nurseries and rice crops were heavily damaged by thrips, brown plant

hoppers (BPH) and army worm. If drought occurs at later stages, grasshoppers can become major pests. Excessive rain at later stages not only reduces productivity through floods but also affects grain fertility, and can induce fungal diseases in the grain, leading to reduced yields, poor grain appearance and reduced grain-milling recovery.

2. *Soil fertility*. Rainfed lowland rice, in most cases, is cultivated on sandy soils with poor response to fertilizer application. Nitrogen and phosphorus deficiencies and iron toxicity are very common in most soils. Some soils are also deficient in potassium and microelements. Low organic matter and water-holding capacity are also common. Rainfed lowland rice productivity can only be increased if appropriate fertilizer is applied to overcome these deficiencies. In addition, fertilizer use for rainfed lowland rice is still limited, compared with dry-season irrigated rice. Occasionally, fertilizers are not even used.
3. *Pests and diseases*. Many kinds of rice pests are found in Cambodia. These are:
    a. *Weeds*. Broadleaved weeds, grasses and sedges significantly reduce rice production in rainfed lowlands. Their effect can be considerable, particularly if poorly controlled at crop establishment.
    b. *Insect pests*. Rice insect pests are numerous, with the major ones able to significantly reduce yields: brown plant hopper, army worm, caseworm, leaf folder, stem borer and gall midge. Hopper burn, a direct effect of brown plant hopper damage, causes big losses of the rice harvest annually.
    c. *Animal pests*. Rats and crabs are also considered as major pests in rice production in Cambodia. Their control depends heavily on community involvement. In recent years, golden apple snails have also become pests in rainfed lowland rice production.
    d. *Diseases*. In Cambodia, rice diseases are fortunately still at low levels. The major ones are blast, brown spot, sheath rot and sheath blight (fungal), bacterial leaf streak and bacterial blight (bacterial) and tungro (viral).
4. *Variety*. Cultivation of improved varieties is still limited in the rainfed lowland rice. In most cases, traditional rice varieties are grown and the rate of their replacement is still very slow. These varieties generally are low yielding but having good adaptation ability into the local environments and with accepted grain quality.
5. *Seed or Varietal impurity*. In Cambodia, throughout the year, farmers cultivate different varieties on their small farms, usually planting them next to each other, with or without isolating distances or bunding (levees) between them. Cross-pollination may occur if these varieties have similar times to flowering and varietal purity can be affected significantly. Harvesting, threshing and storing of seeds are also, in most cases, carried out together or in close proximity. Such practices may lead to those varieties cultivated for long periods in farm fields becoming impure or losing their identity completely. This is particularly true with many traditional aromatic rice varieties for which the aroma decreases or disappears totally after several years of cultivation.

Program Components

CARDI’s Plant-Breeding Program has four major components: germplasm collection and conservation, varietal development, varietal testing and seed production.

Germplasm collection and conservation

With financial support from the Cambodia–IRRI–Australia Project (CIAP) and the Swiss Agency for Development and Cooperation (SDC) for biodiversity, the Program has collected more than 4000 traditional varieties from all provinces of Cambodia, that is, from about 70%–80% of the whole country. These varieties are evaluated for the major traits described in *Descriptors for Rice Oryza sativa* L. (IRRI and IPGRI 1988). Collections are preserved in CARDI’s cold room in Phnom Penh at –20°C temperature with reduced humidity and a duplicate sample is sent to the International Rice Research Institute (IRRI), in the Philippines, for safekeeping. Many of the collected varieties are used directly in various levels of testing, and some are used as donors for specific traits to develop new rice varieties.

Varietal development

At present, rice is the only crop in Cambodia that has well-defined breeding objectives. Ten years ago, when the Program started, Cambodia still had a large food deficit, and breeding for high yield was of priority. As Cambodia regained self-sufficiency in rice, breeding objectives were changed to include improved quality attributes.

Objectives

The current objectives for the rice-breeding program are listed below.

1. *Growth duration and photoperiod sensitivity*. The program has focused mainly on developing rainfed lowland rice varieties with intermediate to late maturity. These lines and/or varieties ideally

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

should also have some photoperiod sensitivity so that they are better adapted to adverse rainfed lowland conditions. Lower priority is given to the development of early maturing rice and deepwater rice as direct introduction of these groups from the IRRI and Thai rice-breeding programs, respectively, is more feasible than for the other groups of rice varieties.

2. *Grain characteristics*. Responding to market demands, breeding and selection focus on long slender grains with translucent endosperm. Lines with chalky grains are strictly discarded.
3. *Plant type*. The ideal plant type for rainfed lowland rice is considered to be intermediate in height, that is, between 100 and 130 cm, with good tillering and a high percentage of spikelet filling.
4. *Biotic stresses*. Lines and/or varieties developed must be resistant to at least some of the major pests and diseases found in the country. As mentioned above, these include BPH, stem borer, blast and tungro.
5. *Abiotic stresses*. In selecting high-yielding lines or varieties for rainfed lowland rice, major objectives include tolerance of the major abiotic factors closely associated with low productivity in rainfed lowland rice: drought, submergence and poor soil fertility.

Breeding methods

The program applies three types of breeding methods: mass selection, pure-line selection and crossing.

- *Mass and pure-line selection*. Mass and pure-line selection are commonly applied together to exploit the best traditional varieties for their established adaptability to local conditions. New lines with higher yield potential than their parents are developed. Collected traditional rice varieties are purified (mass selection), then tested for their performance in the field. Best-performing varieties are then selected for further testing. At the same time, individual plants from the best-performing varieties are selected and developed as individual pure lines. Through this technique, the program could release 15 pure-line varieties originating from Cambodian traditional rice varieties: CAR 1 to CAR 13, Phka Rumchek, Phka Rumduol and Riangchey.
- *Crossing*. A conventional crossing method is also widely used. All generated crosses involve at least one traditional Cambodian rice variety as a parent. Parents are selected according to yield, grain quality (grain types and aroma) and tolerance of drought and submergence. The most frequently used traditional Cambodian varieties for crossing include Somaly, Toul Samrong 2, Neang Minh, Phka Sla, Phka Kgnei, CAR 3, CAR 4, CAR 6 and CAR 11. According to need, breeding materials from IRRI, India, Bangladesh and Thailand have been used as parents in most crosses, including many IRRI lines (Santepheap 1-2, IR66 and IR Kesar), Basmati, Mahsuri, Khao Dawk Ma Li 105, Don (a deepwater line originally from the Thai deepwater breeding program) and Santepheap 3 (originally from India). Breeding for resistance to insects and diseases is still at an early stage, with no lines or varieties yet identified for use as parents.

Achievements

More than 700 crosses have been generated since the program was established in 1989. Several crossing methods have been employed, including single, double and triple crosses, and composite selection. Segregating populations are planted in CARDI's experimental fields and in different targeted regions. Generally, bulk and modified bulk methods are used for early generations (F_2–F_4) and the pedigree method for the remaining generations (F_5–F_7). Selection emphasizes yield potential, growth duration, grain quality (long slender grain type with translucent endosperm) and plant type. Moreover, susceptible reactions to any major biotic or abiotic factor are strictly selected against. Outstanding lines in F_7 or F_8 are then advanced to the observational yield trials (OYT) in the varietal testing program.

Varietal testing

The varietal testing component is divided according to rice ecosystem and crop maturity groups within the country. The ecosystems are rainfed uplands, rainfed lowlands and deep water or floating. Within the rainfed lowland ecosystem, depending on the water level, three main maturity groups of rice exist: early, intermediate and late. However, the testing program for rainfed lowland rice currently recognizes four maturity groups: (1) early maturing (less than 120 days to mature), (2) adapted to favourable conditions, photoperiod-insensitive and intermediate-maturing (120–150 days to mature), (3) adapted to unfavourable conditions, photoperiod-sensitive and intermediate-maturing (flowering from mid-October to mid-November), and (4) late-maturing (flowering beyond mid-November). In addition to the above testing based on ecosystem and maturity group, the program also tests aromatic, premium-grain-quality varieties.

Testing pathway

Four hierarchical layers in the varietal testing pathway have been adopted by the program (Figure 3). These are observational yield trials (OYT), preliminary yield trials (PYT), advanced yield trials (AYT) and on-farm adaptive trials (OFAT).

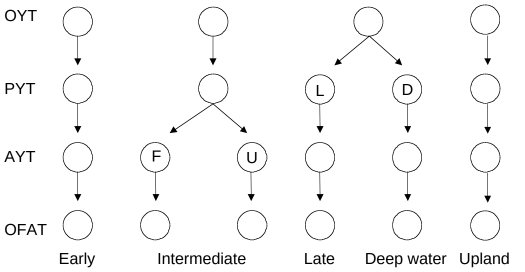


Figure 3. Selection pathway in the Cambodian rice-breeding program. OYT = observational yield trials; PYT = preliminary yield trials; AYT = advanced yield trials; OFAT = on-farm adaptive trials; F = favourable; U = unfavourable conditions; L = late maturing rice; D = deep water.

1. *OYT*: A systematic arrangement is used with one replicate. The trial is generally conducted at 1 to 3 sites with many breeding lines or varieties originating from different sources, including IRRI, the International Network for Genetic Evaluation of Rice (INGER), Thailand, Philippines, India and the Bangladesh Rice Research Institute (BRRI). The rainfed lowland late-maturing and deepwater trials are combined into one OYT, conducted at three locations for late-maturing varieties and representing deep and semi-deepwater environments. This system enables breeders to select the most suitable entries for the two environments without rejecting valuable materials. Only one OYT is conducted for photoperiod-sensitive and insensitive intermediate-maturing entries, which are usually tested at two locations.
2. *PYT*: A randomized complete block design (RCB) with two replicates is used. PYTs are generally conducted at two sites, although the PYT-intermediate is conducted at four sites, representing two favourable (good soils) and two unfavourable (poor soils) environments. Entries in PYT are usually tested for at least two seasons and/or years before being promoted to AYT.
3. *AYT*: A RCB design with four replicates is used. For all ecosystems, except deep water, the trial is composed of nine test entries and one check variety. In the deepwater trial, only eight test entries and two checks are used. One check is the station check and the other is a local check. The local check, which is the most popular traditional deepwater rice variety in a given area, varies from station to station. The AYT of any variety group is generally conducted in at least six locations around the country. Varieties and/or lines that perform well across locations for at least 2 years and with acceptable grain quality will be multiplied. Results of performance for these varieties and/or lines are averaged over locations and seasons and/or years, and are collated in files for their submission to the Cambodian Varietal Recommendation Committee (VRC). Varieties and/or lines that are approved for release by the Committee are given to farmers through the OFAT.
4. *OFAT*: Farmer management practices and resources are used, although farmers receive technical support from researchers in conducting the unreplicated trials from sowing through to harvest. The farmers are given three recommended varieties to test against their best local varieties. Because an OFAT trial is simple, for any group of varieties, it is conducted in more than 100 farmers' fields throughout the country.

Plot size, planting density and fertilizer rate

Plot sizes for the various trials are 2 × 5 m (OYTs and PYTs), 3 × 5 m (AYTs) and 5 × 20 m (OFATs). One border row is removed at harvest for PYTs and AYTs, but not for OYTs and OFATs.

Seedling age at transplanting varies, depending on the maturity group of the varieties being tested: 20–25 days old for the early group and 30–35 days old for the intermediate and late groups. Spacing at 20 × 20 cm between hills is commonly used. Only one seedling is transplanted per hill for OYT but, for PYT and AYT, 2–3 seedlings are planted per hill. For the early and intermediate groups, fertilizers are usually applied at a rate of 60–30–30 kg of N, P_2O_5 and K_2O, respectively, per hectare. For the remaining groups, a rate of 30–15–15 kg of N, P_2O_5 and K_2O, respectively, per hectare is applied.

Evaluation

The *Standard Evaluation System for Rice*, published by IRRI (1980), is followed for recording observations of several main traits. These observations are used to either retain or discard lines. These traits include growth duration (from sowing to harvest), phenotypic acceptability (scored from 1 to 9), plant height, yield, grain shape, grain appearance or chalkiness, aroma and natural reactions to biotic and abiotic stresses.

Variety recommendation

All promising breeding and/or advanced lines or pure lines are carefully examined. A detailed document for those selected is then prepared for the VRC.

Through this process, the Plant-Breeding Program has released 34 varieties, comprising 8 early varieties, 13 intermediate (3 of which are aromatic), 8 late or intermediate to late, 3 deepwater and 2 upland (Table 2).

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Table 2. Varieties released by the Varietal Recommendation Committee for different agro-ecosystems.

No	Variety name	Parentage[1]	Year of release	Recomm. for[2]	Yield range (t/ha)	RP[3]	Growth duration[4] (Days)	Grain type[5]	Sensory test [6]	
									Raw	Cooked
1	IR 66	IR13240-108-2-2-3 / IR9129-209-2-2-2-1	1990	RL-E, DS	4.0-6.5	I	100-115	LS	4.2	2.9
2	IR 72	IR19661-9-2-3//IR15795-199-3-3/IR9129-209-2-2-2	1990	RL-E, DS	3.5-6.0	I	110-120	LS	3.0	2.3
3	Kru	IR4432-53-33// PTB33/IR36	1990	RL-E, DS	3.5-6.0	I	100-115	LS	4.4	3.4
4	Don	SPR7270-18/KNN111	1991	D/F	2.0-4.5	S	3w-Nov	LS	3.5	2.9
5	Khao Tah Petch	Khao Tah Petch	1991	D/F	2.0-4.0	S	3w-Nov	LS	3.5	2.5
6	Tewada	Tewada	1991	D/F	2.0-4.0	S	3w-Nov	LS	3.9	3.0
7	Sita	IRAT3/Dourado Precoce68//TOX490-1	1991	RU	2.5-4.0	I	90-100	M	2.0	2.9
8	Remke	63-83/ROI,SE363G,Dourado Prococe68	1991	RU	2.5-4.0	I	90-100	M	1.7	3.2
9	Santepheap 1	Meedon hmwe/IR21313-39-2	1992	RL-M	4.0-6.0	I	130-140	LS	1.3	3.5
10	Santepheap 2	SPR7215-1-25-1-5/IR20925-238-2-1-3-3	1992	RL-M	4.0-6.0	I	130-140	ELS	3.9	2.6
11	Santepheap 3	Pankaj/Sigadis	1992	RL-M	4.0-6.5	W	135-145	M	1.9	2.2
12	IR Kesar	IR2432-34-2/IR3186864-2-3-3-3	1993	RL-E, DS	4.0-6.0	I	105-120	LS	3.7	3.7
13	CAR 1	PL-Pram'bei kuor	1995	RL-M	2.5-4.0	S	1w-Nov	M	2.6	2.7
14	CAR 2	PL-Sammbark krarharm	1995	RL-M	2.5-4.0	S	1w-Nov	M	2.8	3.4
15	CAR 3	PL-Sra-em Choab Chan	1995	RL-M	2.5-4.5	S	1w-Nov	M	2.1	3.3
16	CAR 4	PL-Charng kaom ropeak	1995	RL-M/L	2.5-5.0	S	2w-Nov	M	2.9	3.3
17	CAR 5	PL-Karn-tuy touk	1995	RL-M/L	2.5-4.5	S	2w-Nov	M	2.8	3.2
18	CAR 6	PL-Seo nam'ng	1995	RL-M/L	2.5-5.0	S	2w-Nov	M	3.0	3.3
19	CAR 7	PL-Chungkung kreal	1996	RL-L	2.5-4.0	S	3w-Nov	M	2.6	2.5
20	CAR 8	PL-Phka sla	1996	RL-L	2.5-4.5	S	3w-Nov	M	2.6	2.7
21	CAR 9	PL-Srau kul	1996	RL-M/L	2.5-4.5	S	2w-Nov	M	3.6	2.5
22	CAR 11	PL-Banla Phdau	1997	RL-M	2.5-4.5	S	1w-Nov	ELS	4.7	3.7
23	CAR 12	PL-Koon trei khmau	1997	RL-L	2.5-4.5	S	3w-Nov	M	3.6	2.8
24	CAR 13	PL-Neang minh tun	1997	RL-L	2.5-4.5	S	3w-Nov	M	3.3	3.4
25	Chulsa	IR28239-94-2-3-6-2 /IR24632-34-2	1999	RL-E, DS	4.0-6.0	I	95-110	LS	3.1	3.1
26	Baray	IR64/IR35293-125-3-2-3//PSBRC4	1999	RL-E, DS	4.0-6.0	I	100-115	LS	3.3	3.5
27	Rumpe	IR48563-123-5-5-2/PSBRC10	1999	RL-E, DS	4.0-6.0	I	100-115	LS	3.8	3.7
28	Rohat	IR24632-34-2/IR31868-64-3-3-3	1999	RL-E, DS	4.0-6.0	I	105-120	LS	3.2	2.5
29	Sarika	SPR7215-1-25-1-5/IR9764-45-2-2//IR28193-13-2-2	1999	RL-M	4.0-6.0	I	130-140	M	2.3	3.0
30	Popoul	IR4568-86-1-3-2/IR26702-111-1//IR20992-7-2-2-2-2-3/IR21567-9-2-2-2-1	1999	RL-M	4.0-6.0	I	130-140	LS	2.4	2.9
31	Riangchey	PL-Moo ha pharl	1999	RL-M	3.5-5.5	S	1w-Nov	LS	3.4	3.2
32	Phka Rumchang	PL-Khao Dawk Mali 105	1999	RL-M/A	3.0-5.0	S	4w-Oct	LS	4.5	3.1
33	Phka Rumchek	PL-Neang Sar	1999	RL-M/A	3.0-5.0	S	4w-Oct	LS	3.4	3.5
34	Phka Rumduol	PL-Somaly	1999	RL-M/A	3.5-5.5	S	1w-Nov	LS	4.4	3.7

---

[1] PL = Pure lined

[2] RL = Rainfed lowland, RU = rainfed upland, D/F = Deepwater/floating, DS = dry season, E = early, M = medium, L = late, M/L = medium/late, M/A = medium/aromatic

[3] RP = Reaction to photoperiod, I = insensitive, S = sensitive, W = weakly sensitive

[4] w = week, 1-4 = first-fourth, Nov = November, Oct = October

[5] M = Medium, LS = long slender, ELS = extra long slender

[6] Average score from more than 100 testers on a scale where 1 = poor/not acceptable, 2 = average, 3 = good, 4 = very good, 5 = excellent.

Seed production

Breeders' responsibilities do not finish with the release of new improved varieties to farmers. They must still maintain the genetic purity of all released varieties. The Program has adopted a three-tiered seed production system and, annually, a large quantity of breeder and foundation seed of all released varieties is produced. Production of registered seed is also carried out for some selected varieties.

1. *Breeder seed production*. The single-panicle progeny approach is used in producing breeder seed for all varieties released by the Program. Typical and healthy panicles selected from the best breeder seed production plot or from the most recent plots are planted separately into different progenies. Each progeny receives the same treatment so any variation within and between progenies is considered to be genetic so that heterogeneous progeny are rigorously discarded as are progeny having different traits to the parental variety. Seed of all remaining progeny is bulked and used to produce foundation seed by the Program or other seed-producing organizations. Breeder seed production plots are maintained in absolutely weed-free conditions.
2. *Foundation seed production*. Bulked breeder seed is planted in rows with one seedling per hill. Roguing is done throughout the growing period. Plants having different traits are discarded and seed of the remaining plants are bulked for producing registered seed for the next season and/or year. Plots are kept free of weeds. High fertilizer input is generally applied.
3. *Registered seed production*. Foundation seed is used and row planting is still followed. Transplanting is the only practice used in producing registered seed at CARDI. Production plots of registered seed are well maintained with high fertilizer input and rigorous weeding. They are regularly rogued to remove all off-type plants. Production of registered seed is usually limited only to varieties in high demand.

Breeding Strategy Research

To increase efficiency of plant-breeding research and to answer more specific problems relating to productivity improvement of rainfed lowland rice, a collaborative project with the ACIAR has been initiated. The three main subprojects are, first, to study the interaction between varieties and the different rainfed lowland environments in the country. This project will also emphasize performance of different genotypes to drought and nutrient deficiencies in some rice soils.

The second subproject will emphasize crop intensification and will involve more work on methods to increase the productivity of rainfed lowland rice by introducing more crops into the system.

The third subproject will look at benefits of direct seeding versus transplanting. Through this project, CARDI's breeding program will work with The University of Queensland to achieve the following objectives:

1. *Determination of the magnitude of the genotype by environment interaction*. This will help the Program determine the number and actual locations of multi-location trials for testing progenies. Of particular interest is whether different soil types require different genotypes.
2. *Development of drought-screening methods*. A field-screening method was developed in Thailand and will be introduced and modified for Cambodian conditions.
3. *Identification of plant traits suitable for direct seeding*. Initially, the genotypic requirements for transplanting and direct seeding will be compared. If a genotype by planting method interaction exists, then the traits required for direct seeding will be determined and breeding methods for direct-seeding varieties established.

The ACIAR project will build on CARDI's earlier experience on determining progeny testing locations for rainfed lowland rice and drought resistance of photoperiod-sensitive and insensitive cultivars.

Acknowledgments

The authors are indebted to the Australian Agency for International Development (AusAID) for its financial support, provided through the Cambodia–IRRI–Australia Project, in implementing the program. Technical support provided by the IRRI Plant-Breeding Division, with Dr. G.S. Khush as the Division's Head and Principal Plant Breeder, is appreciated. Fruitful collaboration with other institutes, particularly the deepwater program of Thailand is acknowledged. Assistance and advice provided by Associate Professor Shu Fukai of The University of Queensland in preparing the manuscript is also acknowledged. Last, but not least, we thank all cooperating farmers, without whose contributions the program would not have been successful.

References

Chaudhary, R.C. and Papademetriou, M.K. 1999. Perspectives of rice production in Asia-Pacific under the current economic and regulatory upheaval. Cambodian Journal of Agriculture, 2, 1–14.

IRRI (International Rice Research Institute). 1980. Standard Evaluation System for Rice: International Rice-Testing Program. Los Baños, Philippines.

IRRI (International Rice Research Institute) and IPGRI (International Plant Genetic Resources Institute). 1988. Descriptors for Rice *Oryza sativa* L. Los Baños, Philippines.

Sahai, V.N., Chaudhary, R.C. and Sovith, S. 1992. Rice Germplasm Catalog of Cambodia, II. Phnom Penh, Cambodia–IRRI Rice Project, 47 p.

Song, C. 2000. Keynote address at the 46th SEAMEO SEARCA Governing Board Meeting, 13 September 2000, held in Phnom Penh, Cambodia.

Breeding for Suboptimal Environments

Gary N. Atlin

Abstract

In plant-breeding, progress through selection is proportional to selection intensity (i_s), the genetic correlation between the selection and target environments (r_G), and the heritability of line means in the selection environment (H_s). The suboptimal environments faced by many small farmers in the developing world tend to be variable and subject to sporadic stresses. On-station trials may exhibit low r_G with performance on-farm, and yield trials conducted in environments subject to high levels of stress often have low H_s. To make gains in difficult environments, breeding programs must (1) maximize the intensity of selection for yield by subjecting large populations to replicated testing; (2) maximize heritability in the selection environment by extensive replication across a representative sample of the target population of environments; and (3) ensure a high genetic correlation between performance in the selection environment and in farmers fields by managing breeding trials appropriately and conducting extensive on-farm trials. Generally positive associations between performance in stress and non-stress environments reported in the literature indicate that combining stress tolerance with responsiveness to favourable conditions may be possible for many cropping systems. Direct selection for grain yield at high levels of precision and selection intensity, as opposed to indirect selection for correlated physiological traits, has proven to be the most effective approach to breeding for stress environments.

MODERN plant breeding has been very successful in improving crop cultivars for favourable environments, but has been less effective in producing cultivars that outperform indigenous germplasm in stressful or low-fertility environments, where the adoption of new cultivars has been more limited (Byerlee and Husain 1993; Maurya et al. 1988). Breeders have long debated the best strategy for developing cultivars for such environments. Among the critical questions in this debate are:

- Should selection be done indirectly, in high-yield environments where genetic variance is usually maximized, or directly, in the presence of the relevant stress?
- Can breeders develop cultivars that combine stress tolerance with responsiveness to favourable conditions, or are separate cultivars needed for high- and low-yield environments?
- Can selection conducted on station result in improved performance on farm in marginal or stress environments?
- Can selection for secondary physiological parameters (e.g. osmotic adjustment or root-pulling resistance) result in improved yields in stress environments?

A simple theoretical framework for addressing these questions has already been developed, and considerable experimental evidence is available on how to design effective breeding programs for stress environments. This paper sets out some general guidelines, derived from this body of theory and experience, for application to rainfed-rice breeding.

Factors Affecting Progress in a Breeding Program

Plant breeding is best considered as a form of indirect selection, because the breeder screens materials in a nursery to select cultivars that will perform well in

---

International Rice Research Institute (IRRI), Metro Manila, Philippines. E-mail: g.atlin@cgiar.org

KEYWORDS: Genetic correlation, Genotype-by-environment interaction, Heritability, Selection intensity, Selection response, Stress environments

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

another environment, namely, the farmers fields of a target cropping system. Performance on farm and in the nursery can be thought of as correlated traits, expressed by a single genotype in separate environments. Theory developed by Falconer (1989) and extended to the analysis of plant-breeding programs by Pederson and Rathjen (1981) and Atlin and Frey (1989, 1990) permits breeding strategies to be evaluated on the basis of predicted response in the target environment resulting from selection conducted in a breeding nursery. When selection is among pure lines or clonal propagules, this response may be modelled according to the formula:

$$CR_T = i_s r_G \sqrt{H_s H_T} \sigma_P \qquad [1]$$

where,

CR_T = response in the target environment correlated with that in selection in a breeding nursery

i_s = standardized selection differential applied to the selection nursery

r_G = genotypic correlation between cultivar yields in the selection and target environments

H_s and H_T = repeatabilities or broad-sense heritabilities in the selection and target environments, respectively, and

σ_P = phenotypic standard deviation in the target environment.

When response is being predicted for a given target environment, H_T and σ_P may be considered constants. Therefore, in comparisons among breeding methods,

$$CR_T \propto i r_G \sqrt{H_s} \qquad [2]$$

Inspection of this relationship indicates three important considerations in designing breeding programs for stress environments:

1. i must be maximized by screening large populations, permitting a high selection intensity to be achieved;
2. r_G (or accuracy) must be maximized by ensuring that performance in the selection environment or screening system is highly predictive of performance in the target stress environments;
3. A high level of H_s (or precision) must be achieved, usually through replicated screening in the presence of the relevant stress.

The best prospects for improving selection response in stress environments are through the design of conventional breeding programs that maximize the intensity, accuracy, and precision of selection as suggested in Equation 2. These parameters, discussed in more detail below, are also the main considerations in deciding whether marker-assisted selection (MAS) techniques or selection for secondary traits are likely to improve selection response in suboptimal environments.

Selection intensity

Selection intensity, or the proportion of the population that is retained after screening, is a critical component of selection response. Selection intensity is a convenient way of expressing *i* or the difference, in phenotypic standard deviation units, between the mean of the unselected population and the mean of the selected fraction.

The question of selection intensity is important in the later phases of a breeding program, when lines are subjected to costly replicated selection for yield. In most breeding programs, because of cost and space considerations, relatively few lines are subjected to replicated selection for yield across locations, even though this is the selection phase most responsible for making gains in stress environments, including rainfed lowland rice production systems. For example, Cooper et al. (1999b) noted that, in the Thai breeding program for rainfed lowland rice, most breeding lines were eliminated from populations under selection before the initiation of replicated yield testing and only 70 lines per year were subjected to multi-locational yield evaluation. About 10% of these lines were subsequently selected for on-farm testing. Increasing selection intensity at this stage, by reducing the proportion of lines selected from 10% to 5%, is expected to increase selection response by about 18% (Becker 1984).

To achieve this increase and still advance the same number of lines for on-farm testing, the number of lines tested in multi-locational trials must be doubled. Although increasing the number of lines screened is expensive, it is a simple and sure way of increasing selection response in both favourable and unfavourable environments, and should not be overlooked. Often, breeding programs can be reorganized to increase the number of lines screened for yield with an increase in cost that is less than proportional to the increase in plot number. These efficiencies should be aggressively sought for to increase *i*.

Correlation of performance between the selection and target environments

The parameter r_G is the correlation of genotype effects in the selection environment with those of the target environment. It indicates the extent to which different alleles are needed to maximize yield in the selection and target environments, and determines the accuracy with which performance in the target environment can be predicted from performance in the selection environment. Parameter values of r_G can range from –1 to 1, although estimates derived from functions of estimated variance and covariance components may fall outside this range. A value of 0 indicates that no association is present between the performance in the selection environment and that in the target environment, resulting in no response to selection.

In breeding for suboptimal environments, r_G between the selection and target environments must be maximized. Sometimes, selection is conducted on station under management regimes that do not represent those used by farmers. Breeders may apply more fertilizer and control weeds more thoroughly than can farmers in the target environment, resulting in higher yields on station than on farm. This type of selection may be justified in terms of selecting for yield potential or maximizing the precision of yield trials, but breeders must ensure that performance on station is predictive of performance under the more stressful on-farm conditions if the objective is to raise yields for resource-poor farmers. If r_G is low, gains from selection made on station will not be expressed on farm.

Fortunately, published reports indicate that r_G is usually positive, even across very different yield levels. For example, Atlin and Frey (1989) compared the performance of about 180 oat lines under low-N and high-N fertility regimes in Iowa. Although the low-N trials yielded less than half as much as the high-N trials, r_G across N levels equalled 1 (Table 1).

Similarly, in a study involving random recombinant inbred rice lines from the cross IR64/Azucena tested under well-watered and drought-stressed upland conditions, mean yield in the stress treatment was only 50% of mean yield in the well-watered treatment, but r_G was 0.98 (IRRI unpublished data, 2000). Sometimes, however, when yield differences are great, r_G can be low. Bänziger et al. (1997), in an extensive series of trials that compared the performance of maize families across N-fertility levels, found that the magnitude of the correlation decreased as the mean yield difference between the test environments increased. On average, low-N trials in this study yielded about 45% as much as the high-N trials, and the mean r_G was 0.38.

Ceccarelli et al. (1992) also reported low values of r_G between well-watered and drought-stressed barley trials. In general, these results indicate that, to make gains in suboptimal environments, the nurseries and breeding trials where selection is conducted must be managed to maximize r_G. This will usually require the use of trial locations and management regimes that represent those of farmers. Often, the best way to ensure that r_G is high is to conduct selection directly on farm, if this can be done without sacrificing precision (discussed below).

It should be noted that the use of managed screening nurseries that reliably and uniformly impose a stress that occurs only sporadically in nature may be necessary to maximize r_G. For example, droughts in rainfed-rice production systems occur sporadically and unpredictably, but can cause devastating yield losses in the years and locations in which they do occur. The use of dry-season drought nurseries is warranted in this case for the artificial imposition of drought. Even though farmers may not normally practise out-of-season planting, yields from such nurseries may be indicative of performance in the occasional but important drought years. Similarly,

Table 1. Published estimates of genetic correlation (r_G) between cultivar yields in low- and high-yield environments (LYE and HYE, respectively).

Species	Region	Stress	Yield (t ha^{-1}) in: LYE	Yield (t ha^{-1}) in: HYE	r_G
Oat[a]	Iowa	Low P	1.14	2.71	0.52
Oat[a]	Iowa	Late planting	1.50	3.97	0.00
Oat[a]	Iowa	Low N	1.24	2.85	1.08
Barley[b]	Syria	Drought	0.22–1.08	1.81–6.77	–0.12
Wheat[c]	Oklahoma	Drought	1.66	3.48	0.20
Maize[d]	Mexico	Low N	2.45	4.45	0.51
Maize[d]	Mexico	Low N	3.77	5.93	0.50
Maize[e]	Mexico	Low N	2.51	5.52	0.38
Upland rice[f]	Philippines	Drought	0.50	1.05	0.98

[a] Atlin and Frey (1989).
[b] Ceccarelli et al. (1992).
[c] Ud-Din et al. (1992).
[d] Lafitte and Edmeades (1994).
[e] Bänziger et al. (1997).
[f] International Rice Research Institute (IRRI), unpublished data, 2000.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

rainfed lowland rice crops are often subject to periods of submergence. Submergence screens (a form of managed-stress environment) have been successfully used for identifying cultivars with high levels of tolerance (Mackill et al. 1999). In managed-stress nurseries, very large populations can be screened at low cost and high precision (Bänziger and Cooper, in press). However, when a new screening system is introduced, it is important to verify experimentally that the r_G between performance in the managed-stress nursery and the target environment is high.

An effective way of maximizing r_G is to conduct selection directly in the target environment, that is, on farm. For on-farm screening, the correlation between the performance in the selection environment and that in the target environment is necessarily 1, assuming that representative farmer-cooperators have been chosen. On-farm screening should therefore be a component of all breeding programs where there is any uncertainty about the predictive power of on-station screening. However, on-farm trials can be expensive, imprecise (discussed below), and subject to high risk of failure. On-farm testing programs must therefore be carefully designed and conducted to avoid wasting money and time, and to maximize the reliability of the data obtained. Robust experimental designs that may alleviate these problems are available (Atlin et al., in press).

Heritability

Repeatability or broad-sense heritability is the proportion of variance among line means that is explained by differences in genotypic effects. It measures the precision with which differences in genotype value can be detected under a given selection protocol. It is a critical component of selection response. If H is low, progress from selection will be negligible. In Equation 3, broad-sense heritability is considered for the selection environment (H_s). H_s, like r_G, is subject to manipulation through the design of a screening program. The factors affecting H_s are easily recognized through inspection of its expression in terms of components of variance:

$$H_S = \frac{\sigma^2_G}{\sigma^2_G + \frac{\sigma^2_{GL}}{l} + \frac{\sigma^2_{GY}}{y} + \frac{\sigma^2_{GLY}}{ly} + \frac{\sigma^2_E}{rly}} \qquad [3]$$

where,

σ^2_G = genotype (G) variance
σ^2_{GL} = genotype × location (GL) variance
σ^2_{GY} = genotype × year (GY) variance
σ^2_{GLY} = genotype × location × year (GLY) variance
σ^2_E = within-trial error variance
l = number of locations
y = number of years, and
r = number of replicates of testing.

The parameters σ^2_G, σ^2_{GL}, σ^2_{GY}, σ^2_{GLY} and σ^2_E are estimated from cultivar trials repeated over locations and years within the target region. It is important for breeding and cultivar testing programs to estimate these parameters, which can be easily calculated from multiple-environment trial (MET) data, using standard statistical software packages such as SAS™ (SAS Institute, Inc., 1996) even for data sets that are not balanced over locations and years.

Equation 3 is used to determine the optimal allocation of testing resources over locations and years within the targeted region. This allocation is determined by the relative magnitudes of σ^2_{GL}, σ^2_{GY}, σ^2_{GLY} and σ^2_E, which are the 'noise' components that reduce the precision of estimates of line means from field trials. Inspection of Equation 3 shows that the effect of these components on H_s decreases with increasing replication within and across locations and years.

Table 2 presents variance component estimates from several cultivar-testing programs. These data indicate that, in most systems, σ^2_{GLY} and σ^2_E are the largest contributors to this 'noise'. The contribution of σ^2_E can be reduced by increasing within-location replication, by adopting improved methods of controlling within-block error (e.g. lattice designs or neighbour analysis), or by increasing the number of locations or years of testing. The contribution of σ^2_{GLY} can only be reduced by increasing replication across locations or years.

The effect that this increased replication has on H_s, and consequently on selection response, is profound (Table 3). For upland rice trials in high-yield environments, increasing testing from 1 to 5 locations in a single year was predicted to nearly triple $H_{s,}$ from 0.19 to 0.53. Because trials in low-yield environments usually have a larger 'noise' component of genotype-by-environment interaction (GEI) relative to the genetic variance (Atlin and Frey 1990), the effect of replication over locations and years on H_s in suboptimal environments is usually even greater than it is in high-yield environments. An extreme example of this phenomenon is observed in the Philippine upland rice trials in low-yield environments (Table 2), which exhibited limited genetic variance.

In these trials, H_s for one 4-replicate trial was predicted to be only 0.07. Increasing the number of trial locations to five in a single year increased predicted H_s by nearly 4 times to 0.26. This increase in precision would nearly double selection response.

Under some circumstances, GEI variance is not 'noise' but evidence of specific adaptation of particular cultivar types to particular environments. When this specific adaptation requirement is large enough to cause rank changes in cultivar performance, subdivision of the target region may be warranted

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Table 2. Genotype (σ^2_G), genotype × location (σ^2_{GL}), genotype × year (σ^2_{GY}), genotype × location × year (σ^2_{GLY}) and within-location residual (σ^2_E) variance components for yield estimated from trials conducted on rainfed lowland rice cultivars at six locations in north and north-east Thailand (1995–1997) and from trials conducted on upland rice cultivars in high- and low-yield environments at four locations in the Philippines (1994–1996).

Species	Region	σ^2_G	σ^2_{GL}	σ^2_{GY}	σ^2_{GLY}	σ^2_E
Rainfed lowland rice[a]	Thailand	7	0	6	32	54
Upland rice: low-yield trials[b]	Philippines	5	0	0	63	27
Upland rice: high-yield trials[b]	Philippines	12	9	0	34	39

[a] Cooper et al. (1999b).

[b] International Rice Research Institute (IRRI), unpublished data, 2000.

(Atlin et al. 2000). For example, some of the variation in rainfed lowland rice cultivar performance across trials in North-East Thailand was shown to be caused by differential response of cultivars of differing growth duration to variation in the time of occurrence of drought. This GEI results from the fact that short-duration cultivars avoid late-season drought, and therefore outperform later cultivars when the onset of drought is relatively late (Cooper et al. 1999a).

Table 3. The effect of location, year and replicate number on broad-sense heritability (*H*), calculated from variance components estimated in 5 high- and 5 low-yield environments at four locations in the Philippines (1994–1996).

Mean yield of trials (t ha^{-1})	Years (no.)	Locations (no.)	*H*
Trials in low-yield environments			
0.69	1	1	0.07
	1	5	0.26
	1	10	0.42
	2	1	0.13
	2	5	0.42
	2	10	0.59
Trials in high-yield environments			
1.79	1	1	0.19
	1	5	0.53
	1	10	0.69
	2	1	0.28
	2	5	0.66
	2	10	0.80

If the stress is reliably associated with particular locations within the target region, then subdivision may be warranted, permitting cultivars with specific adaptation to each subregion to be developed. However, Atlin et al. (2000) have pointed out that subdivision of the target region also usually results in subdivision of testing resources, thereby reducing H_s because of a reduced number of test locations within each subregion. Gains from the exploitation of local adaptation must more than outweigh the disadvantage of reductions in H_s for subdivision to be warranted.

The problem of low heritability in suboptimal environments is a critical one, and generally insufficiently recognized. Little progress from selection can be expected in such environments unless replication of trials across locations and years is extensive. This problem also arises in on-farm and participatory breeding and testing programs, which have been proposed as a solution to the problem of developing cultivars for marginal environments (Witcombe et al. 1996).

Farmer participatory testing is a critical step in evaluating new cultivars, but the small farms on which this testing is done are likely to be at least as heterogeneous as the stations, with the result that H_s in on-farm trials is likely to be low. High levels of replication across locations and years are required to achieve adequate precision in such trials. These levels of replication can be achieved by on-farm testing programs that organize farmers into testing networks, treating individual farms as incomplete blocks (Atlin et al., in press). Farms are considered to be random samples of the target population of environments. For example, a network of 80 farmers may evaluate a population of 100 lines by testing 5 lines each. Each line would thereby be tested in 4 incomplete blocks. The farm-as-incomplete-block (FAIB) model has been successfully used to achieve high levels of replication in the 'mother-baby' trial system, conducted by the East African maize program of the International Maize and Wheat Improvement Center (CIMMYT, its Spanish acronym) (Snapp 1999).

Guidelines for Designing Breeding Programs

Consideration of Equation 2 and the discussion of its component parameters above lead to four general guidelines for designing breeding programs for suboptimal environments:

1. *Breeding programs for suboptimal environments must be large to make real gains for yield*. Initial populations of lines evaluated must be large enough to permit intensive phenotypic selection for highly heritable quality, plant type and pest

resistance traits, while retaining a population with adequate genetic variation for progress to be made in yield trials. If little selection pressure for yield is applied, little progress will be made.

2. *H_s must be maximized through replication of yield trials across locations and years*. Because random GEI variances and within-field heterogeneity are often high in stress environments, progress can only result if large populations are screened at high replication within locations, across locations, and across years. This is expensive, and must involve cooperation between research centres in collaborative networks for the early stages of yield testing, rather than extensive testing at a single centre until advanced stages (Cooper et al. 1999b). Trial locations should be chosen to represent the target region, and be subject to similar stresses.
3. *The genetic correlation between the selection and targeted environments must be maximized*. For the most part, this means (a) ensuring that management of trials and nurseries in which selection is being undertaken is representative of farmer management, and (b) choosing test locations that are representative of the target population of environments and its stresses. Nurseries in which managed levels of stress are purposefully applied may be useful in ensuring that r_G is maximized for stress environments (e.g. drought or submergence) that occur sporadically in the targeted population of environments. It is of critical importance, however, to verify that the results of managed-stress trials are truly predictive of on-farm performance.
4. *All breeding programs should include on-farm trials*. To ensure that selection has been effective, and that progress made on station is transferable to the farm, on-farm trials, managed by farmers, should be the final step in testing a new cultivar.

