Nutrient Cycling in Agroecosystems **67:** 107–115, 2003.

Efficient and flexible management of nitrogen for rainfed lowland rice

B. Linquist[1,*] and P. Sengxua[2]

[1]*Lao-IRRI Project, P.O. Box 600, Luang Prabang, Laos;* [2]*National Agriculture and Forestry Research Institute, Vientiane, Laos;* **Author for correspondence (e-mail: b.linquist@cgiar.org; fax: +856-71-212-310)*

Received 5 June 2002; accepted in revised form 19 November 2002

Key words: Fertilizer N timing, Indigenous N supply, N-use efficiency, Risk avoidance, Soil organic matter, Suboptimal N supply

Abstract

Nitrogen (N) is the most limiting nutrient in the rainfed lowland rice soils of Laos. Indigenous N supply of these soils was low, ranging from 12 to 64 kg N/ha and was correlated with soil organic matter content. Resource-poor farmers and erratic rainfall are characteristic features of Lao rainfed lowland rice systems. Such climatic and economic factors influence farmers' ability to apply N at the 'recommended' time and therefore efficient and flexible recommendations are required. Research on N management focused on the timing of N applications. Splitting the N recommendation into three equal splits at transplanting, active tillering and panicle initiation increased yields by 12% compared to a single application at transplanting. Agronomic efficiency (AE = kg increase in grain yield/kg N applied) was further increased by 9 kg/kg N if a higher proportion of the N was applied during active tillering and panicle initiation when crop N demand is high. Under conditions of suboptimal N supply, the first N application can be applied from transplanting to 30 d after transplanting without lowering grain yield or AE (for medium duration varieties transplanted 1 month after sowing). The last N application can be made between two weeks before to one week after panicle initiation without lowering yield. These findings provide the basis for an efficient (AE of 20 to 25 kg/kg N) and flexible N management strategy for Lao rainfed lowland rice under conditions of suboptimal N supply.

Introduction

Rainfed lowland rice is grown on level to slightly sloping bunded fields with non-continuous flooding of variable depth and duration (Zeigler and Puckridge 1995). This type of rice occupies about 46 million hectares or 35% of the global rice area, mostly in South and Southeast Asia (Maclean et al. 2002). Rainfed lowland rice farmers generally have fewer resources and limited access to credit (Zeigler and Puckridge 1995); therefore, risk avoidance is likely to preoccupy rainfed farmers more than irrigated farmers (Dobermann and White 1999). Large areas of rainfed lowland rice, including those in Laos, are characterized as having poor soils with a high degree of spatial and temporal variability of water availability (Zeigler and Puckridge 1995). This has direct implications for nutrient, and particularly nitrogen (N) management.

These socioeconomic and environmental constraints require that nutrient management strategies provide flexibility to adjust depending on the progress of the season (Dobermann and White 1999) and maximize fertilizer-use efficiency of suboptimal fertilizer rates. Nitrogen management is of particular concern, as it is the most limiting nutrient in Lao lowland rice systems (Linquist et al. 1998). Nitrogen is also required by rice in higher quantities, and is more susceptible to losses than other nutrients (Schnier 1995). Strategies for rainfed lowland rice N management are commonly derived from those for irrigated rice; doing so raises some concerns. Firstly, recommendations for irrigated rice lack flexibility, since water is controlled and N is applied when needed. In the rainfed environment, water is not controlled and soil water conditions oscillate between periods of being anaerobic (standing water) and aerobic (drained). In sandy soils, as are common in Laos, high percolation rates further reduce the time the field has standing water (Fukai et al. 1998). It may not be possible to apply N at the 'recommended' time, since N should be applied to standing water to avoid denitrification losses. Therefore, windows of opportunity need to be identified when N can be applied without compromising yields. Secondly, the objective of N management in irrigated rice is to optimize yields, so N is managed to avoid N deficiencies (i.e. chlorophyll meters or leaf color charts – Peng et al. 1996; Dobermann and White 1999). In the rainfed environment, due to risk and limited capital, N is applied at suboptimal rates. This implies that N deficiencies will occur at some stage during crop growth and research needs to focus on identifying when N deficiencies are least critical.

