

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 semi-arid 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

^aSchool of Land and Food Sciences, The University of Queensland, St Lucia, Qld., 4072, Australia

^bCurrent address: Department of Natural Resources and Environment, 402-406 Mair St, Ballarat, Vic., 3350, Australia

^cCentral Research Institute for Food Crops, Jalan Merdeka 147, Bogor 16111, Indonesia

*Corresponding author: angela.clough@nre.vic.gov.au

KEYWORDS: Raised beds, Red-yellow Podsol, *Sorjan* farming system

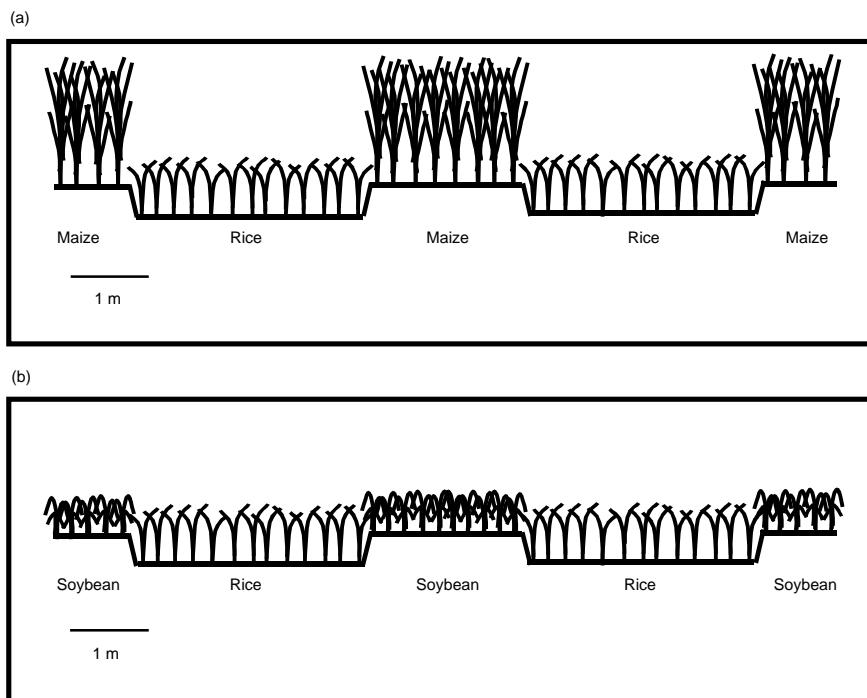


Figure 1. Diagrammatic representation of the *sorjan* farming system in cross-section at Taman Bogo Experiment Farm, Sumatra, during (a) the wet season and (b) dry season.

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 (H₂O) 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 m². All plots in the flat-bed lowland rotation system were separated by small bunds. Plots in the flat-bed upland rotation system were 56 m².

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

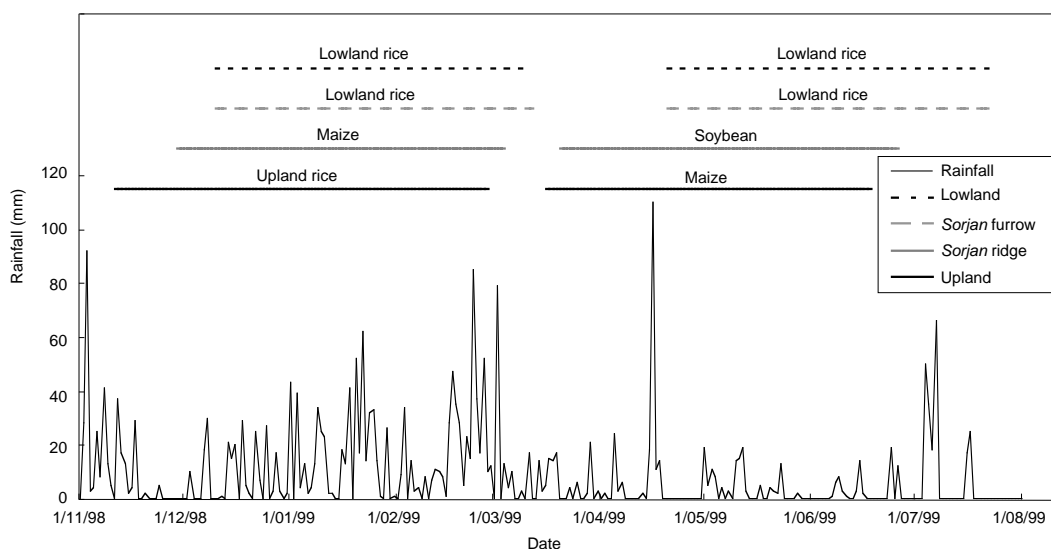


Figure 2. Daily rainfall (mm) from 1 November 1998 to 1 August 1999 at Taman Bogo Experiment Farm, Sumatra. The growing season for each crop in the three systems are indicated by the bars at the top of the figure.

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				
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				
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

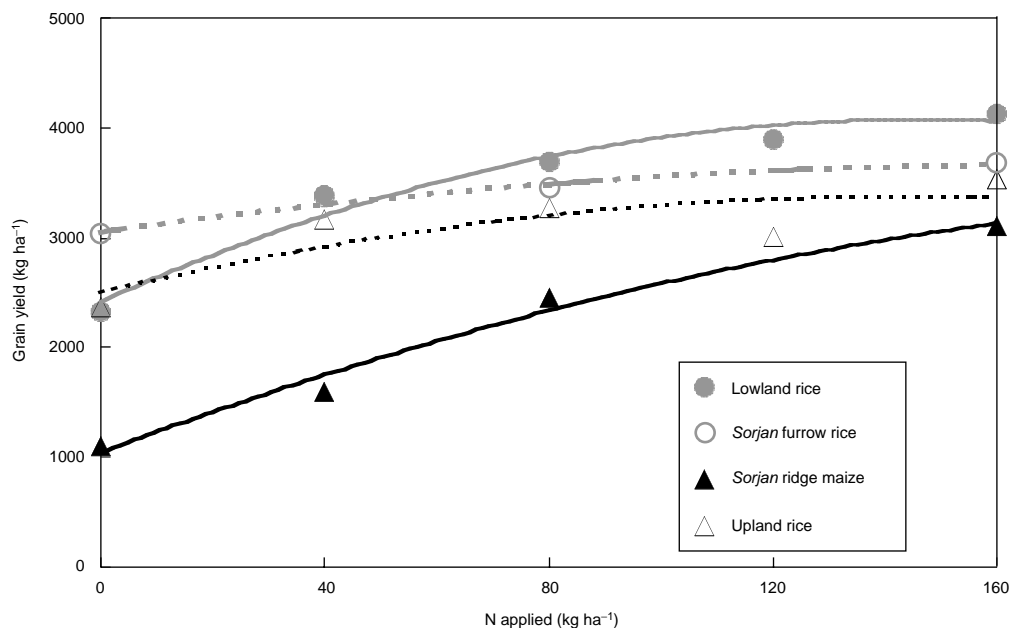


Figure 3. Nitrogen response curves attained for lowland rice and maize grown in the *sorjan* farming system; lowland rice grown in the flat-bed lowland rotation system; and upland rice grown in the flat-bed upland rotation system, wet season, Taman Bogo Experiment Farm, Sumatra.

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

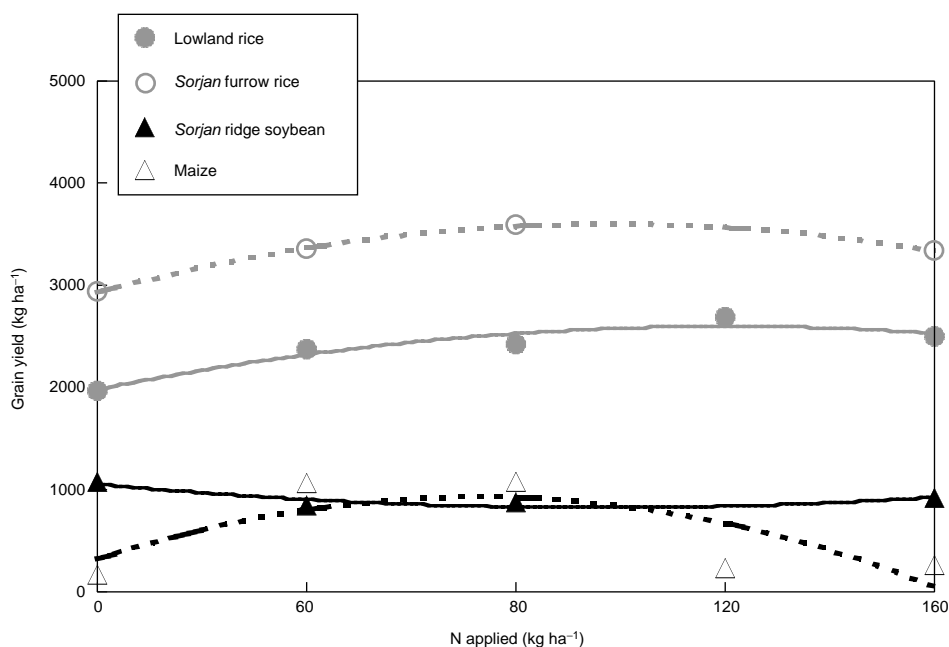


Figure 4. Nitrogen response curves attained for lowland rice and soybean grown in the *sorjan* farming system; lowland rice grown in the flat-bed lowland rotation system; and maize grown in the flat-bed upland rotation system. Fertilizer N available to soybean was residual from N applied to the previous 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 Ponnampereuma, 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 Research 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, I. 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.

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 deep-water—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

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 F₇ 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

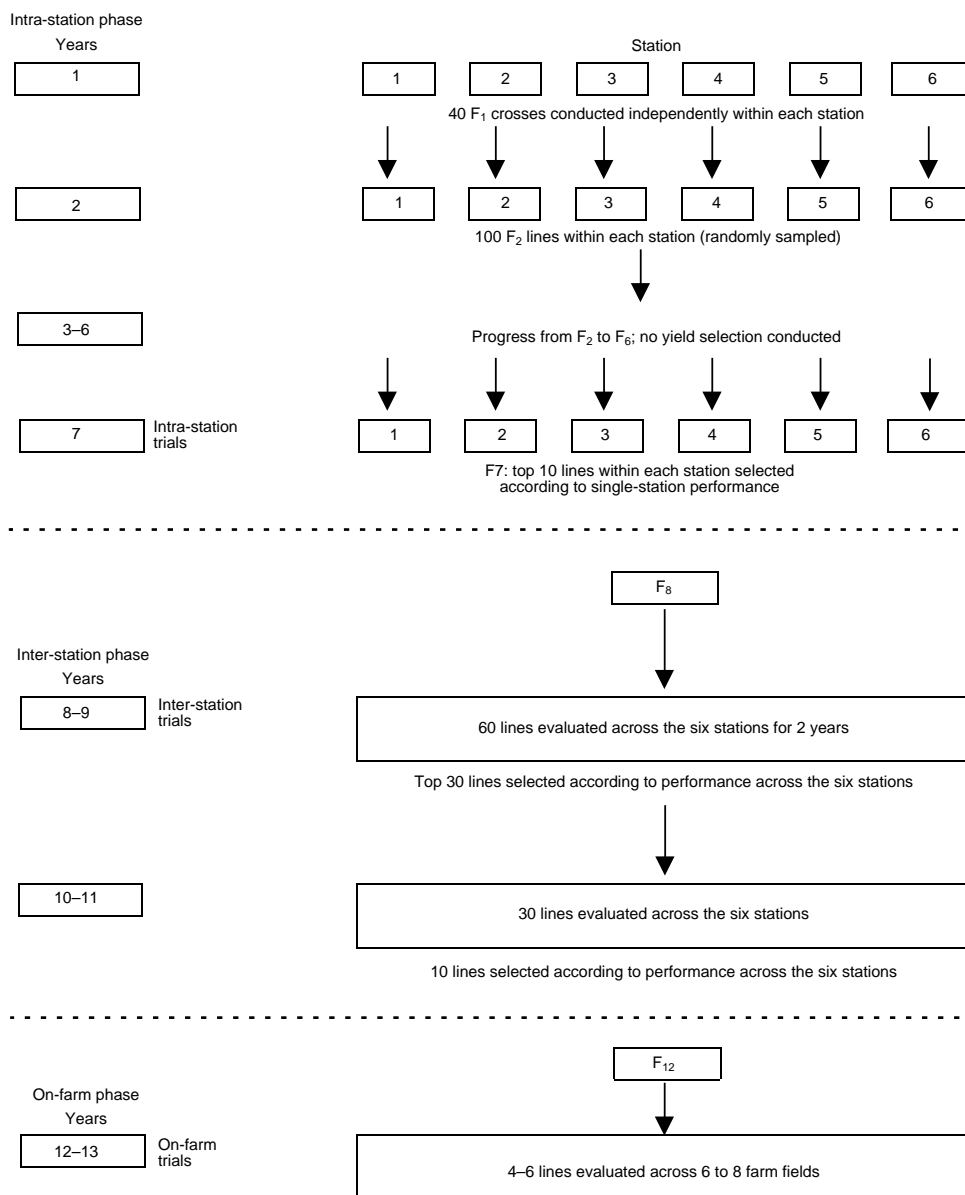


Figure 1. Current rice-breeding strategy for the rainfed lowlands of north and northeast Thailand (after Cooper et al. 1999).

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 ($G \times L \times Y$). Thus, identifying lines with good adaptation across targeted environments was difficult within a short time. Furthermore, because of the large $G \times E$ 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.

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 $G \times E$ interaction was six times larger than that for genotype. In contrast, the $G \times E$ variance component for flowering time and height were smaller than that for genotype. With the large effect of $G \times E$ 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 $G \times E$ 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 $G \times E$ 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 ($G \times L$), genotype by fertilizer ($G \times F$) and genotype by location by fertilizer ($G \times L \times F$) were also significant. However, variance components for G and $G \times L$ were larger than for $G \times F$ and $G \times L \times F$, 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 F₅ and F₆ 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 north-eastern 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 north-east 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 germ-plasm 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 back-crossing 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 F₂ to F₅ or F₆ and seed increase (F₆ or F₇) for yield testing in F₇ or F₈. 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 Phrae 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,

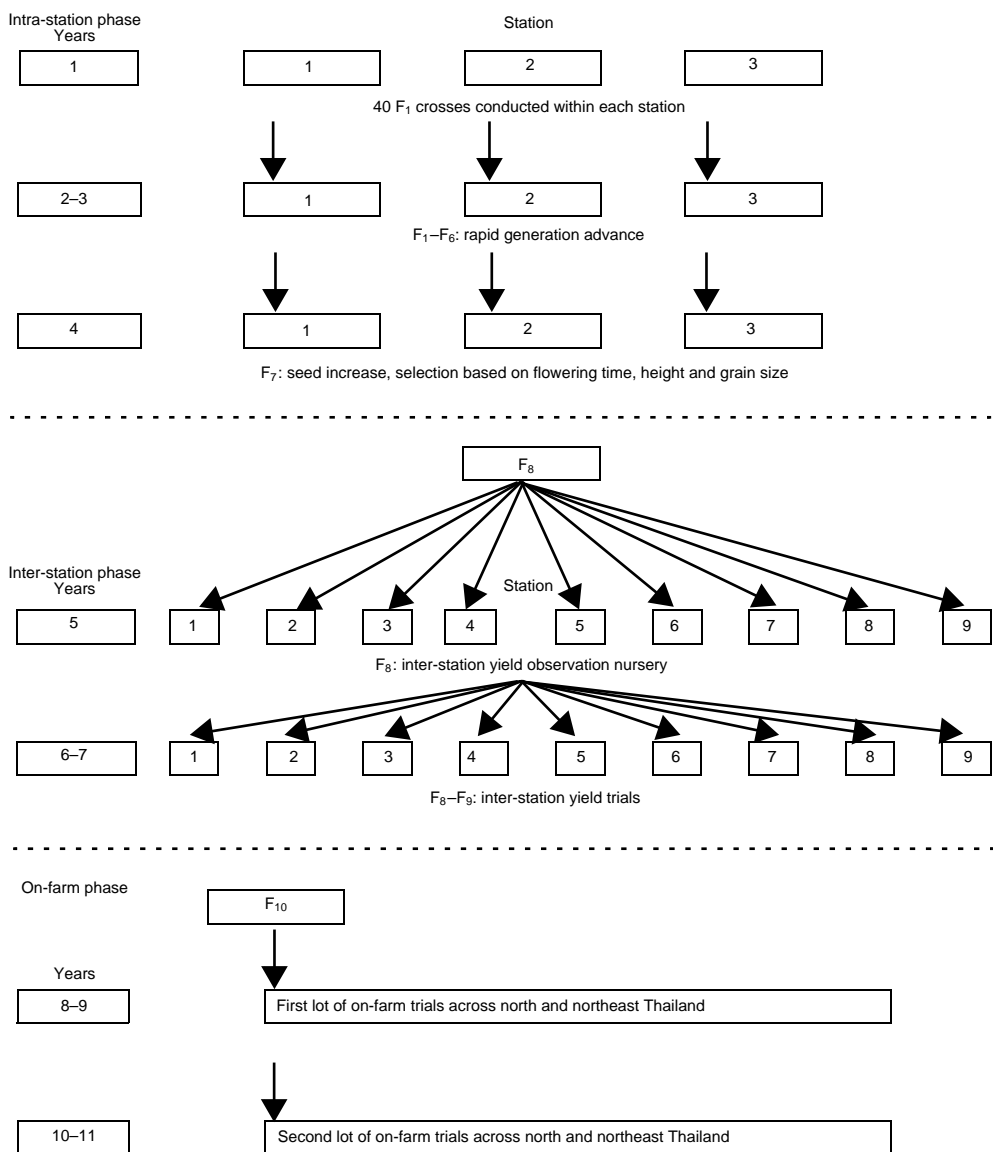


Figure 2. The selection strategy used by the new rice-breeding program for the rainfed lowlands of north and northeast Thailand.