Some Critical Questions Related to Breeding for Suboptimal Environments

The questions posed in the introduction to this paper may be considered in light of the selection theory and research experience discussed above:

- *Should selection be done indirectly, in high-yield environments where genetic variance is usually maximized, or directly, in the presence of the relevant stress?*

  This decision must be made taking into account both H_s and r_G. If r_G is low, then direct selection in the stress environment is nearly always warranted (Atlin and Frey 1990). However, if r_G is moderately high and H_s is reduced in the presence of stress due to GEI or within-location soil heterogeneity, selection in a higher yield, less variable, environment may result in greater gains (Atlin and Frey 1990).
- *Can breeders develop cultivars that combine stress tolerance with responsiveness to favourable conditions, or are separate cultivars needed for high- and low-yield environments?*

  In most cases reported in the literature, r_G between stress and non-stress environments is positive, and is often quite high. This means that cultivars combining high levels of yield potential and stress tolerance can be selected in most situations. The CIMMYT maize program, for example, has been highly successful in developing cultivars that are both stress tolerant and responsive to inputs by selecting on the basis of information from both stress and non-stress environments (Bänziger and Cooper, in press).
- *Can selection conducted on station result in improved performance on farm in marginal or stress environments?*

  If on-station trials are managed to maximize r_G, through the use of management regimes representing farmer practice, and if managed environments predictive of performance under sporadic stresses are used, then on-station performance should predict that obtained on farm. However, on-farm testing as the ultimate step in cultivar development is a necessary test of the breeders' success in replicating production conditions on station.
- *Can selection for secondary physiological traits (e.g. osmotic adjustment or root-pulling resistance) result in improved yields in stress environments?*

  To be useful in breeding for productivity in suboptimal environments, secondary traits must have high r_G with yield, have higher H_s, and be easier and cheaper to measure. Very few secondary traits fulfil these requirements. For example, secondary traits such as anthesis-silking interval, reduced tassel size, decreased leaf rolling, delayed leaf senescence and leaf greenness have been extensively evaluated as selection criteria for improving grain yield under drought in maize, but only the anthesis-silking interval has proven consistently useful (Edmeades et al. 1998).

  In rice, a great deal of effort is currently being devoted to measuring root characteristics and physiological parameters such as osmotic adjustment as indirect selection criteria for performance under drought. Little evidence exists that these traits have a high r_G for yield under drought, or that they can be measured with higher H_s. For example, H was estimated in a sample of 38 cultivars evaluated over two seasons for grain yield under restricted irrigation in the dry season at Los Baños, Philippines. In this system, where

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

yields averaged about 25% of those obtained under full irrigation, H was predicted to be 0.5 for testing in a single year, and 0.75 for evaluation over 2 years. By comparison, for relative water content, *H* was predicted to be less than 10% for line means over 2 years (IRRI, unpublished data, 2000). In this instance, far greater progress would be made by selecting for grain yield under drought than for relative water content.

Conclusions

Suboptimal environments tend to be more variable than high-yield environments, and farmers' economic circumstances may prevent them from investing in inputs that might increase yields and reduce environmental variability. Selection theory and much experience indicate that progress from selection in such environments results from:

1. Maximizing the intensity of selection for yield by subjecting large populations to replicated testing;
2. Maximizing heritability in the selection environment by extensive replication of trials across a representative sample of the targeted population of environments; and
3. Ensuring a high genetic correlation between performance in the selection environment and that in farmers fields by managing breeding trials appropriately and conducting extensive on-farm trials.

Generally positive associations between performance in stress and non-stress environments reported in the literature indicate that combining stress tolerance with responsiveness to favourable conditions may be possible for many cropping systems. Direct selection for grain yield at high levels of precision and selection intensity has proven to be the most effective approach to breeding for stress environments.

References

Atlin, G.N. and Frey, K.J. 1989. Breeding crop varieties for low-input agriculture. American Journal of Alternative Agriculture, 4, 53–57.

Atlin, G.N. and Frey, K.J. 1990. Selecting oat lines for yield in low-productivity environments. Crop Science, 30, 556–561.

Atlin, G.N., R.J. Baker, K.B. McRae, and X. Lu. 2000. The effect of subdividing a target region on selection response. Crop Sci. 40: 1-6

Atlin, G.N., Cooper, M. and Bjørnstad, Å. In press. A comparison of formal and participatory breeding approaches using selection theory. Euphytica.

Bänziger, M. and Cooper, M. In press. Breeding for low-input conditions and consequences for participatory plant breeding—Examples from tropical maize and wheat. Euphytica.

Bänziger, M., Betrán, F.J. and Lafitte, H.R. 1997. Efficiency of high-nitrogen selection environments for improving maize for low-nitrogen target environments. Crop Science, 37, 1103–1109.

Becker, W.A. 1984. Manual of quantitative genetics. Pullman, W.A., Academic Enterprises.

Byerlee, D. and Husain, T. 1993. Agricultural research strategies for favoured and marginal area: the experience of farming systems research in Pakistan. Experimental Agriculture, 29, 155–171.

Ceccarelli, S., Grando, S. and Hamblin, J. 1992. Relationship between barley grain yield measured in low- and high-yielding environments. Euphytica, 94, 49–58.

Cooper, M., Rajatasereekul, S., Immark, S., Fukai, S. and Basnayake, J. 1999a. Rainfed lowland rice breeding strategies for northeast Thailand. I. Genotypic variation and genotype × environment interactions for grain yield. Field Crops Research, 64, 131–151.

Cooper, M., Rajatasereekul, S., Somrith, B., Sriwusit, S., Immark, S., Boonwite, C., Suwanwongse, A., Ruangsook, S., Hanviriyapant, P., Romyen, P., Porn-uraisanit, P., Skulkhu, E., Fukai, S., Basnayake, J. and Podlich, D.W. 1999b. Rainfed lowland rice breeding strategies for northeast Thailand. II. Comparison of intrastation and interstation selection. Field Crops Research, 64, 153–176.

Edmeades, G.O., Bolanos, J., Bänziger, M., Ribaut, J.M., White, J.W., Reynolds, M.P. and Lafitte, H.R. 1998. Improving crop yields under water deficits in the tropics. In: Chopra, V.L., Singh, R.B. and Varma, A. ed. Crop Productivity and Sustainability—Shaping the Future, Proceedings of the Second International Crop Science Congress, New Dehli, India. New Delhi, India, Oxford and IBH, 437–451.

Falconer, D.S. 1989. Introduction to quantitative genetics, 3rd ed. London, Longman.

Lafitte, H.R. and Edmeades, G.O. 1994. Improvement for tolerance to low soil nitrogen in tropical maize. I. Selection criteria. Field Crops Research, 39, 1–14.

Mackill, D.J., Nguyen, H.T. and Zhang, J. 1999. Use of molecular markers in plant improvement programs for rainfed lowland rice. Field Crops Research, 64, 177–185.

Maurya, D.M., Bottrall, A. and Farrington, J. 1988. Improved livelihoods, genetic diversity, and farmer participation: a strategy for rice breeding in rainfed areas of India. Experimental Agriculture, 24, 211–320.

Pederson, D.G. and Rathjen, A.J. 1981. Choosing trial sites to maximize selection response for grain yield in spring wheat. Australian Journal of Agricultural Research, 32, 411–424.

SAS Institute, Inc. 1996. SAS/STAT software: changes and enhancements through Release 6.11, Cary, N.C.

Snapp S. 1999. Mother and baby trials: a novel trial design being tried out in Malawi. *In* TARGET. The Newsletter of the Soil Fertility Research Network for Maize-Based Cropping Systems in Malawi and Zimbabwe. January 1999 issue. CIMMYT, Zimbabwe.

Ud-Din, N., Carver, B.F. and Clutter, A.C. 1992. Genetic analysis and selection for wheat yield in drought-stressed and irrigated environments. Euphytica, 62, 89–96.

Witcombe, J.R., Joshi, A., Joshi, K.D. and Sthaphit, B.R. 1996. Farmer participatory crop improvement. I. Varietal selection and breeding methods and their impact on biodiversity. Experimental Agriculture, 32, 445–460.

Allocating Resources for Variety Trials of Rainfed-Lowland Rice in Cambodia

Edvin L. Javier[1*], D.R. Ledesma[2], Ouk Makara[3] and P. Khon Hel[3]

Abstract

The Cambodia–IRRI–Australia Project funding for rice research will end in 2001, possibly leading to financial constraints for the national rice-variety-testing program. Thus, resource allocation for rainfed-lowland advanced yield trials (AYT) was evaluated, using historical data of four variety groups, for various combinations of test locations, years and replicates relative to the current standard procedure. Changes in the standard error (SE) of variety mean and the number of trials and plots were the criteria used to identify the best allocation of resources. While ensuring that increases in SE were kept minimal, that is, between 0.01 and 0.02 t ha^{-1}, the number of trials and plots for the AYT could be reduced between 20% and 40%, thereby reducing costs, for three variety groups (early maturing, and modern and traditional intermediate-maturing). For the fourth group, the traditional late-maturing group, no variety × environment interaction was found. Although decisions could thus be based on AYT conducted in only a few locations over 1 year, 2 years of testing is preferable, to account for those years with atypical weather. Resource allocation in AYT should be evaluated from time to time, using historical data.

VARIETY testing, a major component of any crop-breeding program, aims to identify varieties that can be recommended for commercial production. It is costly and time consuming. In Cambodia, rice-variety trials are conducted in four stages:

1. *The observational yield trial*, which is composed of many entries. This non-replicated study is conducted for at least one season or year at one or two locations. The most promising materials, according to yield, then enter the next stage.
2. *The preliminary yield trial*, which is conducted with two replicates at a few locations for at least one season or year. The top-yielding materials with respect to the check variety are channelled into the final stage of replicated trial.
3. *The advanced yield trial (AYT)* is conducted at about 10 locations for at least 2 years with 4 replicates at each location. The top 2 or 3 materials, that is, those with yields better than the check variety, are then evaluated in farmers' fields.
4. *On-farm variety trials*, when promising materials are evaluated, using the farmers' own resources and management practices.

The first three trials are managed by researchers while the last one is managed by farmers. The decision to release a variety for use by farmers is based on the results of the AYT and on-farm variety trials.

The Cambodia–IRRI–Australia Project (CIAP) has been supporting the variety-testing program since 1989. Every year, it funds at least 60 researcher-managed, variety yield trials and hundreds of on-farm variety trials for different rice ecosystems in various parts of the country. All trials are monitored regularly by the breeding team at the Cambodian Agricultural Research and Development Institute (CARDI). The external funding from CIAP for variety trials will end in 2001, which may lead to a scarcity of resources. National plant breeders will therefore have to

---

[1] International Rice Research Institute (IRRI), Makati City, Philippines
[2] Asian Vegetable Research and Development Center (AVRDC), Shanhua, Tainan, Taiwan
[3] Cambodian Agricultural Research and Development Institute (CARDI), Ministry of Agriculture, Forestry and Fisheries, Phnom Penh, Cambodia
*Corresponding author: E.L. Javier
E-mail: e.javier@cgiar.org

KEYWORDS: Rainfed lowland rice, Resource allocation, Standard error of variety mean, Variety × environment interaction

determine how resources should be allocated in the variety-testing program.

To determine how to allocate resources, data on multi-locational trials conducted over years are needed (Sprague and Federer 1951). Variances for variety × location, variety × year and variety × location × year are estimated from the results of a combined analysis of variance over locations and years. The theoretical variance, or standard error (SE) of variety mean, is estimated for different combinations of numbers of locations, years and replicates within locations. Differences in the theoretical variance (or SE) reflect differential sensitivity in determining variety differences. The total number of trials and plots, associated with the different numbers of locations, years and replicates, indicates the potential costs of conducting trials. This number is examined, together with the SE, to determine the optimal allocation of resources. This approach was used by Jones et al. (1960), Povilaitis (1970), Gupton et al. (1974) and P. Bonilla (unpublished data, 1986) for tobacco, S. Samonte (unpublished data, 1990) for irrigated lowland rice, and Atlin and McRae (1994) for barley and wheat.

Our study used historical data on the AYT conducted by CIAP. The objectives were to determine the presence of variety × environment interaction in the AYT and to determine how to allocate resources for future variety-testing programs of different rainfed-lowland rice variety groups in Cambodia.

Materials and Methods

The rainfed-lowland rice varieties in Cambodia are categorized into four groups: (1) early maturing, comprising modern, photoperiod-insensitive varieties that can mature in fewer than 120 days; (2) modern intermediate, comprising modern, photoperiod-insensitive varieties that mature between 120 and 150 days; (3) traditional intermediate-maturing varieties that flower between mid-October and mid-November; and (4) traditional, late-maturing varieties that mature between mid-November and December. All groups are tested during the wet season, except the early maturing group, which is also tested in the dry season, receiving partial or full irrigation.

We studied the results of the AYT conducted on the four variety groups described above from 1992 to 1995 by CIAP. In general, an AYT was conducted with 10 entries, using a randomized complete block design with four replicates, at several locations. During each year or season, varietal performance was examined. New entries replaced those that performed poorly. Some testing sites were replaced by other sites in some years or seasons. Since 1991, 30 sites have been used in AYT for early maturing varieties, 30 for modern intermediate-, 24 for traditional intermediate- and 18 for traditional late-maturing.

We developed data sets for each variety group (Table 1). A data set represents the results of AYT involving a common number of varieties evaluated in various locations across several years or seasons. The early maturing group had three data sets: I, which represented wet-season trials; II, dry-season trials; and III, dry- and wet-season trials.

Table 1. Numbers of varieties, locations, years and seasons for data sets of four rainfed-lowland rice variety groups.

Variety group	Set no.	Variety	Location	Year	Season
Early	I	5	9	2	—
	II	6	8	2	—
	III	6	3	2	2
Modern intermediate	I	8	5	3	—
	II	10	6	2	—
Traditional intermediate	I	10	4	2	—
Traditional late	I	10	5	3	—
	II	7	5	4	—

A mixed statistical model was used for analysing grain yield data. Varieties in AYT were highly selected, having been chosen according to yield across locations and years. Thus, variety was defined as a fixed effect. Season was also considered as a fixed effect. Year, location and replicate were considered as random effects.

Estimates of the various components of variance were obtained by equating the observed mean squares to the expected mean squares. The theoretical variances of the variety mean (V_x) for various combinations of numbers of years, locations and replicates were estimated, using the following formula:

$$Vx = (\sigma^2_{vy}/y) + (\sigma^2_{vl}/l) + (\sigma^2_{vyl}/yl) + (\sigma^2_e/rly) \quad [1]$$

where,

σ^2_{vy} = variety × year variance
σ^2_{vl} = variety × location variance
σ^2_{vyl} = variety × year × location variance
σ^2_e = error variance
y = number of years
l = number of locations, and
r = number of replicates.

The optimal allocation of resources for the testing program for each variety group was determined by comparing the changes in the SE (square root of the theoretical variance), together with changes in the total number of trials (number of locations × number of years) and total number of plots (number of trials × number of replicates) for different combinations of years, locations and replicates.

Results and Discussion

Variety × environment interaction

Table 2 shows the analysis of variance for yield, involving relevant sources of variations, for the early maturing group. Variability among early maturing varieties was absent in the wet-season data set (Set I). However, significant variety × year × location interaction was found. This suggests that varieties performed differently under different year–location combinations. Significant differences were found for variety and the variety × location interaction in the dry-season data set (Set II). The interaction indicates that varieties ranked differently from location to location or that the magnitude of differences differed among locations. This also implies that variety recommendation can be location-specific. In Set III, where six varieties were tested at three locations, 2 years and two seasons, highly significant differences were found among entries. However, the genotype × environment interaction was, on the whole, absent. The sample sizes of locations (3) and years (2) may have been too small to detect the interaction.

Variation among varieties was absent for both Sets I and II of the modern intermediate-maturing group (Table 3). Significant variety × year interaction was found for Set II. This implies that varietal ranking or magnitude of varietal differences differed with years.

Highly significant differences were found among varieties belonging to the traditional intermediate-maturing group. However, varietal performance differed from year to year, as in Set II of the modern intermediate-maturing group.

Table 2. Mean squares (MS) for variety and variety × environment interaction components for advanced yield trials of early maturing rice varieties, according to three data sets.[a]

Source of variation	Set I		Set II		Set III	
	DF	MS	DF	MS	DF	MS
Variety (V)	4	1.594	5	6.044*	5	6.832**
V × year (Y)	4	0.722	5	0.520	5	0.388
V × location (L)	32	0.317	30	1.881**	10	1.120
V × Y × L	32	0.523**	30	0.464	10	0.423
V × season (S)	—	—	—	—	5	1.107
V × S × Y	—	—	—	—	5	0.554
V × S × L	—	—	—	—	10	0.848
V × S × Y × L	—	—	—	—	10	0.547
Effective pooled error[b]	216 (118)	0.275	210 (139)	0.288	120 (65)	0.516

[a] Data Set I = wet-season trials; Set II = dry-season trials; Set III = dry- and wet-season trials.
[b] Effective degrees of freedom (DF) due to Satterthwaite are given in parentheses.
** = significant at 1% level; * = significant at 5% level.

Table 3. Mean squares (MS) for variety and variety × environment interaction components for advanced yield trials of modern intermediate-, traditional intermediate- and traditional late-maturing rice variety groups.

Source of variation	Modern intermediate				Traditional intermediate		Traditional late[a]			
	Set I		Set II				Set I		Set II	
	DF	MS	DF	MS	DF	MS	DF	MS	DF	MS
Variety (V)	7	0.619	9	0.930	9	2.910**	9	2.456**	6	1.544*
V × year (Y)	14	0.520	9	1.064*	9	0.572*	18	0.430	18	0.591
V × location (L)	28	0.543	45	0.653	27	0.315	36	0.590	24	0.555
V × Y × L	56	0.425	45	0.451	27	0.205	72	0.427	72	0.340
Effective pooled error[a]	315 (115)	0.707	324 (124)	0.570	214 (125)	0.339	401 (161)	0.402	357 (128)	0.441

[a] Effective degrees of freedom (DF) due to Satterthwaite are given in parentheses.
** = significant at 1% level; * = significant at 5% level.

While significant differences among varieties were found for the traditional late-maturing group, no component of the variety × environment interaction was significant. This indicates that varietal ranking did not change across locations and years. Varietal selection can be based simply on mean yield across environments. This also suggests that the varieties selected for release have wide adaptation.

Several studies conducted in Thailand (Cooper et al. 1999a, b) and Laos (Inthapanya et al. 2000) indicated that the genotype × environment interaction was a large component for yield. The materials used in those studies were random samples of inbred lines and/or varieties from several crosses or countries. In our study, however, the genotype × environment interaction component was not as large, because the data sets used were obtained from results of the AYT, the final stage of replicated testing. Entries in AYT were not random samples of varieties but selected according to their consistent high yields, as reflected in a series of yield trials. Thus, the magnitudes of genotype × environment interaction in our study would most likely differ from those of the Thai and Lao studies. However, it should be noted that other Asian countries also have highly selected materials in replicated trials that are as advanced as those of the AYT in Cambodia, and are aimed at finding superior genotypes for farmers.

Resource allocation

Estimates of the standard error of variety mean were determined for 2–10 locations, 2–4 years and 2–4 replicates within locations for data sets with significant variety × environment interaction. Effects of the number of replicates, locations and years on SE are summarized in Table 4.

Decreasing the number of locations from 10 to 2 increased the SE, given the same number of replicates and years for all data sets. The increase in the SE was more pronounced when the number of locations was reduced to five or less. Similarly, the SE increased when the number of years decreased, given the same number of locations and replicates, and when the

Table 4. Effect of numbers of replicates, locations and years (Y) on standard errors (SE, in t ha^{-1}) of variety means estimated from yield trials of three rice variety groups (early, traditional intermediate and traditional late-maturing).

Replicate	Location	Early (Set I)[a]			Early (Set II)[a]			Traditional intermediate			Traditional late		
		2 Y	3 Y	4 Y	2 Y	3 Y	4 Y	2 Y	3 Y	4 Y	2 Y	3 Y	4 Y
2	2	0.23	0.19	0.16	0.44	0.40	0.38	0.31	0.26	0.23	0.25	0.21	0.18
2	3	0.19	0.16	0.13	0.36	0.33	0.31	0.26	0.22	0.20	0.21	0.18	0.16
2	4	0.17	0.14	0.12	0.31	0.28	0.27	0.23	0.20	0.18	0.19	0.16	0.14
2	5	0.15	0.12	0.11	0.28	0.25	0.24	0.22	0.18	0.16	0.18	0.15	0.13
2	6	0.14	0.11	0.10	0.26	0.23	0.22	0.20	0.17	0.15	0.17	0.14	0.12
2	7	0.13	0.11	0.09	0.24	0.21	0.20	0.19	0.16	0.14	0.16	0.13	0.12
2	8	0.12	0.10	0.09	0.22	0.20	0.19	0.18	0.15	0.14	0.15	0.13	0.11
2	9	0.12	0.10	0.08	0.21	0.19	0.18	0.18	0.15	0.13	0.15	0.12	0.11
2	10	0.11	0.09	0.08	0.20	0.18	0.17	0.17	0.14	0.13	0.15	0.12	0.11
3	2	0.20	0.17	0.14	0.40	0.37	0.35	0.27	0.23	0.21	0.22	0.18	0.16
3	3	0.17	0.14	0.12	0.33	0.30	0.29	0.23	0.20	0.18	0.19	0.16	0.14
3	4	0.15	0.12	0.11	0.28	0.26	0.25	0.21	0.18	0.16	0.17	0.14	0.13
3	5	0.14	0.11	0.10	0.25	0.23	0.22	0.19	0.16	0.15	0.16	0.13	0.12
3	6	0.13	0.10	0.09	0.23	0.21	0.20	0.18	0.15	0.14	0.15	0.13	0.11
3	7	0.12	0.10	0.08	0.21	0.20	0.19	0.17	0.15	0.13	0.15	0.12	0.11
3	8	0.11	0.09	0.08	0.20	0.18	0.17	0.17	0.14	0.12	0.14	0.12	0.11
3	9	0.11	0.09	0.08	0.19	0.17	0.16	0.16	0.14	0.12	0.14	0.12	0.10
3	10	0.10	0.08	0.07	0.18	0.16	0.16	0.16	0.13	0.12	0.14	0.11	0.10
4	2	0.19	0.15	0.13	0.38	0.35	0.34	0.25	0.21	0.19	0.20	0.17	0.15
4	3	0.16	0.13	0.11	0.31	0.29	0.27	0.21	0.18	0.16	0.17	0.15	0.13
4	4	0.14	0.11	0.10	0.27	0.25	0.24	0.19	0.16	0.15	0.16	0.14	0.12
4	5	0.13	0.10	0.09	0.24	0.22	0.21	0.18	0.15	0.14	0.15	0.13	0.11
4	6	0.12	0.10	0.08	0.22	0.20	0.19	0.17	0.14	0.13	0.14	0.12	0.11
4	7	0.11	0.09	0.08	0.20	0.19	0.18	0.16	0.14	0.12	0.14	0.12	0.10
4	8	0.11	0.09	0.07	0.19	0.17	0.17	0.16	0.13	0.12	0.14	0.11	0.10
4	9	0.10	0.08	0.07	0.18	0.16	0.16	0.15	0.13	0.12	0.13	0.11	0.10
4	10	0.10	0.08	0.07	0.17	0.16	0.15	0.15	0.13	0.11	0.13	0.11	0.10

[a] Data Set I = wet-season trials; Set II = dry-season trials.

number of replicates decreased, given the same number of locations and years.

To determine the effect on SE of differing allocations of resources, different combinations of replicates, locations and years that gave a similar number of plots were determined and their SE compared. Given a fixed number of locations, a combination of 2 replicates and 3 years and a combination of 3 replicates and 2 years gave the same number of plots. With 2 locations, the SE of the first combination (0.19) was smaller than that of the second combination (0.20) in Set I of the early maturing group. This was noted for other combinations that could be generated in Set I of the early maturing group.

For modern intermediate- and traditional intermediate-maturing groups, to reduce the SE, increasing the number of years was more effective than increasing the number of replicates. However, year and replicate had similar effects on the dry-season trials (Set II) for the early maturing group.

Given 2 years, the SE of 2 replicates and 3 locations was 0.19, while the SE of 3 replicates and 2 locations was 0.20 for Set I for the early maturing group. The larger effect of increasing the number of locations over increasing the number of replicates on SE was also observed in all possible cases in each variety group.

Consider Set I of the early maturing group: given 2 replicates, the SE of 3 locations and 2 years (0.19) was similar to that of 2 locations and 3 years. With the same number of replicates, the SE of 4 locations and 2 years (0.17) was higher than the SE of 2 locations and 4 years (0.16). For other allocations of resources, the SE of more locations was similar or higher than that of more years. The same pattern was reflected in the traditional intermediate-maturing group. In the modern intermediate-maturing group, location and year had similar effects on the SE. In Set I of the early maturing group, the SE for more locations was always higher than the SE for more years.

In determining the best allocation of resources, various combinations of replicates, locations and years were compared with the standard allocation of resources for conducting AYT in terms of changes in the SE, and total number of trials and plots. A lower SE indicates a more sensitive criterion for differentiating varietal differences. Fewer trials and plots indicate lower costs for conducting an AYT. Given the same number of locations and years, a trial with more replicates is slightly more costly than one with fewer. A trial conducted over more years is less efficient than one over fewer years. Additional years of testing also delay the release and commercial use of a variety. A study in Northeast Thailand (Pandey and Rajatasereekul 1999) showed that the economic losses associated with delayed variety release could be as much as 25% for a rice-breeding cycle that needs 13 years to complete.

For the early maturing group, the AYT trial is conducted in at least 10 locations, and across two seasons and 2 years (standard allocation of resources). Common testing sites for wet and dry seasons are very few. This reflects the actual rice-production situation in Cambodia, where only a few areas grow rice twice a year. Considering resource allocation for the two seasons separately is thus appropriate.

For the wet-season, early maturing group, standard testing procedure had 20 trials and 80 plots, and the SE was 0.10 t ha^{-1}. Ten combinations of resource allocations had no more than a 10% increase in the SE (Table 5). The lowest SE found was for 9 and 10 locations, each with 3 years and 4 replicates. However, these combinations were associated with 50% increase in the total number of trials and plots. Furthermore, additional years of testing delay the selection of promising entries for evaluation in farm fields. The resource allocation that gave the lowest number of trials and thus, the cheapest, involved 7 locations, 2 years and 4 replicates, with an increase in the SE of only 0.01 t ha^{-1}.

Table 5. Number of trials and plots, and the standard error (SE) of variety mean of the standard testing procedure (10 locations, 2 years and 4 replicates, shown in boldface) and selected combinations of locations, years and replicates for early maturing rice variety trials. Figures in italics indicate the cheapest allocation of resources.

Number of			SE (t ha^{-1})	Number of	
Location	Year	Replicate		Trials	Plots
Set I (wet season)					
10	**2**	**4**	**0.10**	**20**	**80**
9	2	4	0.10	18	72
8	2	4	0.11	16	64
7	*2*	*4*	*0.11*	*14*	*56*
10	3	4	0.08	30	120
9	3	4	0.08	27	108
8	3	4	0.09	24	96
7	3	4	0.09	21	84
6	3	4	0.10	18	72
5	3	4	0.10	15	60
10	2	3	0.10	20	60
Set II (dry season)					
10	**2**	**4**	**0.17**	**20**	**80**
9	2	4	0.18	18	72
8	*2*	*4*	*0.19*	*16*	*64*
10	3	4	0.16	30	120
9	3	4	0.16	27	108
8	3	4	0.17	24	96
7	3	4	0.19	21	84
10	2	3	0.18	20	60
9	2	3	0.19	18	54

For the dry-season trials of early maturing varieties, the standard testing procedure had 20 trials and 80 plots. Its SE was 0.17 t ha^{-1}. The combination of 8 locations, 2 years and 4 replicates within locations was the cheapest with 4 trials and 16 plots fewer than the standard. The SE was greater than the standard by 0.02 t ha^{-1}. The least number of plots was reflected by 9 locations, 2 years and 3 replicates. However, it is more expensive than the other resource allocation because it involves more trials (18 versus 16).

In the modern intermediate-maturing group, a promising test entry is channelled into the on-farm variety trial after it has been tested in at least 10 locations for 3 years with 4 replicates within locations. This resource allocation gave an SE of 0.13 t ha^{-1} (Table 6). There were 14 resource allocations with acceptable changes in the SE, of which 9 involved 4 years of testing and thus could not reduce the cost of the AYT. One of the two best options available increased the SE by only 0.01 t ha^{-1} (7 locations, 3 years and 4 replicates). The other best option, with an increase in the SE of 0.02 t ha^{-1}, involved 9 locations, 2 years and 4 replicates. The second option was better because its total number of trials and plots was smaller and, more importantly, reduced the testing cycle by 1 year.

Table 6. Number of trials and plots, and the standard error (SE) of variety mean of the standard testing procedure (10 locations, 3 years and 4 replicates, shown in boldface) and selected combinations of locations, years and replicates for the modern intermediate-maturing rice variety trials. Figures in italics indicate the cheapest allocation of resources.

Number of			SE (t ha^{-1})	Number of	
Location	Year	Replicate		Trials	Plots
10	**3**	**4**	**0.13**	**30**	**120**
9	3	4	0.13	27	108
8	3	4	0.13	24	96
7	3	4	0.14	21	84
10	4	4	0.11	40	160
9	4	4	0.12	36	144
8	4	4	0.12	32	128
7	4	4	0.12	28	112
6	4	4	0.13	24	96
10	4	3	0.12	40	120
9	4	3	0.12	36	108
8	4	3	0.12	32	96
7	4	3	0.13	28	84
10	2	4	0.15	20	80
9	*2*	*4*	*0.15*	*18*	*72*

The standard procedure for testing in the traditional intermediate-maturing group is similar to that of the modern intermediate-maturing group. The SE of the variety mean was 0.11 t ha^{-1} (Table 7). A total of 14 cases with acceptable SE were identified. Cost reductions were not possible in 9 cases for they involved 4 years of testing. The most efficient resource allocation was 9 locations, 2 years and 4 replicates within locations. The proposed allocation of resources increased the SE by 0.02 t ha^{-1}.

Table 7. Number of trials and plots, and the standard error (SE) of variety mean of the standard testing procedure (10 locations, 3 years and 4 replicates, shown in boldface) and selected combinations of locations, years and replicates for the traditional intermediate-maturing rice variety trials. Figures in italics indicate the cheapest allocation of resources.

Number of			SE (t ha^{-1})	Number of	
Location	Year	Replicate		Trials	Plots
10	**3**	**4**	**0.11**	**30**	**120**
9	3	4	0.11	27	108
8	3	4	0.11	24	96
7	3	4	0.12	21	84
10	4	4	0.10	40	160
9	4	4	0.10	36	144
8	4	4	0.10	32	128
7	4	4	0.10	28	112
10	4	3	0.10	40	120
9	4	3	0.10	36	108
8	4	3	0.11	32	96
7	4	3	0.11	28	84
6	4	3	0.11	24	72
10	2	4	0.13	20	80
9	*2*	*4*	*0.13*	*18*	*72*

The absence of variety × environment interaction in the traditional late-maturing group simplifies the allocation of resources for testing. In the combined analysis of variance across 5 locations and 3–4 years, considerable variability was found among the five locations in the two data sets, thus suggesting that the minimum number of testing sites would be five. Theoretically, decisions on test entries can be based on the results of 1 year of AYT. However, at least 2 years of testing is recommended to ensure that decisions are not based on unusual environmental conditions prevailing in a particular year.

Yield is not the only agronomic trait that is used to assess the merits of a test variety. Plant height and time to flowering are also important. However, the expression of these two traits is less influenced by environment than is yield. Thus, basing resource allocation on yield only is a reasonable proposition.

The resource allocations suggested above for the different rice variety groups will substantially reduce the costs of conducting and monitoring variety trials.

They also mean fewer data to handle and shorter times for analysing trial results. Analyses, similar to the one we have just done, should also be conducted from time to time, using historical data from AYT.

References

Atlin, G.N. and McRae, K.B. 1994. Resource allocation in Maritime cereal cultivar trials. Canadian Journal of Plant Science, 74, 501–505.

Cooper, M., Rajatasereekul, S., Immark, S., Fukai, S. and Basnayake, J. 1999a. Rainfed lowland rice breeding strategies for Northeast Thailand, I. Genotypic variation and genotype × environment interactions for grain yield. Field Crops Research, 64, 131–151.

Cooper, M., Rajatasereekul, S., Somrith, B., Sirivut, S., Immark, S., Boonwite, C., Suwanwongse, A., Ruangsook, S., Hanviriyapant, P., Romyen, P., Porn-Uraisanint, P., Skulkhu, E., Fukai, S., Basnayake, J. and Podlich, D.W. 1999b. Rainfed lowland rice breeding strategies for Northeast Thailand, II. Comparison of intrastation and interstation selection. Field Crops Research, 64, 153–176.

Gupton, C.L., Legg, D.D., Link, L.A. and Ross, H.F. 1974. Genotype-environment interaction in Burley tobacco variety tests. Crop Science, 14, 811–814.

Inthapanya, P., Sipaseuth, Sihavong, P., Sihathep, V., Chanphengsay, M. Fukai, S. and Basnayake, J. 2000. Genotypic performance under fertilized and non-fertilized conditions in rainfed lowland rice. Field Crops Research, 65, 1–14.

Jones, G.L., Matzinger, D.F. and Collins, W.K. 1960. A comparison of flue-cured tobacco varieties repeated over locations and years with implications on optimum plot allocation. Agronomy Journal, 52, 195–199.

Pandey, S. and Rajatasereekul, S. 1999. Economics of plant breeding: the value of shorter breeding cycles for rice in Northeast Thailand. Field Crops Research, 64, 187–197.

Povilaitis, B. 1970. Variance components in tobacco cultivar trials. Canadian Journal of Genetic and Cytology, 12, 331–339.

Sprague, G.F. and Federer, W.T. 1951. A comparison of variance components in corn field trials, II. Error, year × variety, location × variety, and variety components. Agronomy Journal, 43, 535–541.

Influence of Seedling Time and Seedling Age at Time of Transplanting on the Productivity of Rainfed Lowland Rice with Different Levels of Photoperiod Sensitivity

Ouk Makara[a*], S. Fukai[b], M. Cooper[b] and H.J. Nesbitt[c]

Abstract

Rainfed lowland rice accounts for over 85% of the total rice-growing area in Cambodia. The cropping season is characterized by irregular rainfall and uncertain water availability. Although most rice genotypes are photoperiod sensitive, they vary in degree, which may influence their adaptation to growing conditions. Under different conditions of water availability, the performance of 10 genotypes possessing different levels of photoperiod sensitivity was determined in two experiments. The first experiment had two seeding times—early and late—and the second, two seedling ages—30 and 60 days for transplanting. Both experiments contained flooded and drained fields. The drained fields were to simulate late-season drought. Late seeding or transplanting with 60-day-old seedlings delayed flowering of all genotypes, but the delay was less in the sensitive than in the insensitive genotypes, having different effects on grain yield according to the genotypes' maturity groups. In the early flowering group, sensitive genotypes had lower yield than insensitive genotypes when seeded late under flooded conditions. This is because, with only a short delay, they flowered too early and yield potential was not realized. A similar response was obtained when the genotypes were transplanted as 60-day-old seedlings under both water regimes. For the late-flowering group, sensitive genotypes were not disadvantaged because they had a long period of growth before flowering. However, under drained conditions, grain yield declined more for late, insensitive genotypes, which, when seeded late, flowered too late.

IN Cambodia, 85.7% of the total rice-growing area is under rainfed lowland rice (Javier 1997), which often grows in low-fertility soils and where rainfall is erratic. Inadequate rains in May and June often delay seeding in nurseries, while inadequate rains in July and August delay transplanting. Short periods of drought (2–8 weeks) may occur at any time during the wet season.

Rice is a short-day crop, but genotypes differ greatly in sensitivity to photoperiod (IRRI 1976). Most rice genotypes growing in the Cambodian rainfed lowlands are photoperiod sensitive, with flowering coinciding with the end of the rainy season. Recently, some insensitive to mildly sensitive genotypes were released by the Cambodia–IRRI–Australia Project (CIAP) for the rainfed lowlands. Makara et al. (1995) stated that, in Cambodia, photoperiod sensitivity permits flexibility in seeding (April to July) and transplanting (20 to 100-day-old seedlings). Lao rice breeders consider photoperiod sensitivity as an essential trait for most rainfed areas (Inthapanya et al. 1995). Similarly, Fukai (1999) confirmed that popular rainfed lowland rice genotypes are mostly sensitive to photoperiod. He therefore suggests that this trait is particularly important for the rainfed lowlands.

The effects of seeding time and seedling age on grain yield and flowering in rice has been intensively studied. Late transplanting results in reduced grain yield (Halappa et al. 1974; Suryanarayana et al. 1975; Fukai and Inthapan 1988; Om et al. 1989). Reddy and

KEYWORDS: Drained conditions, Flowering time, Seeding time, Seedling age at transplanting

---

[a] Cambodian Agricultural Research and Development Institute (CARDI), Phnom Penh, Cambodia
[b] School of Land and Food Sciences, The University of Queensland, Brisbane, Qld., Australia
[c] Cambodia–IRRI–Australia Project (CIAP), Phnom Penh, Cambodia
*Corresponding author: E-mail: pbreed@bigpond.com.kh

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Reddy (1992) found that young seedlings produced higher grain yield than did old seedlings. However, Reddy et al. (1992) found that crops transplanted as 45-day-old seedlings performed better than as 30-day-old seedlings when seeded late. Joseph (1991) concluded that the use of old seedlings, as a result of delayed transplanting, extended the vegetative period. This effect was especially more noticeable for insensitive to mildly sensitive genotypes than for strongly sensitive genotypes (Immark et al. 1997).

Flowering time in rice is affected not only by photoperiod sensitivity, but also by water stress and nutrient deficiencies (Lilley and Fukai 1994; Wonprasaid et al. 1996). Although sensitive genotypes are widely adapted in the rainfed lowlands, little work has been done to study the effect of photoperiod sensitivity on the productivity of rainfed lowland rice under various water availability conditions. This work aimed to determine the effects of late seeding and transplanting old seedlings on different photoperiod-sensitive rice genotypes grown under different water conditions in Cambodia. The results are expected to assist agronomists in recommending the use of photoperiod-sensitive and insensitive rice for different conditions.

Materials and Methods

Ten genotypes (Tables 1A and 1B) used for this study were selected from 25 genotypes for variation in photoperiod sensitivity. To determine the photoperiod sensitivity index (PSI) of these genotypes, a preliminary screening was conducted with the 25 genotypes at the Cambodian Agricultural Research and Development Institute (CARDI) in the municipality of Phnom Penh. A set of these genotypes was seeded twice, each with two replicates. The first seeding was on 18 June 2000 and the second on 19 August 2000. Dates of 50% flowering were recorded for both seeding times. The PSI was determined, using the following formula:

$$\mathrm{PSI} = 1 - (F2 - F1) / (SD2 - SD1) \qquad [1]$$

where,

F1 = date of 50% flowering of the first seeding
F2 = date of 50% flowering of the second seeding
SD1 = date of the first seeding, and
SD2 = date of the second seeding.

Genotypes with a PSI = 0 are completely insensitive, whereas those with a PSI = 1 are strongly sensitive.

Table 1A. Days to flowering (DTF) and grain yield (GY) of tested genotypes seeded on June 15 (ST1) and August 10 (ST2) under flooded and drained conditions at Chrey Veal, Cambodia.

No.	Genotype	PSI[b]	Flooded conditions[a]						Drained conditions[a]					
			DTF			GY (t ha^{-1})			DTF			GY (t ha^{-1})		
			ST1	ST2	t-test	ST1	ST2	t-test	ST1	ST2	t-test	ST1	ST2	t-test
1	IR57514-PMI-5-B-1-2	0.24	117	101	**	1.07	0.54	ns	114	103	*	0.81	0.55	*
2	Santepheap 3	0.26	122	103	*	1.18	0.73	ns	122	107	**	0.98	0.47	*
3	IR66368-CPA-6-P1-3R-0	0.27	111	90	**	1.12	0.55	ns	103	92	**	0.66	0.61	ns
4	DJM1-B-B-SB-SB-3-1-1	0.30	132	111	*	1.03	0.90	ns	129	120	*	1.07	0.26	*
5	IR66368-CPA-91-P1-3R-0	0.47	120	86	**	1.34	0.57	*	119	89	**	1.07	0.50	**
6	IR66327-KKN-8-P1-3R-0	0.48	136	90	**	1.00	0.80	ns	132	96	**	1.16	0.63	*
7	IR66327-KKN-47-P1-3R-0	0.53	119	85	**	1.30	0.68	*	116	85	**	0.85	0.55	*
8	IR66327-KKN-54-P1-3R-0	0.53	129	92	**	1.13	0.68	ns	130	95	**	1.06	0.55	**
9	IR66327-KKN-75-P2-3R-0	0.60	136	96	**	0.96	0.69	ns	134	96	**	0.92	0.46	*
10	Damnoeub Khlanh (acc. 3172)	0.65	144	97	**	1.00	0.74	ns	142	100	**	0.64	0.45	*
	Mean		127	95		1.11	0.69		124	98		0.92	0.50	
	LSD5% (Genotype)		5	2		—	—		3	2		0.17	0.14	
	Seeding time (ST)		**			ns			**			**		
	Genotype (G)		**			**			**			**		
	ST × G		**			ns			**			**		
	Combined over water conditions					DTF			GY					
	Water (W)					*			*					
	W × ST					*			ns					
	W × G					*			ns					
	W × ST × G					*			ns					

[a] t-test = test for the significant difference between all ST of genotypes.
[b] PSI = photoperiod sensitivity index.
* = significant at $P < 0.05$; ** = significant at $P < 0.01$; ns = not significant.