The International Rice Research Institute has been collaborating with the Lao National Rice Research Program since 1991 to develop nutrient management strategies for rainfed lowland rice. The objective of this paper is to present and summarize results from experiments which have focused on N management strategies to use N efficiently at sub-optimal N rates and to provide the necessary flexibility.

Materials and methods

All research was conducted from 1991 to 2000 during the wet season under rainfed conditions, unless otherwise stated. Experiments were conducted on-farm under the supervision of local researchers. Seedlings (25 to 35 d old) were transplanted at a hill spacing of 20 × 20 cm (25 hills/m^2) using 3 to 5 seedlings per hill. Improved glutinous rice varieties (the preferred rice type in Laos) were used in all cases but the specific variety varied depending on location. All varieties were medium duration, ranging from 125 to 145 d (seed to maturity). Urea was the source of N in all experiments and was applied to standing water. Unless otherwise indicated, N was applied in three split applications with the second and third applications being applied at 30 and 50 d after transplanting (DAT), which corresponds to active tillering and panicle initiation for the medium duration varieties used in these studies. Phosphate and K were incorporated before transplanting to ensure that these nutrients were not limiting. The plot size at different sites ranged from 15 to 25 m^2, and all plots were separated by bunds. Grain yield estimates were made from the middle of each plot (avoiding border rows) and yields were adjusted to 14% moisture.

Results presented here represent over 90 experiments that were conducted over a 10 yr period throughout Laos. Climatic conditions varied between years and locations. The analysis of results presented here includes only those experiments where the rice did not suffer from physiological drought or prolonged flooding (water covering the rice canopy). In such cases, N management recommendations would most likely differ.

Indigenous N supply

Indigenous N supply (INS) is defined as the amount of N taken up by the crop from indigenous sources when sufficient amounts of other nutrients are supplied and other nutrient limitations are removed (Dobermann and Fairhurst 2000). INS can be estimated from 'minus-N' grain yields by

$$\text{INS (kg/ha)} = \text{GY} \times 13 \qquad (1)$$

where GY is grain yield (t/ha) in the 'minus-N' plots (where only N is limiting) and 13 is the amount of N (kg/ha) taken up by rice to produce 1 ton of grain (Dobermann and Fairhurst 2000). Based on data from five rainfed lowland rice experiments in Laos, 12.6 kg N/ha (standard deviation = 1.3 kg) was required to produce 1 ton of grain (data not shown).

Between 1991 and 1999, 32 experimental sites (11 from the north and 21 from the south – see Figure 1) had 'minus-N' plots (with P and K added) and soils (0–20 cm) that were analyzed for carbon (Tyurin 1931). Soil carbon was converted to soil organic matter (SOM) by multiplying by a factor of 1.725. INS was estimated using Equation 1 and regression analysis was used to examine the relationship between SOM and INS.

Improving N-use efficiency and management flexibility

For the purposes of this paper, agronomic N-use efficiency (AE) is used as the measure of N-use efficiency. This incremental efficiency from applied N is proportional to the cost–benefit ratio from investment in N inputs (Cassman et al. 1996b) and is calculated as