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-morphological 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., Chanphengsay, 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

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 (Linguist 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
Ikhaio/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, Ikhaio, 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 F₂-F₄ generations. Pedigree breeding methods are occasionally used in F₂-F₄ generations for particular crosses. However, this method is widely used for late generation selection (F₅-F₆).

3. *Variety testing program.* The varietal testing program is divided between the rainfed lowland, rainfed upland and irrigated ecosystems. After F₆,

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 m²) and yields under normal growing conditions estimated.

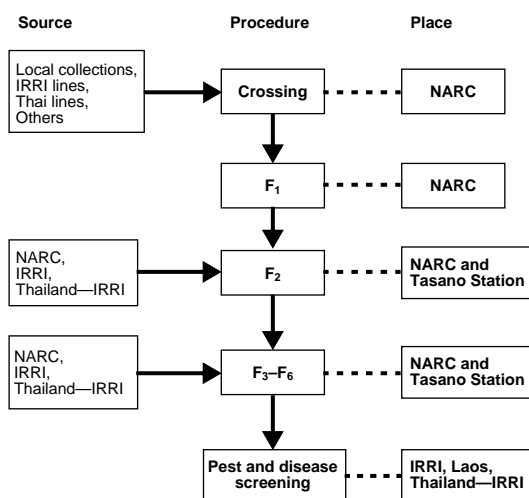


Figure 1. The crossing and selection subcomponent of the Lao rice breeding program.

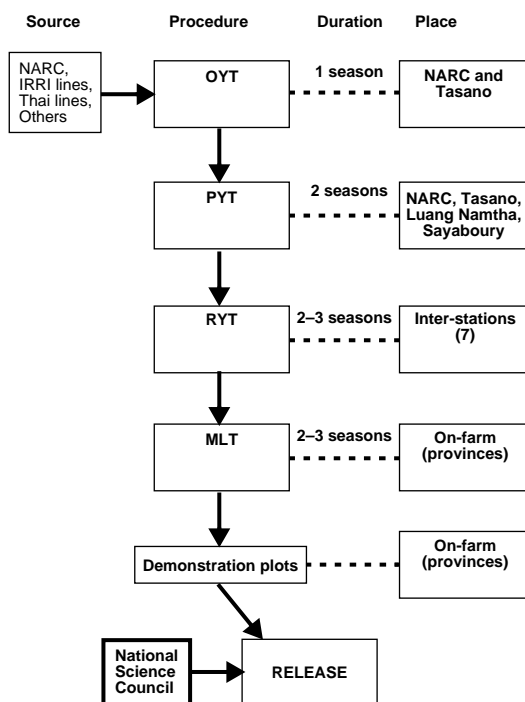


Figure 2. Line-testing stages and variety recommendations in Laos.

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.
- Inthaphanya, 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.
- Inthaphanya, 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

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
<i>Early</i>	347 869	—	—	20
<i>Intermediate</i>	761 032	—	—	44
<i>Late</i>	623 060	—	—	36
Deepwater/floating	84 721	—	5	—
Dry-season rice	243 783	12	—	—

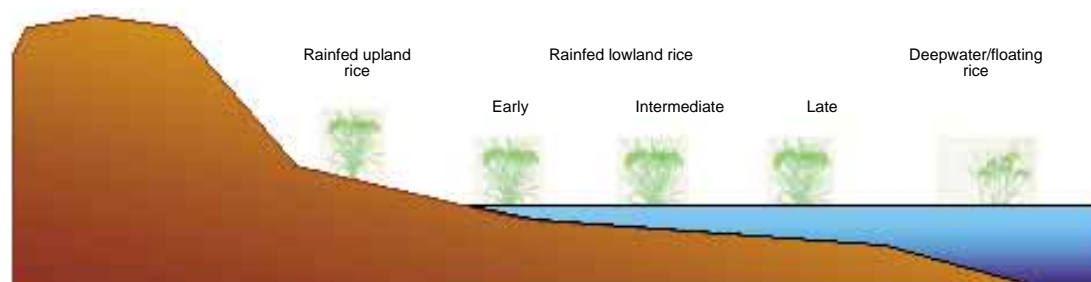


Figure 1. Wet-season rice ecosystems in Cambodia.

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

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 deep-water 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 (F₂-F₄) and the pedigree method for the remaining generations (F₅-F₇). 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 F₇ or F₈ 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).

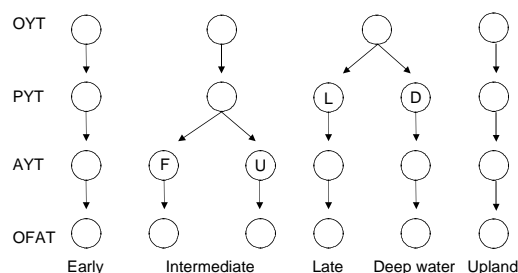


Figure 3. Selection pathway in the Cambodian rice-breeding program. OYT = observational yield trials; PYT = preliminary yield trials; AYT = advanced yield trials; OFAT = on-farm adaptive trials; F = favourable; U = unfavourable conditions; L = late maturing rice; D = deep water.

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 (BRRRI). 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 AYT, 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, P₂O₅ and K₂O, respectively, per hectare. For the remaining groups, a rate of 30–15–15 kg of N, P₂O₅ and K₂O, 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).

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/ROL,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-Sammbarak 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

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:

$$CR_T = i_s r_G \sqrt{H_s H_T} \sigma_P \quad [1]$$

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,

$$CR_T \propto i_s r_G \sqrt{H_s} \quad [2]$$

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:		r_G
			LYE	HYE	
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.

rained 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:

$$H_s = \frac{\sigma_G^2}{\sigma_G^2 + \frac{\sigma_{GL}^2}{l} + \frac{\sigma_{GY}^2}{y} + \frac{\sigma_{GLY}^2}{ly} + \frac{\sigma_E^2}{rl}} \quad [3]$$

where,

- σ_G^2 = genotype (G) variance
- σ_{GL}^2 = genotype \times location (GL) variance
- σ_{GY}^2 = genotype \times year (GY) variance
- σ_{GLY}^2 = genotype \times location \times year (GLY) variance
- σ_E^2 = within-trial error variance
- l = number of locations
- y = number of years, and
- r = number of replicates of testing.

The parameters σ_G^2 , σ_{GL}^2 , σ_{GY}^2 , σ_{GLY}^2 and σ_E^2 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 SASTM (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_{GL}^2 , σ_{GY}^2 , σ_{GLY}^2 and σ_E^2 , 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_{GLY}^2 and σ_E^2 are the largest contributors to this 'noise'. The contribution of σ_E^2 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_{GLY}^2 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

Table 2. Genotype (σ^2_G), genotype \times location (σ^2_{GL}), genotype \times year (σ^2_{GY}), genotype \times location \times 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 sub-optimal 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

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 \times 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 Delhi, 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. Ledesma², Ouk Makara³ and P. Khon Hel³

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-locality trials conducted over years are needed (Sprague and Federer 1951). Variances for variety \times location, variety \times year and variety \times location \times 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 \times 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:

$$V_x = (\sigma^2_{vy}/y) + (\sigma^2_{vl}/l) + (\sigma^2_{vyl}/yl) + (\sigma^2_e/rly) \quad [1]$$

where,

σ^2_{vy} = variety \times year variance

σ^2_{vl} = variety \times location variance

σ^2_{vyl} = variety \times year \times 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 \times number of years) and total number of plots (number of trials \times 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		DF	MS	Set I		Set II	
	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	0.707	324	0.570	214	0.339	401	0.402	357	0.441
	(115)		(124)		(125)		(161)		(128)	

^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 \times 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 \times 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 \times 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 \times 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 \times 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

^aData 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	<i>0.11</i>	<i>14</i>	<i>56</i>
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	<i>0.19</i>	<i>16</i>	<i>64</i>
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 \times 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 \times variety, location \times 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

^aCambodian Agricultural Research and Development Institute (CARDI), Phnom Penh, Cambodia

^bSchool of Land and Food Sciences, The University of Queensland, Brisbane, Qld., Australia

^cCambodia–IRRI–Australia Project (CIAP), Phnom Penh, Cambodia

*Corresponding author: E-mail: pbreed@bigpond.com.kh

KEYWORDS: Drained conditions, Flowering time, Seeding time, Seedling age at transplanting

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:

$$\text{PSI} = 1 - (\text{F2} - \text{F1}) / (\text{SD2} - \text{SD1}) \quad [1]$$

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–P₂O₅–K₂O 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 $W \times ST$, $W \times SA$, $W \times ST \times G$ and $W \times SA \times G$.

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 m² 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 con-

sisted 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.

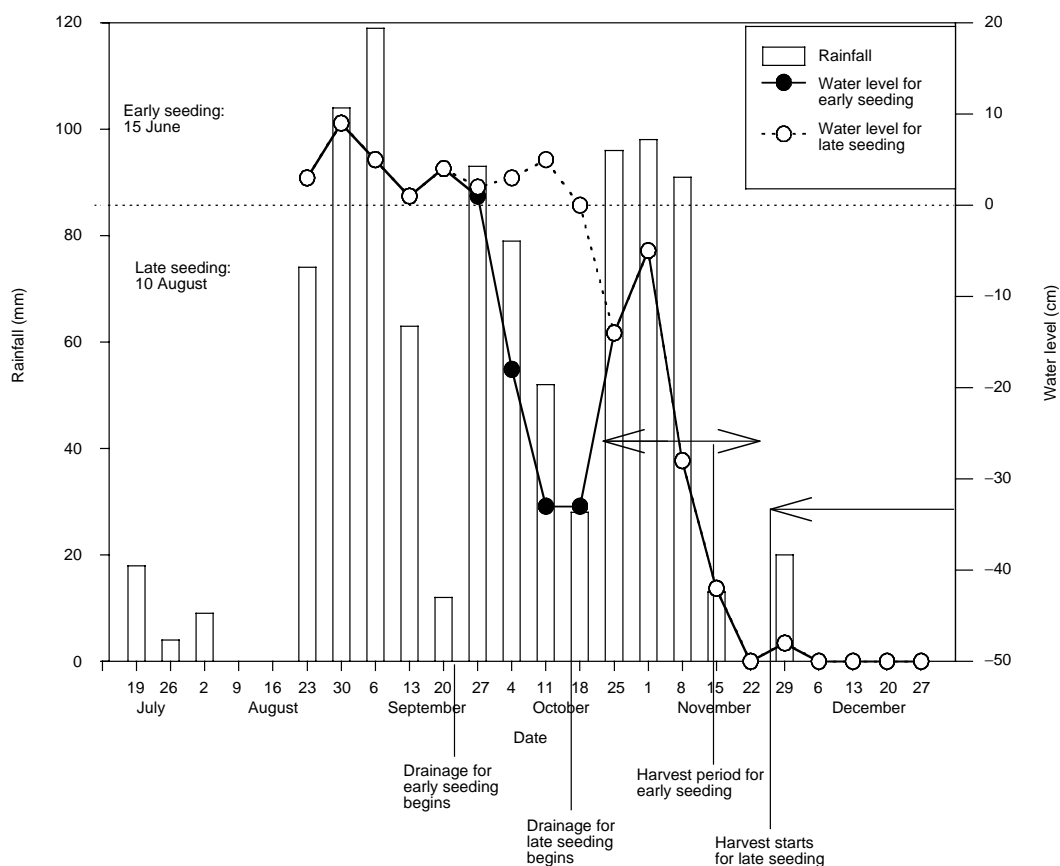


Figure 1. Weekly rainfall and water levels under drained conditions, Chrey Veal, Cambodia, 1999 wet season.

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 $ST \times G$ 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 $ST \times G$ interaction had significant effects on both DTF and GY ($P < 0.01$). Drained conditions reduced GY ($P < 0.05$). The interactions W (water) \times ST, W \times G and W \times ST \times 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

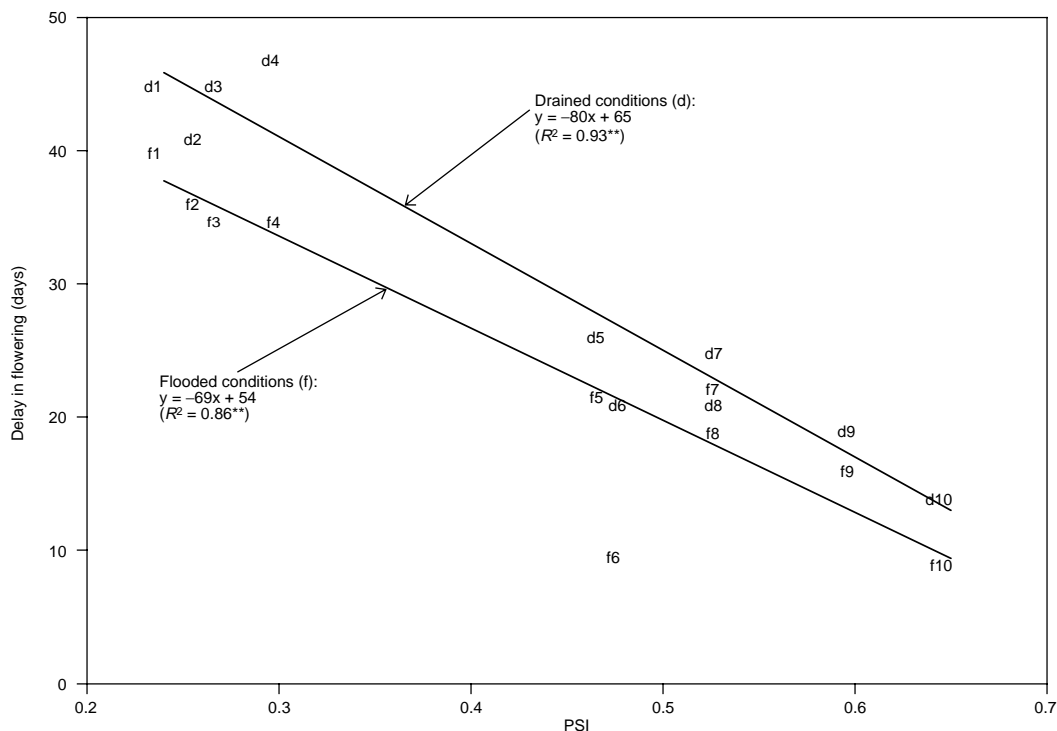


Figure 2. Relationship between the photoperiod sensitivity index (PSI) and delay in flowering as affected by late seeding (57 days later). f = flooded conditions; d = drained conditions; numbers refer to genotypes.

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 \times 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 \times G) interaction was significant ($P < 0.05$). The interactions W \times SA and W \times SA \times G had no effects. Seedling age also affected ($P < 0.01$) total dry matter production under both water conditions (results not shown).