Table 1B. Days to flowering (DTF) and grain yield (GY) of tested genotypes transplanted with 32-day-old (SA1) and 60-day-old (SA2) seedlings under flooded and drained conditions at CARDI, Cambodia.

No.	Genotype	PSI[b]	Flooded conditions[a]						Drained conditions[a]					
			DTF			GY (t ha^{-1})			DTF			GY (t ha^{-1})		
			SA1	SA2	t-test	SA1	SA2	t-test	SA1	SA2	t-test	SA1	SA2	t-test
1	IR57514-PMI-5-B-1-2	0.24	106	135	**	2.68	2.32	ns	107	131	**	2.36	1.86	ns
2	Santepheap 3	0.26	118	138	**	2.22	2.53	ns	118	138	**	2.63	1.60	ns
3	IR66368-CPA-6-P1-3R-0	0.27	94	118	*	2.35	2.19	ns	97	116	*	2.17	1.42	ns
4	DJM1-B-B-SB-SB-3-1-1	0.30	119	143	**	2.56	2.46	ns	123	145	**	2.33	1.57	ns
5	IR66368-CPA-91-P1-3R-0	0.47	116	126	**	2.24	2.01	ns	116	126	**	2.08	1.40	ns
6	IR66327-KKN-8-P1-3R-0	0.48	124	135	*	3.40	2.90	ns	125	135	*	2.17	1.66	ns
7	IR66327-KKN-47-P1-3R-0	0.53	108	123	**	2.59	1.85	*	108	121	ns	2.42	0.92	**
8	IR66327-KKN-54-P1-3R-0	0.53	126	134	**	2.71	2.25	ns	126	134	*	2.44	1.99	ns
9	IR66327-KKN-75-P2-3R-0	0.60	130	137	*	2.10	2.34	ns	126	138	ns	2.13	1.62	ns
10	Damnoeub Khlanh (acc. 3172)	0.65	139	142	*	1.60	1.69	ns	139	144	ns	1.75	1.22	ns
	Mean		118	133		2.44	2.26		118	133		2.25	1.53	
	LSD5% (Genotype)		2	4		—	0.47		5	5		—	—	
	SA		**			ns			*			ns		
	Genotype (G)		**			**			**			*		
	SA × G		**			ns			**			ns		
	Combined over water conditions					DTF			GY					
	Water (W)					ns			*					
	W × SA					ns			ns					
	W × G					ns			*					
	W × SA × G					ns			ns					

[a] t-test = test for the significant difference between all SA of the genotypes.

[b] PSI = photoperiod sensitivity index.

* = significant at $P < 0.05$; ** = significant at $P < 0.01$; ns = not significant.

The 10 rice genotypes finally chosen had PSI that ranged between 0.24 and 0.65 (Tables 1A and 1B). Two experiments were conducted in the 1999 wet season to study the effect of delayed seeding and seedling age on the productivity of these 10 genotypes. Experiment I, which assessed the effects of two seeding times (at 57 days apart), was conducted at the Chrey Veal Research Station in Prey Veng Province. Experiment II, which assessed the effects of seedling age (at 32 and 60 days) at transplanting, was conducted at CARDI. At Chrey Veal, the first seeding date was on June 15 and the second on August 10. Transplanting of 30-day-old seedlings were on July 15 and September 9, respectively. The genotypes in Experiment II were seeded on June 18 and transplanted on July 20 and August 17.

Flooded and drained water conditions were imposed on both experiments. For flooded conditions, water in the fields was maintained at levels ranging from 5 to 20 cm for the whole cropping period. For drained conditions, a 10-cm deep canal was dug throughout the fields to channel water into a hole, 50 cm deep, dug in the corner of each field. The water accumulated in the hole was pumped out from the fields to keep the fields free of standing water during the whole drainage period. At Chrey Veal, drainage began on September 23 for the early seeding and on October 16 for the late seeding treatments. At CARDI, the experiment was drained on September 20. For both experiments, fertilizer was used at the rate of 60–30–30 of $N–P_2O_5–K_2O$ with two splits of nitrogen (half as basal and half at 30 days after transplanting). No pesticides for controlling insect pests, weeds or pathogens were applied to either experiment.

The genotypes were evaluated in a split-plot design (main plots were seeding times or seedling ages, and subplots were genotypes) with three replicates in each water treatment. Plots were 1.2 × 3 m in size, with 20 cm between rows and hills. Two to three seedlings were transplanted per hill. An analysis of variance was conducted, using a residual maximum likelihood (REML) statistical package. A randomized complete block design, with 10 genotypes and 3 replicates, was used to evaluate the effects of genotype at each seeding time (ST) or seedling age (SA). To compare the genotypes (G) between seeding times or seedling ages, a Student's t-test was used. A split-plot analysis was used for the interaction effects of ST × G and SA × G under each type of water conditions, then a combined analysis of water conditions (W) was done for detecting the interaction effects of W × ST, W × SA, W × ST × G and W × SA × G.

Water-table levels were recorded weekly from polyvinyl chloride (PVC) tubes placed in both experiments for both water conditions. The 50% flowering date was recorded. Grain yield was estimated from 1.04 m^2 in the two central rows of each plot. Subsamplings of grain were dried in an electric oven at 70°C for 2 days and weighed after 2 h of cooling.

Results

Variation in the PSI

As mentioned above, the PSI for the 10 genotypes varied between 0.24 and 0.65 (Tables 1A and 1B) forming two groups according to Immark et al. (1997). Group 1, which had coefficients of less than 0.3, was considered as insensitive. This group consisted of genotypes (G) G1, G2, G3 and G4 (see Table 1). Group 2, which had coefficients ranging between 0.3 and 0.7, were considered as mildly sensitive (G5, G6, G7, G8, G9 and G10).

Seeding time

Figure 1 shows the weekly rainfall from mid-July and the water levels under drained conditions from August 23 to 27 December at Chrey Veal. The fields were irrigated during a dry period from early to mid-August. After that, rain was generally favourable until mid-November. Under flooded conditions, the water level was always above the soil surface. Under drained conditions, for both seeding times, water levels dropped quickly after drainage to below the soil surface, except for a period from late October to early November, when the water level rose close to the soil surface after continuous heavy rain. Water levels for both seeding times were similar from October 25 to the end of the experiment. Severe drought, however, did not develop during the drained period.

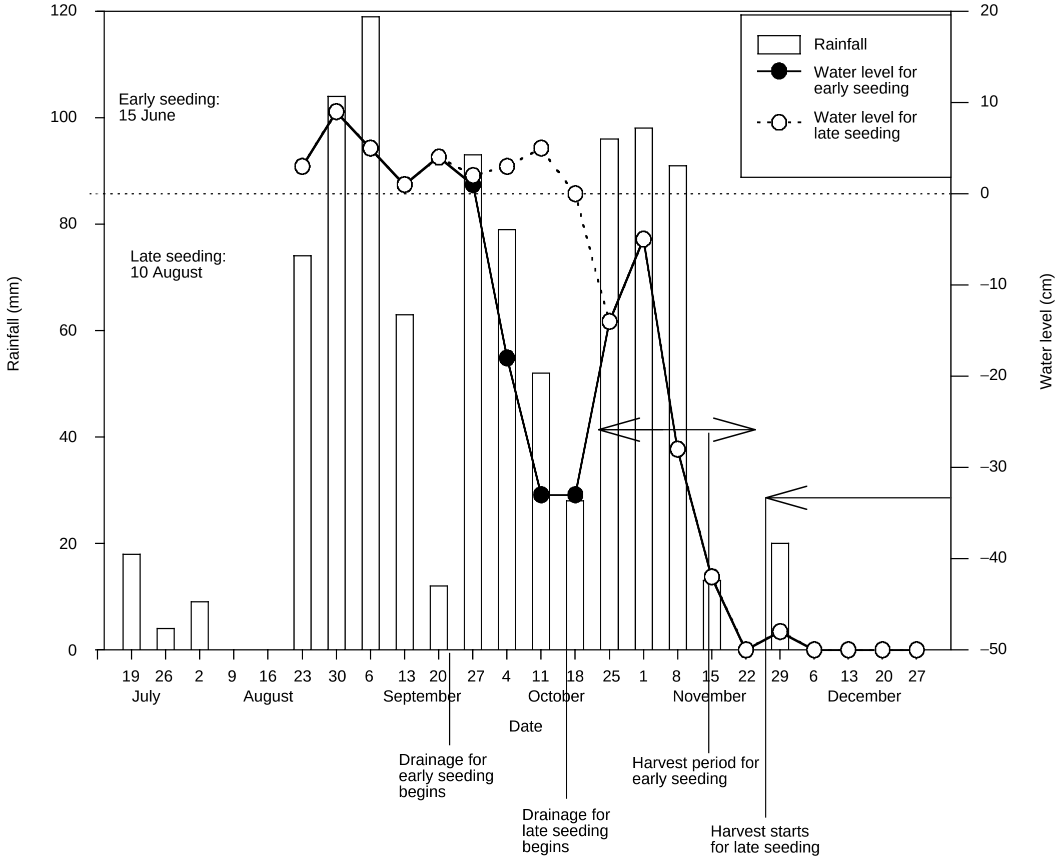


Figure 1. Weekly rainfall and water levels under drained conditions, Chrey Veal, Cambodia, 1999 wet season.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Under flooded conditions, late seeding, on average, significantly reduced days to flowering (DTF) ($P < 0.01$) from 127 to 95 days, but this reduction did not significantly affect grain yield (GY) (Table 1A). Genotype performance was significantly different across seeding times (ST) for DTF and GY ($P < 0.01$). The ST × G interaction had an effect on DTF, but not on GY.

Under drained conditions, on average, late seeding reduced DTF from 124 to 98 days and GY from 0.92 to 0.5 t ha^{-1} ($P < 0.01$). Both genotype and the ST × G interaction had significant effects on both DTF and GY ($P < 0.01$). Drained conditions reduced GY ($P < 0.05$). The interactions W (water) × ST, W × G and W × ST × G also significantly affected DTF but not GY (Table 1A).

Figure 2 shows the relationship between delay in flowering by late seeding (57 days later) and the PSI of all tested genotypes under flooded and drained conditions. Under both types of water conditions, delayed flowering was negatively associated with the PSI ($P < 0.01$). This delay was greater under drained conditions than under flooded conditions. For example, in the insensitive G3, flowering was delayed by 36 and 46 days under flooded and drained conditions, respectively, when seeded 57 days late. In contrast, in the sensitive G10, flowering was delayed by only 10 and 15 days, respectively.

For both water conditions, with early seeding, three pairs of genotypes were matched according to DTF, GY and PSI. Each pair consisted of two genotypes that flowered on similar dates, were not significantly different in grain yield, but contrasted in their photoperiod sensitivity. These were G1 vs. G7, G2 vs. G5 and G4 vs. G9. The first pair flowered earlier, the second pair a few days later and the last pair flowered late.

Under flooded conditions, late seeding shortened the period from seeding to flowering of the sensitive genotypes more than for the insensitive genotypes (Table 1A). Among the sensitive genotypes, G5 and G7 flowered earliest when seeded late, resulting in significantly low grain yields, compared with the early seeding treatment. This is because of the period from seeding to flowering of these genotypes was short (86 and 85 days, respectively).

Under drained conditions, late seeding resulted in later flowering dates in all genotypes, being more marked for insensitive than for sensitive genotypes. Late seeding also reduced grain yield in all genotypes, except G3 (Figure 3). No association was found between flowering date and grain yield when

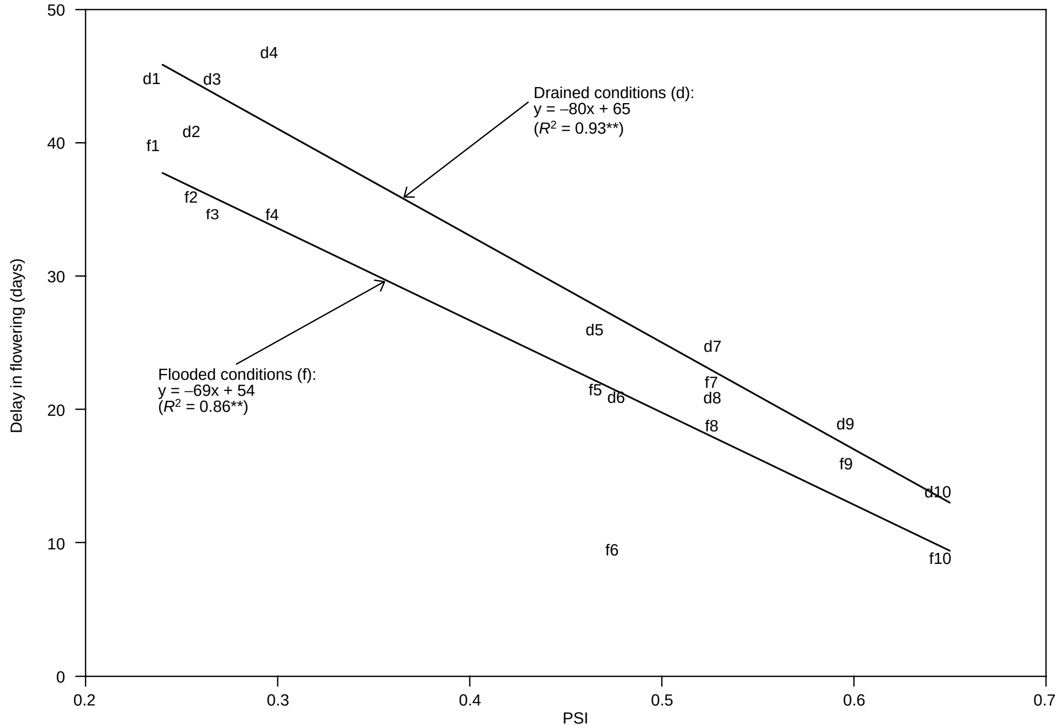


Figure 2. Relationship between the photoperiod sensitivity index (PSI) and delay in flowering as affected by late seeding (57 days later). f = flooded conditions; d = drained conditions; numbers refer to genotypes.

the genotypes were seeded early. However, this association was negative ($P < 0.05$) when seeding was 57 days later. Among the three pairs of genotypes mentioned above, delayed flowering date by late seeding did not affect grain yield of early maturing genotypes in the early seeding treatment, even if they possessed contrasting photoperiod sensitivities (G1 vs. G7; G2 vs. G5). However, grain yield of late-flowering genotypes was reduced when seeding was late. In this pair, insensitive G4 and sensitive G9 flowered at about the same date when seeded on June 15 (129 and 134 days) but, when they were seeded on August 10, insensitive G4 flowered after 120 days, whereas sensitive G9 flowered at 96 days. In this case, G4 was disadvantaged in grain yield, compared with G9, as G4 suffered longer periods of drained conditions and, hence, more water stress than did G9.

Seedling age

At CARDI, rains were favourable from late August to the third week of October (Figure 4). After that date, water was supplied to maintain the water level at 10–15 cm until the last harvest in the flooded fields. Water levels in drained fields dropped below the soil surface immediately after drainage (September 20) and reached a level of -40 cm by October 18.

Genotypes differed significantly in DTF under all growing conditions (Table 1B). However, a significant difference in grain yield was observed only when the crop was transplanted with 60-day-old seedlings under flooded conditions. Seedling age significantly affected DTF but not grain yield under both water conditions. A similar trend was observed for the interaction ($P < 0.01$) of seedling age-by-genotype (SA × G), indicating the different responses of genotypes to SA. Water drainage did not affect DTF. In contrast, a significant difference ($P < 0.05$) was observed for grain yield (averaged over SA). Grain yield of genotypes responded differently to water, because the water-by-genotype (W × G) interaction was significant ($P < 0.05$). The interactions W × SA and W × SA × G had no effects. Seedling age also affected ($P < 0.01$) total dry matter production under both water conditions (results not shown).

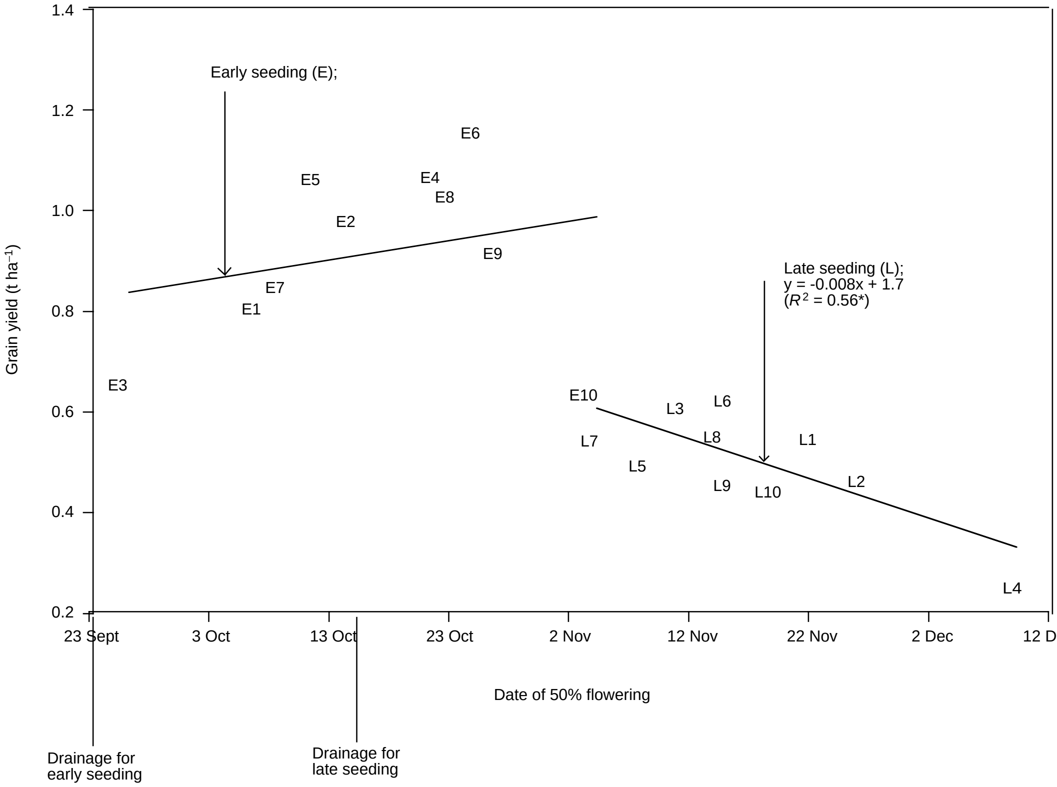


Figure 3. Relationship between grain yield and date at 50% flowering of genotypes tested at early seeding (15 June) and late seeding (10 August) under drained conditions. E = early seeding; L = late seeding; numbers refer to genotypes.

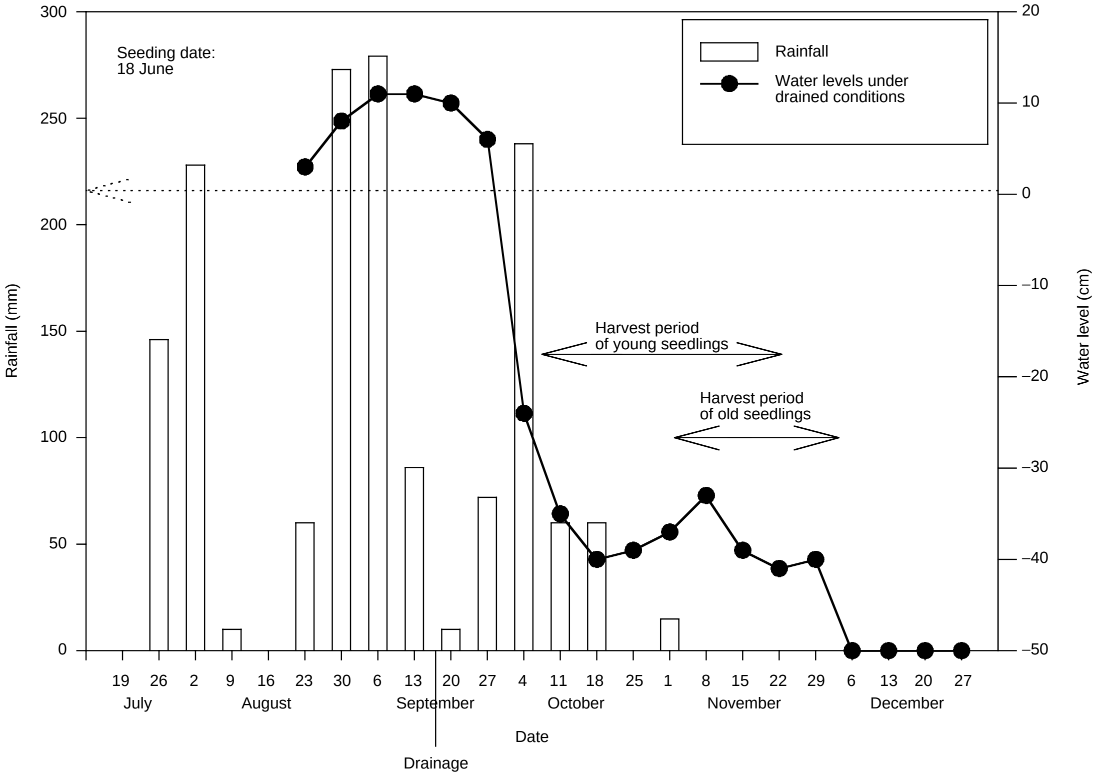


Figure 4. Weekly rainfall and water levels under drained conditions, CARDI, Cambodia, 1999 wet season.

Under both types of water conditions, transplanting old seedlings resulted in delayed flowering in all genotypes, and this delay was negatively associated with the PSI (Figure 5). When old seedlings were transplanted under flooded and drained conditions, flowering in sensitive G10 was delayed by 3 and 5 days, respectively, and, in insensitive G1, 29 and 24 days, respectively.

Under flooded conditions and within pairs—G1 and G7, G2 and G5 and G4 and G9—genotypes flowered on similar dates when transplanted with 32-day-old seedlings (Figure 6). However, when 60-day-old seedlings were transplanted, the insensitive G1, G2 and G4 flowered later than the sensitive G7, G5 and G9, showing that photoperiod sensitivity plays an important role in grain yield when old seedlings are transplanted. Under both water conditions, grain yield of only the early flowering, sensitive G7 was reduced by transplanting with 60-day-old seedlings. This negative effect may be related to the short period between transplanting and flowering. Under flooded conditions and with 32-day-old seedlings, G7 experienced a similar period (108 days) between transplanting and flowering to insensitive G1 (106 days) and these two genotypes yielded similarly.

In contrast, by transplanting with 60-day-old seedlings, G1 and G7 took 75 and 63 days, respectively, from transplanting to flowering. The short period for sensitive G7 resulted in low grain yield. A similar trend was observed when G1 and G7 were grown under drained conditions. Conversely, under both water conditions, the other sensitive genotypes—G5, G6, G8, G9 and G10—experienced longer periods from transplanting to flowering than did G7 so that their grain yield was not so negatively affected.

Transplanting 60-day-old seedlings generally reduced total biomass and hence led to reduced grain yield (Figure 7). The relationship between reduced total biomass and relative grain yield was strong, with R^2 = 0.76** for drained conditions and R^2 = 0.63** for flooded conditions. Transplanting with 60-day-old seedlings under flooded conditions resulted in a smaller reduction in grain yield and total biomass than under drained conditions. Grain yield and total biomass of the early flowering, sensitive G7, which took only 63 days from transplanting to flowering, was more affected by the use of old seedlings under both flooded and drained conditions.

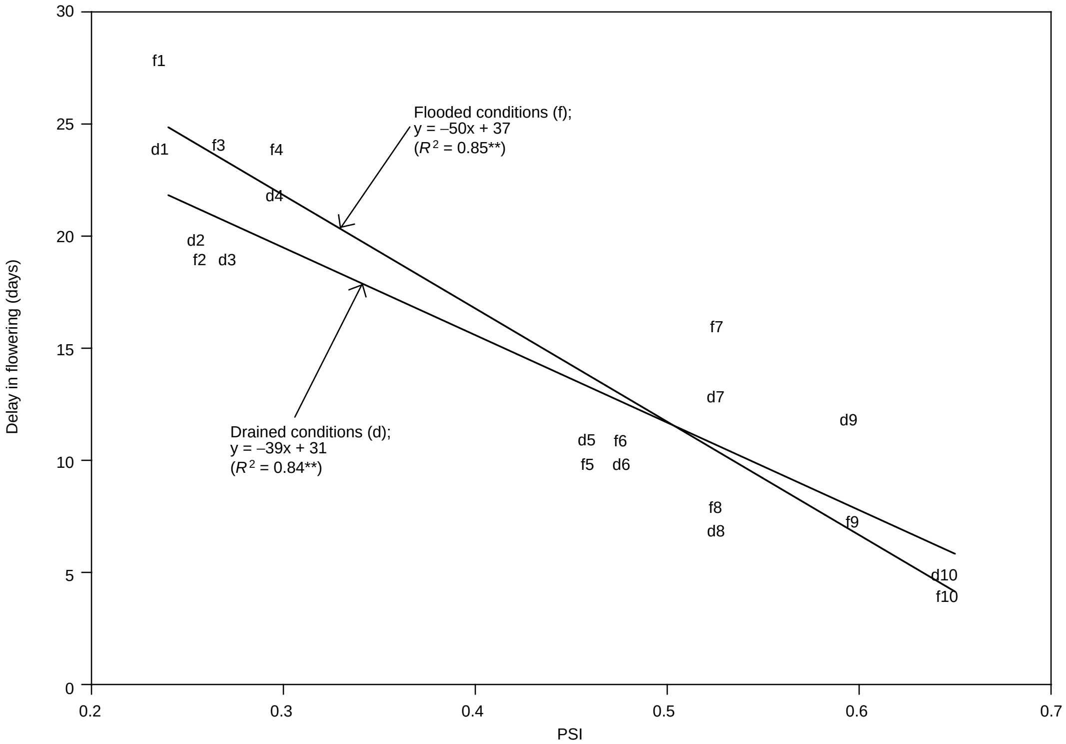


Figure 5. Relationship between delay in flowering and the photoperiod sensitivity index (PSI) as affected by transplanting 60-day-old seedlings. f = flooded conditions; d = drained conditions; numbers refer to genotypes.

Discussion

Effect on phenology

In the rainfed lowlands, delayed seeding and the use of old seedlings is commonly caused by lack of standing water at appropriate times. The results of both experiments in this study clearly show that late seeding or use of old seedlings resulted in significant delays in flowering dates. These delays were negatively associated with the PSI. Thus, delays were greater for insensitive than for sensitive genotypes. These results are similar to those of Immark et al. (1997), who conducted experiments involving 35 genotypes across 12 locations over three seasons in Thailand and Lao PDR. They also found that flowering date was strongly correlated with seeding time or seedling age in insensitive genotypes, but was less affected in sensitive genotypes. This genotypic difference can be explained by a change in day length. Photoperiod-sensitive genotypes begin flowering as the day length shortens. In contrast, flowering of photoperiod-insensitive genotypes is little affected by changes in day length. Our findings that the impact of seeding time and seedling age is strongly affected by the genotype's own photoperiod sensitivity corroborate with those of Fukai (1999).

Flooded conditions

A study conducted by Reddy et al. (1992) showed that young (i.e. 30 days old) seedlings produced higher grain yield than older seedlings (45 and 60 days old) when transplanted in early August. Reddy et al. (1992) obtained contrasting results for later transplanting in September. Results from a simulation model (Fukai et al. 1995) showed that by delaying seeding, the time from seeding to flowering of sensitive genotypes is shortened, due to their photoperiod response, and this reduction in growing period resulted in lower yield potential. Our results indicate that, under flooded conditions, late seeding or old seedling age reduces grain yield especially in early maturing, sensitive genotypes. This phenomenon may be explained by the shorter period from transplanting to flowering by late-seeded genotypes (G5 with 56 days and G7 with 55 days) and by transplanting old seedlings (G7 with 63 days). The short period from transplanting to flowering in sensitive G7 resulted in a low total biomass, causing low grain yield. This result confirms the work of Jearakongman et al. (1995).

For favourable conditions, three different flowering-time pairs of genotypes were obtained. Within the pairs, the genotypes flowered at similar

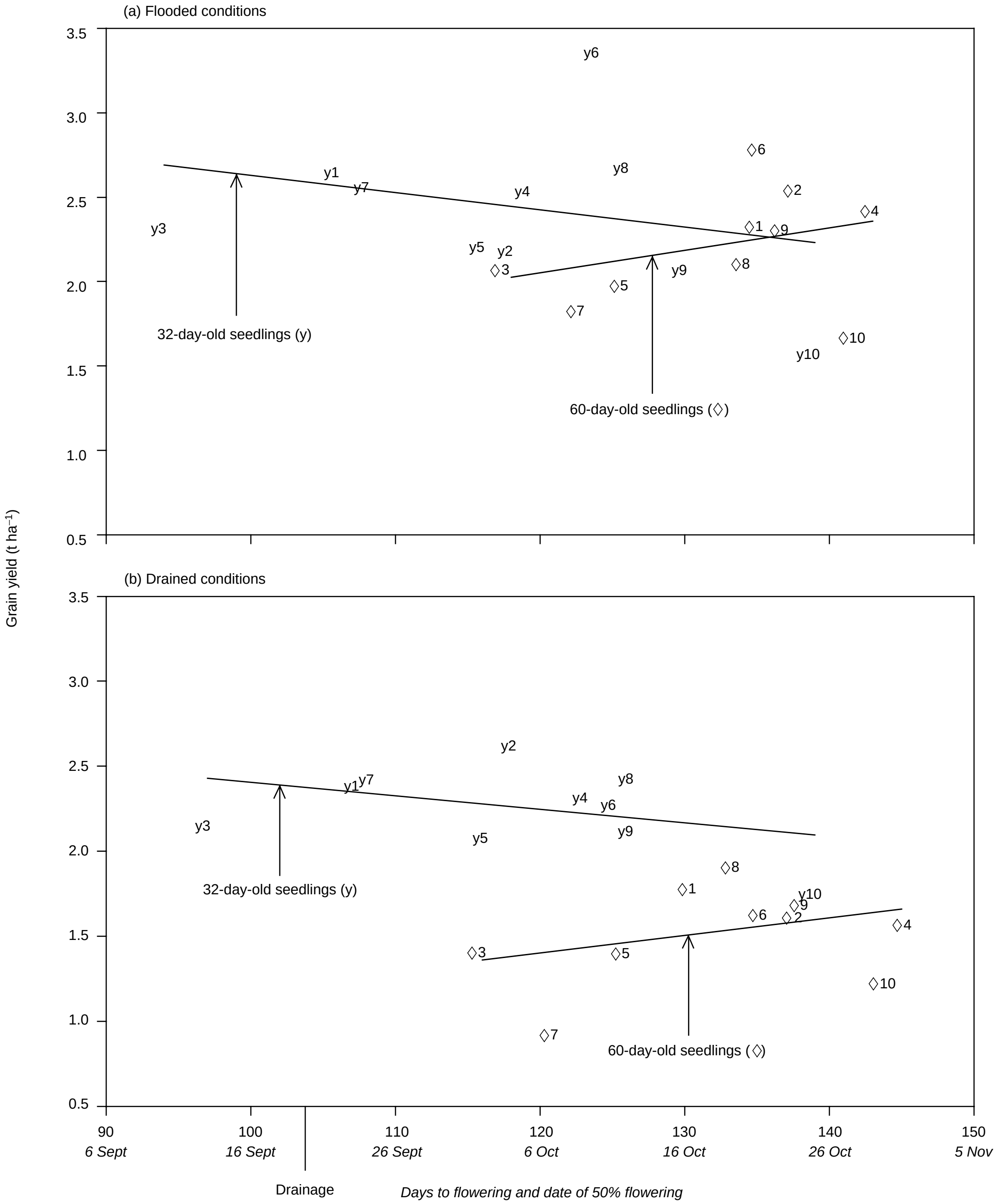


Figure 6. Relationship between grain yield and days to 50% flowering of genotypes tested with 32-day-old seedlings (y) and 60-day-old seedlings (◊) under flooded (a) and drained (b) conditions. Numbers refer to genotypes.

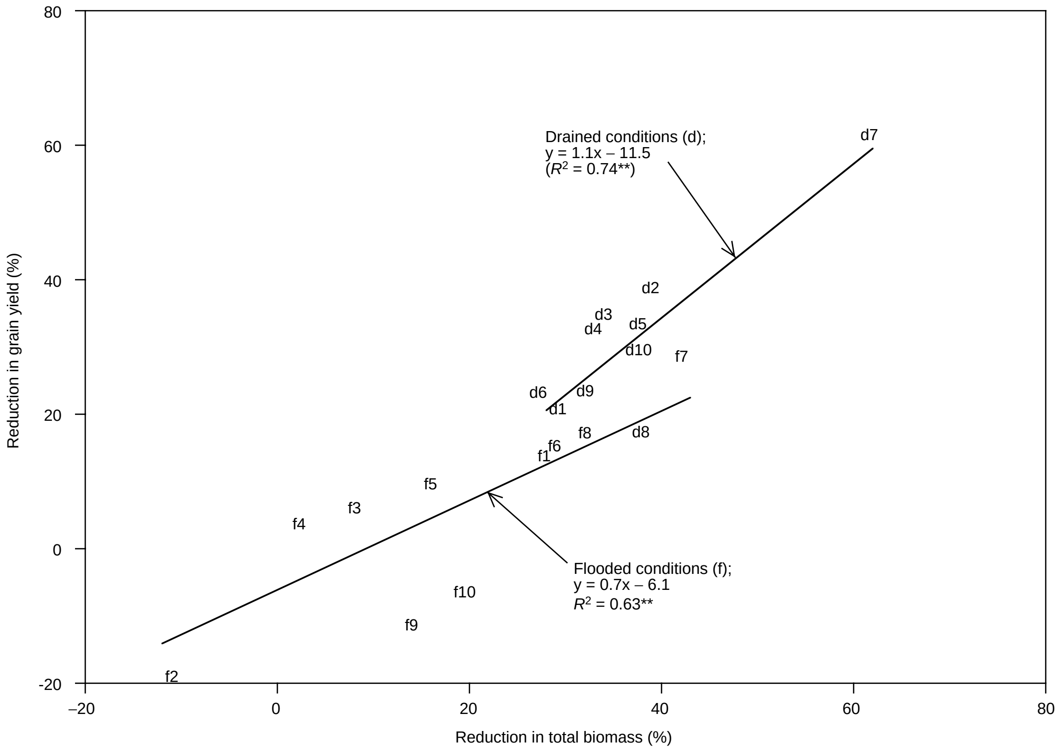


Figure 7. Reduction in grain yield in relation to reduction in total biomass as affected by transplanting with 60-day-old seedlings. f = flooded conditions; d = drained conditions; numbers refer to genotypes.

dates and yielded comparably, but they contrasted in photoperiod sensitivity, responding differently for grain yield when seeded late or transplanted with old seedlings. This indicates an important role of photoperiod sensitivity in successful rice cropping under rainfed lowland conditions.

Makara et al. (1995) pointed out the advantages of using photoperiod-sensitive genotypes under rainfed lowland conditions, suggesting that they permit flexibility in seeding and transplanting times while flowering at the same time. However, the results obtained from this work clearly indicate the advantages and disadvantages of cultivating both photoperiod-sensitive and insensitive groups. Under favourable conditions, the sensitive genotypes did not differ from the insensitive. In contrast, early sensitive genotypes were disadvantaged when they were seeded 57 days late or transplanted with 60-day-old seedlings. In Cambodia, rainfed lowland rice is commonly subjected to drought only in the early season, with favourable water conditions following. Under these conditions, early maturing sensitive genotypes may be disadvantaged.

Drained conditions

Under drained conditions, late seeding reduced grain yield, particularly for the late, insensitive G4. When seeded early, all sensitive genotypes flowered before November 4, whereas insensitive genotypes flowered before October 23. However, when they were seeded late, flowering of sensitive genotypes was less delayed than for insensitive genotypes. The longer the flowering was delayed, the lower the grain yield as the crop suffered longer dry conditions. Thus, the ability of genotypes to develop phenology to match water conditions is important if they are to achieve their yield potential (Jearakongman et al. 1995). The reductions in grain yield of the late seeding treatments did not differ for sensitive and insensitive genotypes in the two early maturing pairs. Yield reduction was greater for the late-maturing insensitive G4 than that for the sensitive G9 in the last pair. However, severe water stress did not develop during the drained period. If severe water stress had developed, the results may have been different, with the later flowering genotypes probably being even further disadvantaged.

Generally, transplanting older seedlings did not significantly reduce grain yield of the late-flowering genotypes. However, sensitivity and flowering time of early flowering genotypes played an important role in determining grain yield. Sensitive G7 flowered on September 24 when transplanted with 32-day-old seedlings (i.e. after 76 days), but when transplanted with 60-day-old seedlings under drained conditions, this genotype flowered on October 6 (i.e. after 61 days). Such a short period may result in reduced total biomass and hence smaller grain yield. Reductions in grain yield and total biomass may become more severe for the early sensitive genotypes, as mentioned for the flooded conditions.

Conclusions

In this study, time to flowering and delay in flowering played very important roles in determining yield of rainfed lowland rice when genotypes were seeded late or transplanted with old seedlings. Late seeding and the use of old seedlings delayed flowering. But this delay was longer for the insensitive than for the sensitive genotypes. A short delay in flowering resulted in low grain yield of early sensitive genotypes when seeded late under flooded conditions. A similar trend was obtained when these genotypes were transplanted with 60-day-old seedlings under flooded and drained (not severe drought) conditions. However, a long delay in flowering caused low grain yield in late, insensitive genotypes when seeded late under drained conditions.

Acknowledgments

Financial support by the Australian Agency for International Development (AusAID) is gratefully acknowledged. The contributions of Pin Channa, It Yath and Say Puthea, who helped conduct the experiments, are appreciated. The authors would also like to acknowledge the Cambodia–IRRI–Australia Project and the Cambodian Agricultural Research and Development Institute (CARDI) for providing the facilities needed for the experiments.

References

Fukai, S. 1999. Phenology in rainfed lowland rice. Field Crops Research, 64, 51–60.

Fukai, S. and Inthapan, P. 1998. Growth and yield of rice cultivars under irrigation in south-eastern Queensland, 1. Effects of sowing time. Australian Journal of Experimental Agriculture, 28, 237–242.

Fukai, S., Rajatsasereekul, S., Boonjung, H. and Skulkhu, E. 1995. Simulation modeling to quantify the effect of drought for rainfed lowland rice in Northeast Thailand. In: International Rice Research Institute. Fragile Lives in Fragile Ecosystems, Proceedings of the International Rice Research Conference, 13–17 February 1995, Los Baños, Laguna, Philippines, International Rice Research Institute (IRRI), 657–674.

Halappa, G., Khan, T.A., Mahadevappa, M. and Venkataramu, M.N. 1974. Optimum time of planting high yielding varieties of paddy in kharif season of tank fed tracts of Karnataka. Mysore Journal of Agricultural Science, 8, 488–492.

Immark, S., Mitchell, J.H., Jongdee, B., Boonwite, C., Somrith, B., Polvatana, A. and Fukai, S. 1997. Determination of phenology development in rainfed lowland rice in Thailand and Lao PDR. In: Fukai, S., Cooper, M. and Salisbury, J. Breeding Strategies for Rainfed Lowland Rice in Drought-Prone Environments. Canberra, ACIAR Proceedings No. 77, 89–96.

Inthapanya, P., Schiller, J.M., Sarkarung, S., Kupkanchanukul, T. and Phannourath, V. 1995. Varietal improvement strategies for the rainfed lowland environment of the Lao PDR: 1995–2000. In: Fukai, S., Cooper, M. and Salisbury, J. Fragile Lives in Fragile Ecosystems, Proceedings of the International Rice Research Conference, 13–17 February 1995, Los Baños, Laguna, Philippines, International Rice Research Institute (IRRI).

IRRI (International Rice Research Institute). 1976. The Flowering Response of the Rice Plant to Photoperiod (3rd ed.). International Rice Research Institute, PO Box 933, Manila, Philippines, 75.

Javier, E.L. 1997. Rice ecosystem and varieties. In: Nesbitt, J.H., Rice Production in Cambodia 1997. Cambodia-IRRI-Australia Project, PO Box 01 Phnom Penh, Cambodia.

Jearakongman, S., Rajatasereekul, S., Naklang, K., Romyen, P., Fukai, S., Skulkhu, E., Jumpaket, B. and Nathabutr, K. 1995. Growth and grain yield of contrasting rice cultivars grown under different conditions of water availability. Field Crops Research, 44, 139–150.

Joseph, K. 1991. Performance of rice varieties as influenced by the use of seedlings and delayed transplanting. Indian Journal of Agronomy, 36, 83–84.

Lilley, J.M. and Fukai, S. 1994. Effect of timing and severity of water deficit on four diverse rice cultivars, III. Phenological development, crop growth and grain yield. Field Crops Research, 37, 225–234.