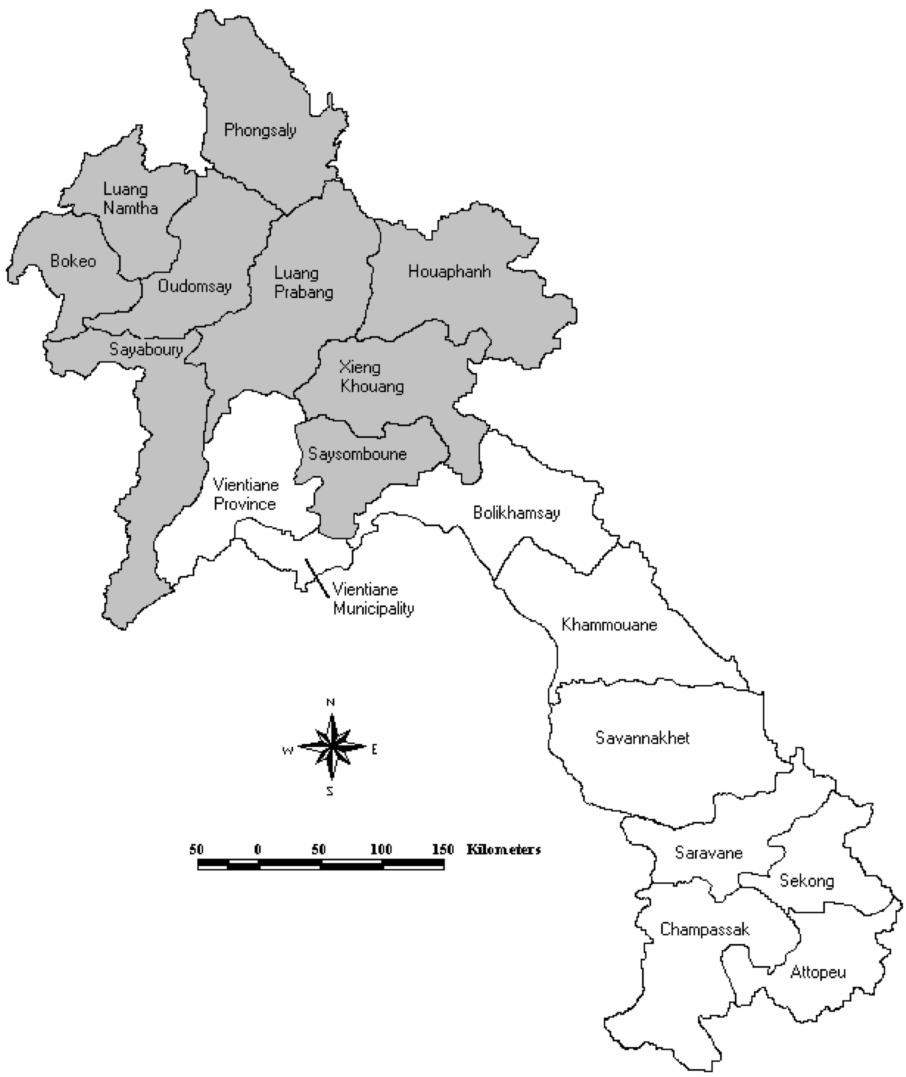

Figure 1. Map of Laos showing the northern (shaded) and southern regions discussed in this paper.

$$AE(kg/kg) = \frac{+N \text{ yield (kg)} - \text{minus-N yield (kg)}}{\text{amount of applied N (kg)}} \quad (2)$$

Splitting the N recommendation

The effect of applying the entire N recommendation at transplanting or in splits was evaluated in 26 on-farm trails using farms as replicates. There were four treatments in which a total of 60 kg N/ha was applied: (1) all N incorporated at transplanting, (2) N split equally between transplanting and 50 DAT, (3) N split equally at transplanting, 35 and 55 DAT, and (4) N split equally at transplanting, 20, 40 and 60 DAT.

Proportion of N in each split

An experiment was conducted to compare the effectiveness of applying 60 kg N/ha in three equal splits vs. applying 10 kg N/ha at transplanting, 25 kg N/ha at active tillering (30 DAT) and 25 kg N/ha at panicle initiation (50 DAT). The latter treatment applies a greater proportion of N when N demand is higher (Cassman et al. 1998). Treatments, including a 'minus-N' control, were replicated four times at six locations.

Timing of the first N application

The importance of incorporating the first N application was evaluated at six locations. Three treatments were replicated four times: (1) a minus-N control, (2) N incorporated immediately before transplanting, and (3) N broadcast on the soil surface immediately after transplanting. Incorporation of N before transplanting was done using a hoe due to the small plot size. A total of 60 kg N/ha was applied in three equal splits (the first N application was 20 kg N/ha). The last two N applications of 20 kg N/ha each were applied at 30 and 50 DAT.