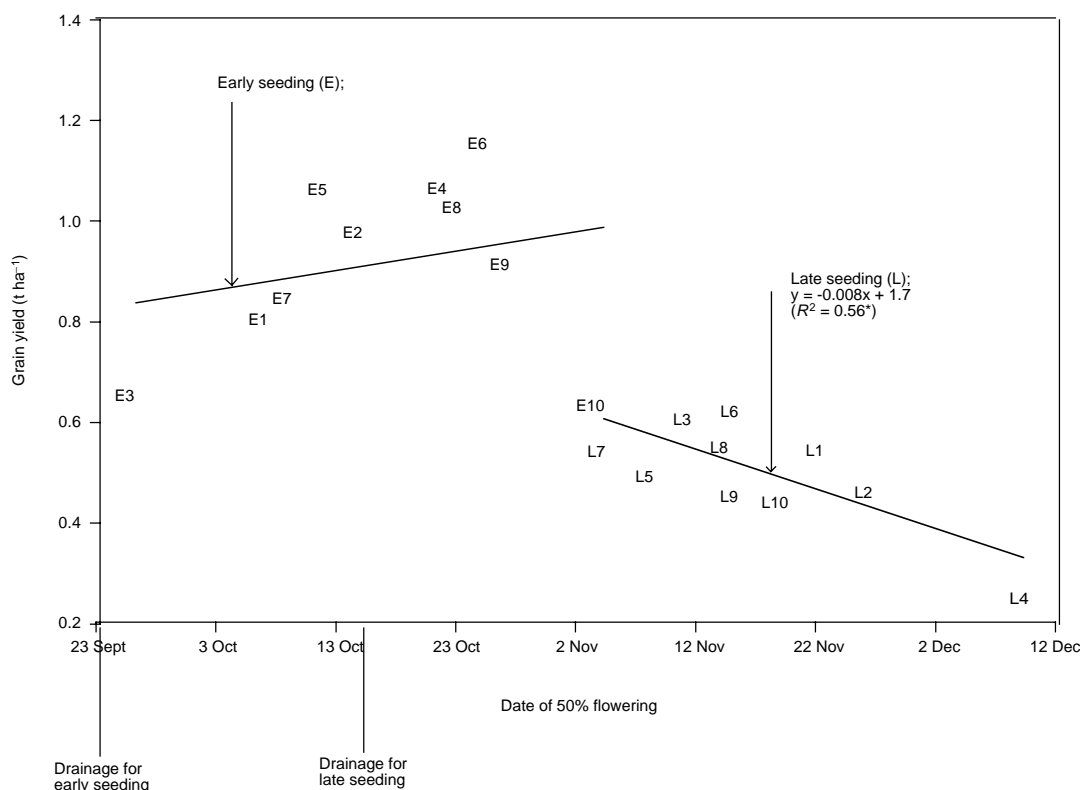


Figure 3. Relationship between grain yield and date at 50% flowering of genotypes tested at early seeding (15 June) and late seeding (10 August) under drained conditions. E = early seeding; L = late seeding; numbers refer to genotypes.

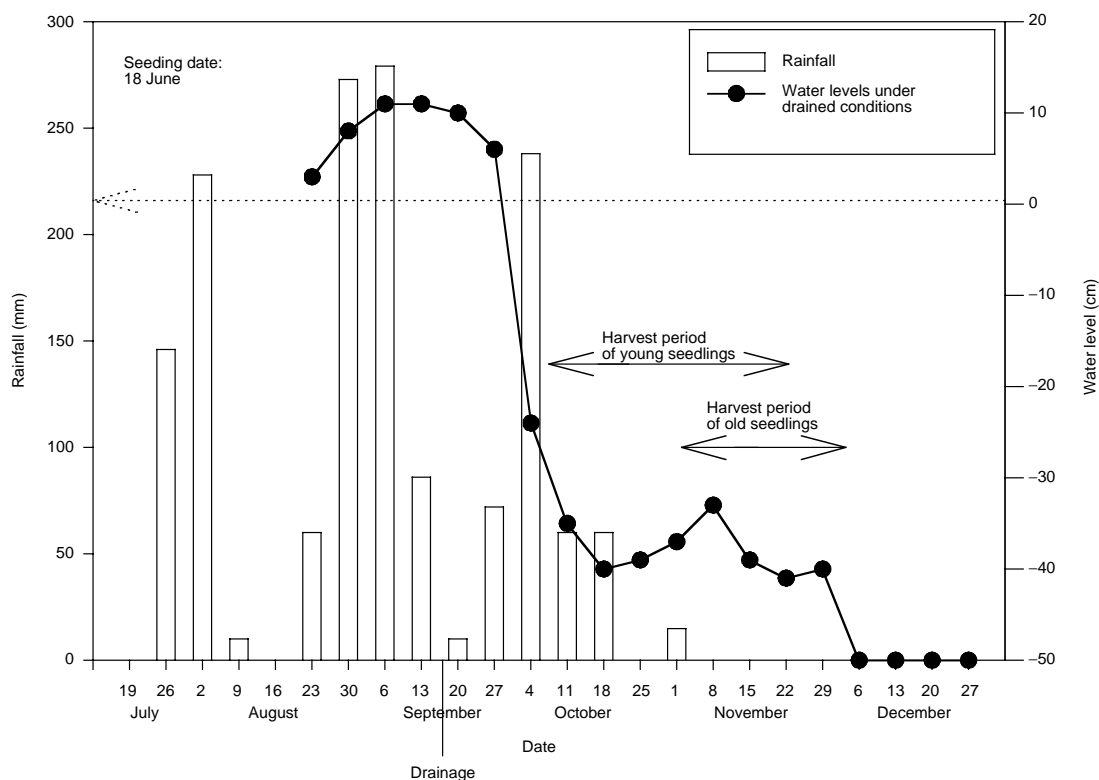


Figure 4. Weekly rainfall and water levels under drained conditions, CARDI, Cambodia, 1999 wet season.

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.

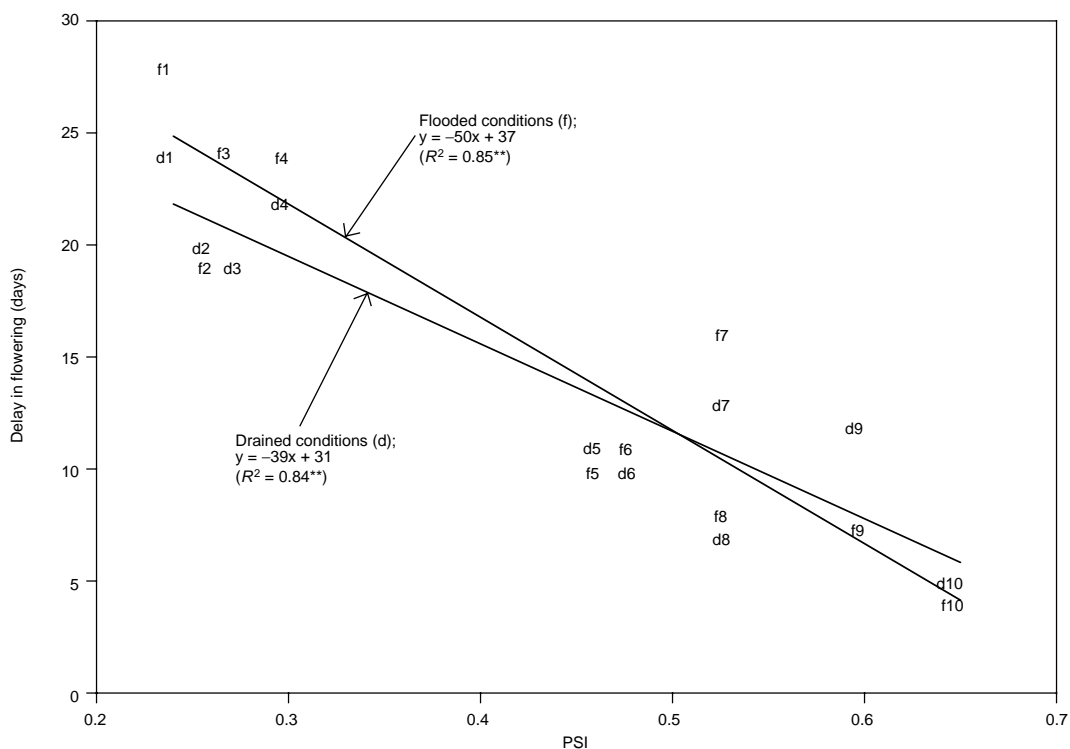


Figure 5. Relationship between delay in flowering and the photoperiod sensitivity index (PSI) as affected by transplanting 60-day-old seedlings. f = flooded conditions; d = drained conditions; numbers refer to genotypes.

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

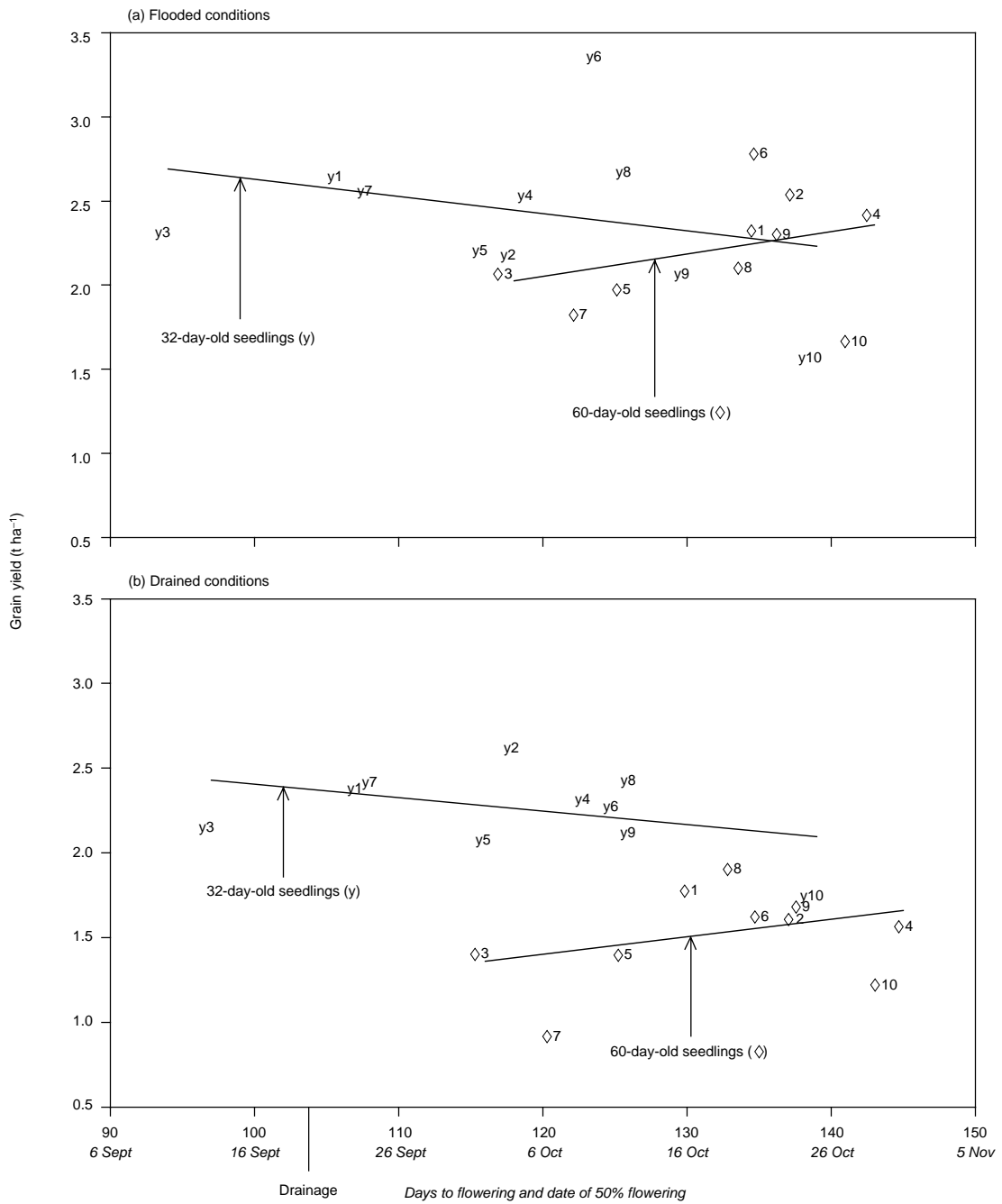


Figure 6. Relationship between grain yield and days to 50% flowering of genotypes tested with 32-day-old seedlings (y) and 60-day-old seedlings (◇) under flooded (a) and drained (b) conditions. Numbers refer to genotypes.

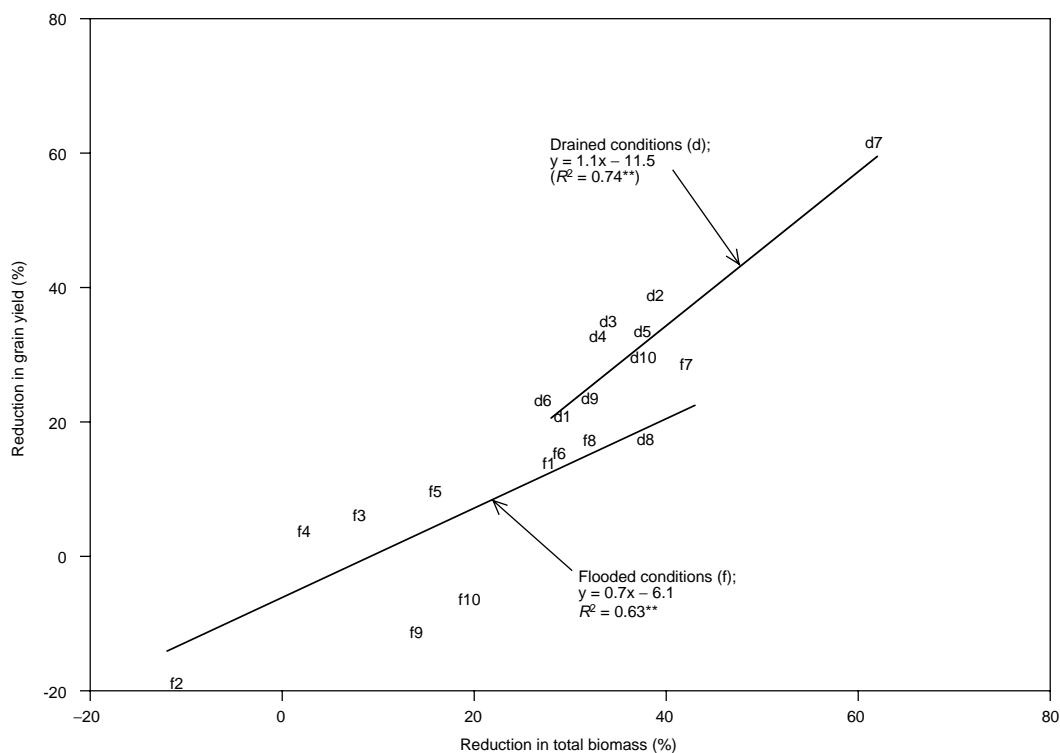


Figure 7. Reduction in grain yield in relation to reduction in total biomass as affected by transplanting with 60-day-old seedlings. f = flooded conditions; d = drained conditions; numbers refer to genotypes.