Makara, O., Chaudhary, R.C. and Javier, E.L. 1995. Conventional and innovative strategy of rice breeding for rainfed lowlands of Cambodia. In: International Rice Research Institute. Fragile Lives in Fragile Ecosystems, Proceedings of the International Rice Research Conference, 13–17 February 1995, Los Baños, Laguna, Philippines, International Rice Research Institute (IRRI), 855–864.

Om, H., Joon, R.K. and Singh, O.P. 1989. Effect of time of transplanting and age of seedling on growth and yield of dwarf rice. Indian Journal of Agronomy, 34, 325–327.

Reddy, B.B., Reddy, M.D. and Reddy, D.R. 1992. Effect of age of seedling on performance of late-planted short-duration rice (*Oryza sativa*). Indian Journal of Agricultural Sciences, 62, 796–799.

Reddy, K.S. and Reddy, B.B. 1992. Effect of transplanting time, plant density and seedling age on growth and yield of rice (*Oryza sativa*). Indian Journal of Agronomy, 37, 18–21.

Suryanarayana, G., Rajashekhara, B.G., Venkataramu, M.N. and Kulkarni, K.R. 1975. Effects of planting dates on the performance of certain japonica and indica cultivars. Mysore Journal of Agricultural Science, 9, 6–14.

Wonprasaid, S., Khunthasuvon, S., Sittisuang, P. and Fukai, S. 1996. Performance of contrasting rice cultivars selected for rainfed lowland conditions in relation to soil fertility and water availability. Field Crops Research, 47, 267–275.

Climatic Data for the Agroecological Characterization of Laos

K. Khounphonh[1], Phytoon[2], J. Basnayake[3], S. Fukai[3], B. Linquist[4*] and M. Chanphengsay[2]

Abstract

Defining agroecological zones helps alleviate constraints to crop productivity and management. Laos has never had its agroecological zones systematically characterized. We therefore began by evaluating climatic data, available from Lao meteorological and hydrological stations. Although each province has at least one meteorological station, most stations are located in central and southern Laos. Because data on hours of sunshine, wind speed and evaporation are few, estimates of potential evaporation are difficult. Despite these deficiencies, progress in agroecological characterization can be made by developing simple maps to characterize rainfall and temperature patterns. Rainfall is the most important climatic factor in the rice-growing areas of the rainfed lowlands, and high and low temperatures can be potential problems in the dry-season rice environment. Maps would therefore be valuable to researchers and policy makers. In this paper, we present a plan for the agroecological characterization of Laos, and suggest possible options in the future when more data become available.

IMPROVING any cropping system depends on successfully combining the accumulated knowledge on crops with an understanding about their environments (Mackill et al. 1996). Rice breeding, for example, has shifted its focus from breeding broadly adapted plants to developing plants for target environments (Buddenhagen 1978; Mackill et al. 1996).

Climate plays a crucial role in defining the cropping system of any given area. This is especially true for rainfed systems where quantifying rainfall patterns becomes crucial to the development of rice varieties and management strategies. Indeed, the International Rice Research Institute (IRRI) has developed a general terminology for rice-growing environments (IRRI 1984). The rainfed lowlands for rice were subgrouped into five environments, classified according to hydrology.

In Laos, 68% of rice is grown in the wet season, primarily under rainfed conditions. Yield losses in any particular year may result from drought or flooding. The risk of either of these occurring varies throughout the country and has not been quantified. To date, Laos has had no systematic analysis of its climate on a national scale.

The National Agriculture and Forestry Research Institute (NAFRI), in collaboration with the Lao Department of Meteorology and Hydrology (DMH), the Australian Centre for International Agricultural Research (ACIAR) and the Lao–IRRI Project, has embarked on an agroecological zoning project for Laos. Simple climatic maps will be the project's first output, with other maps following (e.g. for soils and vegetation), using geographic information systems (GIS) to develop the agroecological zones.

In this paper, we summarize our findings on the type and form of climatic data available in Laos, and suggest a general approach to agroecological classification.

---

[1] Department of Meteorology and Hydrology, Vientiane, Laos
[2] National Agriculture and Forestry Research Institute, Vientiane, Laos
[3] The University of Queensland, Brisbane, Australia
[4] Lao–IRRI Project, Vientiane, Laos
*Corresponding author: Bruce Linquist
E-mail: b.linquist@cgiar.org

KEYWORDS: Agroecological characterization, Laos, Rice

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Sources of Climatic Data

Two primary sources of climatic data exist: meteorological and hydrological stations. Management of these stations falls under the DMH. Other sources of data also exist, which have been established by various international projects, but are not readily available and tend to be logged over relatively short periods.

Laos has 45 hydrological stations (Figure 1), which collect only measurements of daily precipitation. The stations are primarily located in central and southern Laos, with only four located in the north, all in Luang Prabang Province. Laos also has 38 meteorological stations (Figure 1), with at least one, usually more, stations in every province except for the Xaysomboun Special Zone. These stations collect daily climatic data, including rainfall, minimum and maximum temperatures, minimum and maximum humidity, evaporation (pan or piche) and the mean monthly wind speed. Some stations also collect, on a daily basis, hours of sunshine, using a Campbell Stoke sunshine recorder.

The meteorological and hydrological stations are not evenly distributed throughout Laos (Figure 1). The Vientiane Municipality and Province have 8 meteorological and 6 hydrological stations and

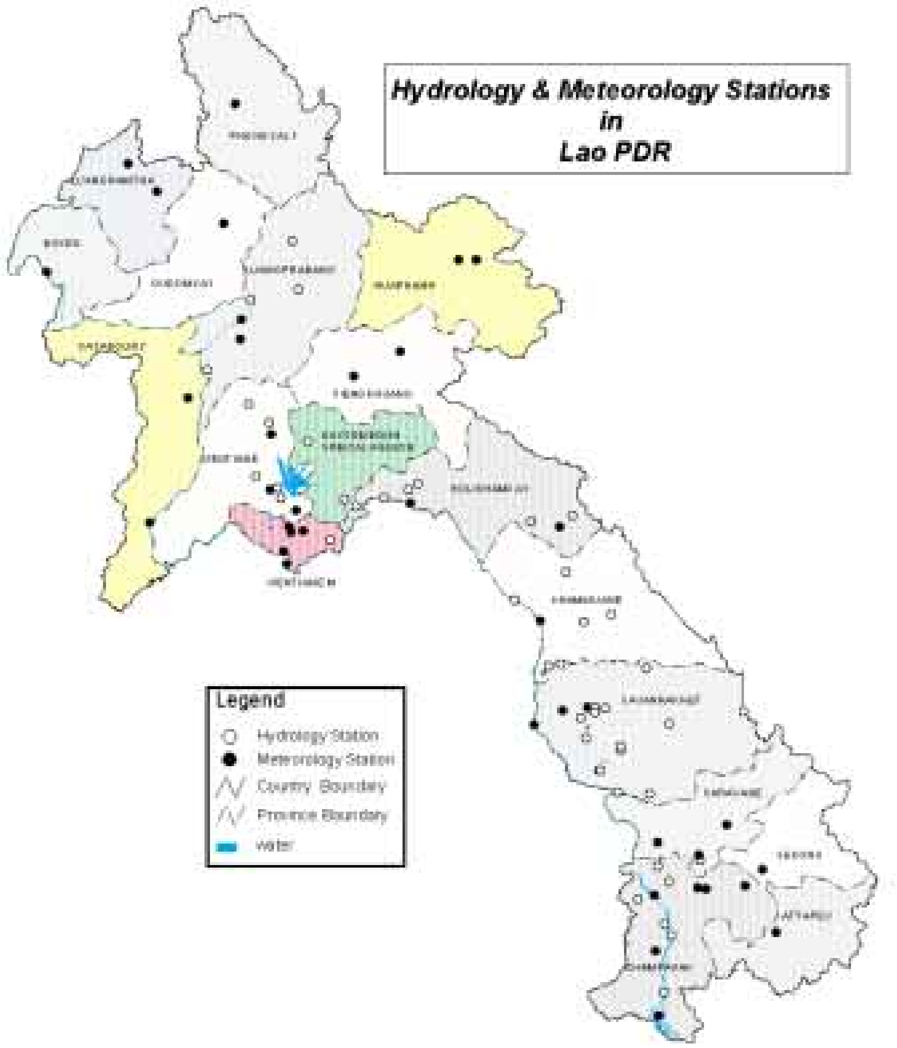


Figure 1. Location of meteorological and hydrological stations in Laos.

Savannakhet Province has 14 hydrological stations. In central and southern Laos, stations are concentrated between the chain of Annamite Mountains (bordering with Vietnam) and the Mekong River (bordering Thailand). In northern Laos, stations are concentrated in the central area between Vientiane and Luang Prabang. Apart from these stations, relatively few are located in the north. In provinces where there are two meteorological stations, these stations are relatively close to each other (i.e. Luang Prabang, Huaphanh, Xieng Khuang and Luang Namtha).

The DMH is expanding the number of stations with assistance from Vietnam. The most recent stations to be developed are Xieng Khuang (Kham), Huaphanh (Samneua), Savannakhet (Sepol) and Champassak (Khong), which were established in 1998 and 1999.

In areas where no stations exist or where current data are few, data can be obtained from strategically located stations near the Lao border in Thailand, China and Vietnam. However, topographical features need to be considered before using such data. For example, few Lao stations operate along the Vietnam–Laos border, which is formed by the ridge of the chain of Annamite Mountains, but rainfall data from Vietnamese meteorological stations would not be useful because the mountain ridge creates a rain shadow effect. However, most of Huaphanh Province lies on the Vietnamese side of the mountain chain and obtaining data from points near the Huaphanh Province—Vietnam border would be beneficial.

Data Availability

In early 2000 and with assistance from Vietnam, the DMH completed the cataloguing of historical data reports. Currently, the DMH, also in collaboration with Vietnam, is digitizing these reports. Although most of the 1985 data have been digitized, the process is still incomplete, making accessing data from each station impossible. Data are missing for some stations because of equipment failure or loss of written records. The number of years during which each station was collecting daily climatic data ranges widely—from 1 to 62 years (Table 1). For climatic characterization, we used only data that have been continuous and are common to other stations.

Rainfall data are available at more sites and years, compared with all other climatic variables (Tables 1 and 2). A total of 83 stations collect daily rainfall data. The number of years with continuous rainfall data ranges from 1 to 49. Most stations with long periods of continuous collection are located in the south, except for Luang Prabang.

Temperature, humidity, dew point and wind speed typically have fewer continuous years of available data, compared with rainfall (Table 1). Within each station, the number of years of continuous data available for each of these parameters is similar. Wind speed is measured at 10 m high. The mean monthly estimate of wind speed is calculated from the mean of four daily measurements.

Evaporation is measured, using either the pan or piche method. Pakse and Khongsedon are the only two sites where both methods are used. Pan evaporation is measured at 8 stations and piche evaporation at 15 stations. The number of continuous years available ranges from 1 to 14. However, at most stations, the number of years is smaller than 7. Pan evaporation measurements need to be used with care as the ground surface around the pans may be bare soil, weeds or grass. Furthermore, tall brush could grow up nearby, restricting normal wind movement.

The number of hours of sunshine is determined with a Campbell Stoke sunshine recorder. Measurements are taken at 17 stations. The number of continuous years available from each station ranges from 1 to 15, with most stations having less than 5 years of sunshine data.

An Approach to Characterization

Ideally, classification of agroecological zones should include hydrology, agroclimate, soil, landform, biological factors and farming systems. However, most of these data are currently not available for Laos. Soil mapping is almost complete, but few data are available on soil hydrology, which is vital for estimating soil water balance. Potential evapotranspiration (PET) is an important measure for water balance estimates but, to calculate PET, temperature, humidity, wind speed and solar radiation are needed. Alternatively, it can be estimated directly from pan evaporation. Because evaporation and solar radiation are not measured at all stations and only a few consecutive and common years are available, any estimate of PET, using available data, would be very rough at best.

Given these limitations in data availability, precise agroecological characterization is not possible, although in 4 or 5 years' time there may be sufficient data to characterize the climate, using PET estimates, provided that the stations continue collecting relevant data. Despite these limitations, significant and useful progress can be made in climatic characterization. The two climatic measurements that have the most potential for providing useful information are rainfall and temperature.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Table 1. Lao meteorological stations, with the number of years for which data have been recorded. Also given is the number of consecutive, complete years (from 1999) with daily data available for specific climatic factors, that is, precipitation (precip.), temperature (temp.), evaporation (evap.), humidity (hum.), dew point, mean monthly wind speed and hours of sunshine. Stations are ordered from south to north.

Province	Station name	Years on record	Precip.	Temp.	Evap. (pan)[a]	Evap. (piche)[a]	Hum.[a]	Dew point[a]	Mean mo. wind speed (10 m)[a]	Sunshine (h)[a]
Champassak	Khong[b]	1	12	1	—	1	1	1	—	1
C	Soukhouma	11	8	7	—	—	7	1	8	1
Attapeu	Attapeu	11	11	8	3	8	8	8	8	4
Sekong	Sekong	6	6	4	2	—	3	3	3	—
C	Pakse	51	49	15	10	5	15	14	14	8
C	Lak 42	17	16	10	—	5	10	10	10	—
C	Paksong	14	14	8	—	—	8	8	1	—
C	Nikhom 34	17	17	10	—	4	10	10	10	—
Saravane	Khongsedon	14	12	5	2	5	4	4	4	—
Sar	Saravane	20	13	10	3	—	10	10	10	4
Sar	Lao Ngam	7	6	6	—	—	6	6	6	—
Savannakhet	Savannakhet	62	28	15	—	—	15	15	15	1
Sav	Seno	50	50	7	—	7	7	7	7	—
Sav	Sepol[b]	1	12	1	—	1	1	1	—	1
Khammuane	Thakhek	20	13	11	—	5	11	11	11	1
Vientiane Municip.	Hatdockeo	32	0	0	0	0	0	0	0	0
V-M	Vientiane	58	50	15	—	—	6	6	6	1
V-M	Naphok	15	3	3	—	—	3	3	3	3
V-M	Veunkham	13	13	6	5	—	6	6	1	2
V-M	Thangone	29	29	7	—	7	7	7	7	—
Borikhamsay	Lak 20	3	3	2	—	2	2	2	0	—
B	Paksan	35	13	3	—	3	3	3	3	—
Xayaboury	Paklay[c]	28	0	0	—	—	—	—	—	—
Vientiane	Napheng	25	6	5	—	5	5	5	5	—
V	Phonehong	29	29	10	1	—	6	6	1	6
V	Vang Vieng	28	28	5	—	5	5	5	1	—
Xayaboury	Xayaboury	31	31	15	—	6	9	15	15	11
Xieng Khuang	Xieng Khuang	47	5	5	—	—	5	5	5	5
Xieng Khuang	Kham	1	1	1	—	1	1	1	—	1
Luang Prabang	Xiengeun	11	11	2	—	2	2	2	2	2
Luang Prabang	Luang Prabang	51	49	15	14	—	6	15	15	15
Bokeo	Bokeo	29	4	4	—	—	4	4	4	4
Huaphanh	Viengsay	24	16	2	—	2	1	2	6	2
Huaphanh	Samneua	1	1	1	—	1	1	1	—	1
Oudomxay	Oudomxay	16	9	9	—	—	9	9	9	1
Luang Namtha	Luang Namtha	7	7	5	—	—	5	5	5	—
Luang Namtha	Sing[c]	?	0	0	—	—	—	—	—	—
Phongsaly	Phongsaly	12	12	4	—	—	3	3	5	—

[a] = data not collected at station.

[b] Stations were originally hydrological stations and were upgraded in 1999 to meteorological stations.

[c] Only rainfall and temperature were collected at these stations.

Rainfall

In the rainfed rice ecosystem, rainfall is the most important climatic factor (Fujisaka 1994). In Laos, rainfall is higher in the south and centre than in the north, but distribution within the year is similar in different regions (Figure 2a). Rainfall varies not so much in absolute amounts, but in terms of timing of onset and cessation and in terms of periods of drought or flood. The rainfed lowland rice systems in Laos are often affected by early and late season droughts (Fukai et al. 1998). Flooding, which causes lodging or complete crop failure, can also be a problem. Although these problems are recognized, little has been done to determine the frequency of such events or to identify the regions where they are most likely to occur. Oldeman (1975, 1980) developed a widely adopted agroclimatic classification for rice and rice-based cropping systems. This classification is based

Table 2. Number of years available of continuous data on daily rainfall (starting in 1999) from hydrological stations in Laos. Stations are ordered from south to north.

Province	Station name	Continuous years	Province	Station name	Continuous years
Champassak	Mounlapamok	12	Khammuane	Sebangfai	2
C	Pathumphone	7	K	Mahaxay	12
C	Phonethong	10	K	Kuanpho	7
C	Batieng	11	K	Hinboun	1
C	Nonghin	12	K	Signo	12
C	Selabam	12	Vientiane Municip.	Naxone	12
C	Champassak	12	Borikhamsay	Nape	7
Savannakhet	Thapangthong	10	B	Tabok	0
S	Senuane	0	Vientiane	Pakkhanhung	6
S	Songkhone	0	B	Tadleuk	10
S	Kengdone	4	B	Pakthouai	12
S	M. Nong	12	B	M. Mai	12
S	Xonbuly	7	V	Thalath	12
S	Kengkok	12	B	M. Kao	12
S	M. Phine	12	V	Hinheup	15
S	Laosoulinha	7	Xaysomboun	Naluang	14
S	Phalan	0	V	Phatang	12
S	B. Dong	12	V	Kasy	12
S	Nakoutchan	7	B	Kengkuang	12
S	Donghen	12	Luang Prabang	Sengkhalok	12
S	Nagnom	0	LP	Hatgna	2
S	B. Veun	12	LP	Pakseng	6
			LP	M. Ngoy	9

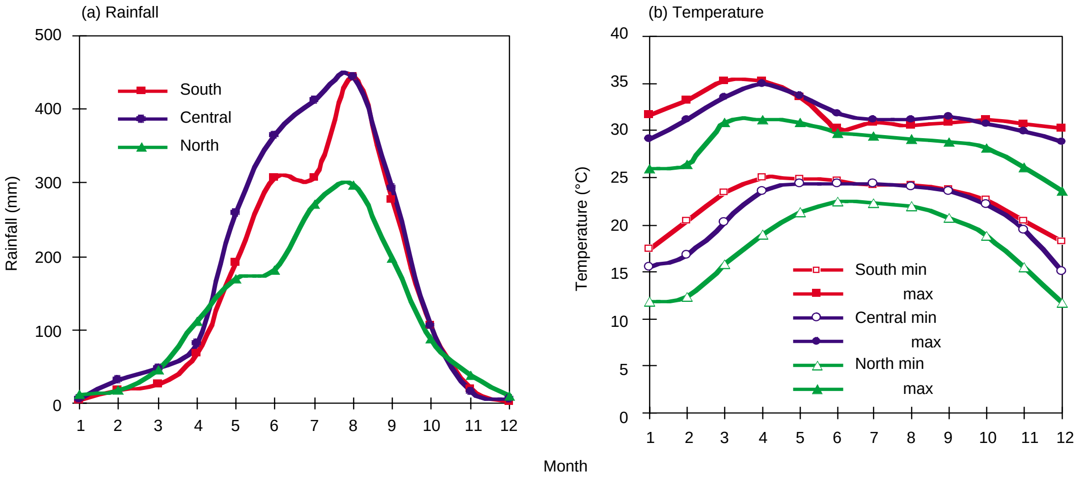


Figure 2. Rainfall and temperature distribution in northern, central and southern Laos.

on the length of the rice-growing season, which is specified as months in which surface flooding can be maintained and is assumed to be the period when monthly rainfall is more than 200 mm. Huke (1982a, b) used this system to uniformly classify all countries in South and South-East Asia. We suggest using a similar approach, but using weeks instead of months.

For characterization purposes, data from each site need to be continuous and common to other sites as rainfall is highly variable across sites and years. The number of continuous years varies greatly between stations (Tables 1 and 2). The objective is to get as many continuous and common years as possible and to get a reasonable spread of locations throughout Laos. Northern Laos has the fewest stations and continuous years of data available, creating difficulties in classifying at a national level. However, as a first step for rainfall characterization at a national level, 9 years of data (1991–1999) can be used. This excludes the important stations of Bokeo, Xieng Khuang and Luang Namtha, which have 4, 5 and 7 years of continuous rainfall, respectively. This selection provides the most years, while still achieving a reasonable spread of collection points (Figure 3). A possible option for increasing data is to obtain data from meteorological stations across the border from the Lao stations in northern Thailand, southern China or northern Vietnam, although this may be difficult and costly.

Additionally, rainfall characterization could be classified separately for central and southern Laos, where most of the rainfed lowland rice is grown and where there are more stations that have a higher number of continuous and common years. Thus, thereby improving the accuracy of the maps. A relatively good spread of data points in the south could be obtained by using 12 years of continuous rainfall data.

In addition to identifying the length of the growing season, as suggested by Oldeman (1980), rainfall data will be useful in identifying drought-prone areas, indicating when drought is most likely to occur within a season and estimating the onset and end of the wet season.

Figure 3. Distribution of 52 stations in Laos having at least 9 years of available rainfall data.

Long-term trends in weather patterns could be studied from the few stations that have more years of data. Fortunately, five stations, spread throughout Laos, have at least 49 years of continuous and common years of data. These stations include Luang Prabang in the north, Vientiane Municipality and Savannakhet (two stations) in central Laos and Champassak in the south. Using these data would provide a reasonable base for determining the probability and timing of drought events for a given season for each region, as annual rainfall varies greatly across years and across locations (Figure 4).

Temperature

In the irrigated environment, high or low temperatures are potential problems during the dry season. Cool temperatures during December and January can affect rice growth at higher elevations in Laos (Sihathep et al., this volume). High temperatures may affect the dry-season rice crop at low altitudes in southern Laos. Currently, most rice is sown in December and transplanted to the field during January. Flowering and grain filling under such conditions occur during late March and April, the hottest time of the year (Figure 2b). Temperatures during flowering can exceed 35°C, a situation that may lead to spikelet sterility (De Datta 1981). As with rainfall, the potential for temperature-related problems to rice production in Laos has not been quantified.

The quantity of temperature data available from meteorological stations is less than that of rainfall (Table 1). Currently, 4 years of continuous and common temperature data are available from stations that are reasonably well spread throughout the country. A close correlation exists between elevation and mean annual minimum ($R^2 = 0.87$) and maximum ($R^2 = 0.98$) temperature (Figure 5). This relationship indicates that for every 100-m change in altitude there is a 0.7°C change in temperature. This is very similar to the relationship found in Java (Oldeman 1975).

In Laos, where 80% of the country is mountainous, any characterization of temperature needs to account for elevation differences. Because temperature data are highly site specific, the location of meteorological stations relative to rice-growing areas is important. It is vital to see whether the relationship between temperature and altitude is similar throughout the year as

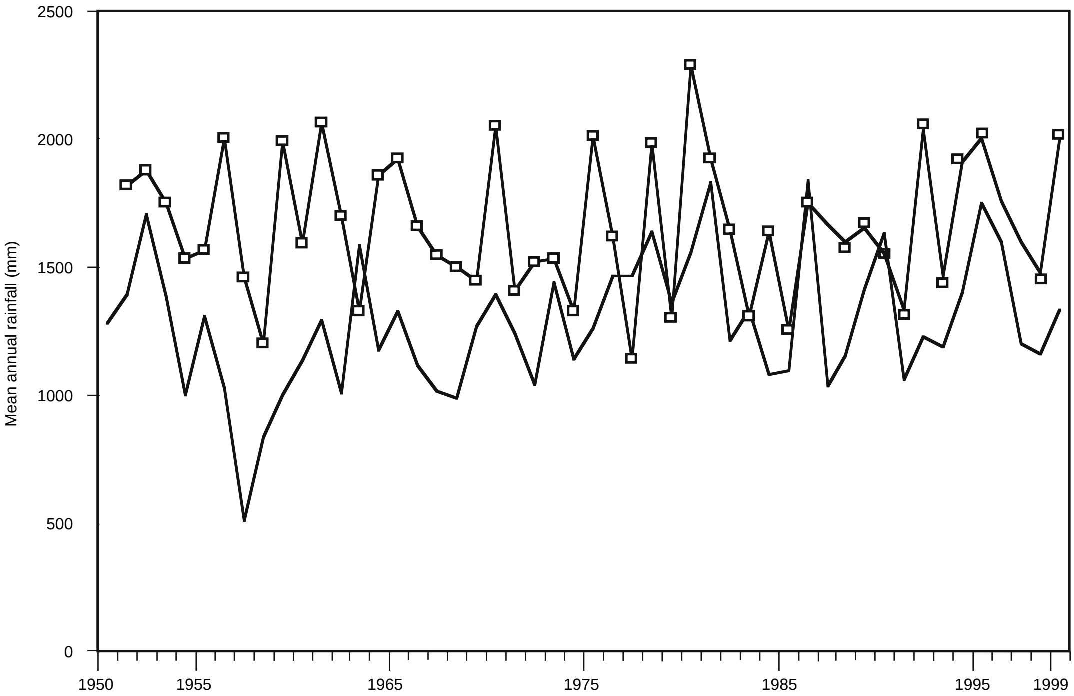


Figure 4. The variability of total annual rainfall for Laung Prabang Province (——) and Vientiane Municipality (—□—), Laos, from 1950 to 1999.

it can be used to estimate temperatures for stations with missing data. If successful, this will help generate a database with a higher number of consecutive years.

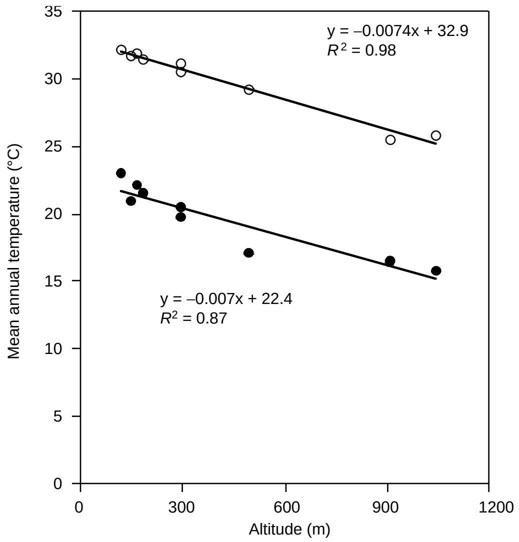


Figure 5. The relationship between mean maximum (○) and mean minimum (●) annual temperatures and altitude in Laos. Data are from nine stations and are the means from 1985 to 1998.

Conclusions

Improving the quantity and quality of climatic data is crucial for the successful agroecological characterization of Laos. Continued monitoring at current meteorological and hydrological sites will provide vital data, and more stations in northern Laos may need to be established. Finding regressions between temperature and altitude in Laos may help improve data sets. Collaboration with neighbouring South-East Asian countries may assist in verifying climatic trends that exist throughout Laos. Data sets over longer periods would provide a more accurate characterization of Lao climate, especially for rainfall. As data become available, maps generated from this characterization can be upgraded. Ideally, 20 years of continuous and common data should be used.

As the stations are upgraded and data collection becomes more reliable, more accurate estimates of other climatic variables (e.g. PET) will become possible. Such data will allow for improved agroecological characterization.

References

Buddenhagen, I.W. 1978. Rice ecosystems in Africa. In: Buddenhagen, I.W. and Pursley, G. ed. Rice in Africa. London, Academic Press, 11–27.

De Datta, S.K. 1981.Principles and Practices of Rice Production. New York, John Wiley and Sons.

Fujisaka, S. 1994. Bringing together rice farmers' science and formal agricultural science. Philippines, International Rice Research Institute (IRRI), 34–35.

Fukai, S., Sittisuang P. and Chanphengsay, M. 1998. Increasing production of rainfed lowland rice in drought prone environments: a case study in Thailand and Laos. Plant Production Science, 1, 75–82.

Huke, R.E. 1982a. Maps of South and Southeast Asia. Philippines, International Rice Research Institute (IRRI).

Huke, R.E. 1982b. Rice by Area and Culture: South, Southeast and East Asia. Philippines, International Rice Research Institute (IRRI).

IRRI (International Rice Research Institute). 1984. Terminology for Rice Growing Environments. Manila, Philippines.

Mackill, D.J., Coffman, W.R. and Garrity, D.P. 1996. Rainfed lowland rice improvement. Philippines, International Rice Research Institute (IRRI).

Oldeman, L.R. 1975. An agro-climatic map of Java. Bogor, Indonesia, Central Research Institute for Agriculture.

Oldeman, L.R. 1980. The agro-climatic classification of rice growing environments in Indonesia. In: Proceedings of a Symposium on the Agrometeorology of the Rice Crop. Philippines, International Rice Research Institute (IRRI), 47–55.

Quantifying the Toposequential Distribution of Environmental Resources and Its Relationship with Rice Productivity

Koki Homma[1*], Takeshi Horie[1], Masao Ohnishi[2], Tatsuhiko Shiraiwa[1], Nopporn Supapoj[3], Naruo Matsumoto[4] and Nobuyuki Kabaki[4]

Abstract

The rainfed lowlands of North-East Thailand comprise numerous micro-watersheds, each measuring only a few square kilometres in area and some metres in altitude. Each carries many tiny paddy fields, whose yields are usually very low and highly variable with respect to time and space. To develop strategies for improving the productivity and sustainability of rainfed-rice cultivation, we quantified the toposequential distribution of land productivity in terms of rice yields within one of these micro-watersheds. Productivity was then related to soil fertility, water availability and cultural practices. Field studies were conducted in 247 fields of the Hua Don micro-watershed in Ubon Province, North-East Thailand, in 1997 and 1998. Rice yields were found to vary from 0 t ha^{-1} in higher fields to about 4 t ha^{-1} in lower fields. Such a toposequential gradient was caused mainly by gradients in soil fertility (including soil organic matter) and water availability down the micro-watershed's slope. The results were then incorporated into a rice growth model that was based on soil organic carbon (SOC) content as a function of relative field elevation in the micro-watershed. The model simulated fairly well the observed toposequential distribution of rice yields for the 247 fields, indicating that increasing SOC in higher fields is key to improving productivity. The simulation also suggested that, under the current situation of rainfed lowland rice cultivation in North-East Thailand, the rice cultivar KDML105 would have higher yields than would a modern variety with shorter growth duration and higher harvest index.

NORTH-EAST Thailand is a representative rainfed rice-producing region of South-East Asia. Yields can be as low as 1.7 t ha^{-1} and are highly variable with respect to time and space. Increase and stable production of rainfed rice is needed to ensure food security for a rapidly growing population. North-East Thailand consists of numerous numbers of small and shallow micro-watersheds, called *nong* in Thai. Some of these micro-watersheds lead into rivers and others are closed. In area, they are usually only a few square kilometres and some metres in altitude.

Paddy fields are found throughout most parts of these micro-watersheds, except for the highest areas, which are used for upland crops, woodland and residences. Rice crops grown in lower areas of micro-watersheds sometimes suffer from floods, while those grown in higher areas suffer from drought.

Soils in higher areas are well known to be, on the whole, less fertile than those in lower areas because of soil erosion and nutrient leaching. Such water and soil conditions imply that rice productivity is highly variable, even within a small area, depending on the topographical positions of the fields. Miyagawa and

KEYWORDS: Model simulation, Rainfed rice, Soil fertility, Toposequence, Water availability, Yield variability, North-East Thailand

---

[1] Graduate School of Agriculture, Kyoto University, Japan
[2] Faculty of Life and Environmental Science, Shimane University, Matsue, Japan
[3] Ubon Rice Research Center (URRC), Ubon Ratchathani, Thailand
[4] Japan International Research Center for Agricultural Sciences (JIRCAS), Tsukuba City, Japan
*Corresponding author: Koki Homma
E-mail: homma@kais.kyoto-u.ac.jp

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Kuroda (1988) classified village paddy fields into three types—lower, middle and higher—and reported that, in a drought year, yields in higher fields were 63% of those in lower fields.

Although many studies showed that drought and poor soil fertility were major constraints to rainfed rice production (Fukai et al. 1998; Wade et al. 1999b), little is known about the toposequential variability in those constraints. Although the Thai Department of Land Development has developed several soil series classifications according to geography and soil characteristics as defined by Moormann et al. (1964), paddy fields belonging to the same soil series often have widely differing rice productivity, depending on their elevations within a micro-watershed.

To improve rice cultivation under rainfed lowland conditions, quantifying yield constraints in terms of the rice fields' toposequential positions in micro-watersheds is important. Better adapted cultivars can be introduced and more appropriate soil and crop management methods can be developed.

The objectives of this study were twofold: (1) to clarify, through field study, the toposequential variations of soil fertility, water availability and rice yield in a micro-watershed in North-East Thailand; and (2) to develop a model for quantifying and simulating toposequential distribution of rice yield, based on the distribution of soil fertility in the micro-watershed under study.

Toposequential Distribution of Soil Fertility, Water Availability and Rice Yield

Study site and methods

The field study was carried out in the closed micro-watershed of Hua Don Village, located at about 25 km north-west from the centre of Ubon Ratchathani City. The area extends along the Se Bai River, a branch of the Moon River. For the 1997 study, we selected seven fields that belonged to one of the farmers (designated as No. II in Figure 1) raising rice in the micro-watershed. Then, in 1998, we expanded the study area to cover 247 fields. These belonged to 10 farmers and encompassed 9.3 hectares, with the elevation between the highest and lowest paddy fields being no more than 3.4 m. The toposequential positions of the paddy fields were determined according to elevation relative to the lowest paddy field in the site, then classified into one of three levels: lower, that is, between 0 and 0.5 m; middle, between 0.5 and 1.5 m; and higher, 1.5 m or higher.

Soils in the study area were classified as belonging to the Pimai and Ubon series, according to the soil map published by the Thai Department of Land Development (Changprai et al. 1971). Surface water depth and yields were determined for all fields, and soil organic carbon (SOC) content for 31 representative fields. Farmers' cultural practices were also recorded, based on observations and interviews with farmers.

Water depths above the soil surface were measured in seven fields in 1997 and in 247 fields in 1998. The water depth of each field was measured at about 1-week intervals, and represented as the average of measurements at four different points in each field. Daily water depth was calculated by linear interpolation between two measurements, and days with water depths higher than 5 mm were counted as numbers of flooded days.

In 1997, dry weight of rice biomass was measured for 21 spots in 7 fields and paddy yields for 275 spots in 194 fields. Each sampled area was about 1 m^2 in 1997 and 0.5 m^2 in 1998. In all the studied fields, either cultivar Khao Dawk Ma Li 105 (KDML105) or its glutinous mutant RD6 was grown. Amounts and dates of chemical fertilizer applications to the fields were recorded by interviewing with farmers. Dates of seeding or transplanting and harvesting for all fields were monitored and recorded.

Soil samples were taken from different fields and used to fill plastic pots in which rice was planted. Soil fertility, using the rice as a test plant, was then evaluated with a phytometer. In 1998, plough-layer soils (0–20 cm) were sampled from 31 fields in the study area. Surface soils from 2 spots in secondary woodland growing alongside the study area were also collected and subjected to the phytometer. Soil sampling was done after the first ploughing in June, and the samples were air dried, cracked, passed through 1-mm-mesh sieves to remove plant residues, then placed in 7-L pots. Each pot contained 5.5 kg of dried soil. Three pots were used for each soil as replicates. Three seedlings of the rice cultivar KDML105 were transplanted into each pot on 30 July and grown under flooded conditions without fertilizer until maturity on 13 November. The plants were then harvested and their dry weight determined. Finally, the soil organic carbon (SOC) content for each soil was measured, using the Walkly–Black method (Walkly and Black 1934).

Data on minimum and maximum temperatures, solar radiation and precipitation were collected at the Ubon Rice Research Center (URRC), which was located about 3 km north-west of the study area.

Results of the field study

Farmers' cultural practices

After the rainy season started in June, farmers began making nursery beds in paddy fields located in the middle of the micro-watershed. One to two-month-old

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

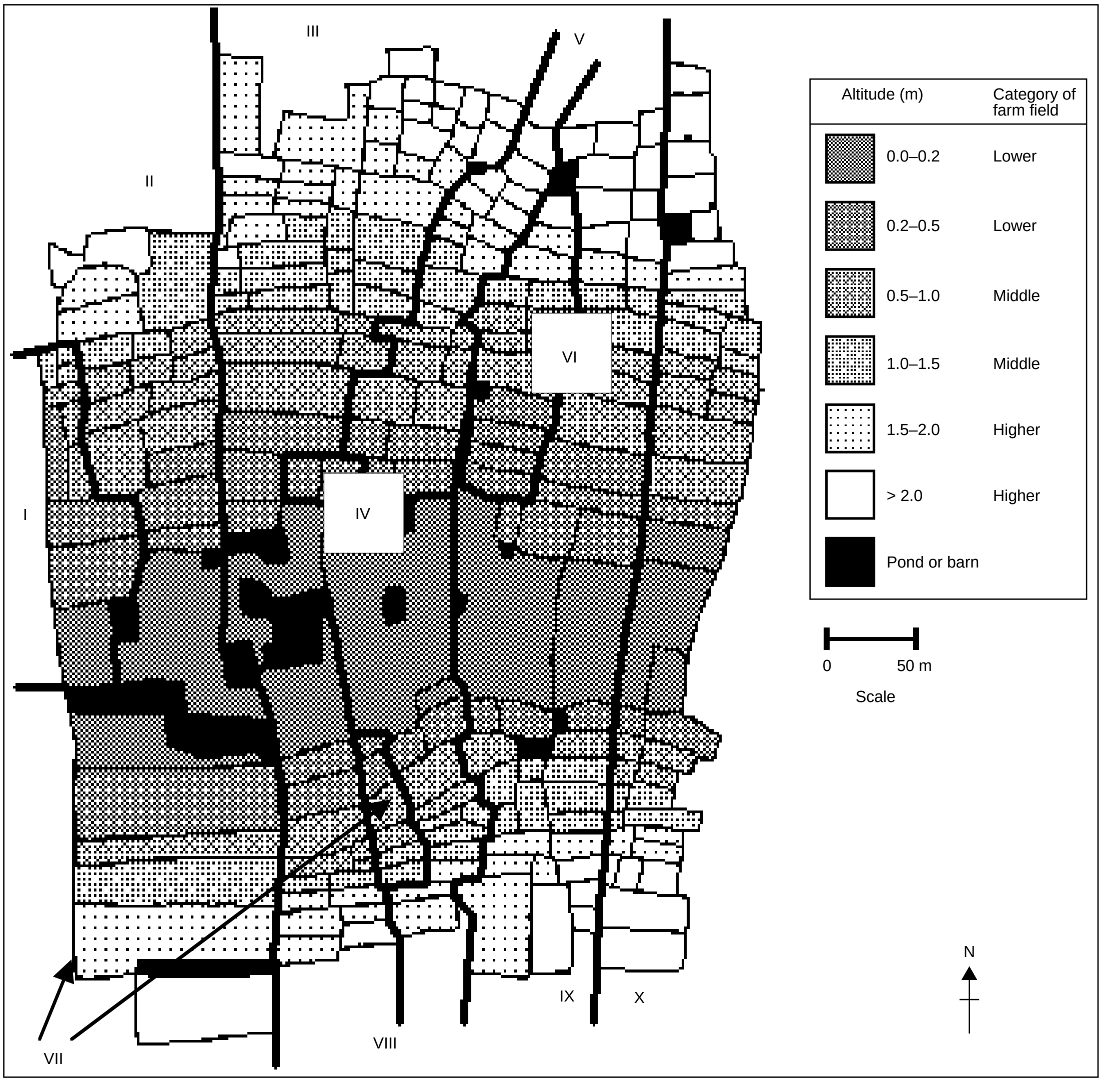


Figure 1. Map of 247 rice fields and their elevations relative to the lowest point in the Hua Don mini-watershed, North-East Thailand. (▬▬ = boundaries between farms I to X; ──── = boundaries between fields.)

seedlings were transplanted between the end of June and mid-August and from lower to higher fields. Some lower fields were direct seeded. In those direct-seeded fields where seedlings failed to establish, seedlings were transplanted. The fields used for nursery beds were either transplanted afterwards or unused.

Most farmers in the study area applied chemical fertilizer twice during rice growth: one after transplanting in all fields was completed, and the other about 30 days before heading (mid-September). The combined chemical fertilizer, 16–16–8% (N–P_2O_5–K_2O) type, was the most popular. Fields in the highest areas of the micro-watershed did not receive fertilizer because of the high risk of water shortages. Neither did the lowest fields receive fertilizer because of the high risk of losing the fertilizer through floods.

Irrigation was by pumping, and hand weeding was conducted only once, at transplanting. The rice cultivars KDML105 and RD6 usually head in mid-October, at the end of the rainy season, when the crop was unlikely to be damaged by water shortages. Rice was harvested successively from the lower to the higher fields during November. Table 1 shows differences in transplanting and harvesting dates and fertilizer application rates for the lower, middle and higher fields.

Toposequential variations in water availability

Annual precipitation in 1997 and 1998 was 1114 and 1186 mm, respectively. Although these are much less than normal (1506 mm, 1987–1996 averages), they were not so rare (1260 mm in 1988 and 1214 mm in 1993). Precipitation patterns at the URRC for 1998 are shown in Figure 2.