The timing of the first N application was further evaluated at 15 locations (each location a replication). The six treatments were the timing of the first N application, which ranged from an application before transplanting to 30 DAT (Table 1). All treatments received 60 kg N/ha applied in three equal splits (20 kg N/ha each), except treatment 6 where the first N application was made at 30 DAT; in this case, the N was applied in two equal splits (30 kg N/ha each) at 30 and 50 DAT. A popular medium duration variety (145 d from seed to maturity), TDK1, was used at all locations. To evaluate the effect of SOM on the response, sites were separated into low and high SOM categories (0.4–0.8% and 1.0–7.8%) and then subjected to a separate analysis of variance.

Timing of the last N application

To evaluate when the last N application is most efficiently made, an experiment was conducted at seven locations during the wet and dry seasons. In the wet season, the last N application was made at 50, 65 or 80 DAT. In the dry season, there was one additional treatment – the last N application at 40 DAT. All treatments were replicated four times. In the wet season, 60 kg N/ha was applied whereas 90 kg N/ha was applied in the dry season. In all cases, the N was applied in three equal splits with the first two applications being at transplanting and 30 DAT. The variety TDK1 was used in all studies. Panicle initiation for TDK1 occurs about 50 DAT; however, this varies because of differences in seedling age and climate. Therefore, to compare results across sites, actual panicle initiation was determined based on the time of flowering, which occurs 25 d after panicle initiation (De Datta 1981). The timing of the last N application was then evaluated relative to panicle initiation estimated this way.

Results

For our purposes, we refer to northern and southern Laos as shown in Figure 1. These regions differ in the extent and importance of lowland rice, climate and soil fertility. Most lowland rice area (80% of total) is situated in the south, where rice is grown on six large plains adjacent to the Mekong River. In the mountainous north, lowland rice cultivation is confined to valley areas. Lowland rice soils in southern Laos tend to be coarser textured (mostly loamy sands and sandy loams) than in the north (mostly loams and clay loams). These soils also have a lower pH than soils in northern Laos (80% have a pH of less than 5.5 compared to 48% of soils in the north) (Linquist et al. 1998).

Indigenous N supply

SOM averaged 1.1% (ranging from 0.5% to 3.2%) in the south and 2.1% (ranging from 1.3% to 3.3%) in the north. In the south and north, 'minus-N' yields averaged 2.2 t/ha (range from 0.9 to 3.5 t/ha) and 3.0 t/ha (range from 1.8 to 4.9 t/ha), respectively. Linquist and Sengxua (2001) reported similar results from a large study involving more than 100 sites ('minus-N' yields averaged 2.1 t/ha in the south and

Table 1. The timing and amount of N applied in an experiment to evaluate when the first N application is most efficiently made. All treatments, except treatment 1, received 60 kg N/ha. The amount of N applied in each application is given in parentheses.

	Nitrogen applications (kg N/ha)		
No.	First	Second	Third
1	None (0)	None (0)	None (0)
2	Incorporated before transplanting (20)	30 DAT (20)	50 DAT (20)
3	1 DAT* (20)	30 DAT (20)	50 DAT (20)
4	10 DAT (20)	30 DAT (20)	50 DAT (20)
5	20 DAT (20)	30 DAT (20)	50 DAT (20)
6	30 DAT (30)	50 DAT (30)	None (0)

* DAT = days after transplanting.

Table 2. Effect of splitting the N rate on grain yield. In all cases, 60 kg N/ha was applied in equal splits. Grain yields are averages from 26 locations.

Number of splits	Timing	Grain yield (kg/ha)
1	Transplanting	3130 c
2	Transplanting and 50 DAT*	3312 b
3	Transplanting and 35 and 55 DAT	3496 a
4	Transplanting and 20, 40 and 60 DAT	3405 ab

*DAT = days after transplanting. Yields with the same letter are not significantly different (P<0.05).

2.9 t/ha in the north). The INS estimated from 'minus-N' yields (Equation 1) ranged from 12 to 64 kg N/ha and averaged 28 and 40 kg N/ha in the south and north, respectively. There was a positive and significant correlation between SOM and INS, indicating that for a 1% change in SOM there is a 10 kg/ha change in INS (Figure 2).