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., Rajatasereekul, 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. Khounphonh¹, Phytoon², J. Basnayake³, S. Fukai³, B. Linquist^{4*} and M. Chanphengsay²

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

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

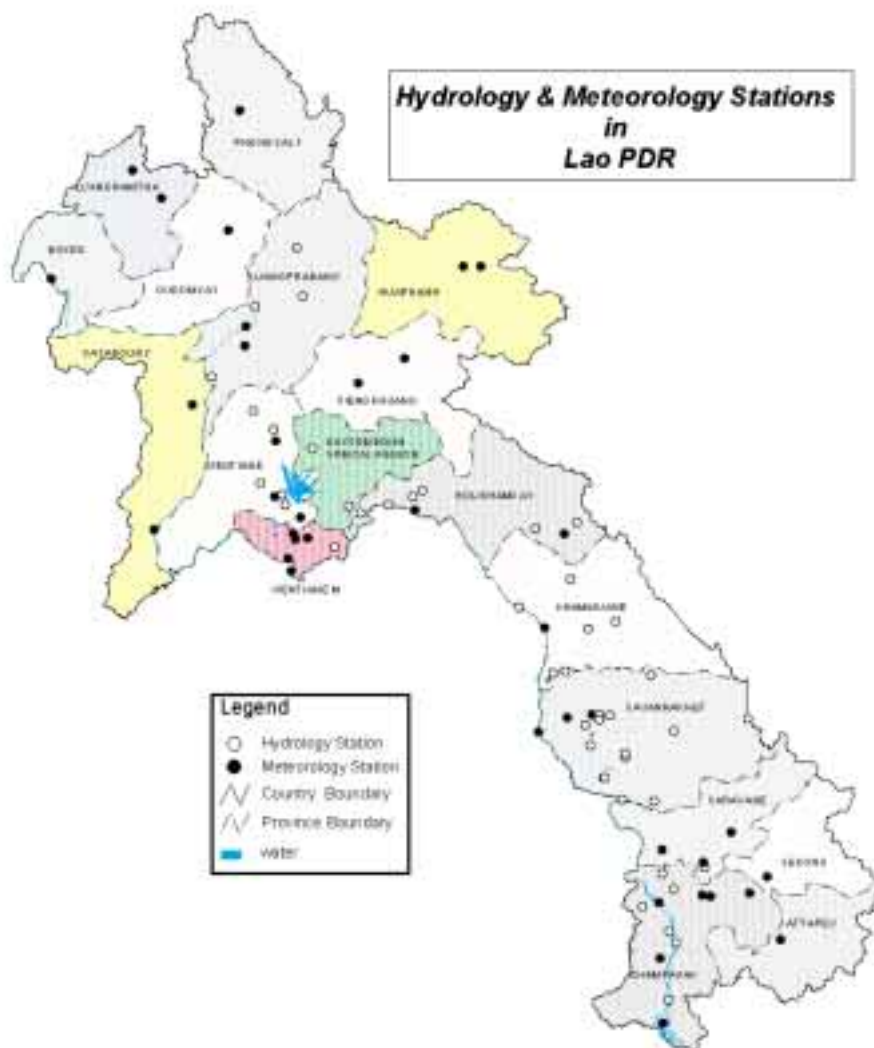


Figure 1. Location of meteorological and hydrological stations in Laos.

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.

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.	Hatdockeyo	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

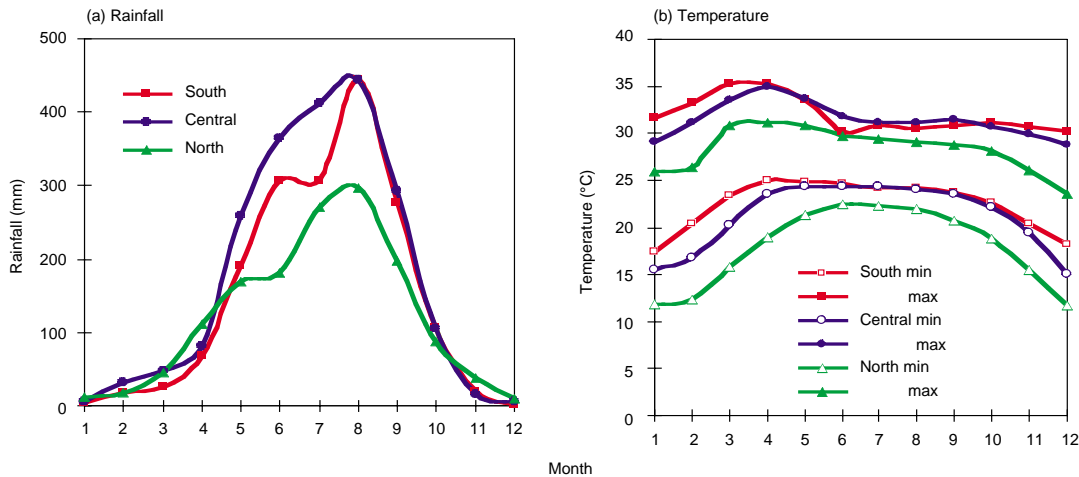


Figure 2. Rainfall and temperature distribution in northern, central and southern Laos.

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 con-

ditions 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

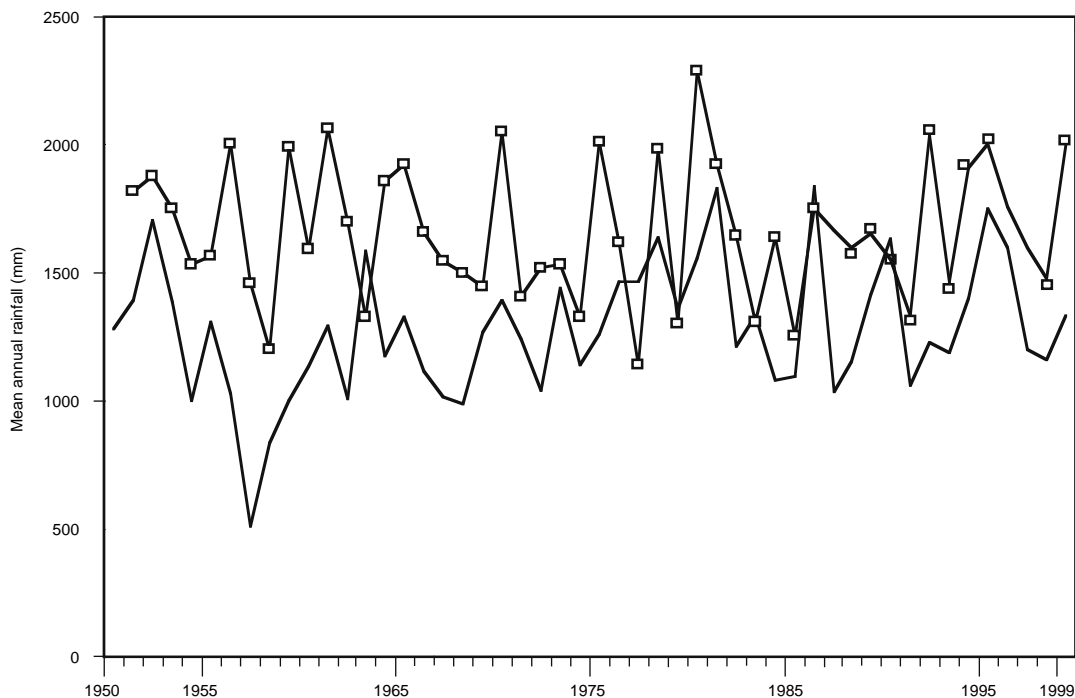


Figure 4. The variability of total annual rainfall for Laung Prabang Province (—) and Vientiane Municipality (—□—), Laos, from 1950 to 1999.

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.

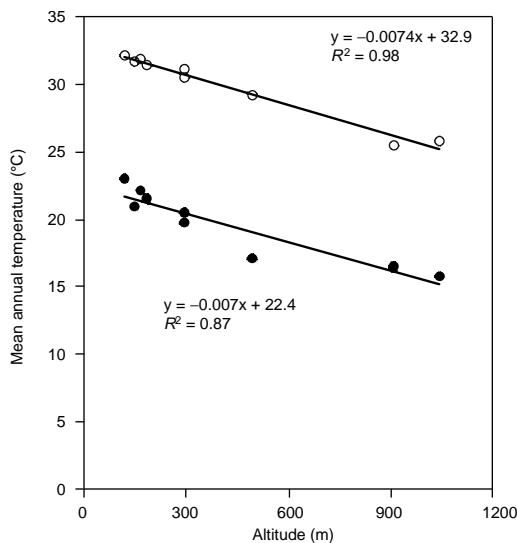


Figure 5. The relationship between mean maximum (○) and mean minimum (●) annual temperatures and altitude in Laos. Data are from nine stations and are the means from 1985 to 1998.

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 Horie¹, Masao Ohnishi², Tatsuhiko Shiraiwa¹,
Nopporn Supapoj³, Naruo Matsumoto⁴ and Nobuyuki Kabaki⁴

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

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

KEYWORDS: Model simulation, Rainfed rice, Soil fertility, Toposequence, Water availability, Yield variability, North-East Thailand

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 m² in 1997 and 0.5 m² 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 Walkley–Black method (Walkley 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

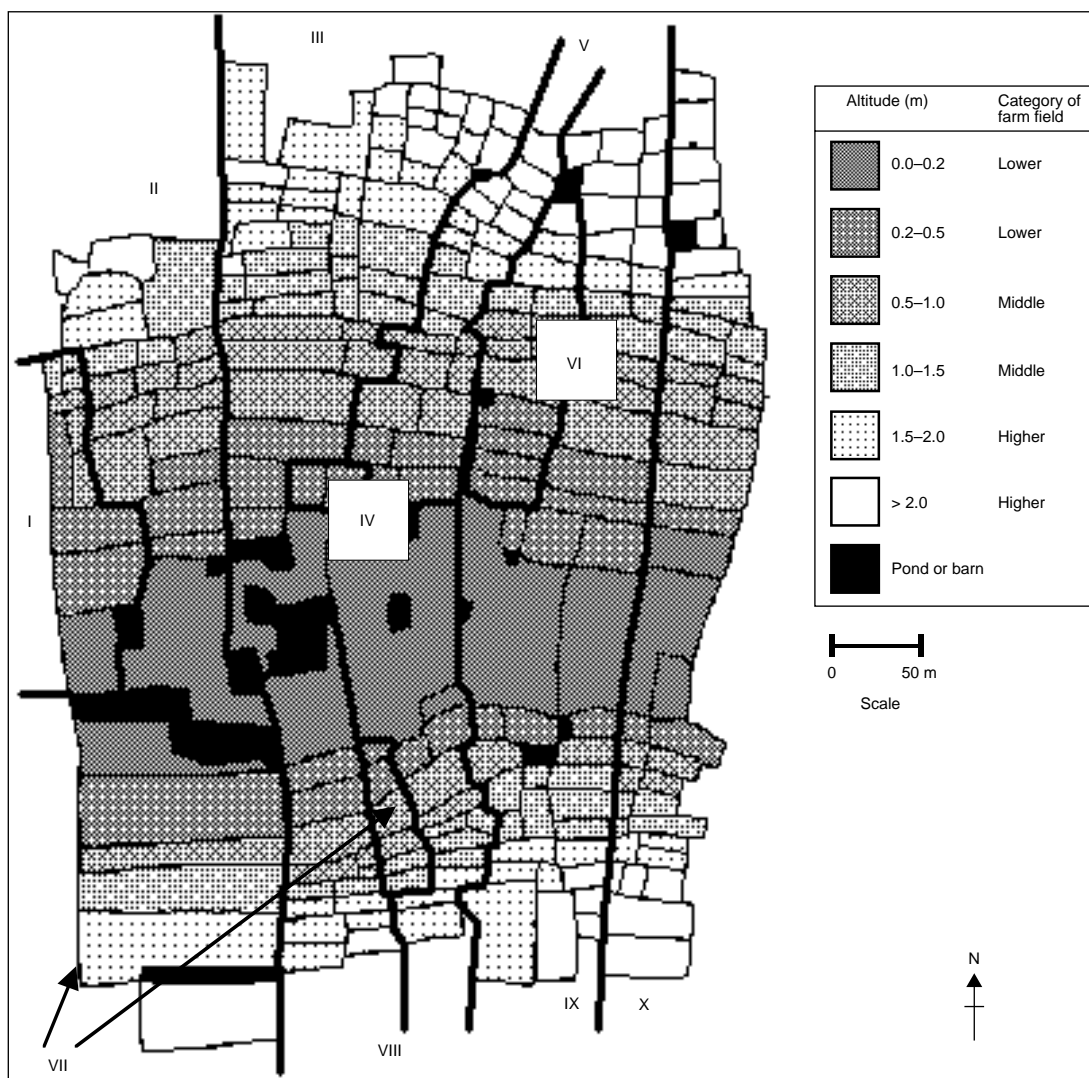


Figure 1. Map of 247 rice fields and their elevations relative to the lowest point in the Hua Don mini-watershed, North-East Thailand. (— = boundaries between farms I to X; — = boundaries between fields.)

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–P₂O₅–K₂O) 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 in 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. ^bDOY = day of the year, for example, 189th ± 11 = 8th July ± 11 days.

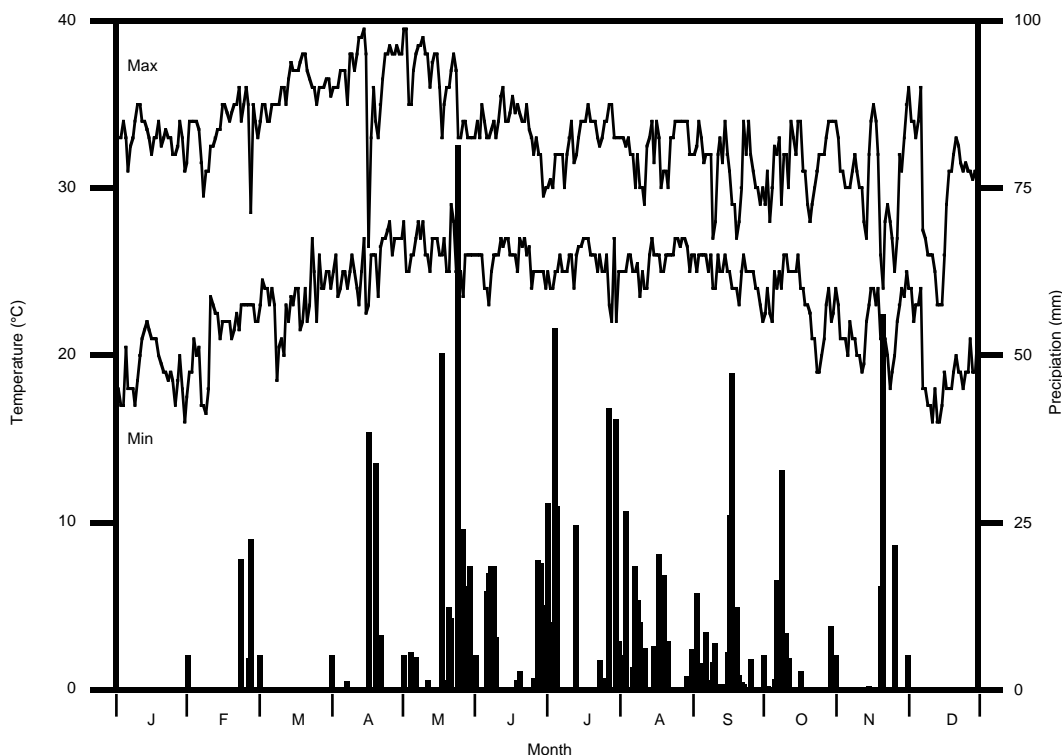


Figure 2. The maximum and minimum temperatures (lines) and precipitation (bars) at the Ubon Rice Research Centre, North-East Thailand, 1998.

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.

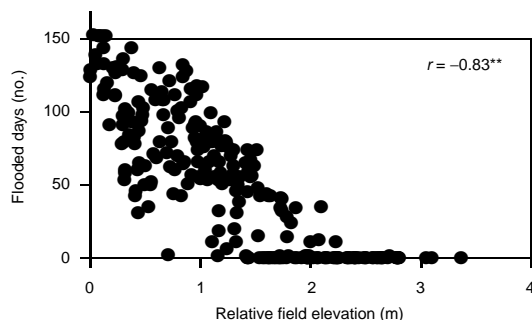


Figure 3. Number of flooded days as a function of relative field elevation of farm fields in the Hua Don study area, North-East Thailand, 1998 wet season (1 May–31 October).

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.

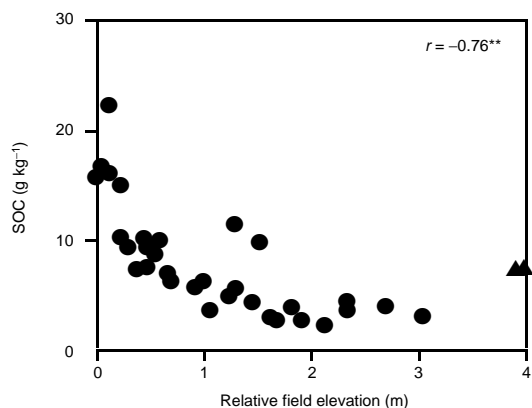


Figure 4. Soil organic carbon (SOC) contents as a function of the relative field elevation of farm fields in the Hua Don study area (●) and secondary woodland (▲), North-East Thailand.

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 produc-

tion 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.