The number of flooded days of the fields during the 1998 rice-growing season is presented as a function of relative field elevation (Figure 3). Although water availability differed considerably among fields, it generally decreased with ascending elevation, in a close negative correlation ($r = -0.83$, $P < 0.01$). Fields at the tops of slopes never had standing water, even after heavy rain, while those in the lowest areas of the micro-watershed had standing water until harvest, even if rain stopped 2 weeks beforehand. On average, over all the fields in the Hua Don micro-watershed, the number of days that fields had standing water was about half of the number of days the rainy season lasted for the year.

Results of a previous 1997 study that we conducted at the same site (Homma et al. 1998) showed that the soil moisture content of the middle fields was maintained at high levels, even when there was

Table 1. Differences in farmer cultural practices for lower, middle and higher rice fields across the toposequence of the Hua Don study area, North-East Thailand, 1998.[a]

Farming activity	Toposequential position (relative elevation in m)		
	Lower (0–0.5)	Middle (0.5–1.5)	Higher (>1.5)
Transplanting (DOY)[b]	189th ± 11[a]	198th ± 11[b]	210th ± 13[c]
Harvesting (DOY)[b]	313th ± 2[a]	315th ± 2[b]	316th ± 4[c]
Fertilizer (N at kg ha^{-1})	26.8 ± 23.7[a]	37.6 ± 18.4[b]	13.7 ± 25.0[c]

[a] Values within a row followed by the same letter are not significantly different at the 5% level. [b]DOY = day of the year, for example, 189th ± 11 = 8th July ± 11 days.

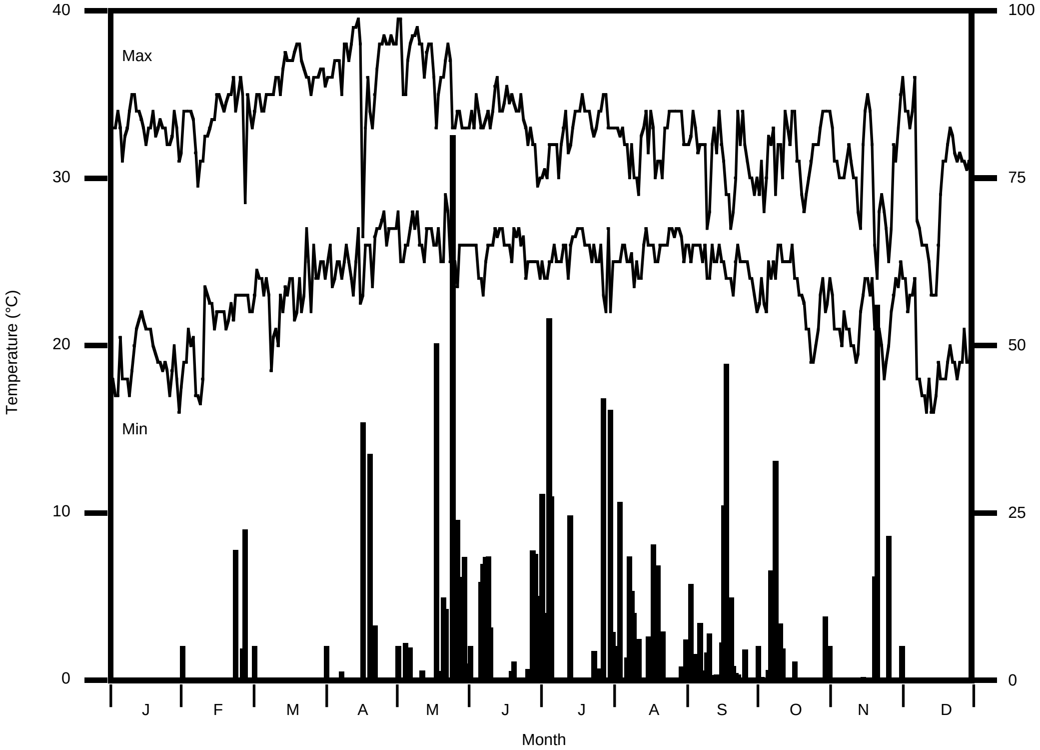


Figure 2. The maximum and minimum temperatures (lines) and precipitation (bars) at the Ubon Rice Research Centre, North-East Thailand, 1998.

no standing water, until the rice crop headed and, thereafter, it gradually decreased. In contrast, standing water in the higher areas was shallow most of the growing period.

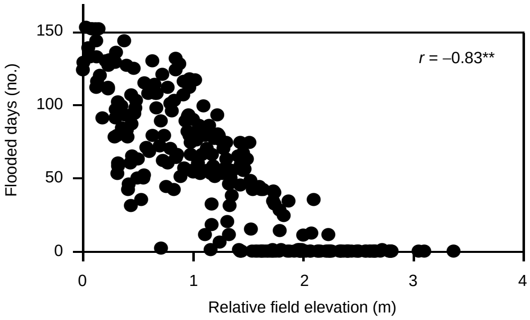


Figure 3. Number of flooded days as a function of relative field elevation of farm fields in the Hua Don study area, North-East Thailand, 1998 wet season (1 May–31 October).

Toposequential variations in soil fertility

The soil organic carbon (SOC) content was inversely proportional ($r = –0.76$, $P < 0.01$) to the relative elevation of fields in the micro-watershed (Figure 4). Soil samples from the woodland, which was at an elevation higher than the highest fields of the study area, had SOC contents that were 2.2 times higher than those of the highest fields.

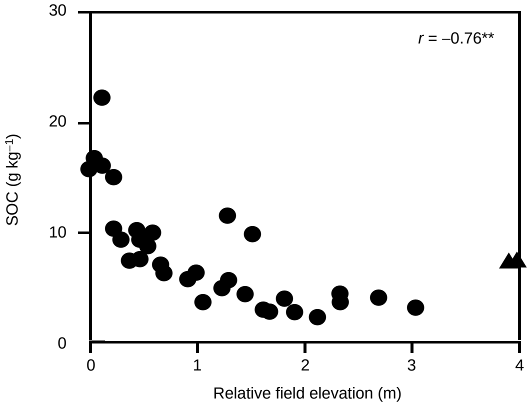


Figure 4. Soil organic carbon (SOC) contents as a function of the relative field elevation of farm fields in the Hua Don study area (●) and secondary woodland (▲), North-East Thailand.

The pot experiment, using soils from different fields in the study area, revealed that the biomass production of pot-grown rice receiving no fertilizer and under flooded conditions was proportional to SOC content (Figure 5). The close correlation ($r = 0.80$, $P < 0.01$) between SOC content and biomass production suggests that SOC is a good index for soil fertility in the study area. Figure 5 also indicates that soil fertility among fields usually differs by more than 5 times. This and the toposequential distribution of SOC imply that rice yield distribution is strongly affected by the gradient of SOC in the study area.

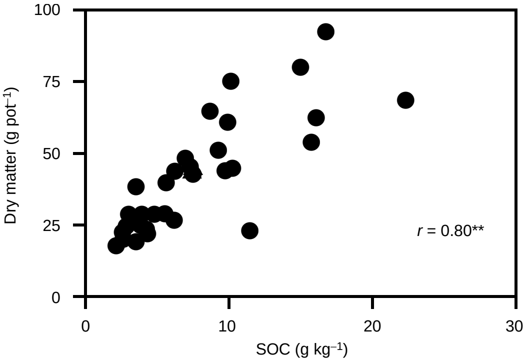


Figure 5. Relationship between soil organic carbon (SOC) content and rice dry matter production as measured by a pot-growth experiement for soils sampled from farm fields in the Hua Don study area (●) and secondary woodland (▲), North-East Thailand.

Toposequential variations in rice yield

Figure 6 shows the relationship between rice biomass and grain yield and relative field elevation obtained for 247 fields. Although wide variations in biomass and grain yield are recognized among fields at the same relative elevation, both growth attributes declined with ascending field elevation. The biomass and grain yield correlated with relative field elevation at $r = –0.60$, $P < 0.01$, and $r = –0.58$, $P < 0.01$, respectively.

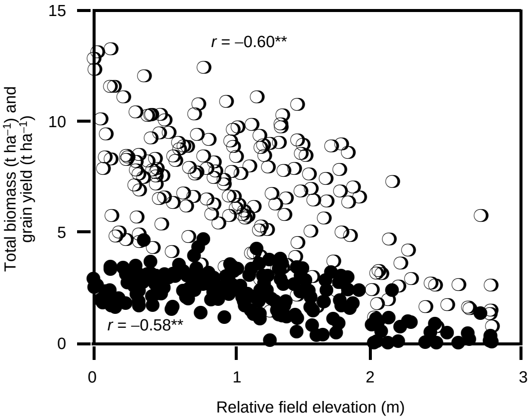


Figure 6. Variation with field elevation in total biomass (○) and grain yield (●) in the Hua Don study area, North-East Thailand, 1998.

The significant effects of field elevation on these growth attributes are also seen in statistical analyses among the lower, middle and higher fields, except for grain yield differences between the lower and middle fields (Table 2). The insignificant yield differences between the lower and middle fields were derived from a slightly lower harvest index of the lower fields, presumably because of lodging in the rice.

Because the number of flooded days and SOC content were both negatively correlated with the relative field elevation (Figures 3 and 4), we need to discover which environmental factors determine the toposequential yield variation observed. The correlation coefficient between the number of flooded days of fields and grain yield was 0.60 ($P < 0.01$) (Figure 7) and that between SOC content and yield was 0.53 ($P < 0.01$) (Figure 8). Thus, the number of flooded days and SOC content of fields affected the toposequential variation in yield to similar extents.

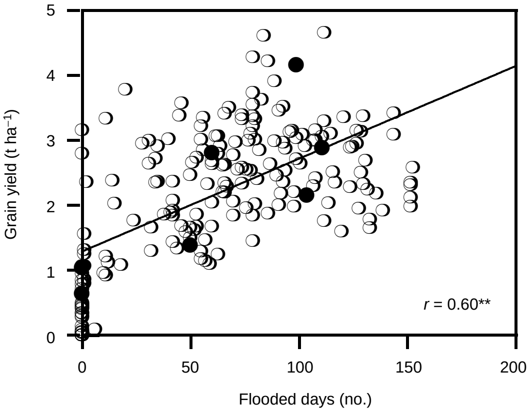


Figure 7. Relationship between number of flooded days and grain yield in the Hua Don study area, North-East Thailand, 1997 (●) and 1998 (○).

However, a large field-to-field variation in yield still existed that could not be explained by either the number of flooded days or SOC content. These unexplained variations in yield may have derived partly from a synergistic effect of the two environmental factors, and partly from farmer-to-farmer difference in cultural practices such as land preparation, fertilizer application rate and weeding. The transplanting date and fertilizer application rate also both correlated with relative field elevation (Table 1) and thus may have also contributed to toposequential yield variation. However, these cultural practices are considered to reflect the farmers' adaptation to the toposequential gradient in the water availability of their fields.

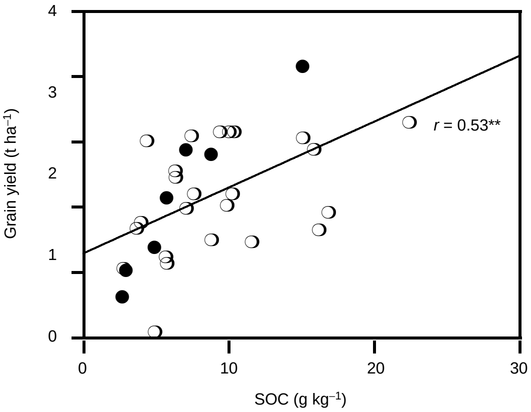


Figure 8. Relationship between soil organic carbon (SOC) content and grain yield in the Hua Don study area, North-East Thailand, 1997 (●) and 1998 (○).

We conclude therefore that enormously large variations exist in rainfed rice yield along the toposequence of fields in any given micro-watershed in North-East Thailand, and that toposequential gradients in both water availability and SOC content of fields are primary factors contributing to toposequential yield variations.

Modelling the Toposequential Distribution of Rice Yield, Using Soil Fertility

We attempted to develop a general model that would evaluate rice production potential of rainfed lowland

Table 2. Differences in rice growth and yield among the lower, middle and higher fields across the toposequence of the Hua Don study area, North-East Thailand, 1998.[a]

Crop parameter	Toposequential position		
	Lower	Middle	Higher
Total dry matter (t ha^{-1})	8.42 ± 2.37^a	7.22 ± 2.28^b	4.12 ± 2.43^c
Grain yield (t ha^{-1})	2.63 ± 0.62^a	2.50 ± 0.86^a	1.13 ± 0.97^b
Harvest index	0.325 ± 0.069^a	0.345 ± 0.055^a	0.225 ± 0.121^b

[a] Values within a row followed by the same letter are not significantly different at the 5% level.

fields in relation to soil fertility and using water availability as a function of toposequence. We first developed a nitrogen-limited rice growth simulation model for simulating growth and yield, based on the toposequential distribution of soil fertility and farmer cultural practices. Our objective was to examine the extent to which the observed toposequential yield variation can be explained by soil fertility and farmer cultural practices.

The model was synthesized by incorporating the processes related to soil N budget and plant N uptake into a previous model for simulating rice growth and yield based on plant N developed by Ohnishi et al. (1999a). This section briefly describes the synthesized model's structure and the results of applying it to simulate the toposequential distribution of rice yield in the micro-watershed of the Hua Don Village. Details of the model will be fully described in a later paper.

Overview of the model

The N-limited type model for simulating the growth and yield of rainfed lowland rice in North-East Thailand is schematically represented in Figure 9. The ontogenetic development of rice is quantified by a continuous variable of the developmental index (DVI), of which values are defined as 0.0 at emergence, 1.0 at panicle initiation, 2.0 at heading and 3.0 at maturity. Under this defining condition, the value of DVI at any moment of rice development is given by integrating the daily developmental rate (DVR) with respect to time. The DVR itself is a function of daily photoperiod and temperature. On the basis of rice growth experiments for various cropping seasons at the URRC and at Kyoto University (Japan), the DVR response function to photoperiod and temperature was determined for cultivar KDML105, one of the two most widely grown rice genotypes in North-East Thailand, using the SIMPLEX method (Horie and Nakagawa 1990; Ohnishi et al. 1999a).

The crop's dry weight at any moment of growth is calculated by integrating daily growth rate with time. The crop growth rate itself is given by multiplying daily solar radiation interception with radiation conversion efficiency. The radiation interception rate is a function of the crop's leaf area index (LAI). In this model, LAI is given as a linear function of plant N content, and the radiation conversion efficiency as a

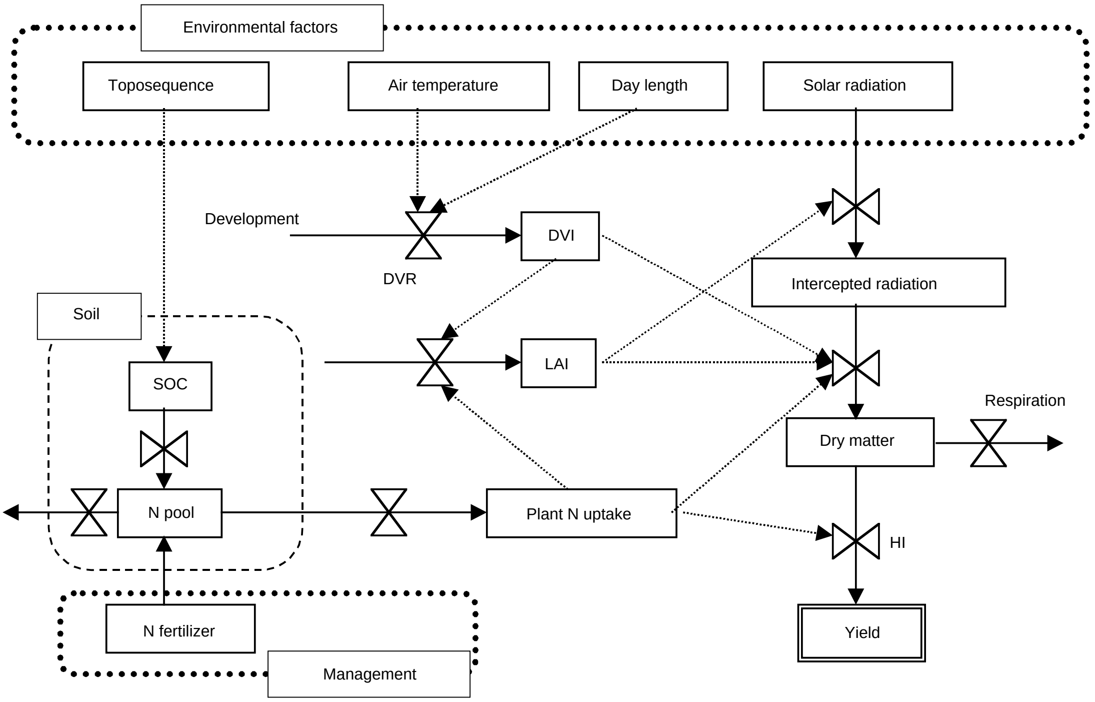


Figure 9. Flow chart of the model for simulating nitrogen-limited growth and yield of rice in relation to toposequential distribution of soil organic carbon (SOC) content and weather conditions. DVR = developmental rate; DVI = developmental index; LAI = leaf area index; N = nitrogen; HI = harvest index.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

curvilinear function of the N content (Ohnishi et al. 1999a). The plant N content is given by integrating time with the daily N uptake rate, itself a function of the size of the soil inorganic-N pool and the DVI. The size of the soil inorganic-N pool at any moment is calculated by integrating with time, the rates of soil-N mineralization, fertilizer N application, plant N uptake and N loss. Based on our previous study (Homma et al. 1999), the N mineralization rate (ΔN_{min}, kg ha^{-1}) was given as a function of the soil organic carbon (SOC, g kg^{-1}) content as follows:

$$\Delta Nmin = 0.657 \exp \{-3.52 / SOC\} \qquad [1]$$

The SOC content was represented as a function of the relative elevation of fields (RE, m) by approximating the relationship shown in Figure 4 by the following equation ($r = 0.86$, $P < 0.01$):

$$SOC = 12.37 \exp \{-0.622\ RE\} \qquad [2]$$

The paddy rice yield is given by multiplying rice biomass with the harvest index (Horie et al., 1992).

The values for all the model's parameters were specified according to the results of (1) field experiments on 'KDML105' under different N management practices at the URRC (Ohnishi et al. 1999a), and (2) the field studies in the study area. The N-limited rice growth model with those specified values of parameters explained fairly well the growth and yield of 'KDML105' grown under different N management practices and under no severe water stress conditions at the URRC (Ohnishi et al. 1999a).

A set of parameters for a high-yielding rice variety (HYV) was also prepared for the simulation by adopting the crop parameters of for 'IR64' as specified by Matthews et al. (1995). The HYV was a photoperiod-insensitive genotype, which had a higher harvest index and shorter time to maturity than did 'KDML105'. Daily solar radiation and temperature data obtained at the URRC in 1998 were used for the simulation. Daily photoperiods were calculated from latitude and were used for the simulation. Observed data for rice transplanting dates and farmer N applications were used to simulate rice growth and yield of 247 fields in the study area.

Simulation results

Figure 10 gives, for the rice cultivar KDML105, the DVR response curve to the daily photoperiod under different temperatures. The high photoperiod sensitivity of this cultivar is well illustrated in Figure 10 by the sudden decline of its DVR at its critical photoperiod (12.8 h).

The developmental process towards heading for 'KDML105' emerged on the first day of each month was also simulated (Figure 11). The model effectively simulates the commonly accepted phenomenon that all 'KDML105' crops seeded at any time during May–August attain heading at almost the same time in October.

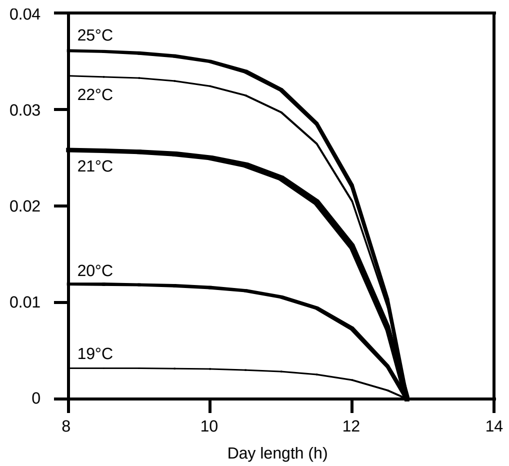


Figure 10. The response curves for the developmental rate (DVR) of rice cultivar KDML 105 to day length and temperature, from seedling emergence (0) to panicle initiation (>0.03).

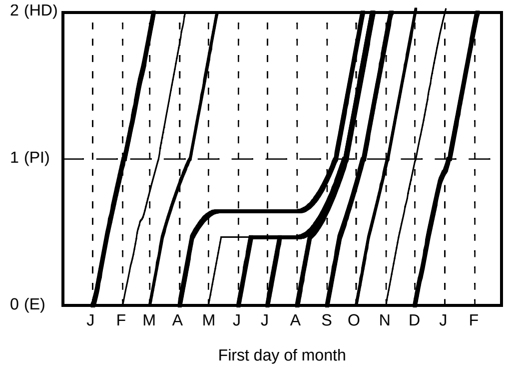


Figure 11. Simulated time courses of the developmental index (DVI) for rice cultivar KDML 105 according to the month of emergence (E), Ubon Province, North-East Thailand. PI = panicle initiation; HD = heading.

Rice yields were simulated for all 247 fields in the Hua Don micro-watershed by taking into account farmers' actual transplanting dates and fertilizer application rates, and compared with measured yields (Figure 12). The model overestimated the actual yields in the micro-watershed because the model did not account for yield loss to water stress, weeds, pests and diseases. Despite this, the model fairly well simulated the toposequential distribution of rice yield in the micro-watershed. The simulated yield average for higher fields was 1.65 t ha^{-1}, indicating that those fields have a very low production potential, even if no water stress existed. The poor yield potential of those fields is due not only to less fertilizer application and later transplanting, but also to very low SOC contents, as described already.

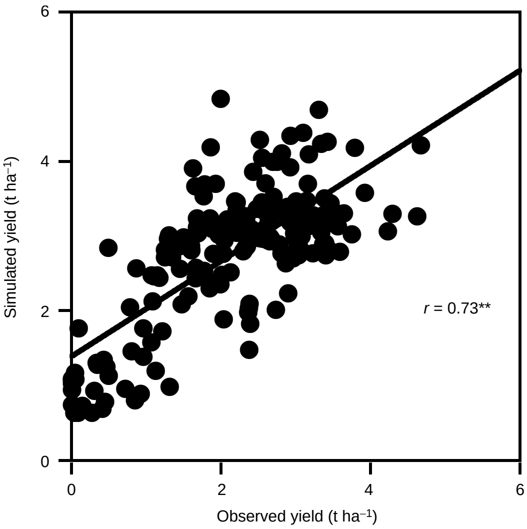


Figure 12. Comparison between observed and simulated rice yields of farm fields in the Hua Don micro-watershed, North-East Thailand, 1998. Yield is given as paddy with 14% moisture content.

Effects of rice genotypes, N applications and transplanting dates on the average yield over 247 fields in the micro-watershed were simulated by the model (Figure 13). The simulated yields for 'KDML105' linearly declined with the delay in transplanting date and showed a weak response to applied N, which agreed well with observations. The HYV showed no yield response to transplanting date because of its photoperiod insensitivity. The HYV showed higher response to applied N than did 'KDML105' because it has a larger harvest index. The superiority of the HYV in this region was evident only at the latest transplanting (16 August) and with a N application of more than 60 kg ha^{-1}. Otherwise, the yield of 'KDML105' exceeded that of the HYV.

These simulation results agree well with the experimental results obtained at the URRC (Ohnishi et al. 1999b), suggesting, therefore, that later maturing genotypes such as 'KDML105' are better adapted to the very poor soil fertility conditions of North-East Thailand, because they can accumulate more N over their longer growing period.

Discussion

Wade et al. (1999b) suggested the existence of toposequential variation in rainfed rice yields within small areas, a phenomenon that is also well known to farmers. However, the data that explicitly showed this were very few. Miyagawa and Kuroda (1988) reported that rice yields in a village differed according to toposequence in a drought year, but not significantly so in a bumper year. This study, conducted in a micro-watershed located in Ubon Province, North-East Thailand, showed that the rice crop's dry matter and grain yield drastically changed according to relative field elevation.

Many factors are involved in the toposequential gradient of rainfed rice yield in the micro-watershed. These are gradients in water availability and soil fertility, transplanting date and fertilizer application rate, as shown in the foregoing section. The toposequential gradients in water availability in terms of number of flooded days and in soil fertility in terms of soil organic carbon (SOC) are shown to have similar significant effects on toposequential yield variations (Figures 7 and 8). Delay in transplanting with ascending relative elevation of fields shortened the rice-growing period by as many as 16 days (Table 1), causing yield reduction in higher fields, as suggested from the simulation results (Figure 13). The smaller amounts of fertilizer applied to the higher fields (Table 1) may also have caused their lower yields. However, both the delay in transplanting and the differential fertilizer application for different fields are associated with the farmers' adaptation to the toposequential gradient in water availability in the fields. Therefore, the toposequential gradients in water availability and SOC content are considered to be primary factors in the steep gradient for yield.

The effect of SOC content on the toposequential yield variation was examined, using the N-limited rice growth model. This model was developed according to the concept that biomass production of potted rice was proportional to SOC content under irrigated conditions (Figure 5) and on the results of a previous study by Homma et al. (1999) that the N-mineralization rate of soils was closely related to SOC content.

Rice yields of 247 fields were simulated by the model, using actual transplanting dates and fertilizer application rates for each field. Even though the current model does not explicitly account for the water factor, it explained fairly well the observed yield variability in the micro-watershed (Figure 12). However, this does not mean that toposequential gradient of the micro-watershed's rice production potential is determined mostly by the gradient in

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

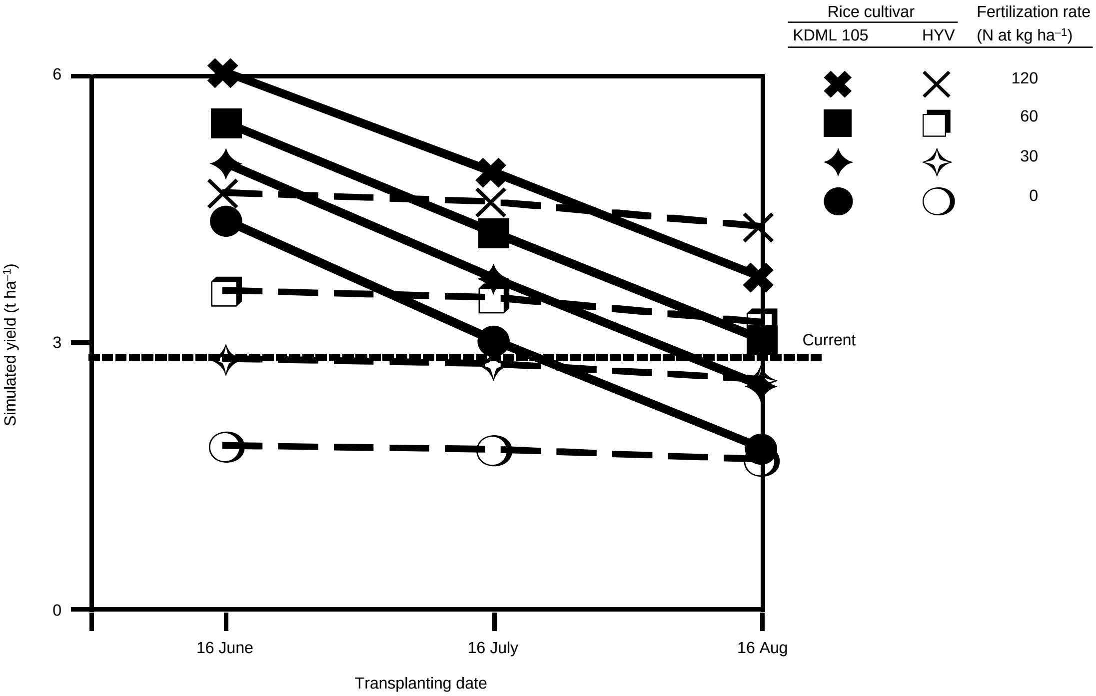


Figure 13. Simulated responses to transplanting date and fertilizer N application for yields of rice cultivar KDML 105 and a high-yielding variety (HYV), averaged over 247 fields in the Hua Don micro-watershed, North-East Thailand. For the HYV, crop parameters for rice cultivar IR64 were adapted. The line designated as 'current' indicates the simulated average yields for the current cultivar, transplanting dates and nitrogen applications practised in this area.

SOC alone, because the actual transplanting dates and fertilizer application rates adopted for the simulation were the results of farmers adapting to the toposequential gradient in water availability. Nevertheless, the simulation results suggest that the steep toposequential gradient in the yield of rainfed rice is strongly associated with that in SOC content.

Soil organic matter has many roles, including nutrient supply and soil structure improvement (Hamblin 1985; Jenkinson 1988). Although rice production in North-East Thailand is mostly restricted by N deficiency (Nakamura and Matoh 1996; Wade et al. 1999a), farmers generally apply only small amounts of chemical N fertilizer. This suggests that N derived from the decomposition of organic matter plays an important role in these poor soils, and that SOC content is a good index for soil fertility. Willett (1995) reported that organic matter is also important for increasing the cation-exchange capacity of the sandy soils in North-East Thailand.

Many studies report that soil fertility declines with time after forest is cleared for paddy fields in the tropics (Greenland and Lal 1977; Oldeman et al. 1991). Our study showed a loss of SOC content in higher fields through deforestation and its accumulation in the lower fields (Figure 4). Soil moisture, clay contents and amount of incorporated organic matter also affect SOC content. In this study, whether SOC content is declining or is being maintained could not be judged from the data obtained.

In North-East Thailand, except for some farmyard manure, rice residues form the only source of organic matter for the fields. Previous studies showed that soil fertility increased with the incorporation of rice straw (Chairoj et al. 1996; Naklang et al. 1999). Rice residues may therefore comprise one key to sustainable production under the current situation of rainfed-rice farming in North-East Thailand. Introducing high-yielding rice varieties (HYV) with higher harvest indexes may not effectively improve the productivity of rainfed rice under the current situation, but it may also reduce sustainability because of the small quantities of rice straw and other residues being incorporated.

References

Chairoj, P., Kimura, M. and Takai, Y. 1996. Long-term effects of fertilization on paddy soil fertility for sustainable rice production. In: Attanandana, T., Kheoruenromme, I., Pongsakul, P., and Vearasilp, T. ed. Proceedings of the International Symposium on Maximizing Sustainable Rice Yields through Improved Soil and Environmental Management. Khon Kaen, Thailand, Funny Publishing 797–804.

Changprai, C., Chotimon, A., Thunduan, V., Thipsuwan, C., Lepananontha, J. Kittiyarak, S. 1971. Detailed reconnaissance soil map of Ubon Ratchathani province. Bangkok, Thailand, Soil Survey Division, Department of Land Development.

Fukai, S., Sittisuang, P. and Chanphengsay, M. 1998. Increasing production of rainfed lowland rice in drought prone environment. Plant Production Science, 1, 75–82.

Greenland, D.J. and Lal, R. 1977. Soil conservation and management in the humid tropics. Bath, UK, John Wiley.

Hamblin, A.P. 1985. The influence of soil structure on water movement, crop root growth and water uptake. Advances in Agronomy, 38, 95–158.

Homma, K., Inamura, T., Horie, T., Ohnishi, M., Yamamoto, S., Khonboon, Y., Thongthai, C. and Supapoj, N. 1998. Studies on potential productivity and production constraints of rice in rainfed paddy fields in Northeast Thailand. III. Growth and yield in relation to water availability. Japanese Journal of Crop Science, 67, extra issue 1, 16–17. (In Japanese.)

Homma, K., Horie, T., Ohnishi, M., Inamura, T., Shiraiwa, T., Thongthai, C., Supapoj, N., Matsumoto, N. and Kabaki, N. 1999. Spatial distribution of soil fertility and its relation to the productivity of rainfed rice in a small basin area in Northeast Thailand. In: Proceedings of the International Symposium on "Can Biological Production Harmonize with Environment?" Tokyo, The University of Tokyo and The United Nations University, 49–52.

Horie, T. and Nakagawa, H. 1990. Modeling and prediction of developmental process in rice. I. Structure and method of parameter estimation of a model for simulating developmental processes toward heading. Japanese Journal of Crop Science, 59, 685–695.

Horie, T., Yajima, M. and Nakagawa, H. 1992. Yield forecasting. Agricultural Systems 40, 211-236.

Jenkinson, D. 1988. Soil organic matter and its dynamics. In: Wild, A. ed. Russells soil conditions and plant growth. London, Longman, 564–607.

Matthews, R.B., Horie, T., Kropff, M.J., Bachelet, D., Centeno, H.G., Shin, J.C., Mohandas, S., Singh, S., Defeng, S. and Lee, M.H. 1995. A regional evaluation of the effect of future climate change on rice production in Asia. In: Matthews, R.B., Kropff, M.J., Bachelet, D. and Van Laar, H.H. ed. Modeling the Impact of Climate Change on Rice Production in Asia. Place? UK, CAB International, 95–139.

Miyagawa, S. and Kuroda, T. 1988. Effects of environmental and technical factors on rice yield in rain-fed paddy fields of Northeast Thailand. Japanese Journal of Crop Science, 57, 773–781.

Moormann, F.R., Montrakun, S. and Panichapong, S. 1964. Soils of Northeastern Thailand: A Key to Their Identification and Survey; Soil Survey Report. Bangkok, Thailand, Soil Survey Division, Department of Land Development.

Nakamura, K. and Matoh, T. 1996. Nutrient balance in the paddy fields of Northeast Thailand. Southeast Asian Studies, 33, 575–587.

Naklang, K., Whitbread, A., Lefroy, R., Blair, G., Wonprasaid, S., Konboon, Y. and Suriya-Arunroj, D. 1999. The management of rice straw, fertilizers and leaf letters in rice cropping systems in Northeast Thailand. 1. Soil carbon dynamics. Plant and Soil, 209, 21–28.

Ohnishi, M., Horie, T., Homma, K., Kondo, S., Takano, H., Inamura, T., Chamnean, T. and Supapoj, N. 1999a. Modeling and evaluation of productivity of rainfed rice in Northeast Thailand. In: Horie, T., Geng, S., Amano, T., Inamura, T. and Shiraiwa, T. ed. Proceedings of the International Symposium on "World Food Security and Crop Production Technologies for Tomorrow". Kyoto, Kyoto University, 173–176.

Ohnishi, M., Horie, T., Homma, K., Supapoj, N., Takano, H. and Yamamoto, S. 1999b. Nitrogen management and cultivar effects on rice yield and nitrogen use efficiency in Northeast Thailand. Field Crops Research, 64, 109–120.

Oldeman, L.R., Hakbeling, R.T.A. and Sombroek, W.G. 1991. World Map of the Status of Human-Induced Soil Degradation, An Explanatory Note, Global Assessment of Soil Degradation (GLASOD). 2nd revised edition. Wageningen, Netherlands, ISRIC and UNEP.

Wade, L.J., Amarante, S.T., Olea, A., Harnpichitvitaya, D., Naklang, K., Wihardjaka, A., Senger, S.S., Mazid, M.A., Singh, G. and McLaren, C.G. 1999a. Nutrient requirements in rainfed lowland rice. Field Crops Research, 64, 91–107.

Wade, L.J., Fukai, S., Samson, B.K., Ali, A. and Mazid, M.A. 1999b. Rainfed lowland rice: physical environment and cultivar requirements. Field Crops Research, 64, 3–12.

Walkly, A. and Black, I.A. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification to the chromic acid titration method. Soil Science, 37, 29–38.

Willet, I.R. 1995. Role of organic matter in controlling chemical properties and fertility of sandy soils used for lowland rice in Northeast Thailand. In: Lefroy, R.D.B., Blair, G.J. and Craswell, E.T. eds. Proceedings of a Workshop on Soil Organic Matter Management for Sustainable Agriculture. Ubon, Thailand, ACIAR, 109–114.

Implementing the FAO Methodology for Agroecological Zoning for Crop Suitability in Laos: A GIS Approach

Thavone Inthavong[1]*, S.P. Kam[2], C.T. Hoanh[2] and Sisavang Vonghachack[1]

Abstract

This paper describes the case study of implementation of the FAO methodology for agroecological zoning for crop suitability in the Lao PDR—a GIS approach which was developed by the National Agriculture and Forestry Research Institute (NAFRI), with assistance from the International Rice Research Institute (IRRI) and ACIAR project.

The objectives of this study are characterization and mapping of agroecological zones in identifying suitable crops and developing optimum production systems for increasing agricultural production on a sustainable basis.

The study analyzed the needs of the crops in terms of both climate and soil. Spatial interpolation techniques were used to generate gridded climate surfaces, which were used for delineating the length-of-growing period (LGP) zones and thermal regimes. The calculations were then made of the potential yields of each crop in each LGP zone and were then modified to take account of constraints such as water and biotic stresses. The agroclimatic ratings were further downgraded if soil conditions, slope and texture were less than ideal. All these calculations were carried out for two different levels of farming inputs—the high and low input levels.

The result was a qualitative crop suitability assessment which, in final form, maps the areas suited to the production of each crop within each LGP zone.

THE Lao PDR is a landlocked country, located between 14° and 22° N latitude and 100° and 108° E longitude. It stretches about 1100 km from north to south, bordering with the Republic of Vietnam in the east, the Republic of China and Myanmar in the north, the Kingdom of Thailand in the west, and the Kingdom of Cambodia in the south.

Some 75% of the country is hilly to mountainous, reaching maximum heights of 2820 m in the north and 1980 m in the southeast. The rest of the country consists of flat to gently undulating lowland, alluvial plains and terraces alongside the Mekong River at elevations of 250–300 m.

The climate is tropical, dominated by monsoons, especially the southwest monsoon from May to October, which brings up to 75% of the annual rainfall. The average annual rainfall is between 1300 and 1800 mm. Rainfall exceeding 3000 mm is not uncommon at higher elevations in the south. Temperatures are highest in April and early May. The coolest period is from October to February or November to March, depending on location.

The importance of rational planning for effective land-use to promote agricultural production is well recognized. The ever-increasing need for food to support the country's growing population demands a systematic appraisal of its soil and climatic resources to recast an effective and alternate land-use plan. Soil, climate and other physiographic variables, largely determine the suitability of different crops and their yield potential. Increasing population, urban and rural expansion on the other hand will put considerable pressure on the country's natural resources resulting in environmental degradation. Efforts in characterization and mapping of agroecological zones may go a long way in identifying

---

[1] National Agriculture and Forestry Research Institute (NAFRI), Dong Dok, Vientiane, Laos

[2] International Rice Research Institute, Los Baños, Philippines

*E-mail: montatip@laotel.com

KEYWORDS: FAO land evaluation methodology, Crop suitability, Agroecological zoning, GIS

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

suitable crops and developing optimum production systems for increasing the agricultural production on a sustainable basis.

The National Agriculture and Forestry Research Institute (NAFRI) with assistance from International Rice Research Institute (IRRI) and ACIAR project is now in the process of developing agro-ecological zone maps for land suitability assessment for the Lao PDR. This process using the FAO approach adopted here can serve as a model for establishing a coordinated, synergistic, and cost effective research and production agenda within a NAFRI-ACIAR context.

Approach and Methodology

An agro-climatic zone is a land unit term of major climates, suitable for a certain range of crops (FAO, 1996). An ecological zone is an area of the earth's surface characterized by distinct ecological responses to macroclimate as expressed by soils, vegetation, faunas and aquatic systems. Agroecological zones are derived from the agroclimatic region by taking into account other physical factors such as landformand soils.

The FAO approach to agro-ecological zoning (AEZ)

The FAO approach to agro-ecological zoning (AEZ) provides the procedure for small-scale crop suitability assessment based on climate and soil requirements for alternative land use types (i.e. crop, level of input, production type, etc.). It is simply a form of land inventory and semi-quantitative evaluation of land resources (FAO 1996). In this study we adopted the FAO AEZ methodology for evaluating suitability for major selected crops for the Lao PDR. The overall suitability of a crop is a combination of the soil suitability rating (Step 1 in Fig. 1) the agroclimatic suitability rating (Steps 2–6 in Fig. 1). The main steps of the methodology, which was implemented in a raster-based GIS include the following.

Climatic data from meteorological stations with long-term records were used to delineate the thermal and the length of growing period (LGP) zones (Steps 2 & 3).

The next step was to include data on soils. This information was used on the basis of the assessment of soil requirement of crops. The climate inventory was then combined with the soil map to produce the land inventory.

Calculations were then made of the maximum possible (i.e. constraint-free) yield of each crop in each LGP zone. This yield was then adjusted down to take account of agroclimatic constraints in each zone for each crop, including rainfall variability, pests, diseases and difficulty in harvesting. This adjusted anticipated crop yield, expressed as with a percentage of the constraint-free yield, is used to determine the agroclimatic rating (ACR) for the crop. The ACR for a crop is defined as very suitable, suitable and unsuitable if the anticipated crop yield is more than 80%, 40–80%, and less than 20% of the constraint-free yield, respectively.

The soil needs of each crop were then matched with the soil conditions prevailing in each grid cell, and the agroclimatic rating further downgraded if soil conditions were less than ideal. The combined ACR-soil rating, which constitutes the overall crop suitability assessment, was then mapped as very suitable, suitable, marginally suitable, or not suitable for the production of each crop. All these calculations were carried out for two different levels of farming inputs (high and low input levels). How crops are farmed (the amount of fertilizer used, the degree of mechanization, etc.) has an important bearing on both crop yield and the total area under which a crop can be grown.

Geographic Information System (GIS) implementation

In implementing the raster approach for evaluating for crop suitability, we employed the strategy of dual representation of the raster data structure (Kam and Hoanh, 1998). A collection of thematic map data layers may be represented either as geo-registered gridded map surfaces/images or as an array of records in a tabular data matrix, with each record representing a grid cell. The topological relationships of the grid cells are retained in the tabular form by geo-referencing each grid cell, i.e. including its raster file coordinates and/or the map coordinates of the grid nodes or the grid centroids. The tabular form can be linked with the image form by using coupling mechanisms that are provided or otherwise can be developed between GIS software and spreadsheet/ relational database management system (rdbms) software.

This dual representation of the raster data structure allows us to take advantage of the strengths of each form of representation for specific purposes in data handling, processing and manipulation. We make use of spatial analysis tools in the GIS to generate gridded surfaces, e.g. producing interpolated gridded climate and soil surfaces, displaying map outputs from analysis and modeling, and carrying out further spatial analysis of model outputs. On the other hand, the tabular equivalent of the raster map provides a compact and storage-efficient means of consolidating large numbers of map layers (e.g. time series climate surfaces at weekly intervals) into one or a few tabular

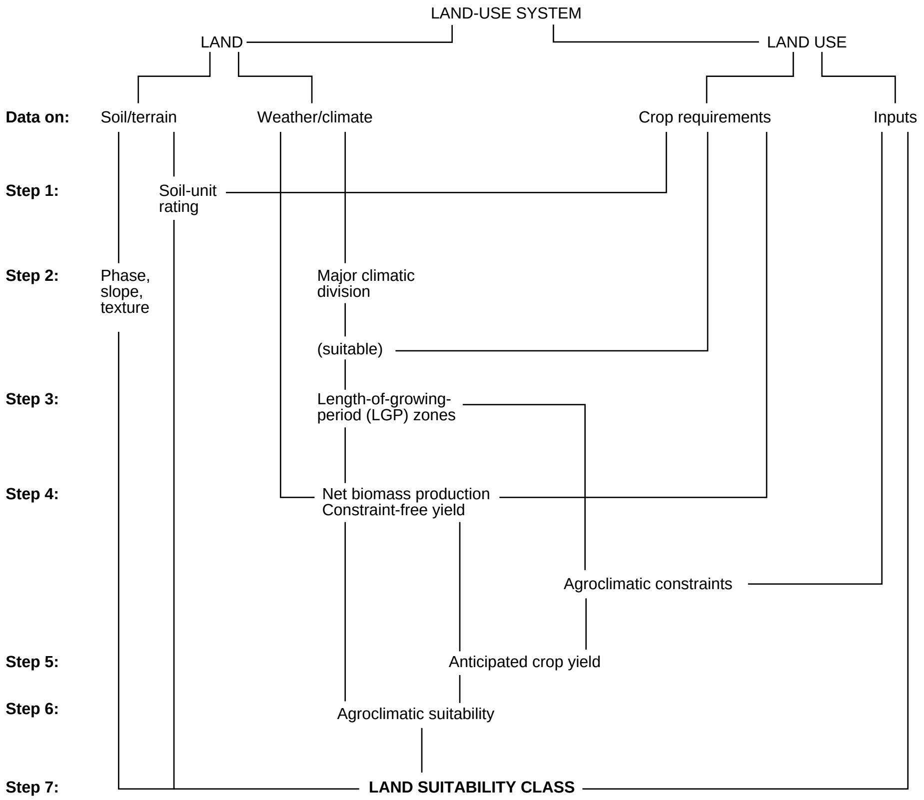


Figure 1. All agroecological zoning matching procedures in their relational context.

arrays/files. Each thematic layer is represented by one column or field in the matrix, which is implemented either in spreadsheets (e.g. Microsoft Excel) or in rdbms files (e.g. Microsoft Access). Once consolidated into a tabular array, we can take advantage of the powerful macro/programming and a wide range of other data analysis tools and extensions of the spreadsheet and rdbms software to handle complex computations for the AEZ model.

The model

The AEZ model, which was executed in Excel 97 using the macro programming language, was coupled with IDRISI, a raster-based GIS, and run on the input gridded surfaces for rainfall, potential evapotranspiration (PET), temperature(T24), radiation (Rg), water storage, soil condition and slope class. The outputs include estimates of constraint-free yield, anticipated yield and agro-ecological rating of each crop in each LGP zone for two levels of farm inputs. These output tables can be converted into raster files that can be imported into GIS for display and further GIS analysis. This model can be run in two modes: point-based and raster-based.

The data

Soil data

The system of soil classification used by the Soil Survey and Land Classification Center (SSLCC) in Vientiane (Phommasack,1993) was derived from the FAO/UNESCO's legend soil map of the world, revised legend showing 12 soil types and 38 soil units with scale 1/250,000. There are two categories: soil groups and subgroups (units). Classification is based on soil properties (diagnostic horizons and properties) observed in the field or inferred from those observations or on laboratory measurements (Phommasack and Vonghachack,1995).

A soil group consists of soils that are developed on similar materials and similar environmental conditions (physiography, topography, and slopes and drainage condition). Within a soil group, subgroups are differentiated according to the chemical-physical properties of soils and/or soil diagnostic properties.

Each soil unit is characterized by its 'internal properties' (depth, drainage class, texture class, inherent fertility, electrical conductivity, pH, CaCO3 content, and gypsum content), and by the 'external property' (slope angle).

This information was used in AEZ on the basis of assessment of soil requirements of crops, and the soil units were rated for each input level as suitable, marginally suitable or not suitable for growing each of the crops in the country.

Soil-unit rating

A comprehensive rating table was constructed by matching all tabulated soil-related crop requirements against the properties specified for each soil unit in the soil map of the Lao P.D.R. The Four (suitability) ratings were used:

S1—'very suitable' or 'suitable'
S2—'marginally suitable'
N1—'not suitable but limitations ameliorable'
N2—'not suitable with limitations of a permanent nature'

Table 1 lists the comparative suitability of some soil units for selected crops at high and low input levels.

Climate data

The four climatic variables used in AEZ model are rainfall, PET, temperature (T24) and radiation (Rg) of the 32 meteorological stations in the country having historical daily weather records. Five stations viz. Vientiane, Luangprabang, Pakse, Xayabouly and Savannakhet, had complete sets of variables needed for estimating rainfall, T24 and Rg with 14 years of data (1985–98). Thakher had 12 years of data (1987–98). Phonehong, Oudomxay, Saravan, Lak 42, Nikom 34 and Veunkham had 9 years of data. The data records for the remaining stations varied from 1 to 8 years.

The PET used in this AEZ model was estimated from data on sunshine hours, wind speed, minimum and maximum temperature, and minimum and maximum relative humidity obtained at selected meteorological stations of the Laotian Department of Meteorology and Hydrology.

Generating gridded climatic surfaces

In order to provide the spatial dimension and geographical coverage for the country, we used GIS tools to interpolate point-based climatic data to generate climate surfaces. The locations of the weather stations were digitized and checked for logical and geographical consistency. Geo-statistical techniques, namely variography and kriging (Goovaerts, 1997), were used to generate rainfall and PET surfaces at 5 km cell resolution using the data from 59 meteorological stations for rainfall and 56 stations for PET. The resulting maps at weekly time steps, i.e. 52 surfaces each of average weekly rainfall and PET, constituted the GIS input layers into AEZ model.

The main Components of the AEZ model:

Determine Length of Growing Period zones

The availability of water determines the 'length of growing period' of crops at a particular place. LGP is calculated as follows:

- The beginning of the possible growing period is arbitrarily set at the moment when the precipitation rate (PREC) first equals half the rate of potential evapotranspiration ($0.5*ET_0$) after a dry spell. A 'humid period' occurs whenever the precipitation rate exceeds the full rate of potentail evapotranspiration.
- The dry season towards the end of the growing period is considered to begin when the precipitation

Table 1. Example of soil unit ratings for AEZ.

Unit	Rice		Maize		Cassava		Sweet potato	
	Low input	High input	Low input	High input	Low input	High input	Low input	High input
Haplic Alisols(ALh)	S1	S1	S2	S1S2	S1	S1	S2	S1
Haplic Luvisols(LVh)	S1	S1	S1	S1	S1	S1	S1	S1
Haplic Acrisols(ACh)	S1	S1	S2	S1S2	S1	S1	S2	S1
Eutric Regosols(RGe)	S2	S2	S1	S1	S1	S1	S1	S1
Eutric Cambisols(CMe)	S1	S1	S1	S1	S1	S1	S1	S1
Eutric Fluvisols(FLe)	S1	S1	S1	S1	S1	S1	S1	S1
Dystric Regosols(RGd)	S2	S2	S2	S1	S2	S1	S2	S1
Ferric Alisols(ALf)	S2N2	S2N2	S2N2	S2	S2N2	S2N2	S2N2	S2N2
Ferric Luvisols(LVf)	S2N2	S2N2	S2	S1S2	S2N2	S2N2	S2N2	S2N2
Ferric Acrisols(ACf)	S2N2	S2N2	S2N2	S2	S2N2	S2N2	S2N2	S2N2

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

rate has become equal to or less than half the potential evapotranspiration rate.

- The possible growing period extends into the dry season and ends only after all available stored soil moisture has been depleted. The amount of available moisture is assumed equal to the precipitation surplus during the humid period with a maximum of 100 mm water storage for all soils which was taken from the output of water balance model (Kam, et al., 1999).

Compute net biomass production and constraint-free yield for selected crop

Net biomass production

The net biomass production (i.e. the maximum possible production of dry matter) is estimated by:

- defining the gross assimilate production as a function of solar irradiance, temperature, and physiological properties of the crop,
- correcting for losses of assimilates due to maintenance respiration,
- correcting for losses of assimilates due to growth respiration.

The constraint-free crop yield is computed by multiplying the net biomass production with the harvest index for the crop.

Gross assimilate production:

The gross assimilate production is calculated by matching measured global radiation against theoretically required (interception of) photosynthetically active radiation (PAR) for uninhibited production of assimilates. Table 2 presents the theoretical irradiance of PAR on clear days (Ac, in cal cm^{-2} d^{-1}), and the gross rate of assimilate production by a hypothetical reference crop (kg day^{-1}) on clear days(bc) and on overcast days(bo).

The time fraction of cloud cover

The time fraction of cloud cover can be directly measured or it can be inferred by comparing the irradiance measured with the theoretical irradiance. If it is assumed that the irradiance of PAR under an overcast sky amounts to 20% of that under a clear sky, the measured incoming PAR (taken as 50% of the total radiation measured) can be conceived as divided as follows.

$$fo = (Ac - 0.5*Rg)/0.8 * Ac$$

where

fo is time fraction of cloud cover (d d^{-1})

Ac is theoretical photosynthetically active radiation on a clear day (cal cm^{-2} d^{-1})

Rg is measured total incoming radiation (cal cm^{-2} d^{-1})

The gross rate of assimilate production by a hypothetical reference crop (with a permanently closed canopy and growing in the optimum temperature range) is:

$$bgm = fo * bo + (1 - fo) * bc$$

where

bgm is gross assimilation rate of reference crop (kg ha^{-1} d^{-1})

Table 2. Theoretical irradiance of photosynthetically active radiation on clear days (Ac, cal/cm^2.d), and daily gross assimilation rate (CH_2O, kg/ha.d) of the crop canopy on clear (Bc) and overcast (Bo) days for a reference crop with a closed canopy and a maximum assimilation rate of 20 kg/ha.

		15	15	15	15	15	15	15	15	15	15	15	15
N. Hemisphere		Jan	Feb	March	April	May	June	JuIy	Aug	Sept	Oct	Nov	Dec
S. Hemisphere		July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
0 degree	Ac	343	360	369	364	349	337	342	357	368	365	349	337
	Bc	413	424	429	426	417	410	413	422	429	427	418	410
	Bo	219	226	230	228	221	216	218	225	230	228	222	216
10 degree	Ac	299	332	359	375	377	374	375	377	369	345	311	291
	Bc	376	401	422	437	440	440	440	439	431	411	385	370
	Bo	197	212	225	234	236	235	236	235	230	218	203	193
20 degree	Ac	249	293	337	375	394	400	399	386	357	313	264	238
	Bc	334	371	407	439	460	468	465	451	425	387	348	325
	Bo	170	193	215	235	246	250	249	242	226	203	178	164
30 degree	Ac	191	245	303	363	400	417	411	381	333	270	210	179
	Bc	281	333	385	437	471	189	483	456	412	356	299	269
	Bo	137	168	200	232	251	261	258	243	266	182	148	130
40 degree	Ac	131	190	260	339	396	422	413	369	298	220	151	118
	Bc	218	283	353	427	480	506	497	455	390	314	241	204
	Bo	99	137	178	223	253	268	263	239	200	155	112	91

Real field crops

Real field crops differ from the hypothetical reference crop. Their maximum assimilation rate (Pmax) is not a steady 20kg ha^{-1} h^{-1}, but is different for different crop-adaptability groups and is also temperature-dependent (Table 3).

Table 3. Maximum assimilation rate (Pmax in kg/ha/h) as a function of the crop adaptability group and the daytime temperature (Tday). Source: Higgins and Kassam, 1981.

	Crop-adaptability Group	Maximum assimilation rate				
		Daytime temperature(C)				
		10	15	20	25	30
1	I	15	20	20	15	5
2	II	0	15	32.5	35	35
3	III	0	5	45	65	65
4	IV	5	45	65	65	65

This difference must be taken into account in calculations of the gross assimilation rate of real field crops (b_{gma}) using the equation below:

$$b_{gma} = (fo * bo) * (1 + 0.2 * y) + (1 - fo) * bc *(1 + 0.5 * y) \quad (4.3)$$

with

$$y = (P_{max} - 20)/20 \quad (4.31)$$

where

b_{gma} is gross assimilation rate of field crop with closed canopy at maximum growth and constant assimilation rate P_{max} (kg ha^{-1} d^{-1})

y is a factor for the difference between the momentary maximum assimilation rate of a field crop (P_{max}) and the fixed maximum assimilation rate of the reference crop (20 kg ha^{-1} h^{-1})

P_{max} is maximum assimilation rate of field crop (kg ha^{-1} h^{-1})

The net rate of assimilate production by a field crop (with a closed canopy at the time of maximum growth) is found by reducing b_{gma} by the rate at which assimilates are lost by respiration.

Losses by maintenance respiration differ among crops and are temperature dependent. The FAO AEZ set C_{30}, the rate of maintenance respiration at 30°C, to 0.0283 kg kg^{-1} d^{-1} for leguminous crops and 0.0108 kg kg^{-1} d^{-1} for non-legumes. They suggested a quadratic relation to describe the temperature dependence of the maintenance respiration rate:

$$C_t = C_{30} * (0.044 + (0.0019°C^{-1}) * T_{24h} + (0.001\,^{o}C^{-1}) * T_{24h}{}^2) \quad (4.5)$$

where

C_t is mass fraction of gross assimilate production (as CH_2O)lost through maintenance respiration with respiration with respect to dry crop mass at temperature T_{24h}(kg kg^{-1} d^{-1})

C_{30} is rate of loss of gross assimilate production by maintenance respiration at 30°C, set to 0.0283 kg kg^{-1} d^{-1} for leguminous crops and at 0.0108 kg kg^{-1} d^{-1} for non-legumes.

T_{24h} is average temperature (24-hour mean) over the growth cycle (°C).

Losses of assimilates by growth respiration are estimated at 0.28 kg kg^{-1} for all crops and at any temperature: the production of structural plant matter amounts to 72% of the net production of assimilates. In other words, the conversion efficiency (Ec) is assumed to be 0.72.

A full closed canopy corresponds to a 'leaf surface to ground surface ratio' of 5.0 or greater. The 'leaf surface to ground surface ratio' is known as the leaf area index (LAI). If the canopy of the field crop does not fully cover the ground surface at the time of maximum growth (e.g because of a low planting density), the calculated net biomass production needs correction. Figure 2 presents a correction factor (L_m) to adjust calculated net biomass production for incomplete ground cover (i.e LAI less than 5.0) at the time of maximum growth.

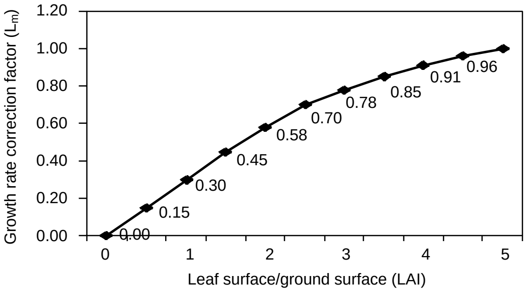


Figure 2. Correction factor for incomplete ground cover (L_m) as a function of the leaf area index (LAI) at the time of the crop's maximum growth.

A generally applicable expression of the potential net biomass production of 'major crop' (B_{na}) would thus be:

$$B_{na} = 0.36 * b_{gma} * Ng *Lm/(1 + 0.36 * C_t * Ng)$$

where

Bna is potential net production of dry matter by field crop (kg ha^{-1})

b_{gma} is overall gross rate assimilate production (kg ha^{-1} d^{-1})

Ng is length of growing cycle (d)

Lm is correction factor for incomplete ground cover

Ct is rate of loss of bgma by maintenance respiration at actual temperature (kg kg^{-1} d^{-1})

0.36 is half the conversion efficiency (= 0.5 * Ec)

Only part of the total net biomass production is of economic value, and is harvested as produce. The constraint-free crop yield (b_{yu}) is calculated by multiplying the net biomass production by the harvest index (hi) for the crop. Table 4 lists the hi values for selected crops.

Table 4. Indicative harvest index (hi) of high-yielding varieties of major crops under rainfed condition.

Crop adaptability Group		Harvest index (hi)
I	wheat (bread and durum wheat)	0.40
	white potato	0.60
	phaseolus bean (temperate and trop. Highland. cvv.)	0.30
II	phaseolus bean (tropical cvv.)	0.30
	soya	0.35
	rice	0.30
	cotton	0.07
	sweet potato	0.55
	cassava	0.55
III	pearl millet	0.25
	sorghum (tropical cvv.)	0.25
	maize (tropical cvv.)	0.35
IV	sugar-cane (sugar at 100E 12% of fresh cane)	0.25
	sorghum (temperate and trop. Highland cvv.)	0.25
	maize (temperate and trop. Highland cvv.)	0.35

The constraint-free crop yield amounts to:

$$B_{yu} = B_{na} * hi$$

where

B_{yu} is constraint free yield (kg ha^{-1})

hi is harvest index (0–1)

Determine anticipated yield based on LGP and yield reducing factors

The net biomass production and constraint-free yield indicate the potential performance of crops because they are determined solely by the average temperature and radiation regimes of the site during cropping. No consideration was given to agro-climatic constraints imposed by rainfall variability, climate-related pests and diseases, and impeded workability or harvesting. Such constraints need to be considered if one wishes to establish anticipated crop yields for the various LGP zones.

Group of agro-climatic constraints are expressed in terms of reduction ratings on an ordinal scale to reflect the severity of constraints in each LGP zone for each level of input. Four groups of constraints are recognized.

(a) constraints resulting from moisture stress during the growing period
(b) constraints concerning yield losses due to pests, diseases and weeds
(c) constraints concerning factors affecting yield formation and quality
(d) constraints arising from difficult workability and handling of produce.

The severity of a particular group of constraints is rated as follows:

Rating 0: slight constraint, if any, causing no significant yield loss
Rating 1: moderate constraints, resulting in yield losses of 25%
Rating 2: severe constraint, resulting in yield losses of 50%.

The anticipated crop yield is obtained with a relative loss inventory to a reference yield level. The calculated constraints-free crop yield is used as the reference yield for high-input level. The yield reference for low–input farming was arbitrarily set at 25% of the calculated constraint-free yield.

Note that the reductions from reference yield to anticipated yield are made consecutively according to the presence (or absence) of constraints and the severity of their occurrence for each crop, in each LGP zone and at each level of input.

Table 5 is an excerpt from the comprehensive inventory of likely agro-climatic constraints to maize in the major climatic division of tropical and subtropical (summer rainfall) areas, differentiated by LGP zone and level of input.

Table 5. Severity of Agro-climatic constraints to maize in tropical and subtropical areas with summer rainfall. Source: FAO, 1978.

LGP(d)	Ratings		
	low-input (abcd)	high-input (abcd)	
75–80	2120	2020	Rainfall variability
90–119	2110	2010	Silk drying
120–149	1100	1000	
150–179	0000	0000	
180–209	0000	0000	
210–239	0100	0001	
240–269	0101	0002	
270–299	0101	0102	Borers
300–329	0101	0102	Leaf-spot, leaf-blight
330–364	0112	0112	Streak virus, wet produce
365	0222	0222	Workability

Note:
a constraints resulting from moisture stress during the growing period
b constraints concerning yield losses due to pests, diseases and weeds
c constraints concerning factors affecting yield formation and quality
d constraints arising from difficult workability and handling of produce.

Compute Agro-climatic rating (ACR)

The ratio of the anticipated crop yield and the reference crop yield is an expression of the impact of agro-climatic constraints on cropping (at high or low input). Four agro-climatic suitability classes are distinguished.

VS	Very Suitable. The anticipated yield amounts to 80% or more of the reference yield at the specified input.
S	Suitable. The anticipated yield is between 40 and 80% of the reference yield.
MS	Marginally. The anticipated yield is between 20 and 40% of the reference yield at the specified input.
NS	Not Suitable. The anticipated yield amounts to 20% or less of the reference yield at the specified input.

The agro-climatic suitability classification is combined with the soil unit rating using the following rules:

- The land suitability class is the same as the agro-climatic suitability class if the soil-unit rating is S1.
- The land suitability class is one class lower than the agro-climatic suitability class if the soil-unit rating is S2.
- Soil-unit rating N1 and N2 imply that the land suitability class is NS.

Once the modifications for soil-unit rating have been made, the land suitability assessment is further adjusted to account for limitations imposed by the slope of the land and the texture designation of the mapping unit according to the rules discussed above.

For example, for each crop the soil units themselves are rated as suitable (S1) if the soil has no or only minor limitation to production, marginally suitable (S2) if production is affected markedly, and not suitable if crop production is not possible or very limited. The S1 soil rating does not affect agroclimatic suitability. A crop grown on S2 soil has its agroclimatic suitability downgraded by one class, for example from suitable to marginally suitable.

Results and discussion

The results of AEZ study are presented in the map of Agro-ecological zoning for major crops widely grown in the Lao P.D.R. This will help the policy makers have an overall viewpoint on area and will also be very helpful to recast an effective and alternate land use plan for optimum production systems for increasing the agricultural production on a sustainable basis.

Figure 3 shows the mapped Agro-ecological rating for lowland rice and maize, assuming a low level of farming inputs.

Geographic Information System, used in conjunction with the FAO Methodology for Agro-ecological Zoning, is a powerful tool to map and evaluate land suitability using available data. The mapped outputs can be used for determining crop management strategies for the Lao P.D.R.

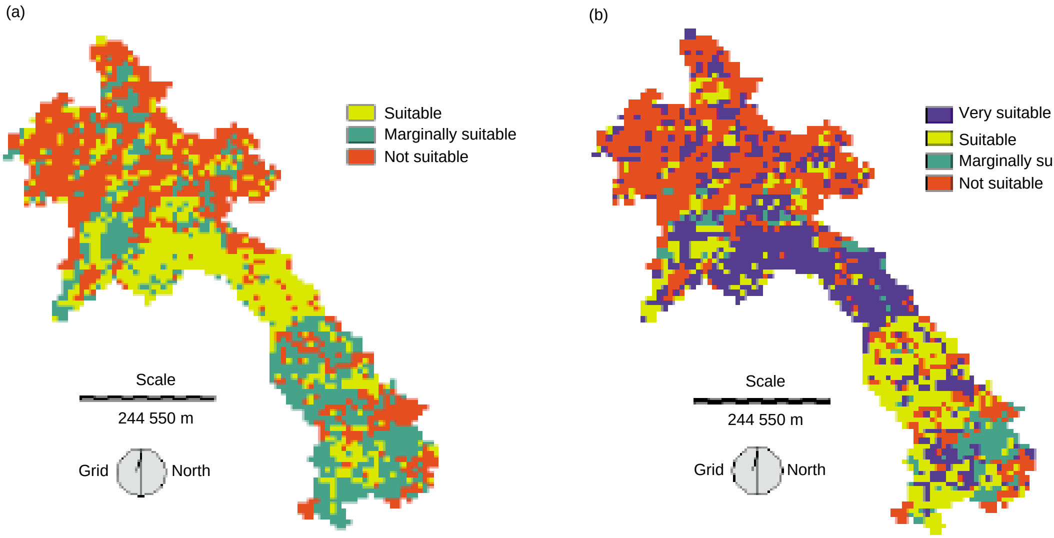


Figure 3. Agroecological rating for (a) rainfed lowland rice, and (b) maize, assuming a low level of farming inputs.

However, there are some drawbacks, the most severe being that time series data for rainfall, temperature and radiation are not available for continuous years over a common time period. The common period is less than 15 continuous years for many stations (Khounphonh et al., 2001). The spatial interpolation technique to generate gridded surface of long term average weekly rainfall, evapotranspiration and radiation were used on meteorological data in within country and only a few stations on surrounding countries.

Although the agro-ecological zoning for crop assessment model has been developed recently, there are still some problems that limit its use. First, although the agronomic data and other observations of crop performance are essential for classifying agro-ecological zoning for crop suitability, they have been used to a limited extent for developing the system. The reason is that there are not so many rigorous research investigations on crop response to conditions in the Lao PDR. Second, there is lack of local information on the effects of yield reducing factors such as rainfall variability, pest, diseases and the difficulties of harvest, which is needed to estimate anticipated crop yield.

Conclusion

In this paper, we have attempted to describe how a simple implementation of the FAO Methodology for Agro-ecological Zoning for Crop Suitability linked with GIS can be used for assessment of the potential agricultural use of the Lao PDR. The role of GIS is in generating spatially coherent input maps into the model as well as for providing tools for spatial display in addition to spatial analysis and interpretation of model results. The model is intentionally designed to be able to utilize minimum data sets that are likely to be available in the country, e.g. long-term average climatic data at weekly rather than daily time steps.

The results of this study provide the basic information for agriculture planning at the country level. However, the improving of climatic data (rainfall, evapotranspiration . . . etc. with standard time period of years) and soil data are essential input into the model.

References

Fao, 1978. Agroclimatology data for Asia. Vol 1 and 2. FAO Plant Production and Protection Series 23. Rome, 1978.

Fao, 1996. Agro-ecological zoning guidelines food and agriculture organization of the united nations. Rome, 1996.

Goovaerts, P. 1997. *Geostatistics for natural resources evaluation.* Oxford University Press, New York.

Higgins, G.M. and Kassam, A.H., 1981. Regional assessments of land potential: a follow-up to the FAO/Unesco Soil Map of the World. Nat-Resour. Paris, UNESCO. Oct/Dec 1981. v. 17 (4) p. 11–23.

Kam, S.P., and Hoanh, C.T. 1998. Implementing GIS in a decision support system for analyzing the balance between rice supply and demand. Proceedings of the Fourth Seminar on GIS and Developing Countries GIS-DECO ’98, Pretoria, South Africa.

Kam, S.P., Tuong, T.P., Bouman, B., Fajardo, S. and Peyes, J.P. 1999. Regional water balance study for selecting crop establishment methods and crop duration in rainfed lowland rice in Northeast Thailand. Paper presented at the International Workshop on Characterizing and Understanding Rainfed Rice Environments. 6–10 December, 1999. Bali, Indonesia.

Khounphonh, K., Phytoon, Basnayake, J., Fukai, S., Linquist, B., Chanphenxey, M. 2001. Climate data for agro-climatic characterization in Laos. (ACIAR proceedings, this volume)

Phommasack, T. and Vonghachack, S., 1995. Qualitative Land Evaluations. Soil survey and Land Classification Center (SSLCC), 1995.

Phommasack, T., 1993. Methodology of soil Survey and Land Classification. Soil survey and Land Classification Center (SSLCC).

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

A GIS-Based Crop-Modelling Approach to Evaluating the Productivity of Rainfed Lowland Paddy in North-East Thailand

Y. Kono[1*], S. Tomita[2], Y. Nagata[3], K. Iwama[4], E. Nawata[2], K. Junthotai[5], R. Katawatin[5], K. Kyuma[4], S. Miyagawa[6], T. Niren[4], C. Noichana[5], T. Sakuratani[2], A. Sributta[5], and K. Watanabe[2]

Abstract

This study aims to develop a method for evaluating the productivity of rainfed agriculture at the regional level. The major method is GIS-based crop modelling, which is applied to lowland paddy in North-East Thailand. We estimated and mapped the potential yields and attainable yields under water limitations. Water-limited yields were found to be affected by not only rainfall but also by macro- and micro-scale topography and soil characteristics, reflecting the complexity of the water environment. The overall outcome of potential and water-limited yield estimates satisfactorily fitted the empirically understood conditions of the region, although some minor modifications of the model were still required. Our results indicated that the GIS-based crop-modelling approach is effective for evaluating the regional-level productivity of rainfed agriculture.

Introduction

This study aims to develop a methodology for evaluating the productivity of rainfed lowland paddy. The basic idea was to evaluate the productivity of an existing agricultural production system by means of comparing it with its potential productivity.

The importance of this viewpoint is clearly understood when we think about food security in the future. The world population is expected to reach between 10 and 15 billion in the middle of the next century, and food production will therefore have to be increased. This raises the questions of where and how we can increase it. Sustainable land-use planning is another crucial issue that we are now facing, and we need to reserve some lands for environmental purposes such as biodiversity and forest resources conservation. Where should we stop food production and begin allocating lands for environmental conservation?

Economic analysis is the most popular approach to these questions. We can estimate the costs and benefits of expanding agricultural lands and intensifying current agricultural systems for food security analysis, and the costs and benefits of land use for agricultural and environmental purposes for environmental conservation analysis. These economic analyses give us a clear idea of economically rational agricultural development and land use planning, although the cost-and-benefit evaluation still includes arbitrary processes. A weak point of these economic analyses is that results depend entirely on

---

[1] Center for Southeast Asian Studies, Kyoto University, Japan
[2] Graduate School of Agriculture, Kyoto University, Japan
[3] Media Center, Osaka City University, Japan
[4] School of Environmental Science, The University of Shiga Prefecture, Japan
[5] Faculty of Agriculture, Khon Kaen University, Thailand;
[6] Faculty of Agriculture, Gifu University, Japan
*Corresponding author: Yasuyuki Kono
E-mail: kono@cseas. kyoto-u.ac.jp

KEYWORDS: Crop modelling, Geographic information system, Land productivity, Lowland paddy, North-East Thailand, Potential productivity, Rainfed agriculture

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

the price of related goods and labour, and these prices, of course, fluctuate over time and from region to region. The economic approach is, therefore, effective for analysing the current situation and is suitable for short-term planning, but it is unsuitable for long-term planning and cross-regional analyses.

This study uses an agricultural scientific approach, which, even though lacks integrated perspectives for agricultural and land use analyses and focuses only on limited aspects, has the advantages of stability and objectivity of evaluation and of being more suited for application to long-term and cross-regional analyses. Potentiality of land use and the gap between current and potential productivity, which this study will evaluate, should provide a key standard for scientific and fair discussion on such issues as food security and environmental conservation.

Many methods for evaluating land productivity have been proposed, both at the global and continental levels, and at the individual farm level. The latter were mostly proposed by crop scientists, and the former have recently been explored by remote-sensing specialists. In most cases, global models have developed under sweeping assumptions and simplified local conditions. They show global trends, but the results are difficult to validate. While these models can provide warnings, their outcomes are difficult to apply directly to regional and local policy making. In contrast, farm-level models carefully follow the physiological processes of crop growth and can simulate the effects of changes in production environment and technique. But they need detailed parameters of crop characteristics and inputs from the natural setting, which results in low applicability. A wide gap separates the models at the two levels, and knowledge accumulated on one side is not fully used on the other side.

This study, therefore, tries to bridge the two levels. Our target is to evaluate regional productivity, for which both quantitative analysis of agricultural production and mechanistic analysis of crop growth and cultivation techniques must be considered. Land productivity is evaluated in terms of potential and water-limited attainable yields. The former is limited only by temperature and solar radiation, whereas the latter is also limited by water availability. Rainfed agriculture is still widespread in monsoon Asia. The increasing demand for fresh water by industries and urban populations will limit expansion of irrigated land, making the extensive replacement of rainfed by irrigated agriculture difficult. Anticipated climatic changes are also expected to affect rainfed agriculture severely. For these reasons, we focus particularly on water-limited rainfed lowland paddy.

Study Area

We studied the whole of North-East Thailand, an area of about 160 000 km^2 and occupying one third of Thailand's territory. The topography of the study area is gently undulating, with altitudes between 150 and 200 m above mean sea level. Three large tributaries of the Mekong River—the Mun, Chi and Songkhram Rivers—flow in an easterly direction across the area to the Mekong. The alluvial plains of these rivers are narrow, and most of the land has an erosional geomorphic surface. Annual rainfall ranges between 900 and 2200 mm, being lower in the south-west and higher in the north-east (Figure 1).

The dominant mode of agriculture is the single cropping of rainfed lowland paddy, which occupies about 70% of the total agricultural land. Irrigated lands are distributed only along the major rivers. Rainfed paddy production is unstable because of large year-to-year fluctuations and erratic seasonal distribution of rainfall. Paddy yields average 1.5 t ha^{-1} for the whole study area, but they vary widely from year to year and place to place. They are even affected by micro-topography and show substantial differences within the same toposequence (Fukui 1993; Homma et al. 1999).

Methodology

Overall framework

A combination of a geographic information system (GIS) and crop modelling was adopted as the framework on which to build the method for evaluating the productivity of rainfed lowland paddy (Kono et al. 1999). First, a source GIS was prepared, which included the natural conditions and the current agricultural production. Second, a crop model was developed, based on the results of field experiments and validated by the results of field monitoring. The crop model had three modules—water, planting schedule and yield—and estimated potential and water-limited attainable yields. Third, by incorporating the estimates, an integrated GIS of land productivity was created, and all results mapped.

Data collection

Land and climatic conditions

Available sources of information on land conditions are a topographic map at the scale of 1:50 000, a soil map at the scale of 1:100 000 and a land-suitability map at the scale of 1:50 000. The soil map and the land-suitability map were made by the Department of Land Development, Thailand, and are based on the same information. Although both include information not only on soil but also on landform, the soil

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

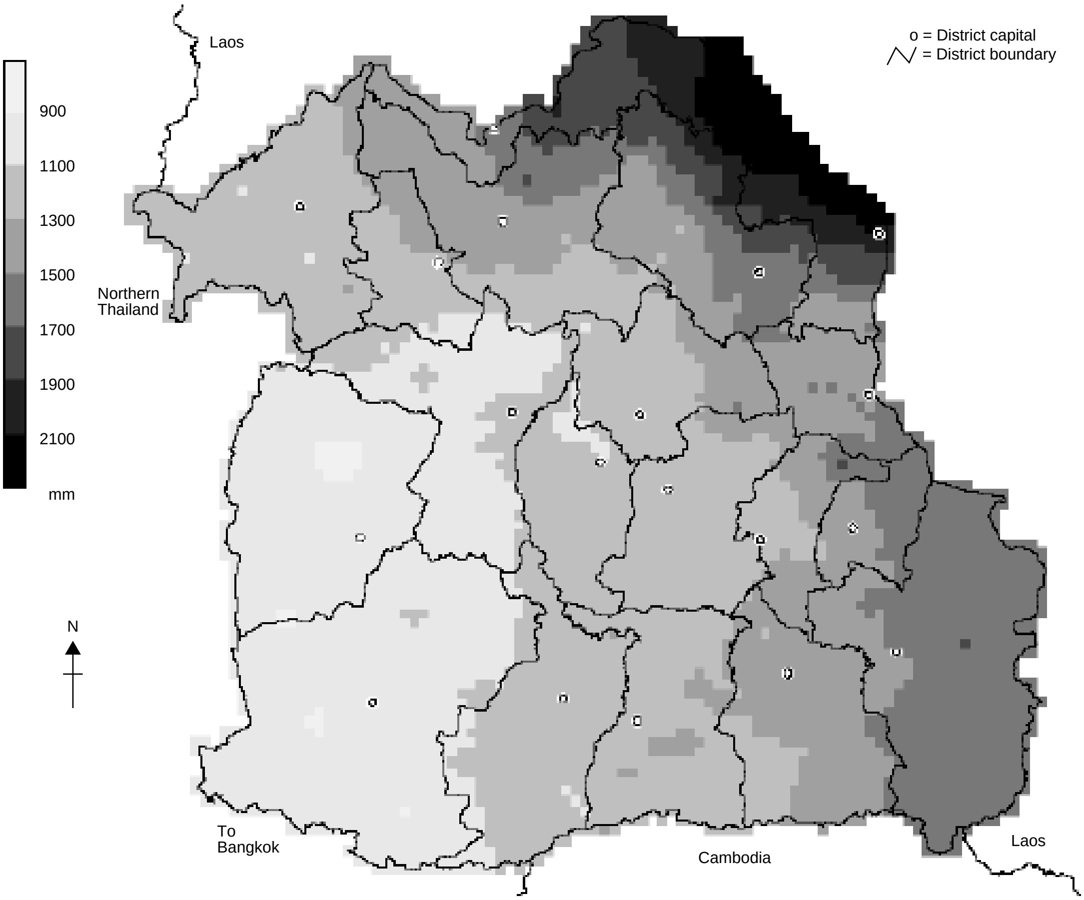


Figure 1. Average annual rainfall, North-East Thailand.

map was selected as the major source for our study because it could be easily digitized.

Climatic data were obtained from the Meteorological Department, Thailand. These included daily rainfall at 327 stations; mean, maximum and minimum temperatures at 77 stations; sunshine duration at 6 stations during 1951 to 1998; and daily cloud cover at 10 stations during 1982 to 1998. After the data was carefully screened, 3-minute-mesh data sets of rainfall, temperature and solar radiation of the whole area were created by interpolating the observed data, of which solar radiation was estimated from sunshine duration. These data sets were on a daily basis and covered 20 years, from 1979 to 1998.

Field experiments, field monitoring and questionnaire survey

Field experiments were carried out for 3 years, from 1996 to 1998, at the Ubon Rice Research Center. The dominant nonglutinous variety in the study area, 'Khao Dok Mali 105', was selected for the present study. These experiments provided a set of parameters for the crop model (Table 1).

Field monitoring was conducted in 161 farmers' paddy fields scattered all over the study area and covering areas with different land and climatic conditions. Twenty-seven fields were surveyed for 4 years from 1996 to 1999, and the remainder were

Table 1. Set of crop-related parameters obtained from field experiments, North-East Thailand.

Parameter		Unit	Value
Abbreviation	Definition		
N_{min}	Nitrogen mineralization rate	g m^{-2}	0.028
GFP	Grain-filling period	day	30
RUE_{max}	Maximum radiation-use efficiency	g MJ^{-1}	1.534
N_c	Critical leaf nitrogen concentration for RUE	g m^{-2}	1.497
R_m	Maintenance respiration rate at 27°C	g g^{-1}	0.003775
HI	Harvest index		0.4

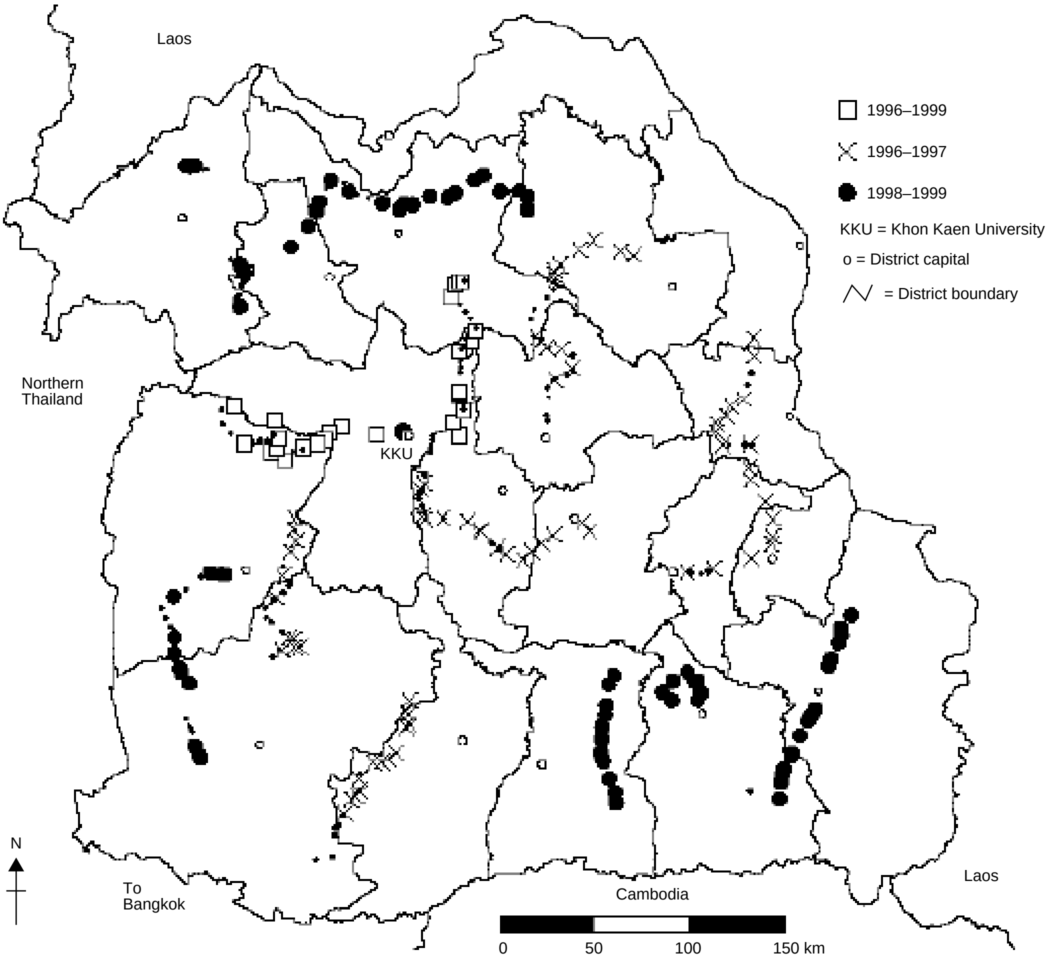


Figure 2. Study area and locations of surveyed plots, North-East Thailand.

surveyed either in the first 2 years or in the second 2 years (Figure 2). We visited each field every 3 weeks throughout the year and observed water conditions, crop growth, crop damage, weed incidence and cultivation progress. Every time, soil samples were taken at depths of 20 and 50 cm and soil moisture contents were measured. Digital photos of crops were also taken and filed for visual monitoring of crop growth (http://huapli.media.osaka-cu.ac.jp/mapnet/archives/) (Nagata 2000). Paddy yields were surveyed by quadrat sampling and measuring yield components. Physical and chemical properties of soil were measured in 42 representative fields. A questionnaire was administered to farmers to obtain information on year-to-year changes in production, cultivation techniques, land use history and farm economy.