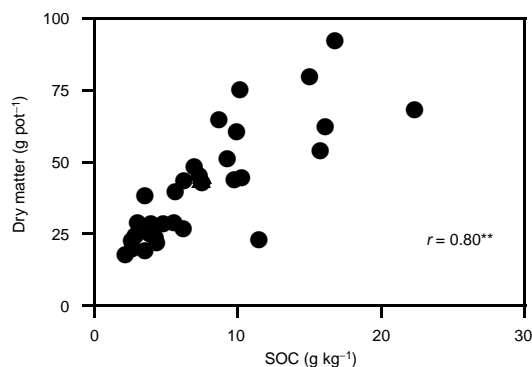


Figure 5. Relationship between soil organic carbon (SOC) content and rice dry matter production as measured by a pot-growth experiment for soils sampled from farm fields in the Hua Don study area (●) and secondary woodland (▲), North-East Thailand.

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.

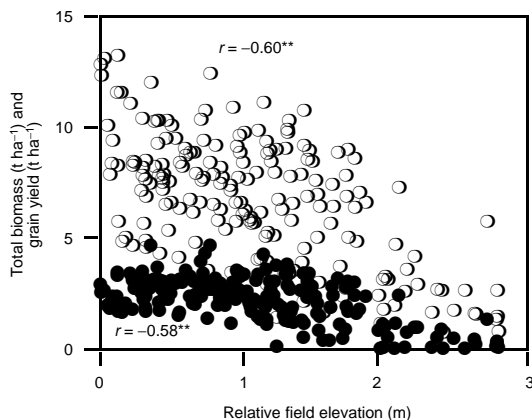


Figure 6. Variation with field elevation in total biomass (○) and grain yield (●) in the Hua Don study area, North-East Thailand, 1998.

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.

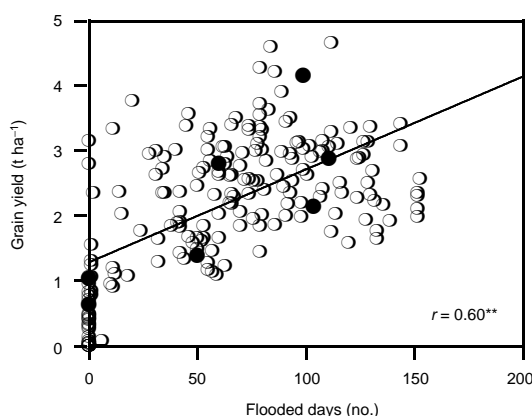


Figure 7. Relationship between number of flooded days and grain yield in the Hua Don study area, North-East Thailand, 1997 (●) and 1998 (○).

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.

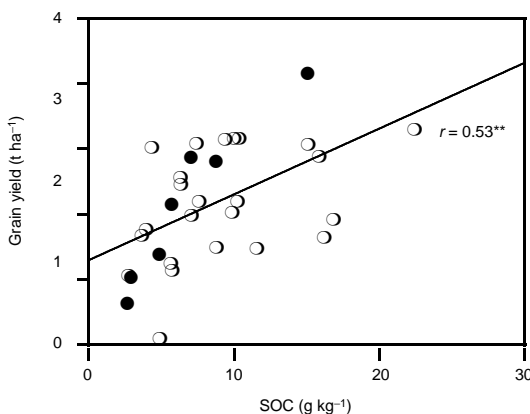


Figure 8. Relationship between soil organic carbon (SOC) content and grain yield in the Hua Don study area, North-East Thailand, 1997 (●) and 1998 (○).

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

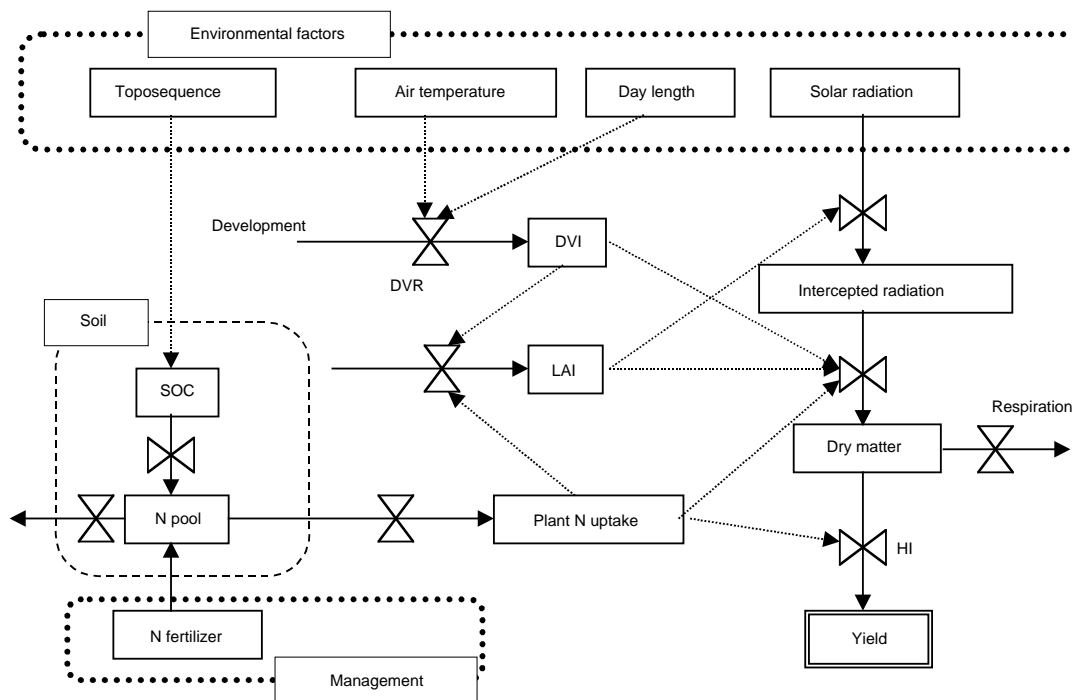


Figure 9. Flow chart of the model for simulating nitrogen-limited growth and yield of rice in relation to toposequential distribution of soil organic carbon (SOC) content and weather conditions. DVR = developmental rate; DVI = developmental index; LAI = leaf area index; N = nitrogen; HI = harvest index.

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:

$$\Delta N_{\min} = 0.657 \exp \{-3.52 / \text{SOC}\} \quad [1]$$

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 ($r = 0.86$, $P < 0.01$):

$$\text{SOC} = 12.37 \exp \{-0.622 \text{ RE}\} \quad [2]$$

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.

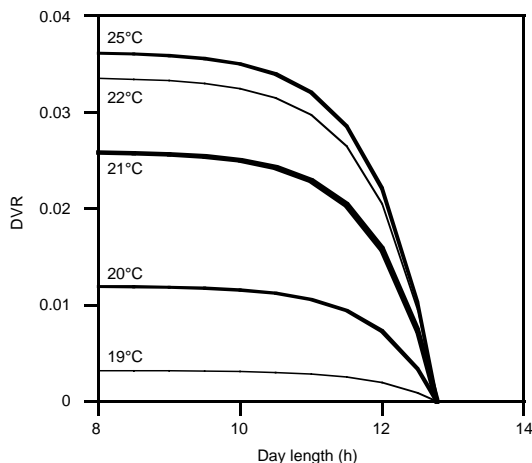


Figure 10. The response curves for the developmental rate (DVR) of rice cultivar KDML 105 to day length and temperature, from seedling emergence (0) to panicle initiation (>0.03).

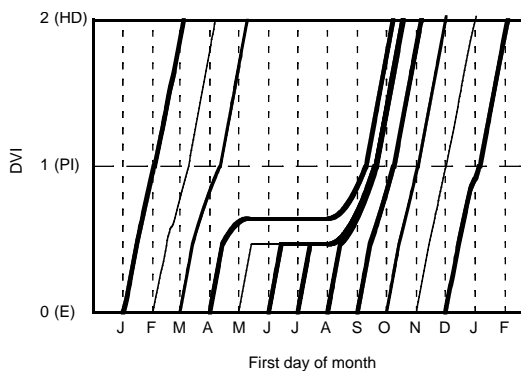


Figure 11. Simulated time courses of the developmental index (DVI) for rice cultivar KDML 105 according to the month of emergence (E), Ubon Province, North-East Thailand. PI = panicle initiation; HD = heading.

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.

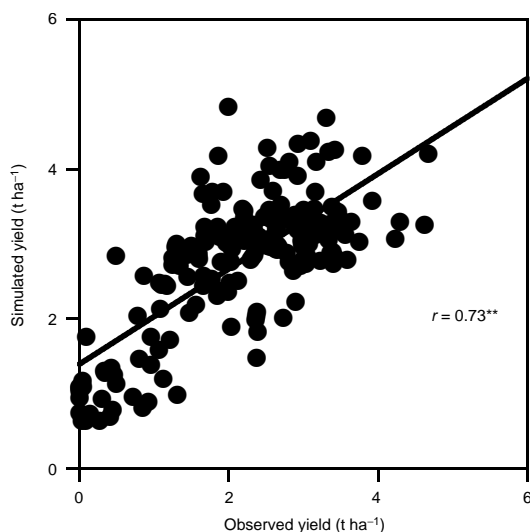


Figure 12. Comparison between observed and simulated rice yields of farm fields in the Hua Don micro-watershed, North-East Thailand, 1998. Yield is given as paddy with 14% moisture content.

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

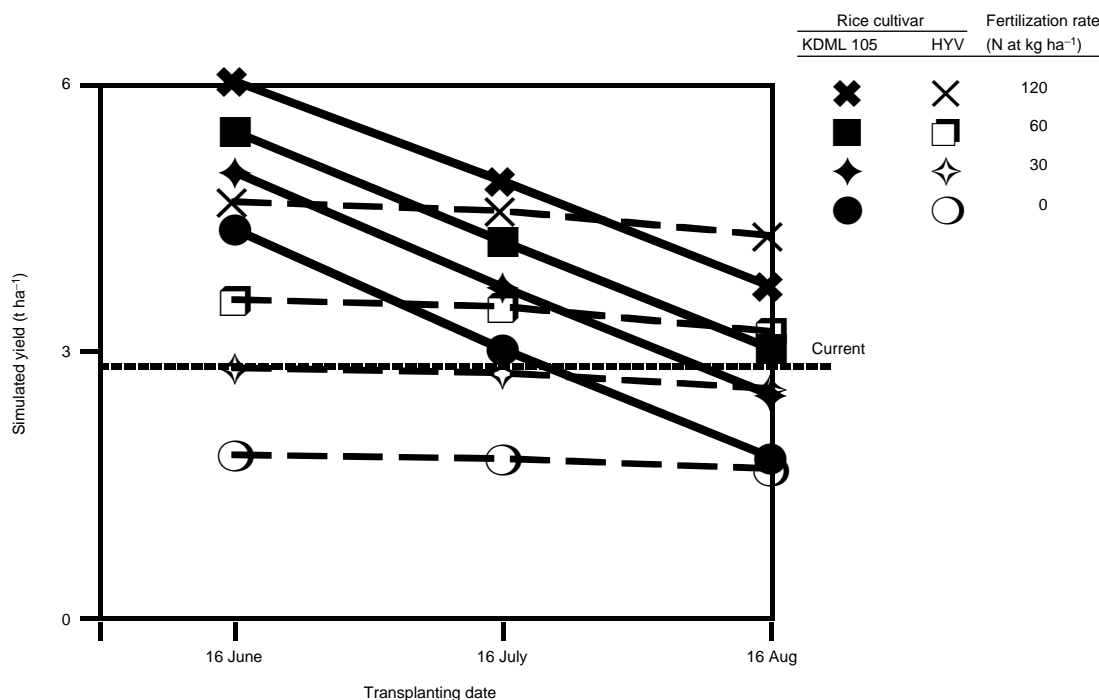


Figure 13. Simulated responses to transplanting date and fertilizer N application for yields of rice cultivar KDML 105 and a high-yielding variety (HYV), averaged over 247 fields in the Hua Don micro-watershed, North-East Thailand. For the HYV, crop parameters for rice cultivar IR64 were adapted. The 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 (Chairaj 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., Lapananontha, 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. Kam², C.T. Hoanh² and
Sisavang Vonghachack¹

Abstract

This paper describes the case study of implementation of the FAO methodology for agro-ecological 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 agro-ecological zones may go a long way in identifying

¹National Agriculture and Forestry Research Institute (NAFRI), Dong Dok, Vientiane, Laos

²International Rice Research Institute, Los Baños, Philippines

*E-mail: montatip@laotel.com

KEYWORDS: FAO land evaluation methodology, Crop suitability, Agroecological zoning, GIS

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 landform and 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

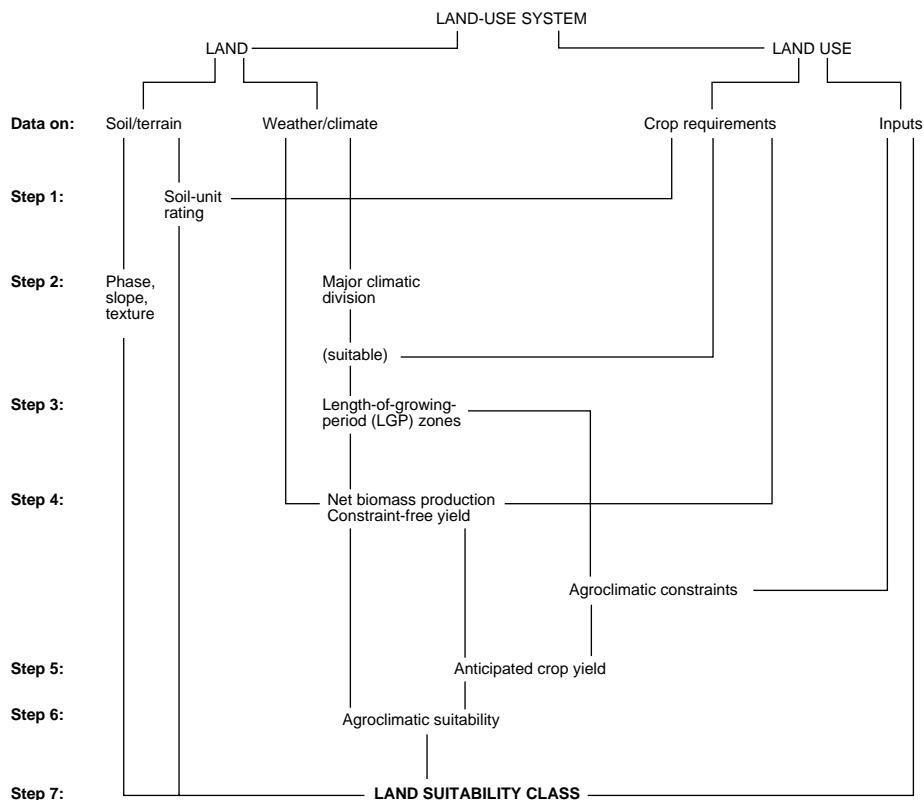


Figure 1. All agroecological zoning matching procedures in their relational context.

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 ($0.5 \cdot ET_0$) after a dry spell. A 'humid period' occurs whenever the precipitation rate exceeds the full rate of potential 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

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/cm².d), and daily gross assimilation rate (CH₂O, 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	
N. Hemisphere		Jan	Feb	March	April	May	June	July	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	483	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 (P_{max}) is not a steady $20\text{ kg ha}^{-1} \text{ h}^{-1}$, but is different for different crop-adaptability groups and is also temperature-dependent (Table 3).

Table 3. Maximum assimilation rate (P_{max} in kg/ha/h) as a function of the crop adaptability group and the daytime temperature (T_{day}). 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:

$$b_{gma} = (f_o * b_o) * (1 + 0.2 * y) + (1 - f_o) * b_c * (1 + 0.5 * y) \quad (4.3)$$

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} ($\text{kg ha}^{-1} \text{ d}^{-1}$)

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 ($20 \text{ kg ha}^{-1} \text{ h}^{-1}$)

P_{max} is maximum assimilation rate of field crop ($\text{kg ha}^{-1} \text{ h}^{-1}$)

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 $0.0283 \text{ kg kg}^{-1} \text{ d}^{-1}$ for leguminous crops and $0.0108 \text{ kg kg}^{-1} \text{ d}^{-1}$ for non-legumes. They suggested a quadratic relation to describe the temperature dependence of the maintenance respiration rate:

$$C_t = C_{30} * (0.044 + (0.0019^\circ\text{C}^{-1}) * T_{24h} + (0.001^\circ\text{C}^{-1}) * T_{24h}^2) \quad (4.5)$$

where

C_t is mass fraction of gross assimilate production (as CH_2O) lost through maintenance respiration with respect to dry crop mass at temperature T_{24h} ($\text{kg kg}^{-1} \text{ d}^{-1}$)

C_{30} is rate of loss of gross assimilate production by maintenance respiration at 30°C , set to $0.0283 \text{ kg kg}^{-1} \text{ d}^{-1}$ for leguminous crops and at $0.0108 \text{ kg kg}^{-1} \text{ d}^{-1}$ for non-legumes.