Another questionnaire survey on agricultural production was also sent to all subdistrict agricultural extension officers (known as *kaset tambol*), in cooperation with the North-East Regional Agricultural Extension Office (NERAEO) and the Center of Excellence (COE) project of the Center for Southeast Asian Studies, Kyoto University (NERAEO and MAPNET 2000). We received a 100% response after repeated contacts with officers. Questions were on area planted and harvested, variety, planting method, fertilizer application, agricultural chemicals and yields of paddy, cassava, sugar cane and maize.

Paddy field distribution and GIS

Satellite image analysis is becoming a major method for identifying land cover and use. We therefore tried it for the Khon Kaen and Yasothon Provinces (Niren and Iwama 1999) but, so far, results are unsatisfactory. Generally speaking, paddy fields were underestimated and upland fields overestimated. One reason is that obtaining clear images in the rainy

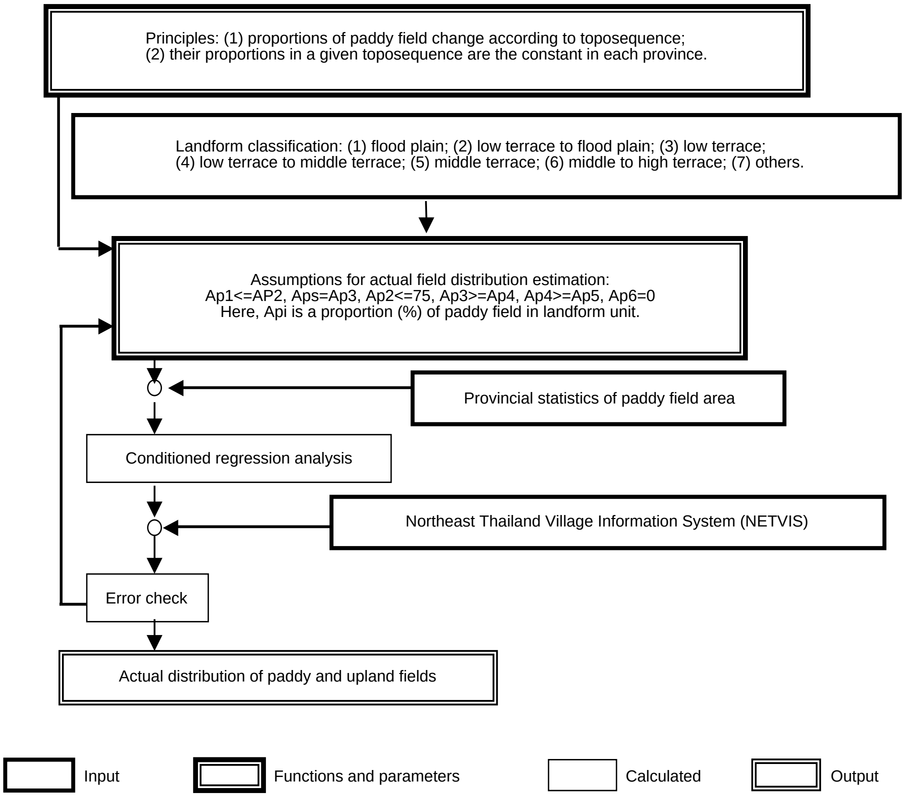


Figure 3. Flow chart for estimating paddy field distribution in North-East Thailand.

season, when crops are in the field, is almost impossible, so we have to use images from the dry season. Another reason is that most of North-East Thailand is covered by an erosional geomorphic surface. Geomorphic formation of land is highly correlated to land cover and use in alluvial plains, so that land cover classification is accurate, even when off-season satellite images are used. But this correlation becomes weak with erosional surfaces, resulting in a less accurate satellite image analysis when dry-season images are used.

The current paddy field distribution was, therefore, empirically estimated from data on landform, agricultural statistics and the North-East Thailand Village Information System (Figure 3) (Nagata 1996). The results with the spatial unit of a 3-minute mesh, which is equal to a 5-km square, show that the proportion of paddy fields in almost all areas of the Chi–Mun Basin is 40% to 70%, whereas it is 20% to 50% in the Songkhram Basin (Figure 4). The western area of the region shows a much lower proportion of paddy fields, reflecting its mountain-dominated topography.

Finally, a source GIS database was created to include information of land, climate, agricultural production and administration (Table 2).

Crop modelling

Water module

The water module simulates daily soil moisture content from daily climatic records (Figure 5). First, paddy fields were classified by land type, then

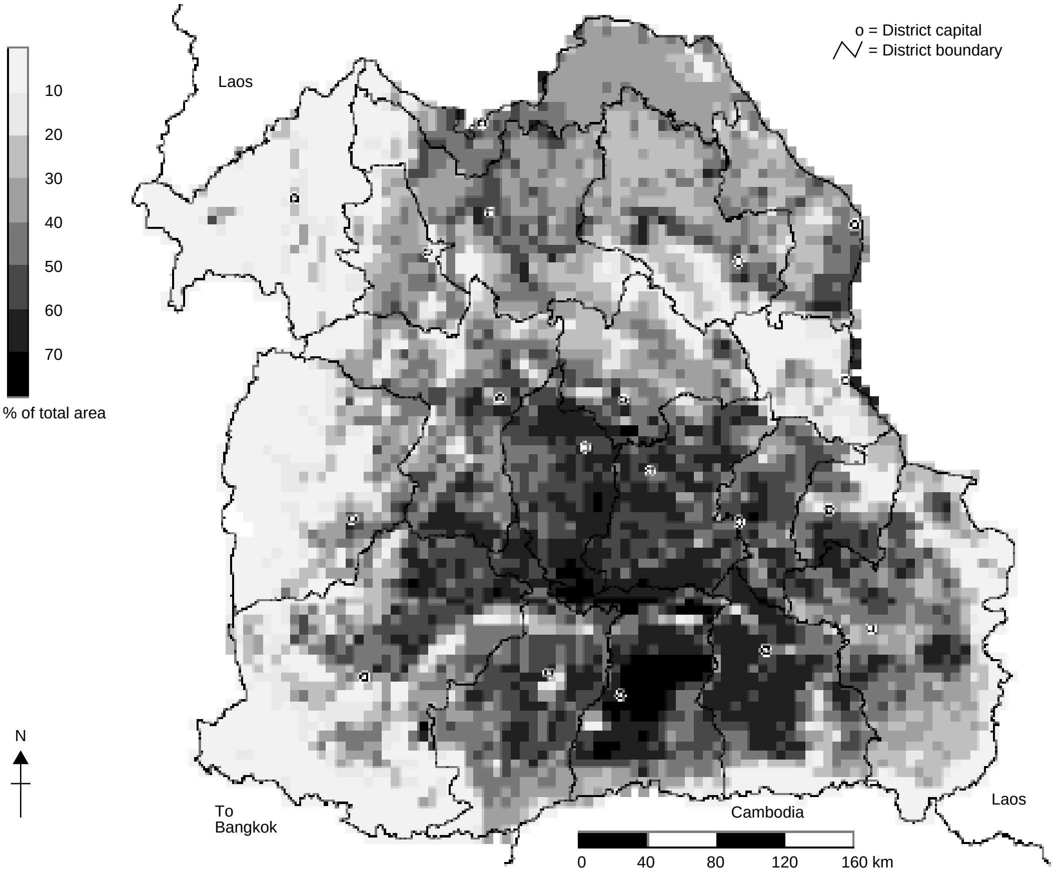


Figure 4. Estimated paddy field distribution in North-East Thailand.

Table 2. GIS layers for including information related to rainfed agriculture in North-East Thailand.

Category	Contents	Type of data	Original scale	Data source
Land	Soil series	Vector	1:100 000	DLD[a]
Climate	Daily temperature (1979–1998)			
	Daily solar radiation (1979–1998)	3-minute mesh		Estimated from MD[b] data
	Daily rainfall (1979–1998)			
Administration	Location of provincial capital	Vector	1:50 000	
	Boundaries of province, district and subdistrict	Vector	1:50 000	
Agricultural production	Area and yield of paddy, sugar cane and cassava	Vector	Province and district level	Agricultural statistics[c]
	Cropping calendar of paddy (1993–1996)	Vector	District level	NERAEO[d]
1997 cultivation	Various items of paddy, cassava and sugar cane cultivation	Vector	Subdistrict level	Original
Field distribution	Paddy field	3-minute mesh		Original

[a] Department of Land Development (DLD), Thailand.
[b] Meteorological Department (MD), Thailand.
[c] Published by Office of Agricultural Economics, Thailand.
[d] North-East Regional Agricultural Extension Office (NERAEO).

Table 3. Parameters given to each land type found in North-East Thailand.

Code	Land type			Coefficient of surface runoff/ run-in	Effective soil depth (mm)	Maximum water depth (mm)	Percolation and capillary rise rate (mm day^{-1})	
	Landform	Soil texture	Soil depth				pF = 1.8	pF = 3.0
1	Flood plain	Loamy to clayey	Deep	1.45	200	600	0	–0.3
2	Low surface	Sandy	Deep	1.3	200	600	2	–0.3
3	Low surface	Loamy	Medium to deep	1.3	200	400	1	–0.3
4	Low surface	Clayey	Shallow	1.3	100	200	1	0
5	Low surface	Clayey	Medium to deep	1.3	200	400	0	–0.3
6	Middle surface	Sandy	Deep	1.0	200	600	5	–0.3
7	Middle surface	Loamy	Shallow	1.0	100	200	5	0
8	Middle surface	Loamy	Medium	1.0	200	400	4	0
9	Middle surface	Loamy	Deep	1.0	200	600	4	–0.3
10	Middle surface	Clayey	Shallow	1.0	100	200	6	0
11	Middle surface	Clayey	Deep	1.0	200	600	3	–0.3
12	High surface	Sandy	Shallow	0.9	100	200	8	0
13	High surface	Sandy	Deep	0.9	200	600	8	–0.3
14	High surface	Loamy	Shallow	0.9	100	200	7	0
15	High surface	Loamy	Medium	0.9	200	400	7	0
16	High surface	Loamy	Deep	0.9	200	600	7	–0.3
17	High surface	Clayey	Shallow	0.9	100	200	6	0
18	High surface	Clayey	Medium	0.9	200	400	6	0
19	High surface	Clayey	Deep	0.9	200	600	6	–0.3
20	Mountain and rock	Loamy to clayey	Shallow to deep	—	—	—	—	—
21	No data							

parameters related to topography and soil were assigned to each land type.

In the soil map, North-East Thailand is divided into 373 soil series from the viewpoint of landform and soil property. Because the number of soil series is too large to provide different sets of parameters for each soil series, we had to simplify the soil series. To do so, we selected landform, soil texture, soil depth and kind of clay mineral as the representative indices of the study area's land conditions and the physical and chemical properties of its soils.

The Department of Land Development has criteria to evaluate these properties, resulting in lands being first classified into 97 types. This number is still too large for further analysis. We therefore modified the criteria as follows: first, the Department criteria classifies clay minerals into three classes, montmorillonite, non-montmorillonite and no data, of which

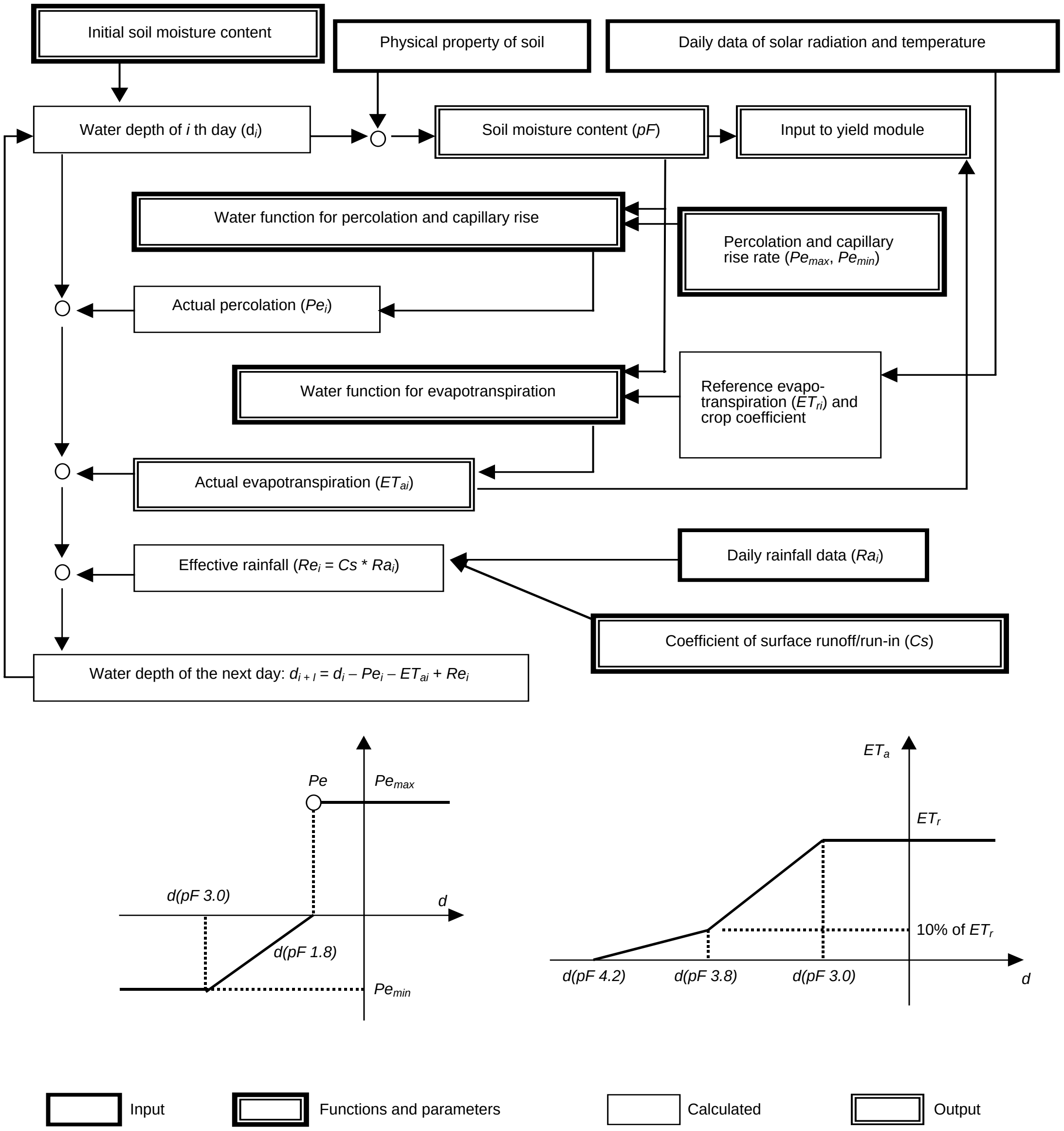


Figure 5. Flow chart of the water module used for crop modelling.

montmorillonite occupies only 0.4% of the total area and non-montmorillonite occupies 84%. This indicates that this criterion does not have substantial meaning, so it was omitted from the indices. Second, the numbers of classes of landform, soil texture and soil depth were reduced, respectively, from 9 to 5, 9 to 4 and 6 to 4. When the new criteria were applied, the soil series were classified into 21 land types (Table 3).

Then, parameters of coefficient of surface runoff/run-in, effective soil depth, maximum water depth and percolation and capillary rise rate were assigned to each land type. After repeated trial and error, they were fixed as shown in Table 3. A constant effective soil depth throughout the growing period does not take into account that the rice plant's rooting depth varies during growth and by physiological stress.

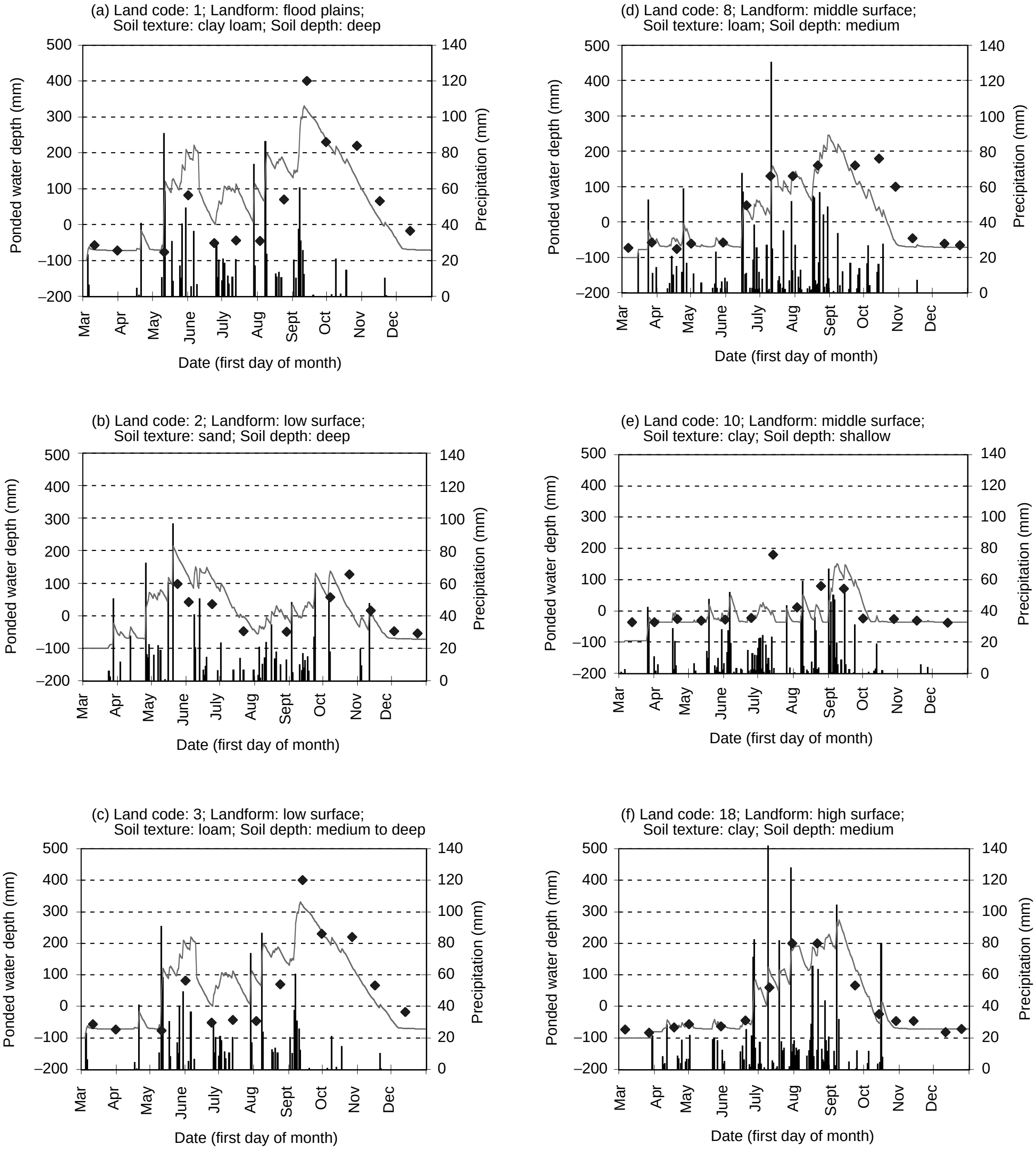


Figure 6. Estimated water conditions compared with observed conditions in North-East Thailand. —— = estimated value; ◆ = observed value; ▬ precipitation.

Two water functions were also assigned. The water function for percolation and capillary rise describes the relationship between soil moisture content and vertical movement of soil moisture. The water function for evapotranspiration describes the relationship between soil moisture content and the ratio of actual evapotranspiration to reference evapotranspiration. These functions were also tested against the results of field monitoring.

Using these parameters and functions, soil moisture content or ponded water depth was simulated on a daily basis. The results of estimation show a wide range of variation by land type as well as climatic conditions. They were satisfactory when fields were not submerged, but included large errors when fields were deeply submerged (Figure 6). One cause of these errors was probably inaccurate measuring of water depths at field monitoring. However, these errors do not significantly affect the occurrence of water stress and yield estimation.

Planting schedule module

The planting schedule module estimates the date of transplanting. Transplanting is the prevalent method of planting paddy, although dry seeding has spread since the early 1990s as a result of the country's rapid economic growth and labour migration from the study area to Bangkok and its suburbs (Konchan and

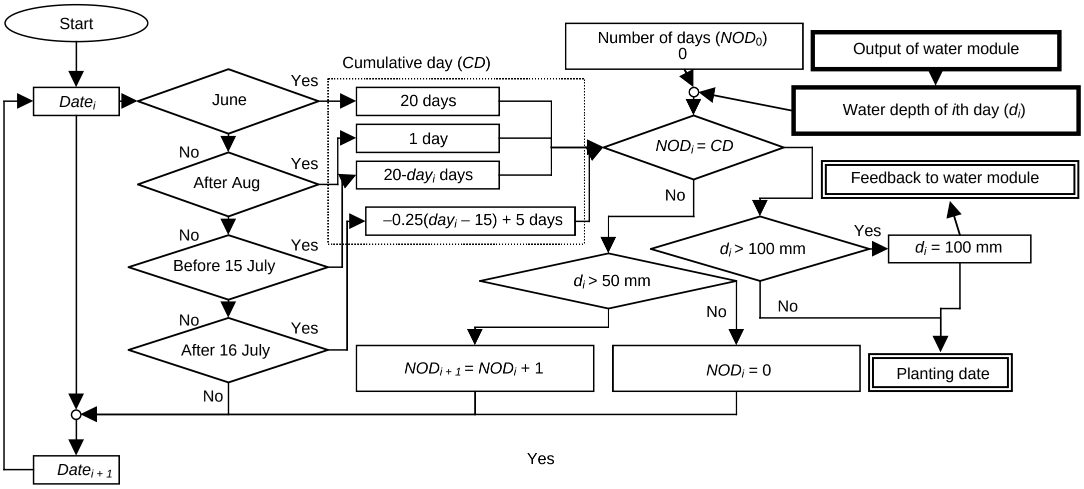


Figure 7. Flow chart of the planting schedule module used for crop modelling.

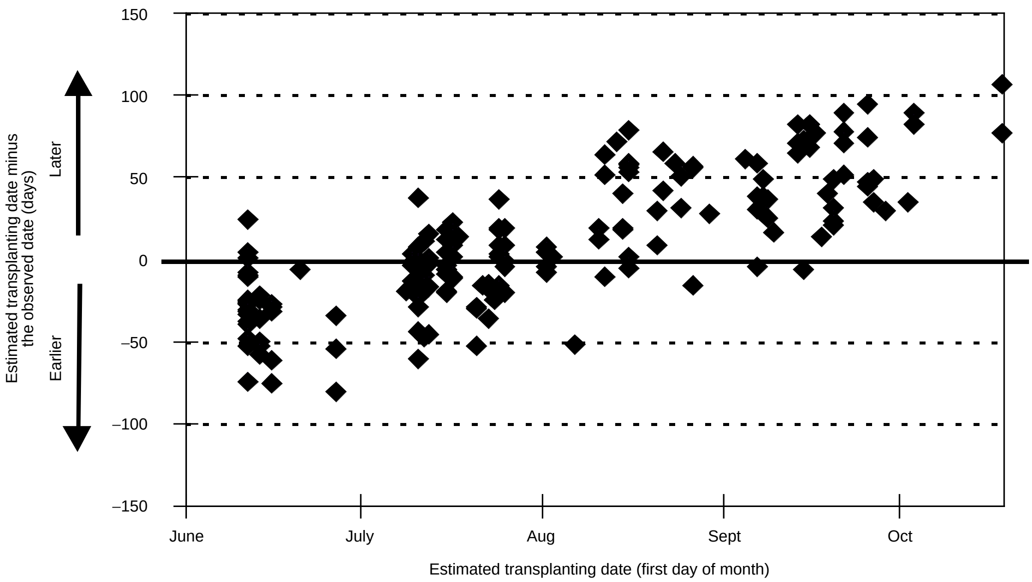


Figure 8. Estimated transplanting date compared with the observed date in North-East Thailand.

Kono 1996). According to the questionnaire survey of subdistrict extension officers, 71% of wet-season rainfed paddy was transplanted, whereas 28% was dry-seeded. The yields of dry-seeded paddy were 20% to 30% less than that of transplanted paddy in the early 1990s but, because the difference is becoming negligibly small (Miyagawa et al. 1999), we assumed all paddy fields to be transplanted.

The transplanting season in the study area extends for 4 months from June to September according to factors such as area and the seasonal pattern of rainfall. Farmers' criteria for deciding when to transplant also differ from place to place and even from household to household, but the basic necessary conditions are that (1) seedlings are ready to be transplanted, and (2) there is enough water to prepare land and secure the initial growth of the transplanted seedlings. By assuming that seedlings are prepared on time, only the second condition was adopted as the principal condition of the planting schedule module.

Water requirements at transplanting must be considered in terms of water depth and duration of ponding. The required minimum and maximum water depths are assumed to be 50 and 100 mm, respectively, based on field monitoring results and informal interviews with farmers. The actual depth may be less if the rains are late and farmers are in a hurry to transplant, but this is risky and will result in a poor harvest. Water depth requirements are, therefore, assumed not to change with time. However, the needed duration for water depths to be 50 mm or more can change with time. At the beginning of the

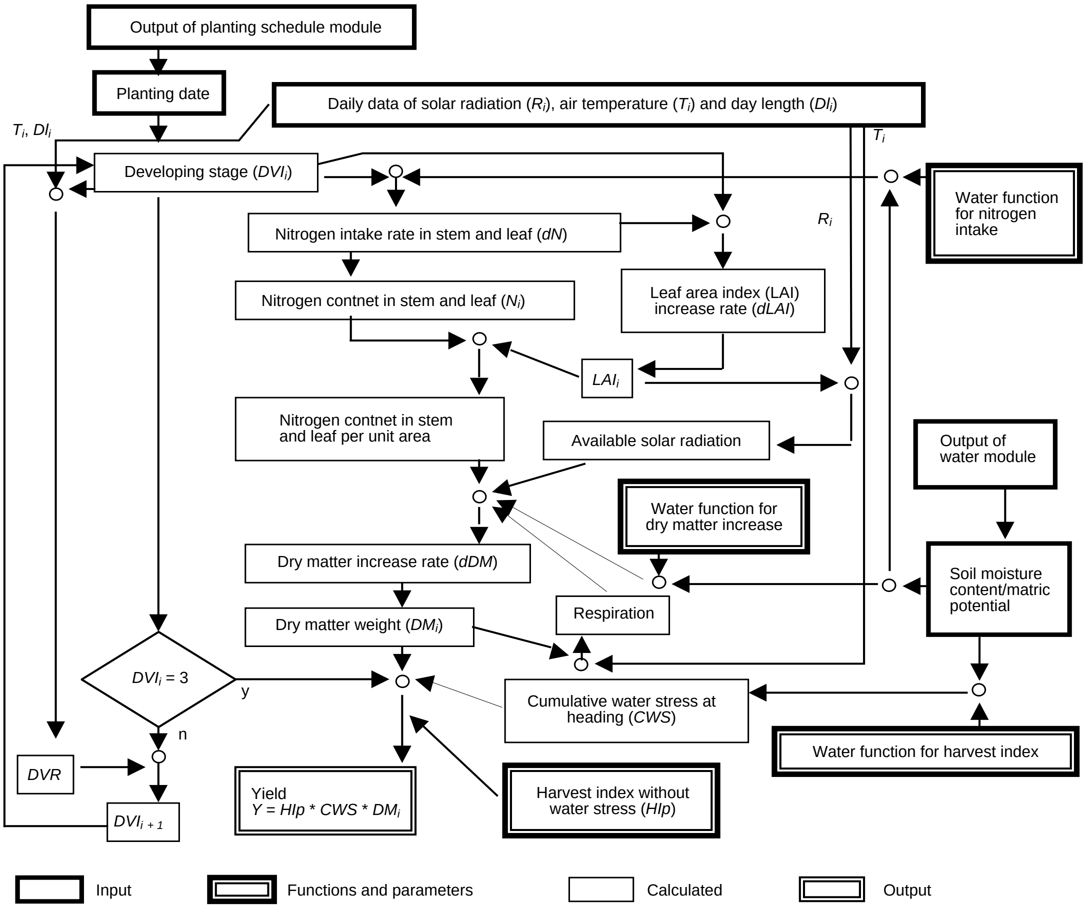


Figure 9. Flow chart of the yield module used for crop modelling.

transplanting season, farmers work more carefully, taking time to plough and harrow the land and to transplant. But, later in the season, they must hurry because they may not be able to grow paddy if they do not transplant immediately. The required duration is therefore assumed to be 20 days in June, and 1 day in August and September. It decreases linearly from 20 to 5 days and from 5 days to 1 day in the first and second half of July, respectively (Figure 7).

Estimated planting dates were compared with the observed dates (Figure 8). The estimates are somewhat unsatisfactory, being earlier than the observed ones at the beginning of the season and later at the end of the season. One reason for the late end-of-the-season estimates is that farmers are in a hurry to transplant and will transplant, even when the water is shallow or no ponds are left. The reason for early beginning-of-the-season estimates is not known. Various factors are thought to affect the actual planting dates and incorporating them all is probably very difficult. Therefore, the above-mentioned requirements were only tentatively adopted for the present study.

Yield module

The yield module simulates crop growth and yield formation from climatic data, estimated date of transplanting and daily water conditions during the growing period (Figure 9). This module was developed by adding three water functions to the Simulation Model for Rice-Weather Relations (SIMRIW) (Horie 1987; Ohnishi et al. 1999). SIMRIW is a physiological model, in which the growing stage of paddy is estimated by the increase of a developmental index (DVI), and the quantitative growth of paddy is basically estimated by means of radiation-use efficiency. The significant advantages of this model are its structural simplicity and wider applicability.

Three water functions express the relationships between (1) soil moisture content and nitrogen intake rate in stem and leaf; (2) soil moisture content and dry matter increase rate; and (3) cumulative water stress at heading and the harvest index. The water functions for nitrogen intake and dry matter increase are set at soil moisture content equalling pF = 1.8 or more and decreasing linearly to zero when they are

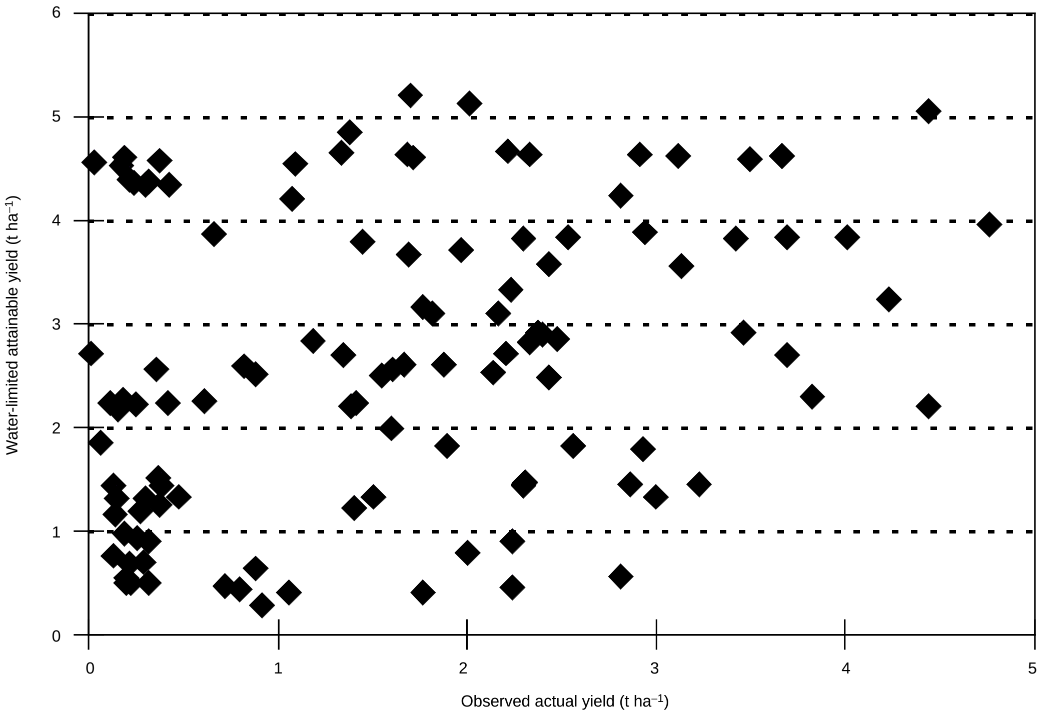


Figure 10. Estimated water-limited attainable yields compared with actual yields in North-East Thailand.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

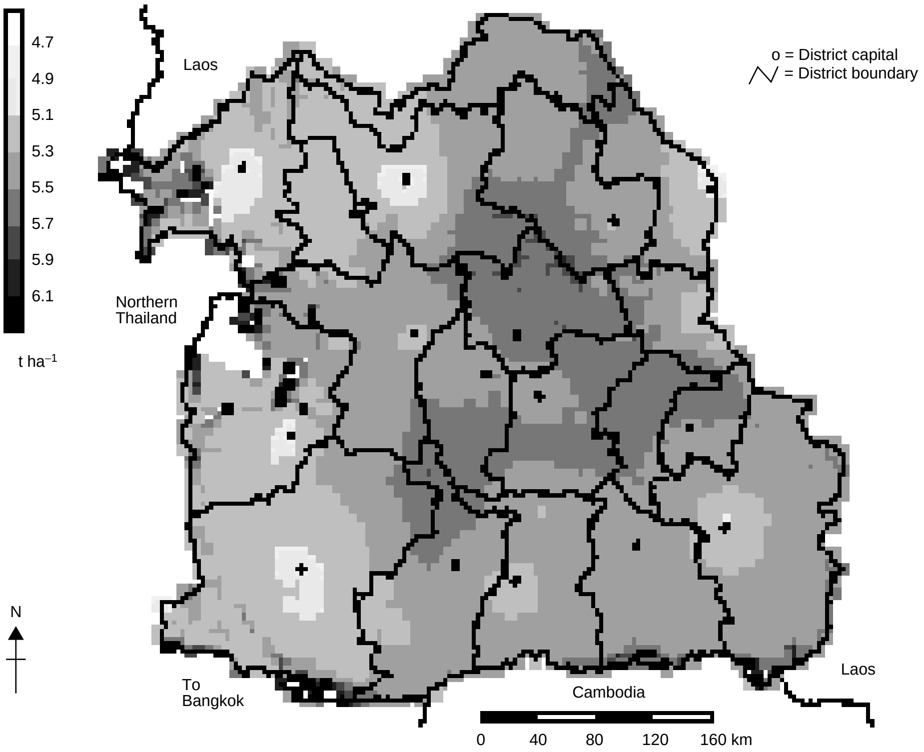


Figure 11. Estimated potential yields averaged over 20 years, North-East Thailand.

at pF = 4.2. A cumulative water stress of the water function for harvest index is calculated from soil moisture content during the period from 3 weeks before to 3 weeks after heading (Tsuda et al. 1994). Its value varies from one to zero according to the magnitude of water stress during heading.

The simulated water-limited yields were compared with the observed yields (Figure 10). They show almost no correlation, and actual yields were higher than the water-limited yields in about 24% of monitored plots. This implies that water-limited yields are underestimated. Two reasons probably cause this error: (1) an inadequate estimate of transplanting date. Late estimates of transplanting dates shorten the growing period from transplanting to heading, which results in underestimating water-limited yields. (2) An inadequate screening of rainfall records. Rainfall records were screened on a monthly basis, but checking on a daily basis seems to be required. This also suggests the need for and importance of precise rainfall records in yield estimates of rainfed agriculture.

Results and Discussion

Potential and water-limited attainable yields

Potential and water-limited yields of each mesh were estimated from the paddy field distribution and the simulated yields for 20 years from 1979 to 1998. The average potential and water-limited yields and the coefficients of variation for the water-limited yields were also calculated. Potential yields are 5–6 t ha^{-1} (Figure 11). They are slightly higher in the north-east than in the south and west, but do not differ greatly between areas within North-East Thailand, which reflects the region’s homogeneous temperature and solar radiation conditions.

In contrast, water-limited yields show a wide range of spatial and yearly variation from no harvest to no damage (Figures 12 and 13).

Four major tendencies can be seen:

1. Water-limited yields are higher in the east than in the west, which reflects the spatial distribution of rainfall.

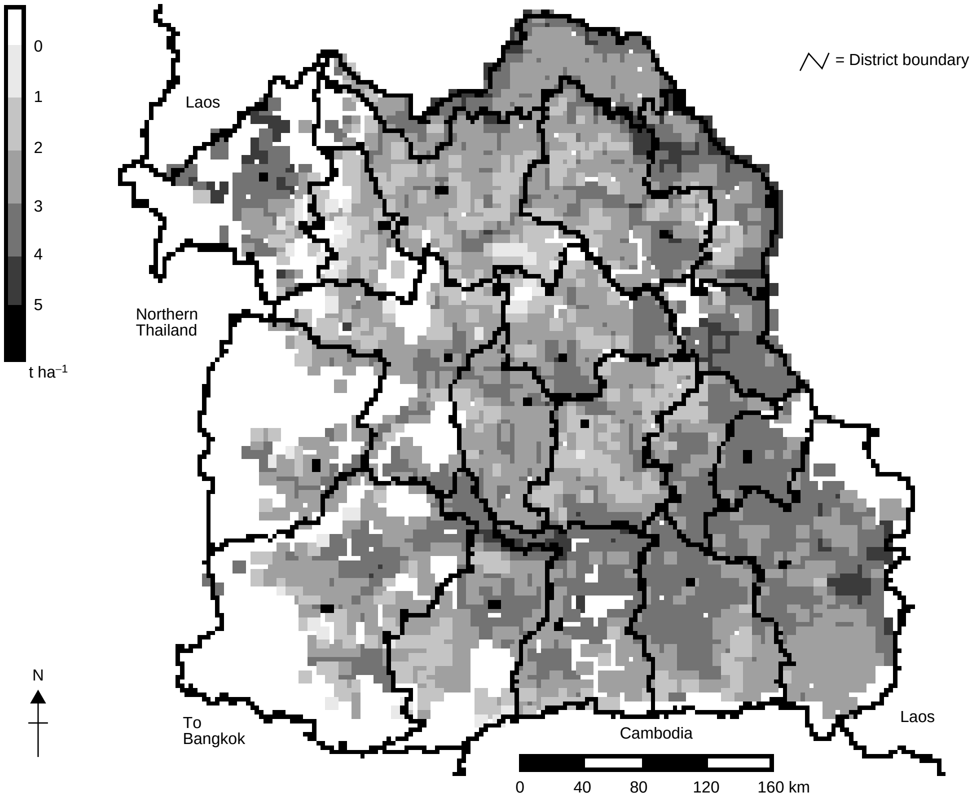


Figure 12. Attainable yield averaged over 20 years, North-East Thailand.

2. They are higher along major rivers such as the Mun, Chi and Songkhram, which reflects the alluvial soil distribution.
3. Areas with higher yields show lower coefficients of variation and vice versa, implying a high correlation between high yield and stable yield.
4. The west of the region shows a different spatial pattern of average yields and coefficients of variation to that of other areas of the region.

The contrast between high- and stable-yielding areas and low- and unstable-yielding areas is clearest in the west of the region, with changes being gradual in other parts. This reflects differences in geomorphic structure across areas. Topography in the west is of a mountain-valley type, similar to that in northern Thailand and Laos.

These findings indicate that water is the most influential determinant of yielding ability in lowland paddy, and the water environment is an integrated environment, affected not only by rainfall, but also by macro- and micro-scale topography and soil.