T_{24h} is average temperature (24-hour mean) over the growth cycle ($^\circ\text{C}$).

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 (E_c) 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.

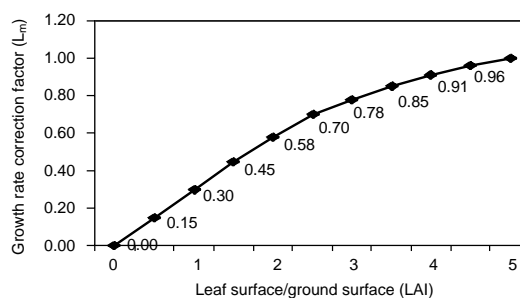


Figure 2. Correction factor for incomplete ground cover (L_m) as a function of the leaf area index (LAI) at the time of the crop's maximum growth.

A generally applicable expression of the potential net biomass production of 'major crop' (B_{na}) would thus be:

$$B_{na} = 0.36 * b_{gma} * N_g * L_m / (1 + 0.36 * C_t * N_g)$$

where

B_{na} is potential net production of dry matter by field crop (kg ha^{-1})

b_{gma} is overall gross rate assimilate production ($\text{kg ha}^{-1} \text{ d}^{-1}$)

N_g is length of growing cycle (d)

L_m is correction factor for incomplete ground cover

C_t is rate of loss of b_{gma} by maintenance respiration at actual temperature ($\text{kg kg}^{-1} \text{ d}^{-1}$)

0.36 is half the conversion efficiency ($= 0.5 * E_c$)

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
III	cassava	0.55
	pearl millet	0.25
	sorghum (tropical cvv.)	0.25
IV	maize (tropical cvv.)	0.35
	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 agro-climatic 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.

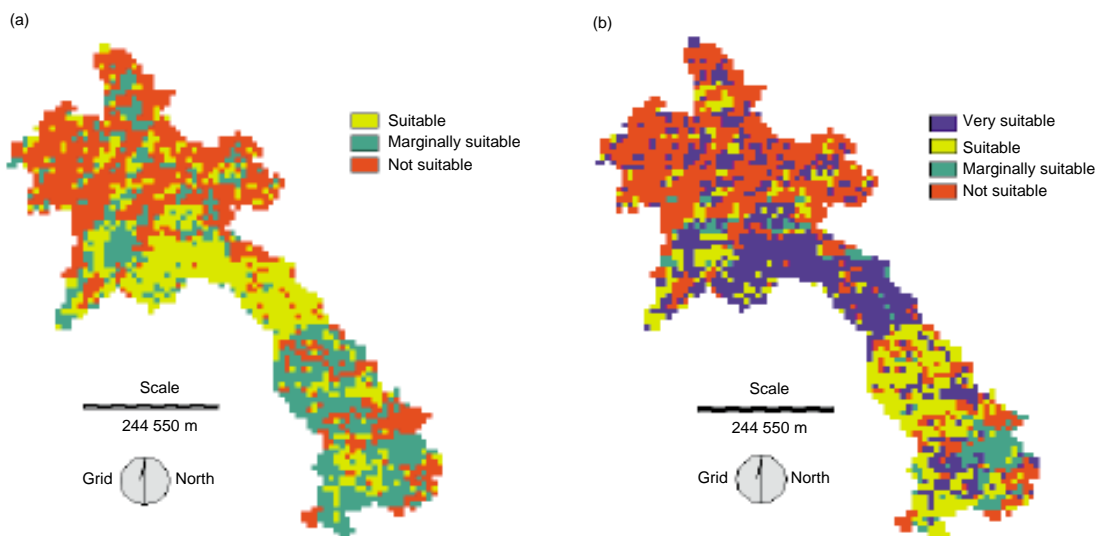


Figure 3. Agroecological rating for (a) rainfed lowland rice, and (b) maize, assuming a low level of farming inputs.

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).

A GIS-Based Crop-Modelling Approach to Evaluating the Productivity of Rainfed Lowland Paddy in North-East Thailand

Y. Kono^{1*}, S. Tomita², Y. Nagata³, K. Iwama⁴, E. Nawata², K. Junthotai⁵,
R. Katawatin⁵, K. Kyuma⁴, S. Miyagawa⁶, T. Niren⁴, C. Noichana⁵,
T. Sakuratani², A. Sributta⁵, and K. Watanabe²

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

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 km² 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

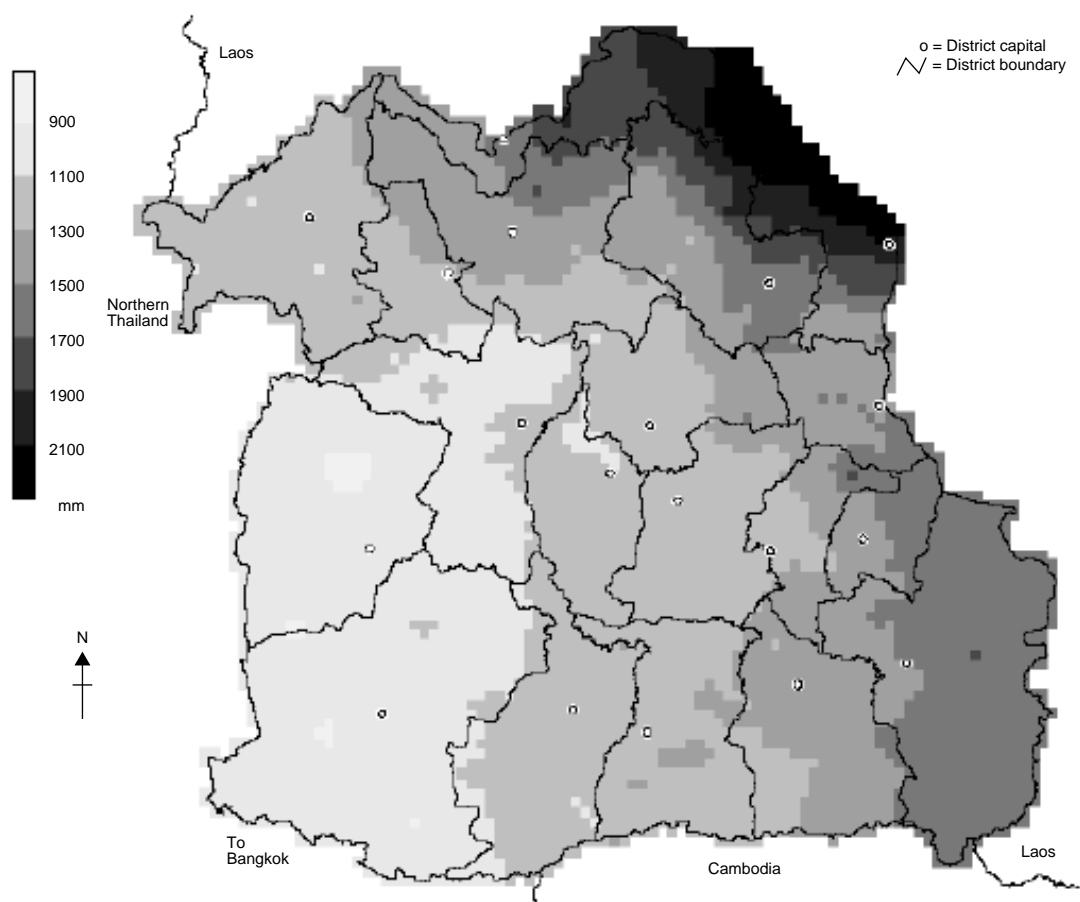


Figure 1. Average annual rainfall, North-East Thailand.

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.

Abbreviation	Parameter	Unit	Value
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

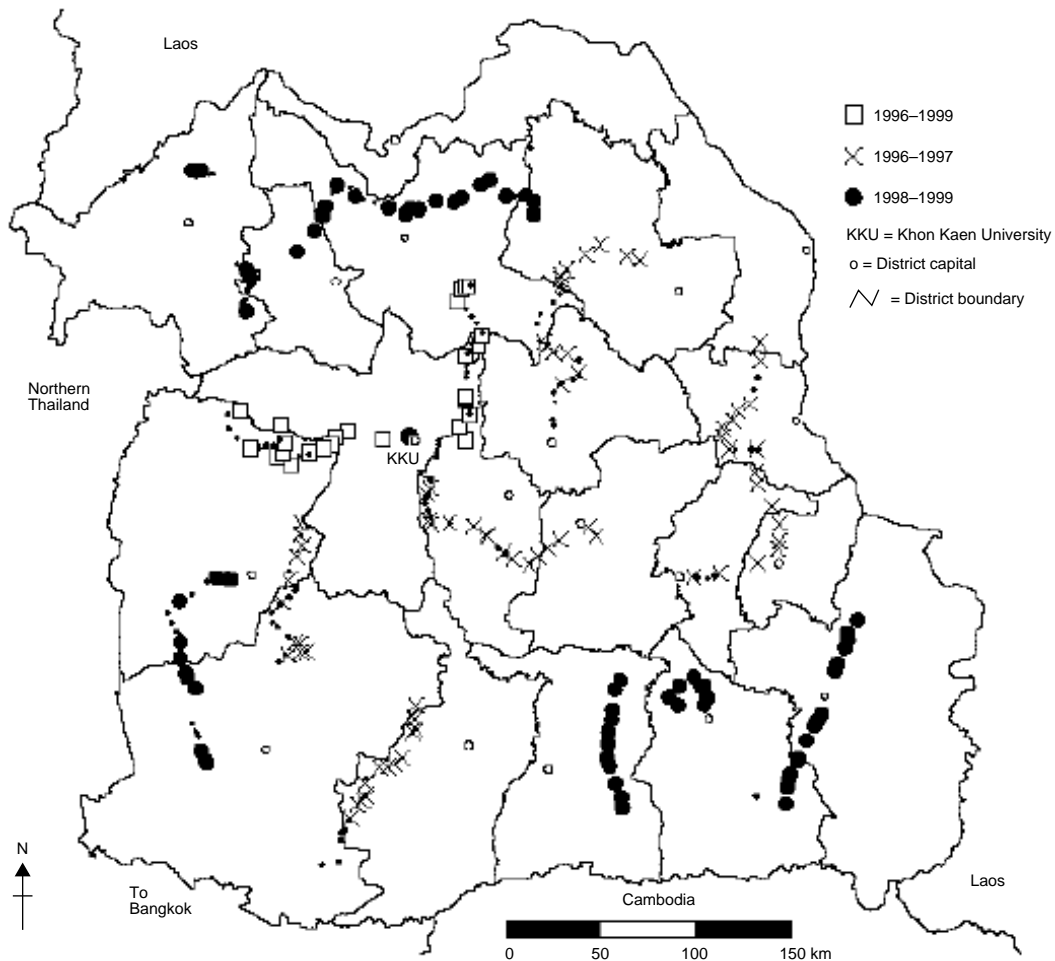


Figure 2. Study area and locations of surveyed plots, North-East Thailand.

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

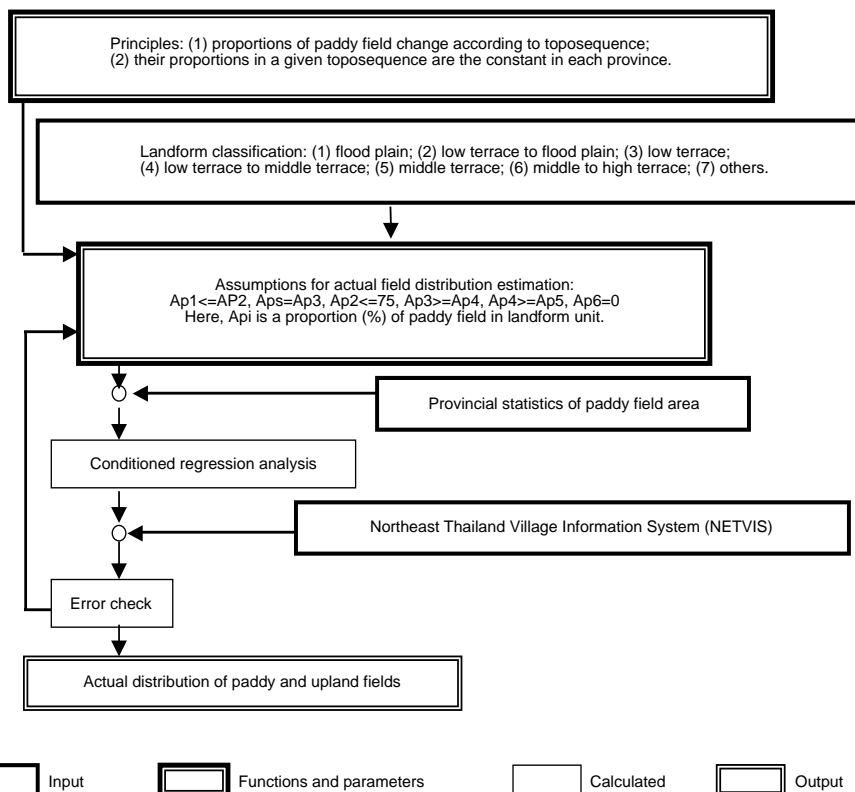


Figure 3. Flow chart for estimating paddy field distribution in North-East Thailand.

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

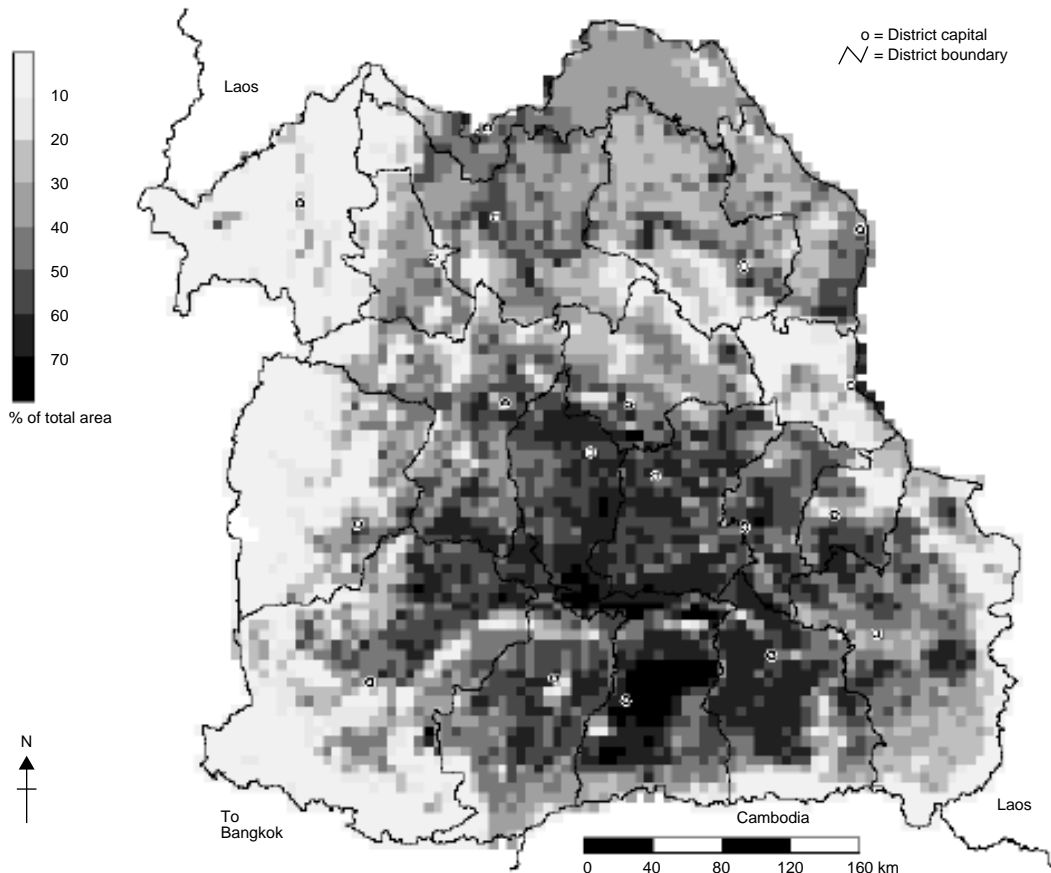


Figure 4. Estimated paddy field distribution in North-East Thailand.