Yield gaps

Gaps between water-limited attainable and actual yields, caused by such factors as inadequate cultivation practices and insufficient fertilizer application, was preliminarily analysed, using the 1997 questionnaire survey as the base. Actual yields ranged between 0 and 3 t ha^{-1} at the subdistrict level (Figure 14).

Areas with yields of less than 1 t ha^{-1} were concentrated in the south-west and north, whereas areas with

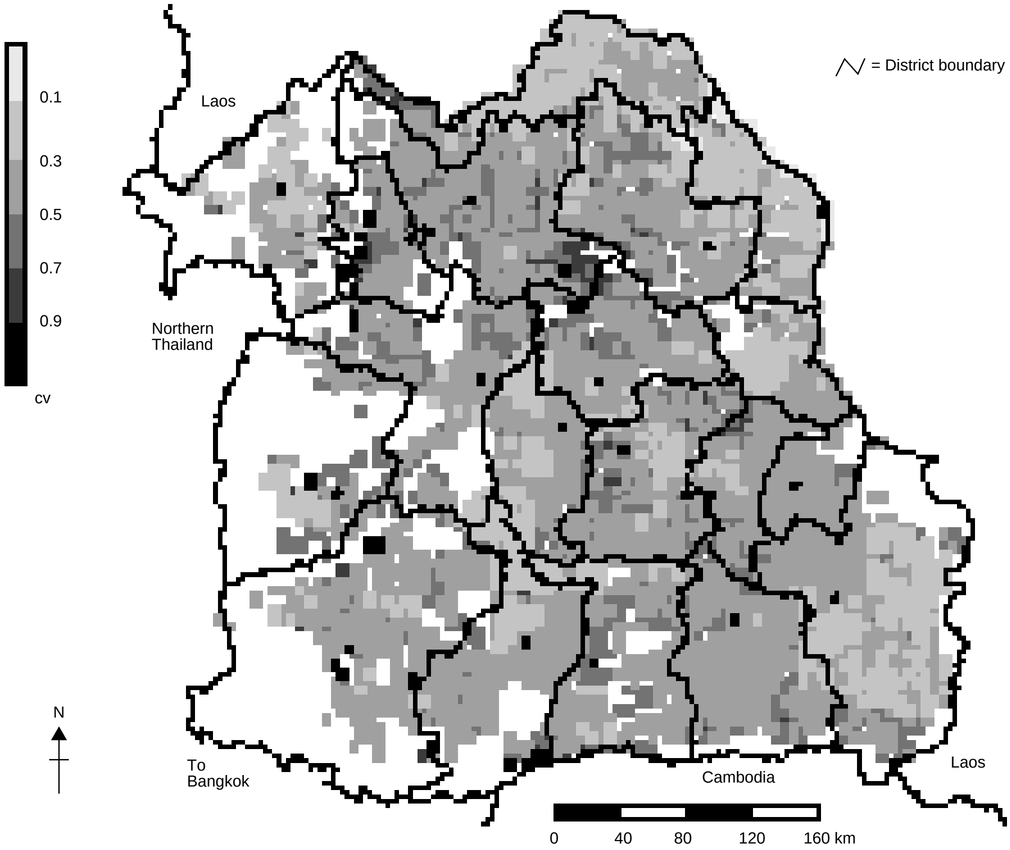


Figure 13. Coefficient of variation (cv) of attainable yields averaged over 20 years, North-East Thailand.

yields of more than 2 t ha^{-1} were scattered widely in almost all provinces. The water-limited yields of the same year are lower than the average water-limited yields, particularly in the west (Figure 15).

The yield gaps at the subdistrict level (Figure 16) were calculated from the maps shown in Figures 14 and 15. They are more than 1 t ha^{-1} in the east and south, but less than 1 t ha^{-1} in the centre and south-west. They are unreasonably negative in some subdistricts. These errors are thought to be caused by inadequate land-type classification, particularly in the mountainous parts, as well as by inadequate estimates of transplanting dates and insufficient screening of rainfall records.

The available information on yield gaps indicates two points:

1. Yield gaps are bigger in areas where the production environment is favourable and water-limited yields are high.
2. The yield gap is smaller in areas where transportation conditions are favourable, particularly in the south-west.

These findings suggest that paddy yields can be increased through the technological development of rainfed paddy cultivation under a moderate water environment and by improving marketing conditions in remote areas. However, the model should be improved before firm conclusions are drawn.

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

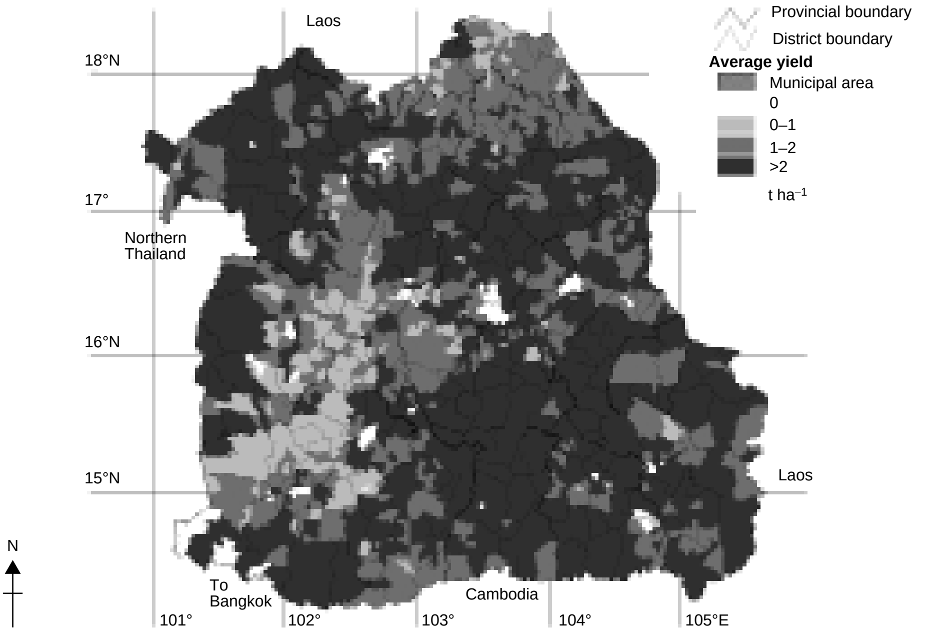


Figure 14. Actual yields at subdistrict level, North-East Thailand, 1997.

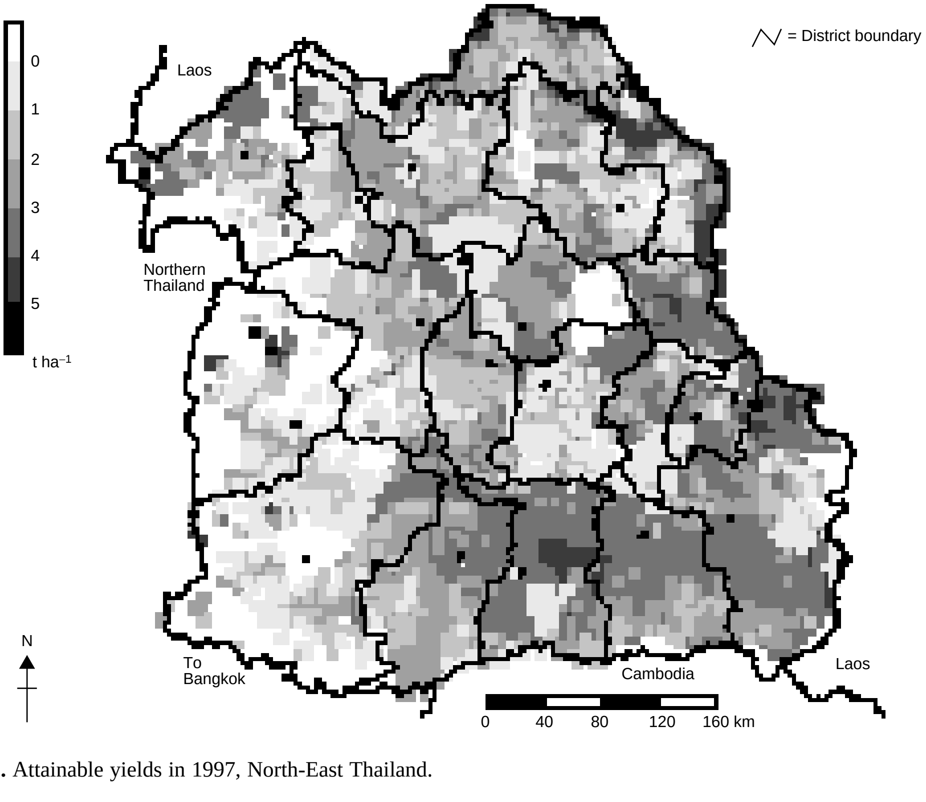


Figure 15. Attainable yields in 1997, North-East Thailand.

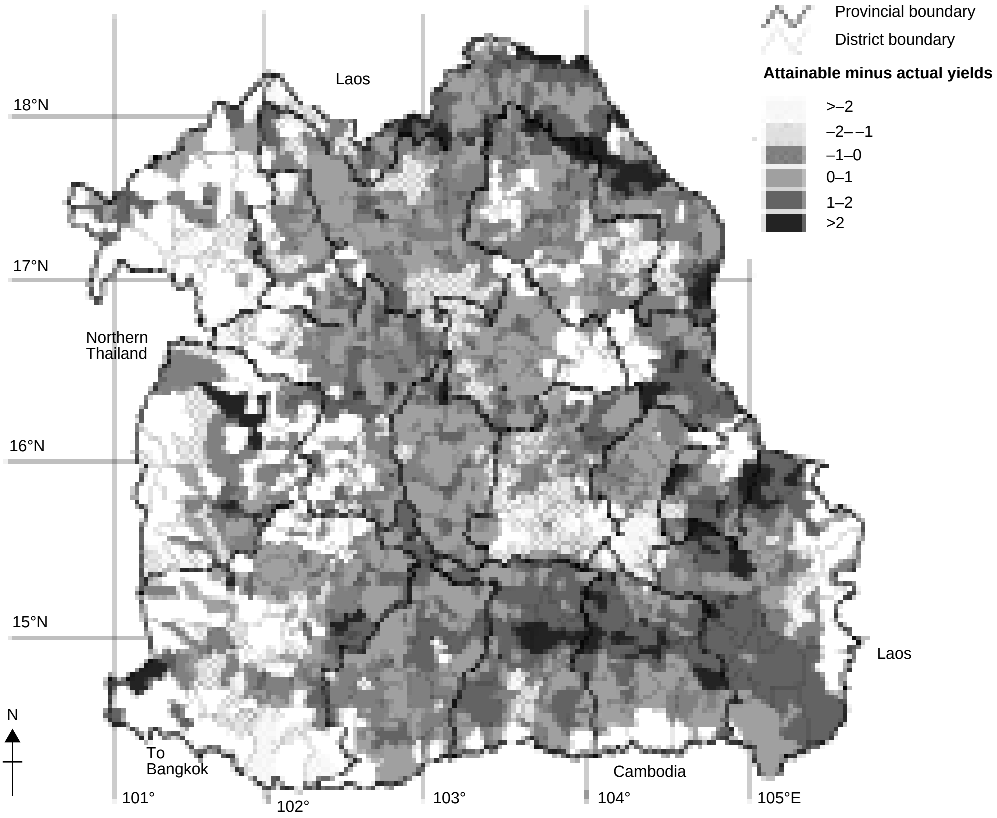


Figure 16. Differences between attainable and actual yields in 1997, North-East Thailand.

Conclusions

This study aimed to develop a method for evaluating the regional-level land productivity of rainfed agriculture. The overall outcome satisfactorily fits the empirically understood conditions of North-East Thailand, although minor modifications are needed, particularly with respect to estimating transplanting dates, screening rainfall records and classifying land types. Nevertheless, our results indicated that a GIS-based crop-modelling approach is effective for evaluating land productivity on a regional basis.

Yield gap analysis based on potential and attainable land productivity evaluation can be a strong tool for identifying determining factors of current agricultural production and to find methods of overcoming its constraints, although this study involved only a preliminary analysis of the yield gap.

The next step of model development will involve the following two points:

1. Improving the model itself, for example, by incorporating parameters for important environmental stresses other than water deficit. In the case of North-East Thailand, soil salinity and slope are believed to have substantial effects on agricultural productivity.
2. Applying the model to cross-crop analysis. This analysis should indicate suitable crop distribution in terms of agricultural production.

Acknowledgments

Our study was financially supported by a grant-in-aid from the Ministry of Education, Science, Sports and Culture of the Government of Japan. The authors also extend their sincere thanks to the staff of the Faculty of Agriculture (Khon Kaen University) and the Ubon Rice Research Center, who logistically and academically supported us. Thanks are also extended

to the National Research Council of Thailand, who approved and supported the study.

References

Fukui, H. 1993. Food and Population in a Northeast Thai Village. Honolulu, HI, University of Hawaii Press, 421 p.

Homma, K., Horie, T., Ohnishi, M., Inamura, T., Shiraiwa, T., Thongthai, C., Supapoj, N., Matsumoto, N. and Kabaki, N. 1999. Spatial distribution of soil fertility and its relation to the productivity of rainfed rice in a small basin area in Northeast Thailand. In: Can Biological Production Harmonize with the Environment? Tokyo, Asian Natural Environmental Science Center, University of Tokyo, 49–52.

Horie, T. 1987. A model for evaluating climatic productivity and water balance of irrigated rice and its application to Southeast Asia. Southeast Asian Studies, 25 (1), 62–74.

Konchan, S. and Kono, Y. 1996. Spread of direct-seeded lowland rice in Northeast Thailand: farmers' adaptation to economic growth. Southeast Asian Studies, 33 (4), 523–546.

Kono, Y., Fukui, H., Inamura, T., Iwama, K., Junthotai, K., Katawatin, R., Kyuma, K., Miyagawa, S., Nagata, Y., Nawata, E., Niren, T., Noichana, C., Sakuratani, T., Sributta, A., Tomita, S. and Watanabe, K. 1999. Methodology for regional level land productivity evaluation: a case study of rainfed agriculture in Northeast Thailand. In: Can Biological Production Harmonize with the Environment? Tokyo, Asian Natural Environmental Science Center, University of Tokyo, 23–26.

Miyagawa, S., Kono, Y., Nagata, Y. and Nawata, E. 1999. Technical changes in rainfed rice cultivation in Northeast Thailand. In: World Food Security and Crop Production Technologies for Tomorrow. Kyoto, Graduate School of Agriculture, Kyoto University, 169–172.

Nagata, Y. 1996. Northeast Thailand Village Information System (NETVIS) Material 1986, 1988, 1990, 1992. Kyoto, Organizing Committee for Global Area Studies, Kyoto University

Nagata, Y. 2000. Development of the MAPNET Image Archives, an automatic photo image archive accumulated by e-mail. Bulletin of Osaka City University Media Center, 1, 47–54 (in Japanese).

NERAEO (The North-Eastern Regional Agricultural Extension Office) and MAPNET (Modeling Agricultural Productivity in Northeast Thailand) Project. 2000. Subdistrict Level Agricultural Survey of Northeast Thailand, 1997, NERAEO and MAPNET, p. 45.

Niren, T. and Iwama, K. 1999. GIS and remote sensing for natural and socio-economic parameters. In: Can Biological Production Harmonize with the Environment? Tokyo, Asian Natural Environmental Science Center, University of Tokyo, 53–54.

Ohnishi, M., Horie, T., Homma, K., Konda, S., Takano, H., Inamura, T., Thongthai, C. and Supapoj, N.. 1999. Modeling and Evaluation of Productivity of Rainfed Rice in Northeast Thailand. In: World Food Security and Crop Production Technologies for Tomorrow. Kyoto, Graduate School of Agriculture, Kyoto University, 173–176.

Tsuda, M., Yamaguchi, H., Takami, S. and Ikeda, K. 1994. Effects of panicle water potential on water stress susceptibility in rice. Japanese Journal of Crop Science, 63 (2), 200–207.

Increasing Productivity of Lowland Rice in the Mekong Region

Shu Fukai

Abstract

The International Workshop on *Increased Production for Lowland Rice in South-East Asia*, held in Vientiane in October 2000, contributed greatly to our understanding of methods available to minimize constraints to lowland rice production in the Mekong Region, particularly Laos, Cambodia and North and Northeast Thailand. This paper summarizes key findings in the Workshop, and suggests areas of further research and development for increasing productivity of lowland rice in the region, including the development of technologies to breed stress-tolerant cultivars, thereby increasing rice productivity under limitations of water, nutrient and low temperatures. Further comments were made on increasing irrigated-rice production in the region and on developing GIS maps for agroecological characterization. Increased international cooperation within the region and with agencies outside the region is suggested to help increase rice production in the Mekong Region.

THE International Workshop on *Increased Production for Lowland Rice in South-East Asia* was held in Vientiane, Laos, during 30 October–2 November 2000 to coincide with the beginning of a new ACIAR project, *Increased productivity of rice-based cropping systems in Lao PDR, Cambodia and Australia*. Based on the papers presented and discussions held during the Workshop, as well as information available elsewhere, this paper attempts to identify key issues for future research and development activities to increase lowland rice production in the Mekong Region. Some of these issues will be addressed in the new ACIAR project, which will continue at least until 2005.

Most papers presented in the Workshop are for lowland rice production in Laos and Cambodia and, to a lesser extent, in Thailand. Laos, Cambodia and Northern and Northeast Thailand are part of the Mekong Region, their rice production systems having several similarities (see next section). As a result, rice production technologies, developed and shown to be beneficial in one country, can be applied, without major modifications, to other countries in the region.

The Workshop consisted of seven sessions, including a final one of group discussions on topics covering three key physical factors that constrain lowland rice production in the region: drought, low soil fertility and low temperatures. For the other six sessions, the papers presented and discussed were in the following areas:

1. Rice-production systems in Laos and Cambodia (6 papers)
2. Efficient water-use systems and minimizing drought problems (5 papers)
3. Nutrient limitations (5 papers)
4. Low-temperature problems (4 papers)
5. Breeding strategies for stress environments (8 papers)
6. Agroecological characterization (4 papers)

Most of the papers presented in the Workshop are also included in these published proceedings. Some papers, although presented in specific sessions, also contained information useful to other sessions.

This paper is arranged in sections based on this grouping of subject areas, except for *Increasing irrigated lowland rice production* and the final section *International cooperation*, which are added.

School of Land and Food Sciences, The University of Queensland, Brisbane, Qld., Australia.
E-mail: s.fukai@ mailbox.uq.edu.au

KEYWORDS: Agroecological characterization, Drought resistance, Low temperatures, Lowland rice, Soil fertility

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

Lowland Rice-Production Systems and Constraints in the Mekong Region

Northern and Northeast Thailand, Laos and Cambodia have similar rice-production systems and growing environments. In these three countries, the rainfed lowland ecosystem occupies more than 60% of the total rice-growing area and, hence, is the predominant form of rice production. The region, together with eastern India and Bangladesh, is the main area for the rainfed lowland rice ecosystem in the world (Wade et al. 1999). Rice-production systems and constraints are described for Laos by Schiller et al. and Pandey (this volume) and for Cambodia by Makara et al. (Rice production systems in Cambodia, this volume). Rainfed lowland rice production in Northern and Northeast Thailand is described elsewhere, for example, by Fukai et al. (1997). Throughout most of the region, rice is the main crop, although it is usually grown only once—in the wet season—because not enough rain falls in the dry season to grow a second crop, whether of rice or other crop. Hence, the region is classified as a typical rice-monocropping area.

A characteristic of the rainfed lowland rice production is the large yearly fluctuations in grain production, as observed in Laos and Cambodia (Pandey, this volume). Drought and flood are major problems for rainfed lowland rice in each of the three countries, and contribute to the yearly fluctuations. Low soil fertility is another major constraint to rice production. Agriculture in the region is predominantly subsistence, and on-farm income is generally low. Because of the high variability in rainfall and therefore the high risk to production, farmers usually avoid purchasing inputs such as fertilizer. Under these low-input systems, farmers grow traditional cultivars and yields are generally low. However, yields have increased in recent years, particularly in Laos and Cambodia. In the Mekong Region, population density is lower than in most other Asian regions and, hence, new technologies for rice production need to be labour efficient to result in increased rice production per unit labour input (Pandey 1997).

However, there is variation in the rice-production characteristics within the region, for example, large amounts of high-quality rice are exported from Thailand, where the market economy is much more advanced than in either Laos or Cambodia. Associated with this is the importance of grain quality in determining the overall value of the Thai rice crop. Although the area occupied by irrigated rice is generally small in the region, it is expanding very rapidly in Laos (Schiller et al., this volume) and, to a lesser extent, in Cambodia. In Laos, governmental irrigation schemes are expanding and rice crops are also grown in the dry season, whereas in Cambodia, irrigation water from rivers and underground sources is used mostly to supplement rainfall for wet-season rice. Overall, double cropping is uncommon in the region, except in Cambodia and, to a lesser extent, Laos, where supplementary irrigation sometimes permits the growing of two crops of rice in one year (Chea et al.; Sarom et al., this volume).

In Thailand and some parts of Cambodia, where farm labour is in short supply, direct seeding, particularly broadcasting, is widely practised for wet-season cropping. Although direct seeding per se does not affect yield (Rickman et al.; Sipaseuth et al., this volume), weed control becomes more important. In Cambodia, land preparation methods and agronomy of broadcast rice has been studied at the farm level (Rickman et al., this volume). Adequate land preparation and levelling are key to good crop establishment and reduced weed problems for direct-seeded rice. In contrast, in Laos, direct seeding is uncommon, although recent research has indicated its potential, particularly in those areas where labour costs are high or labour is scarce.

In Cambodia, some areas have water that stands too high to grow rice in the wet season. Hence, 'recession rice'—rice that is planted after the water level drops—is grown at the end of the wet season (Makara et al., Rice production systems in Cambodia, this volume).

Increasing Productivity under Water-Limiting Conditions

Drought is a major production constraint for rainfed lowland rice, being particularly severe in Northeast Thailand. It also affects large areas of rice cultivation in Laos. In these countries, late-season drought is common, amounting to yield losses as high as 35% in Thailand (Jongdee et al. 1997). Although losses to drought are smaller in Cambodia than in the other two countries, early season drought is common. This delays transplanting, obliging the transplanting of old seedlings. Early season drought also occurs frequently in Laos and Thailand and, in some years, large areas are abandoned because of failure to transplant.

Toposequential positions of lowland fields, even on the same farm, affect the pattern of drought development. Farmers plant at different times and use cultivars of different growth durations to match water availability at different positions (Homma et al., this volume). Under these circumstances, using photoperiod-sensitive cultivars is an advantage because, irrespective of planting date, they flower when there is a high probability of standing water in the field and thus avoid late-season drought. However, photoperiod-sensitive cultivars usually produce lower yields than do photoperiod-insensitive cultivars under well-watered conditions (Makara et al., Photoperiod sensitivity, this volume). This means that the advantages of using photoperiod-sensitive cultivars with appropriate flowering times must be weighed against their lower yield potential when water conditions are favourable. Resource-poor farmers in this region seek to avoid risk of yield loss in any one season (i.e. they grow photoperiod-sensitive cultivars), rather than maximize production over a longer time frame with photoperiod-insensitive cultivars.

These results suggest the importance of quantifying drought development patterns for the region and stabilizing yields of improved cultivars. Drought environment characterization has been hindered by the toposequential variation that exists, even within a small area in the region, particularly in Thailand and Laos. The effect of different toposequential positions of rice fields on lateral water movement and water balance in lowland fields also needs to be quantified.

Intensive research has been carried out to identify the mechanisms of drought-resistant genotypes (Pantuwan et al.; Kamoshita et al.; Sibounheuang et al., this volume). Some of this work was conducted in the field to determine, first, the genotypic variation of yield under dry conditions, then the physiological factors that would explain the variation in yield. This approach contrasts with that often adopted by others, where detailed physiology and genetics of putative drought-resistance traits are examined first. Such work is often conducted on too few genotypes and with traits that do not relate to grain yield under the prevailing drought conditions.

Pantuwan et al. and Sibounheuang et al. (this volume) demonstrated that a genotype's ability to maintain high leaf-water potential is important for attaining high yield under drought that occurs just before flowering. Although flowering may be delayed by drought, the delay is less in genotypes that can maintain high leaf-water potential. These authors' work can lead to a selection program based on screening parental material for maintenance of leaf-water potential, and on screening larger numbers of materials for delay in flowering under drought. Whether a physiology-based selection program, combined with yield testing in the right environments, can result in genotypes with higher yield is yet to be demonstrated. This information will be needed in the near future to determine whether indirect selection, based on these traits, will make the breeding program more efficient in developing drought-resistant cultivars.

The raised-bed system commonly practised in Indonesia may be useful for stabilizing yields for lowland environments of uncertain water supply. In this system, rice is commonly grown in furrows and upland crops on the beds, although rice can be grown in both furrows and beds. Clough et al. (this volume) demonstrated the importance of including upland crops of high economic value to maintain the system's overall viability. Another advantage of this system would be the ease of introducing double cropping, particularly rice-upland crop combinations (Borrell and van Cooten, this volume). Trials to maximize economic returns in the raised-bed system are continuing in Cambodia.

Increasing Productivity under Nutrient Limitations

One constraint to rainfed lowland rice production in the region is the prevalence of light-textured sandy soils. They have low water and nutrient retention capacity. The frequent losses of standing water in the rainfed lowlands cause reduced nutrient availability and therefore large yield reductions (Bell et al., this volume). Increased understanding of root functions, particularly nutrient uptake under fluctuating water conditions is required (Bell et al.; Kamoshita et al., this volume).

Increased organic amendments and lime can enhance soil nutrient pools, as well as the microbial biomass. The maintenance of an adequate microbial biomass is essential for a long-term nutrient balance (Reichardt et al., this volume). Loss of soil organic matter from the upper part of a toposequence is believed to be a major reason for low yields and yield variation within a small area (Homma et al., this volume).

One way to increase soil fertility level is to double crop rice with legumes such as mung bean in areas where supplementary irrigation is available. Legumes may not be always successful in providing high yield, but the crops may still contribute N to the rice fields, as was observed in Cambodia (Chea et al., this volume). Use of green manure crops, however, may contribute more to the N economy of the lowlands. But, in Laos, the high input of resources, particularly of P, needed to grow green manure crops and the high labour needed to incorporate the material, with no immediate cash benefit from it, mean that farmers are unlikely to adopt green manure cropping (Linquist and Sengxua, this volume). Long-term nutrient-balance studies need to be established for various cropping systems so that sustainable cropping systems can be developed for rainfed lowland rice in the region.

Extensive research in Cambodia, Laos and Northeast Thailand indicate that N and P are the two most limiting nutrients for grain yield (Bell et al.; Seng et al.; Inthapanya et al.; Linquist and Sengxua, this volume), followed by K and S in some fields. In

Cambodia, fertilizer recommendations are made for each soil type identified according to the Cambodian Agronomic Soil Classification System. The system allows easy recognition of different soil types for use in broad-scale agronomic research (Seng et al., this volume). The cultivar-by-soil type interaction also needs to be identified (see section on *Developing sound breeding systems for stress environments*).

Responses to N and P fertilizers in different soils and different areas are well recorded in the region (Bell et al.; Linquist and Sengxua; Seng et al., this volume), with fertilizer responsiveness apparently being less in Northeast Thailand than in Laos and Cambodia. Timing of split N applications is important, because rice yields increase if N is applied when the crop demand for N is high (Linquist and Sengxua, this volume).

Cultivars respond differently to fertilizer applications, with some cultivars being more efficient in taking up and using N or P to produce higher grain yield (Inthapanya et al., this volume). This makes the selection of appropriate cultivars important for efficient fertilizer use. The combined use of appropriate fertilizer rates and cultivars enhances rainfed lowland rice production greatly in Laos (Schiller et al., this volume), and extension efforts are needed for the fertilizer and cultivar package to be widely adopted. Accessibility to modern high-yielding cultivars and fertilizers is key to adoption in Laos (Pandey, this volume).

Increasing Irrigated Lowland Rice Production

Irrigated lowland rice currently occupies a small area in the region, but it is expanding rapidly in Laos (Schiller et al., this volume). Because irrigated rice is new to the region, no comprehensive attempt has yet been made to identify limiting factors for irrigated-rice production in Laos. Recent research indicates that low temperatures limit dry-season irrigated rice in northern Laos (Sihathep et al.; Farrell et al., this volume, and see next section). However, even without severe low-temperature problems, yield level is currently about 4 t ha^{-1}, suggesting that substantial yield improvement can be achieved by developing new technologies for irrigated-rice production in Laos.

A sound agronomic package is also needed for dry-season irrigated rice, including cold-tolerant cultivars. Although cultivars that perform well in the wet season are often used in the dry season, different cultivars may be needed for different seasons. Cultivars with higher yield potential and selected for the dry season would be expected to respond well to fertilizer, particularly N (Sipaseuth et al., this volume). High planting density appears to benefit dry-season irrigated rice (Sipaseuth et al., this volume). However, transplanting more seedlings increases labour intensity, and high planting density may not be readily adopted in areas where labour is often in short supply. One way of overcoming this problem is to direct seed, particularly to broadcast. When no adverse conditions prevail at establishment, broadcasting results in a higher established plant density than does transplanting. Assured water availability at seeding will result in improved crop establishment, compared with direct-seeded rice under rainfed lowland conditions. With the use of controlled irrigation water, weeds can also be reduced. Thus, developing a direct-seeding technology for dry-season irrigated rice is warranted.

It should be pointed out that, in Laos, the irrigated area is commonly double cropped with rice. Therefore, a cropping system should be devised that would increase the yield of the dry-season rice crop without adversely affecting the yield of wet-season rice. Thus, optimal time for planting and choice of cultivars for the dry-season crop must be determined, taking into account crop duration in the wet season. Therefore, cropping system research to increase overall productivity is required for irrigated-rice areas in Laos.

Where irrigation water is limited, as in some parts of Cambodia, the water may be used to extend the crop season, so that two crops can be grown during the wet season. Use of supplementary irrigation allows planting of photoperiod-insensitive rice (e.g. IR66 in Cambodia) early in the wet season, followed by traditional rice (Chea et al., this volume). While this intensified cropping system is advantageous in many cases, the socioeconomic aspects need to be considered if a stable cropping system is to be developed. Double cropping requires extra labour and resources and, hence, the potential risk increases with increasing cropping intensity, particularly if supplementary irrigation water is not available or is limited in quantity and timing. Consideration should be also given to the use of an upland crop in double cropping to diversify cropping systems in Cambodia. This requires not only sound agronomy and water management of the upland crop, but also sound marketing.

Minimizing Low-Temperature Problems

A major constraint to dry-season irrigated-rice production in northern Laos comprises low temperatures, particularly at seeding and during seedling growth before transplanting (Sihathep et al.; Farrell et al., this volume). In northern Laos, securing a sufficient number of healthy seedlings for transplanting was a major problem in the 1999–2000 dry

Increased Lowland Rice Production in the Mekong Region
edited by Shu Fukai and Jaya Basnayake
ACIAR Proceedings 101
(printed version published in 2001)

season when the region experienced its coldest December since 1974. This experience also led to a reduced dry-season crop for 2000–2001, even though the season had favourable temperatures. There is an urgent need to estimate the frequency and magnitude of low temperature damage that occur in different parts of northern Laos (see also the section on *Agro-ecological characterization*).

Experience in other countries, particularly Korea and Japan, shows that the effect of low air temperatures at crop establishment can be minimized by using appropriate seedbed protection measures. This may be the most cost-effective method of minimizing low temperature damage in northern Laos. On-farm trials are needed on the cost-effectiveness of various protectors (e.g. plastic cover) in terms of different materials used and capacity to increase seedbed temperatures. Water temperatures rather than air temperatures are more important during early growth (Shimono et al., this volume). The use of warmer water would be another way to improve crop growth in cool environments.

Although low temperatures during the reproductive stage can reduce rice yield (Lee; Shimono et al., this volume), the chance of this occurring is not high in most of northern Laos, provided the crop is seeded at an appropriate time (Sihathep et al.; Farrell et al., this volume). Low temperature occurrence should be quantified for different growth stages so that the best agronomy package, including appropriate times for seeding, can be developed for different locations to minimize the chance of low temperatures occurring at critical stages.

Some cultivars tolerate low temperatures during crop establishment and the reproductive stage. These cultivars have been selected successfully, using low temperature screens, in Korea and Japan (Lee; Farrell et al., this volume). Other cultivars, recently released in northern Thailand, are well adapted to the dry season and may also be suitable for the conditions of northern Laos. The International Network for Genetic Evaluation of Rice (INGER) provides different sets of materials for testing, some of which would be suitable for various cold areas (Javier, this volume). These materials from different countries need to be tested in northern Laos, whether directly as cultivars or as parents to cross with otherwise more locally adapted cultivars (Boualaphanh et al., this volume).

Developing Sound Breeding Systems for Stress Environments

Rice-breeding systems in Thailand, Laos and Cambodia are similar, although the Thai breeding program is by much the largest (Jongdee; Boualaphanh et al.; Sarom et al., this volume). The International Rice Research Institute (IRRI) has provided significant inputs for all these countries, particularly in the development of rainfed lowland rice cultivars, thereby greatly assisting the effectiveness of their breeding programs. In Cambodia, the crossing program concentrates on developing mostly intermediate- to late-maturing cultivars, because the early maturing photoperiod-insensitive cultivars developed at IRRI can often be released directly. In Laos and Cambodia, improved photoperiod-insensitive cultivars with high yield potential and early flowering have been adopted. Lao farmers typically grow a variety of cultivars, some of which are modern high-yielding cultivars (HYV), although most are traditional (Pandey, this volume).

The Thai breeding program is being modified (Jongdee, this volume) to focus on (1) improved coordination among breeders at different stations, (2) increased yield testing at many locations and of early generations in the selection program, (3) use of a rapid generation advance technique to shorten the selection program and (4) increased on-farm testing. These changes are expected to produce, over a shorter period than does the current program, new cultivars that are adapted to large areas of rainfed lowlands in Thailand. Because the Lao program uses lines developed in Thailand, the changes in the Thai program will have a spin-off for the Lao breeding program.

A screening method for drought tolerance in rainfed lowland rice has been developed in Thailand (Pantuwan et al., this volume). This screen is conducted in a dry location in the country and uses delayed planting in the wet season, followed by water drainage before flowering to induce drought stress. The screen can be used for direct selection for grain yield—after considering genotypic variation in phenology, particularly for time to flowering—or for indirect selection for drought resistance traits. In the breeding programs of the Mekong Region, most work is based on direct selection of yield, an approach that can be used, at least initially, to develop drought-resistant cultivars. The effectiveness of the structured drought-testing environment developed in Thailand now needs validation under drought conditions elsewhere in the Mekong Region. Furthermore, the effectiveness of indirect selection based on drought resistance traits needs to be evaluated for consistency in trait expression and effectiveness in enhancing grain yield at different locations.

While some traits, such as short delay in flowering under drought, appear promising as selection criteria, the wide applicability of traits conferring resistance under different drought conditions urgently needs testing. Indirect selection may be enhanced by using molecular markers (Jongdee, this volume). Indirect selection based on particular traits needs to meet certain important criteria such as high genetic correlation with grain yield and high heritability of the traits before they can be used as selection criteria (Atlin, this volume). These criteria need to be met by the particular drought resistance traits proposed and, until they are met, direct selection in appropriate selection environments may be more effective in developing drought-resistant cultivars.

Estimating the genotype (G)-by-environment (E) interaction for grain yield from multi-location trials can provide vital information on the number of locations and years needed for testing materials. The breeding program's resources would then be more efficiently used, as shown in the case of rainfed lowland rice in Cambodia, where the number of trials could be reduced by 20%–40%, with only a small increase (up to 0.02 t ha^{-1}) in the standard error (Javier and Toledo, this volume). However, in Cambodia the G × E variance component for yield is rather small relative to the G variance component, compared with Thailand, where a large G × E has been repeatedly reported. It would be interesting to find out whether the smaller G × E for grain yield in Cambodia indicates that the selection environments in Cambodia are more uniform than in Thailand.

Multi-location trials can be extended to include trials established from direct seeding in Thailand and Cambodia, thereby indicating the degree of effort a breeding program needs to apply to develop cultivars for direct seeding.

The fertilizer level at which selections are made does not appear to have a significant influence on the outcome of selected materials (Inthapanya et al., this volume). The use of a moderately high level of fertilizer in the selection program is therefore justified, particularly for a relatively small breeding program such as the Lao program. However, in all the region's countries, multi-location trials have shown a large genotype-by-location interaction for grain yield (Inthapanya et al., this volume). If the interaction is consistent across years, then cultivars especially adapted to given locations may be developed. The interaction may be caused by soil types or particularly adverse soil conditions. The consistency of the genotype-by-location interaction needs to be examined and, if possible, exploited for the development of cultivars adapted to specific areas.

Agroecological Characterization

Rice-growing areas can be characterized for their climatic and soil environments, and maps, using GIS technology, may be produced to depict agroecological zones. Agroecologcal maps can be used in many ways, for example, to identify areas that are prone to low temperatures or drought, or are suitable for double cropping. Such maps can be used for crops other than rice.

One problem in developing these maps is that the countries, for example, Laos, have few reliable long-term data (Khounphonh et al., this volume). Data from neighbouring countries may be used to develop GIS-based maps. Maps of single variables (e.g. minimum temperatures) can be developed first, followed by those that combine variables (e.g. water balance based on rainfall, evaporation and soil characters). Crop modelling may then be combined with GIS so that complex interacting variables such as the time water stands in lowland fields may be evaluated for each country (Inthavong et al.; Kono et al., this volume). One strength of this approach is that the current crop yield can be evaluated in relation to potential yield in different locations, and thus factors limiting yield can be quantified for a region. This was successfully achieved for Northeast Thailand by Kono et al. (this volume).

Another challenging issue for developing agroecological maps, particularly for rainfed lowland rice production, is the large spatial variability within the toposequence of a small area (Homma et al., this volume). The soil nutrient environment can differ markedly within a small area, because fields located at the upper parts of a toposequence have lost soil organic matter, whereas those farther down have accumulated it. This variation in levels of soil nutrients and water causes variation in yield within the area. Thus, it is essential to include the micro-environmental variation due to toposequence, together with the macroenvironmental variation within a region, before large-scale maps can be successfully used to increase production of rainfed lowland rice. Good environmental characterization is also required for plant breeding, particularly for understanding the causes of large G × E interactions for yield. Maps that incorporate the microenvironment variation can meet that purpose.

International Cooperation

Because of the similarity of rice-growing environments in Northern and Northeast Thailand, Laos and Cambodia, these countries should be treated as one region for the purpose of conducting future research and development activities for lowland rice production. Similarity in growing environments, particularly the frequent occurrence of drought and flood and generally low soil fertility in rainfed lowlands, indicates that the agronomy and cultivar requirement for rice in these countries are similar. Transferring advanced lines from neighbouring countries within the region has been successful. Technologies, plant materials and research ideas should also be exchanged among the neighbouring countries to develop productive rice-based cropping systems. For example, experience in direct-seeding research and development in Cambodia (Rickman et al., this volume) can be directly used in Thailand and Laos. The screening method for developing drought-resistant cultivars in the region has already been mentioned.

Mechanisms of cooperation among the region's countries should be developed, involving external research agencies such as IRRI and the ACIAR. The achievements of the ACIAR rice project in Thailand in 1992–1999 have been successfully used to develop research and development programs in Laos and Cambodia. Development of externally funded cooperative projects, involving all three countries, should be encouraged to hasten the development of technologies that can be used in the countries.

Sometimes, technologies developed outside the region may also be appropriate for minimizing the constraints existing within the region, for example, the techniques and cold-tolerant cultivars used to minimize low-temperature problems. Because the low-temperature problem of northern Laos and northern Thailand is shared with Korea, Japan and Australia (Lee; Farrell et al., this volume), further increased international cooperation would help increase the region's rice production.

Acknowledgments

I thank all those who participated in the Workshop for providing the findings and ideas on which this paper is based.

References

Fukai, S., Cooper, M. and Salisbury, J. ed. 1997. Breeding Strategies for Rainfed Lowland Rice in Drought-Prone Environments, Proceedings of an International Workshop held at Ubon Ratchathani, Thailand, 5–8 November, 1996. Canberra, ACIAR Proceedings No. 77, 248 p.

Jongdee, S., Mitchell, J.H. and Fukai, S. 1997. Modelling approach for estimation of rice yield reduction due to drought in Thailand. In: Fukai, S., Cooper, M. and Salisbury, J. ed. Breeding Strategies for Rainfed Lowland Rice in Drought-Prone Environments, Proceedings of an International Workshop held at Ubon Ratchathani, Thailand, 5–8 November, 1996. Canberra, ACIAR Proceedings No. 77, 65–73.

Pandey, S. 1997. Rainfed lowland rice research: challenges and priorities for the 21st century. In: Fukai, S., Cooper, M. and Salisbury, J. ed. Breeding Strategies for Rainfed Lowland Rice in Drought-Prone Environments, Proceedings of an International Workshop held at Ubon Ratchathani, Thailand, 5–8 November, 1996. Canberra, ACIAR Proceedings No. 77, 1–12.

Wade, L.J., Fukai, S., Samson, B.K., Ali, A. and Mazid, M.A. 1999. Rainfed lowland rice: physical environment and cultivar requirements. Field Crops Research, 64, 3–12.