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)	3-minute mesh		Estimated from MD ^b data
	Daily solar radiation (1979–1998)			
Administration	Daily rainfall (1979–1998)	Vector	1:50 000	Agricultural statistics ^c
	Location of provincial capital	Vector	1:50 000	
Agricultural production	Boundaries of province, district and subdistrict	Vector	Province and district level	NERAEO ^d
	Area and yield of paddy, sugar cane and cassava	Vector	District level	
1997 cultivation	Cropping calendar of paddy (1993–1996)	Vector	Subdistrict level	Original
Field distribution	Various items of paddy, cassava and sugar cane cultivation	Vector		
	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

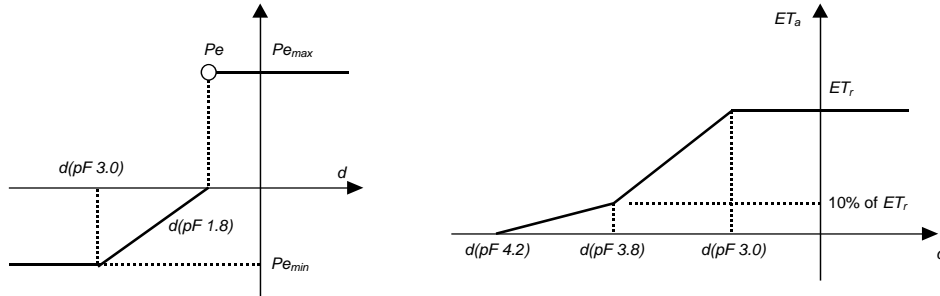
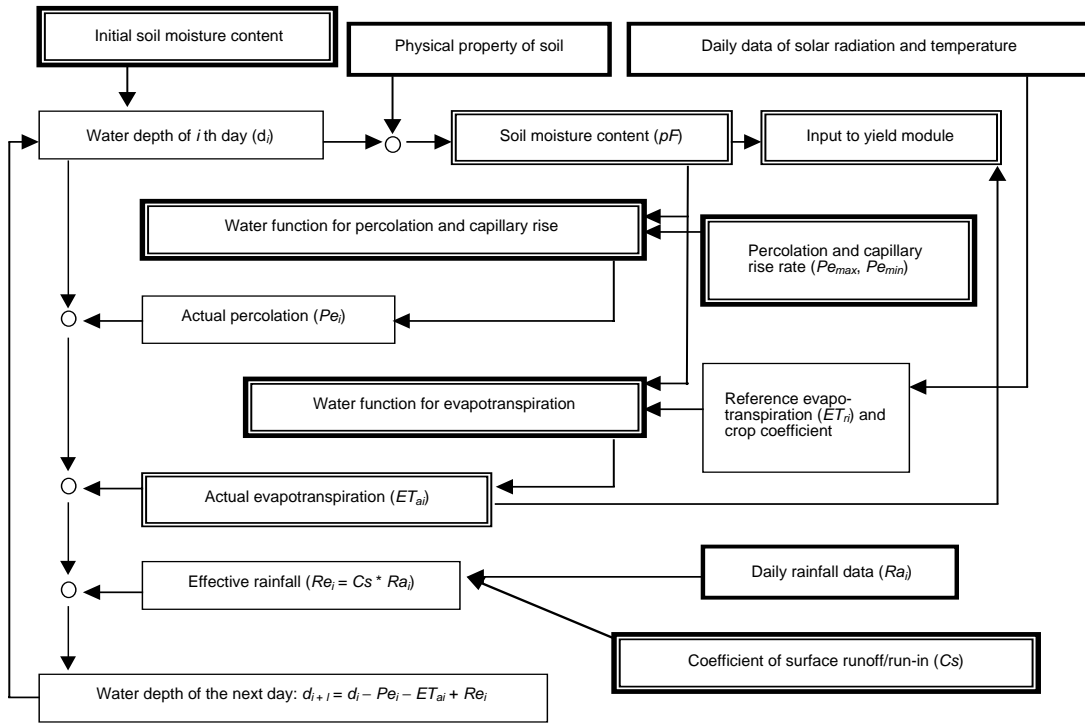


Figure 5. Flow chart of the water module used for crop modelling.

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.

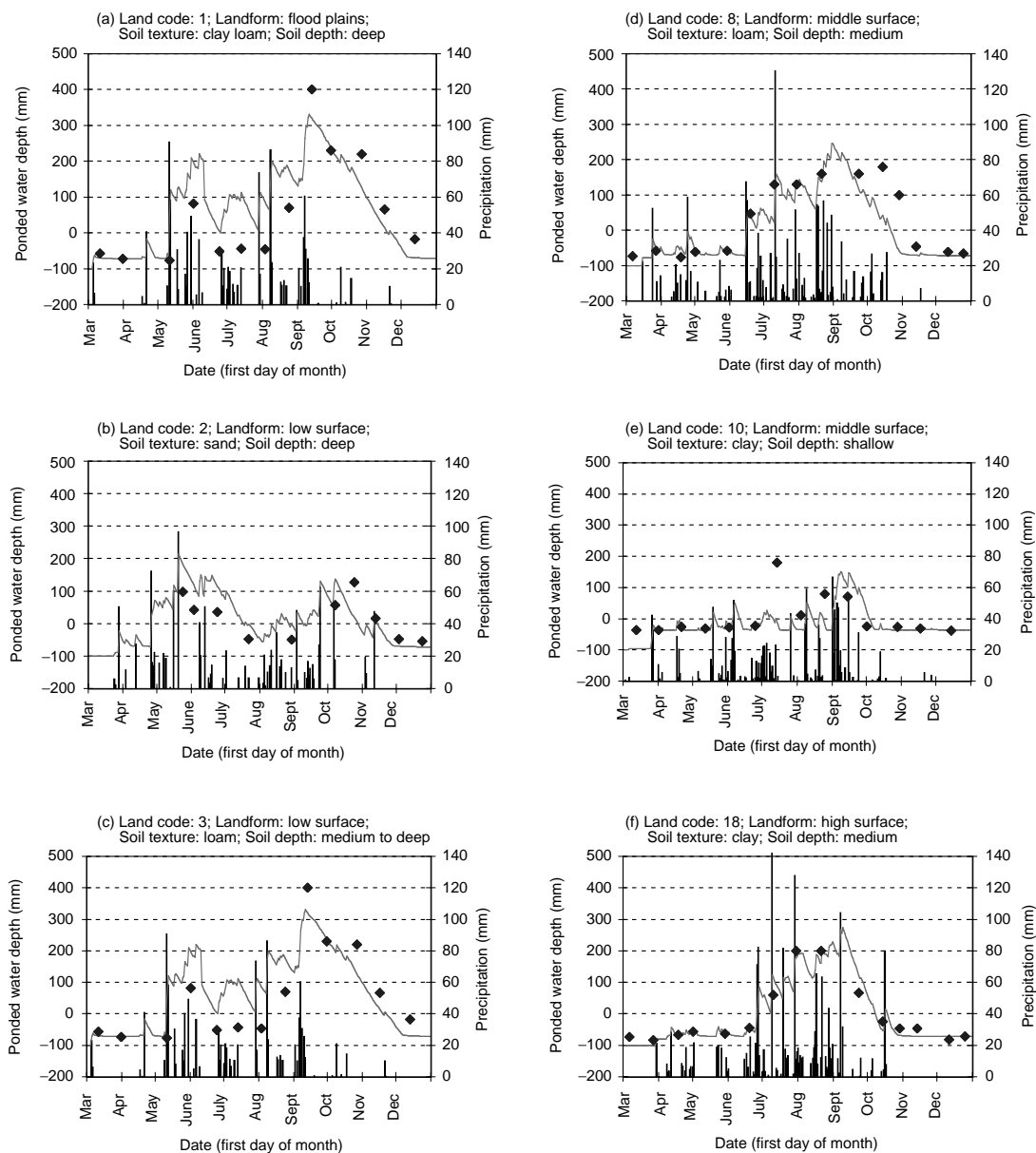


Figure 6. Estimated water conditions compared with observed conditions in North-East Thailand. — = estimated value; ◆ = observed value; ■ = precipitation.

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 pondered 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

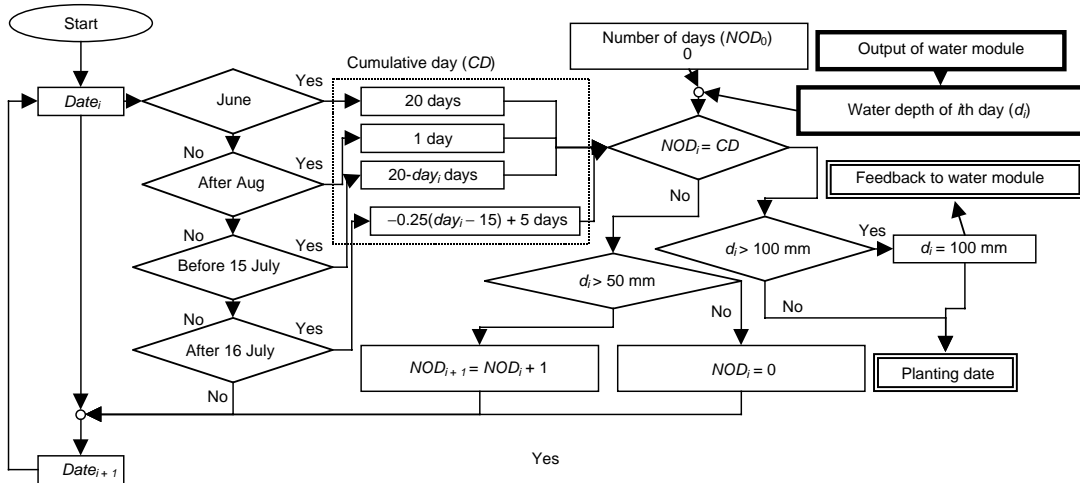


Figure 7. Flow chart of the planting schedule module used for crop modelling.

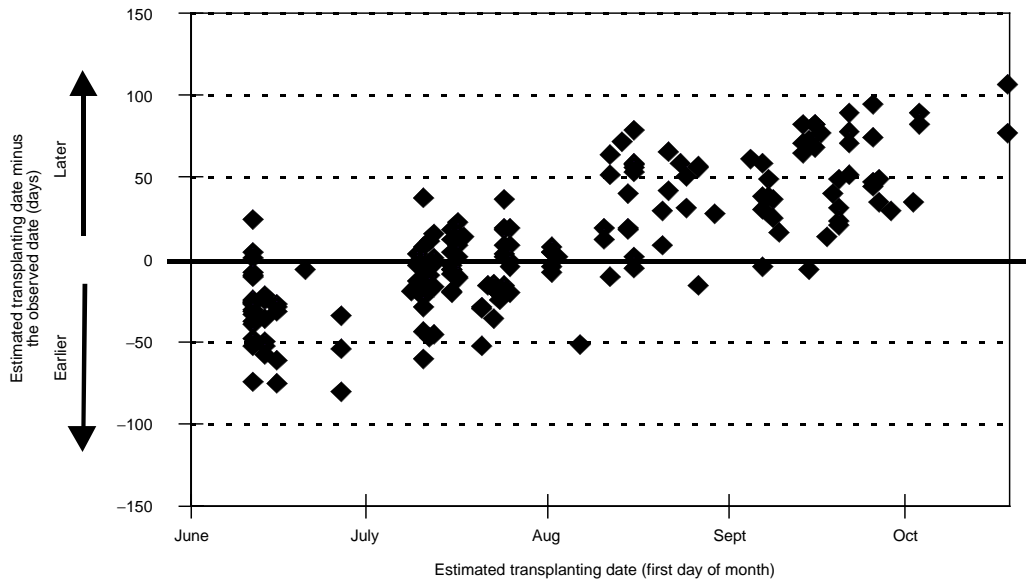


Figure 8. Estimated transplanting date compared with the observed date in North-East Thailand.

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

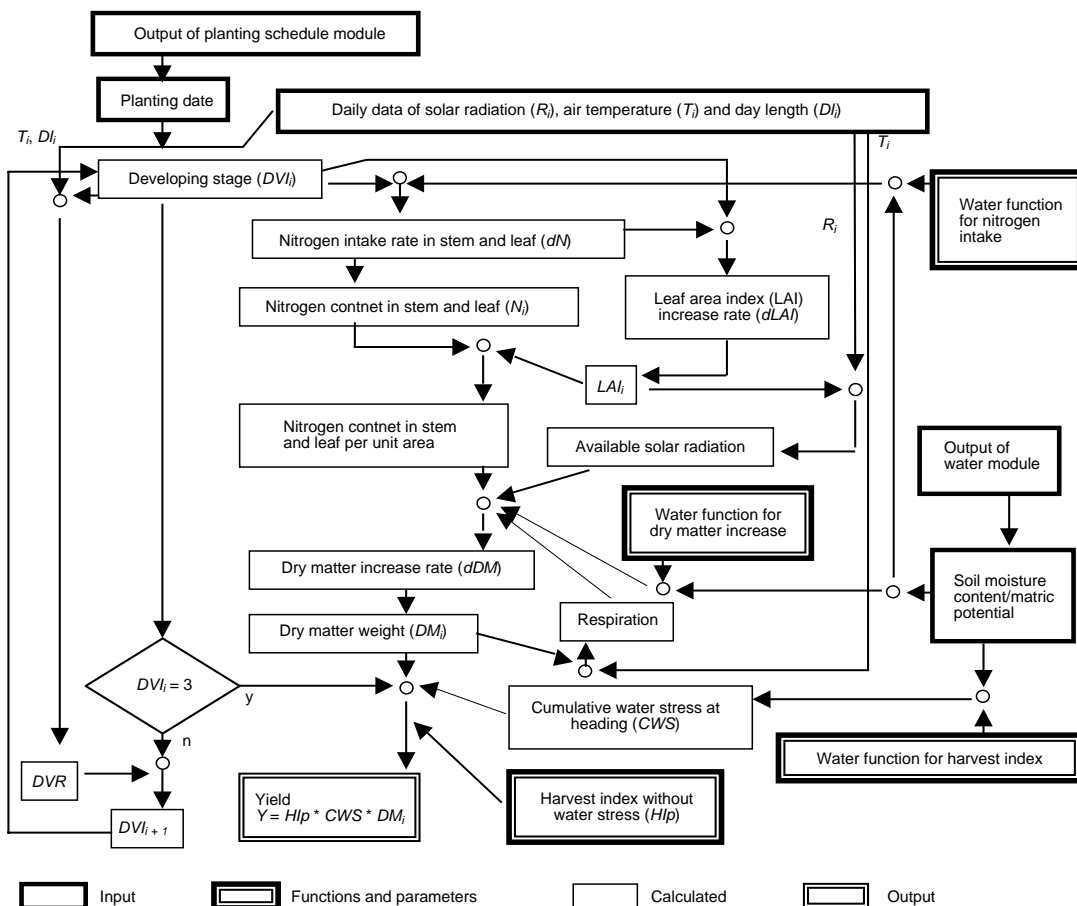


Figure 9. Flow chart of the yield module used for crop modelling.

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

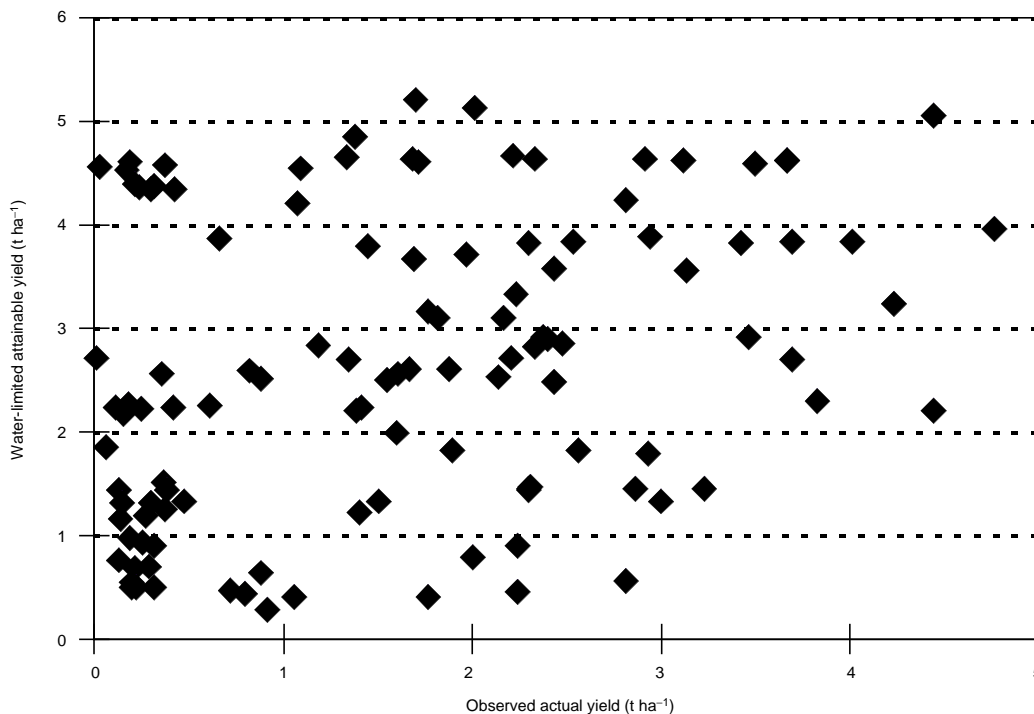


Figure 10. Estimated water-limited attainable yields compared with actual yields in North-East Thailand.

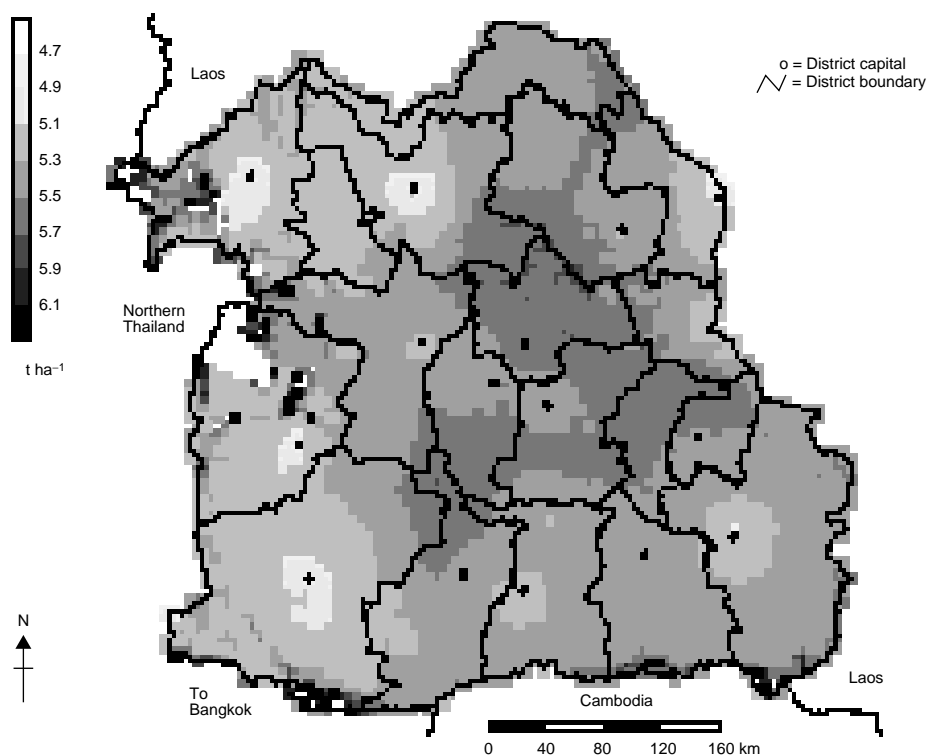


Figure 11. Estimated potential yields averaged over 20 years, North-East Thailand.

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.

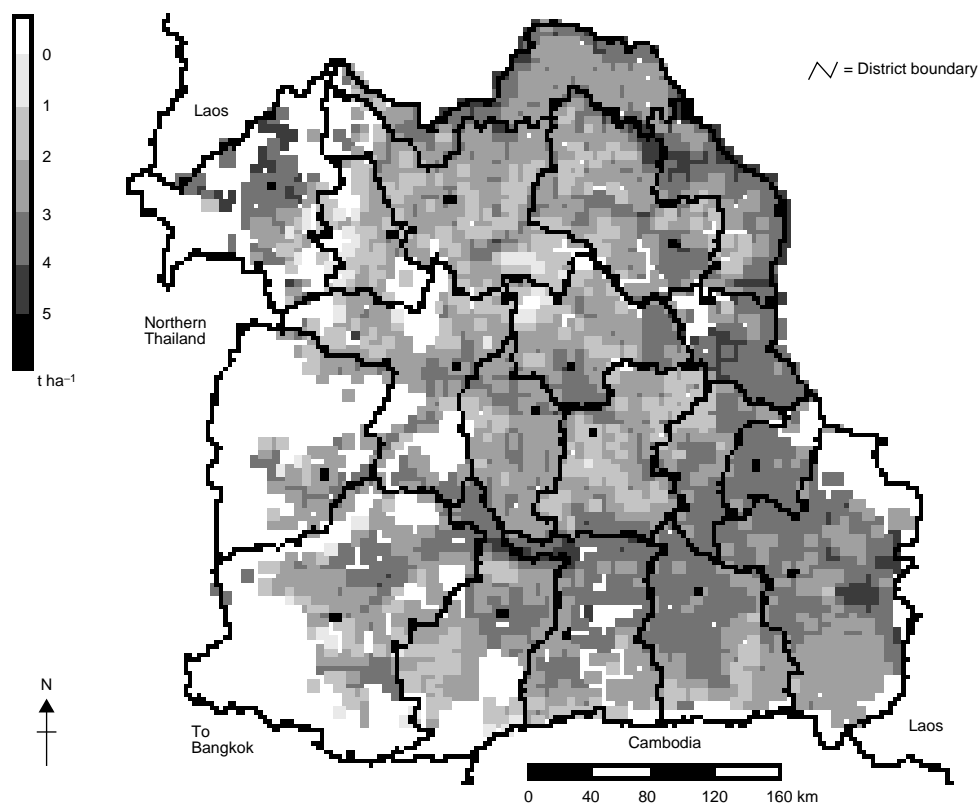


Figure 12. Attainable yield averaged over 20 years, North-East Thailand.

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

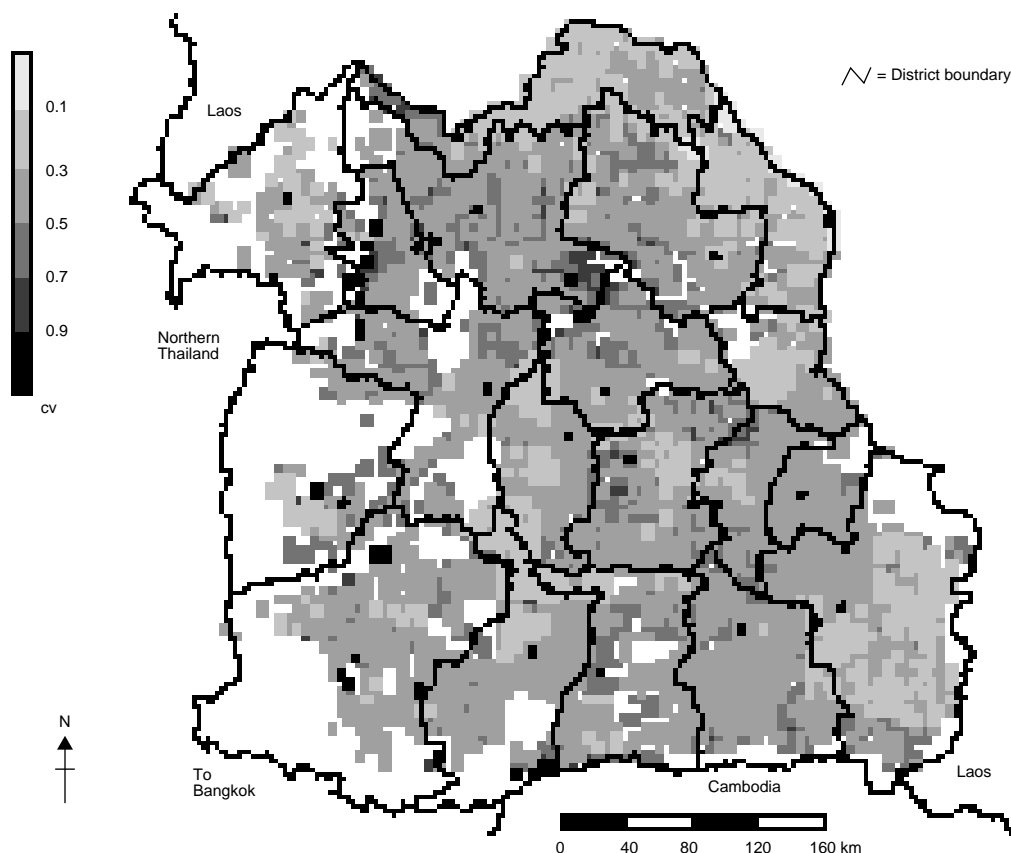


Figure 13. Coefficient of variation (cv) of attainable yields averaged over 20 years, North-East Thailand.

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.

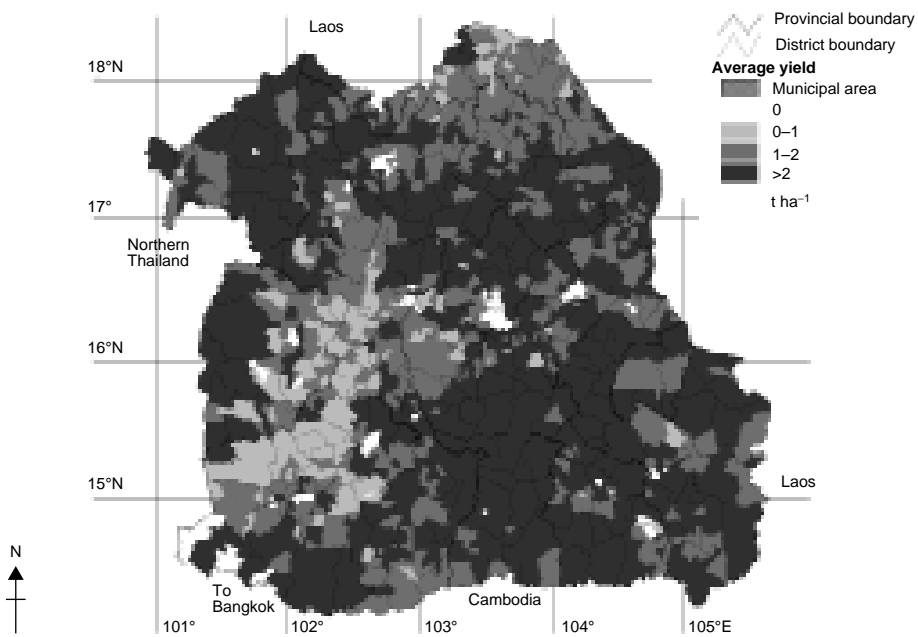


Figure 14. Actual yields at subdistrict level, North-East Thailand, 1997.

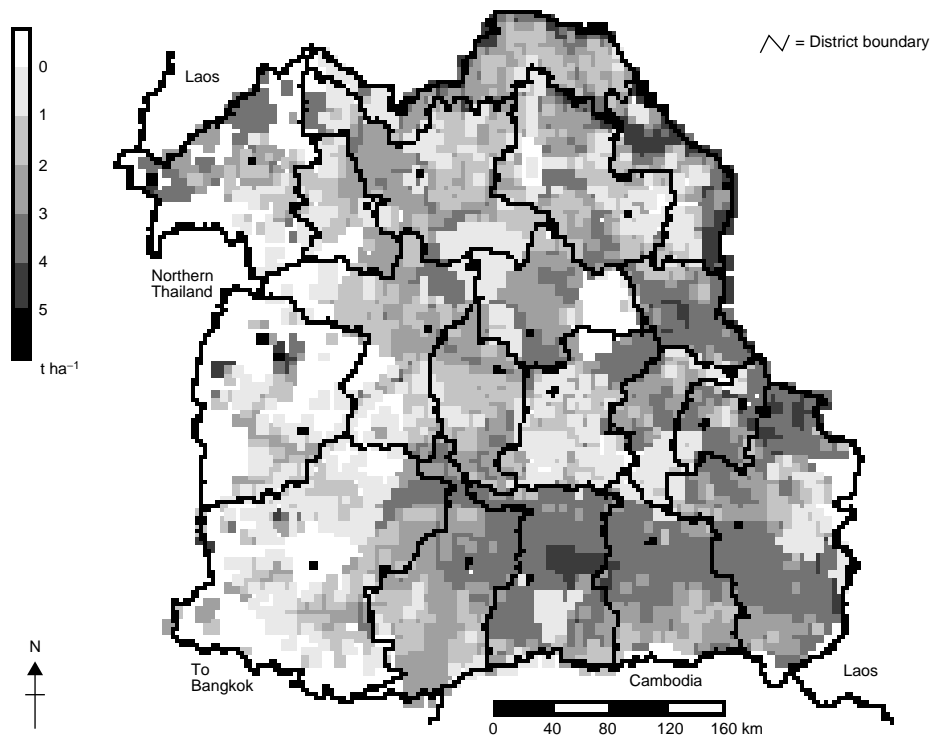


Figure 15. Attainable yields in 1997, North-East Thailand.

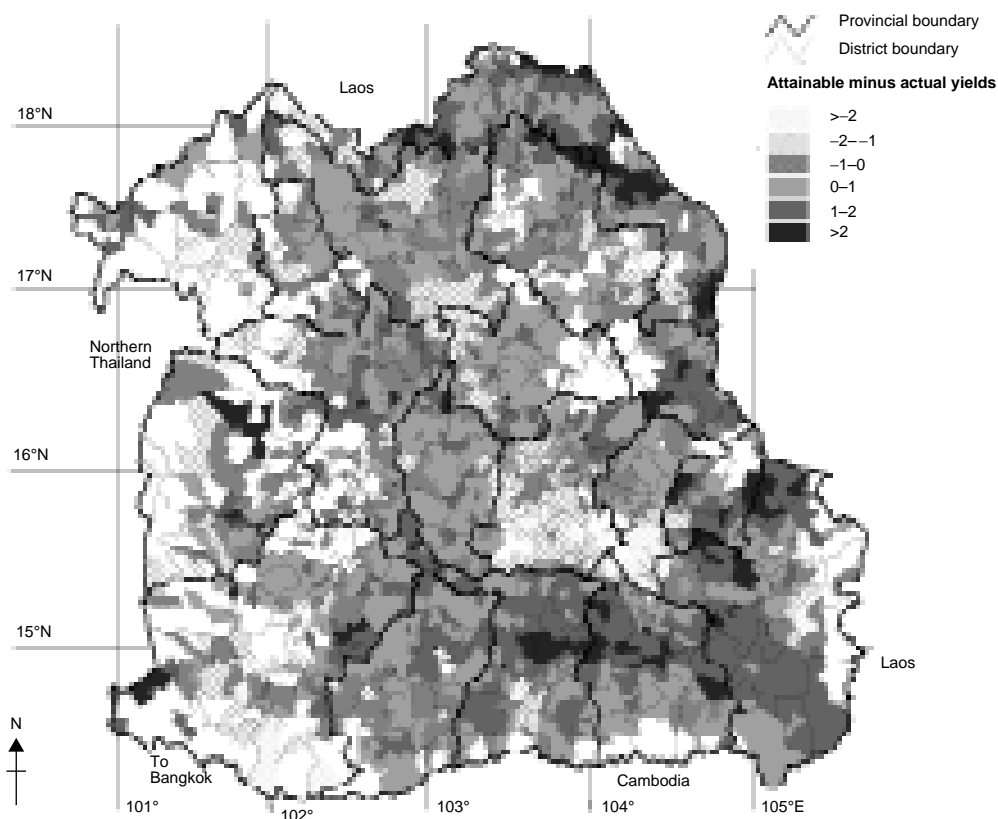


Figure 16. Differences between attainable and actual yields in 1997, North-East Thailand.

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. Sub-district 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

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 photo-period-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, photo-period-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 (Linguist 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 North-east Thailand indicate that N and P are the two most limiting nutrients for grain yield (Bell et al.; Seng et al.; Inthapanya et al.; Linguist 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

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 photo-period-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. Agroecological 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.