Improving N-use efficiency and flexibility

Splitting the N recommendation

In studies evaluating the benefit of splitting the N rate, three or more splits gave higher yields than one or two splits (Table 2). Splitting the N rate three times, as opposed to applying all the N at transplanting, increased yields by 0.37 t/ha, corresponding to a 12% increase in yield and a 4.1 kg/kg N increase in AE.

Proportion of N in each split

When N was applied in three equal splits (20 kg N/ha each), yields averaged 3.6 t/ha across all locations (Table 3). When a greater proportion of the N was applied during active tillering and panicle initiation, yields averaged 4.1 t/ha (yield increased by 0.5 t/ha and AE by 9 kg grain/kg N). Analysis of the significant site by treatment interaction indicates that applying a greater portion of the N later during crop growth gave higher yields at three sites, whereas at the remaining sites, yields were similar for the two N management strategies. Importantly, at no sites did applying a greater portion of the N later during crop growth result in lower yields than when N was applied in three equal splits.

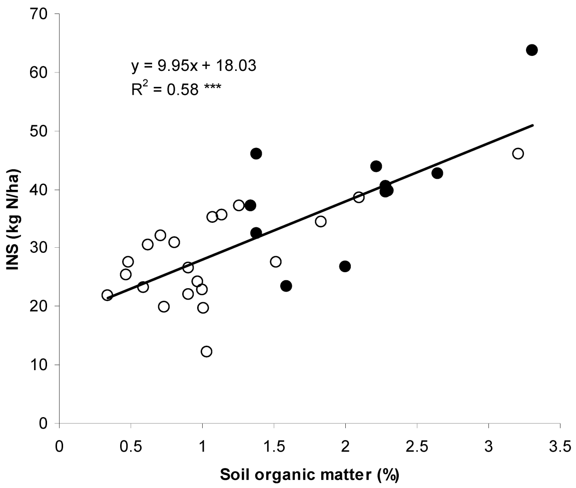

Figure 2. The relationship between soil organic matter and soil indigenous N supply (INS) in minus-N plots (received P and K fertilizer). Values are from 11 field experiments in northern Laos (filled circles) and 21 in southern Laos. *** indicates significance at P<0.001.

Timing of the first N application

There was no benefit of incorporating the first N application versus broadcasting it immediately after transplanting (Table 4). Yields for both methods averaged 4.0 t/ha, which was 1.6 t/ha higher than when no N was applied.

In other studies evaluating the timing of first application (transplanting to 30 DAT), yields, averaged across sites, increased by 1.39 t/ha in response to N (Table 5), corresponding to an AE of 23.2 kg/kg N. Incorporating N before transplanting gave similar yields as when N was broadcast immediately after transplanting, similar to the results in Table 4. Furthermore, the first N application could be applied up

Table 3. The effect of applying N in three equal splits at transplanting (TP), 30 DAT (active tillering = AT) and 50 DAT (panicle initiation = PI) versus applying a greater portion of N during AT and PI. Data are the averages of seven locations.

Treatment kg N/ha applied at TP-AT-PI	Yield (kg/ha)	Agronomic efficiency (kg/kg N)
0-0-0	2458 c	–
20-20-20	3615 b	19.3
10-25-25	4141 a	28.1
Site	***	
N	***	
Site × N	***	

*** indicates significance at P< 0.001. Yields with the same letter are not significantly different (P<0.05).

Table 4. Comparison of incorporating the first N application or applying the N after transplanting and not incorporating. Yields are averages from six locations. In the plus N treatments, 60 kg N/ha was applied in three equal splits (20 kg N/ha each).

N treatment	Grain yield (kg/ha)
No N	2451 b
N incorporated before transplanting	3880 a
N applied 1 d after transplanting	4120 a
Site	***
N treatment	***
Site × N	ns

*** Significant at the 0.001 level; ns = not significant. Yields with the same letter are not significantly different ($P<0.05$).

to 30 DAT (active tillering for this variety) with no effect on yield. When sites were separated based on SOM (and hence INS – see Figure 2) there was no yield difference due to the timing of the first N application in either the low or high SOM groups.

Timing of the last N application

To evaluate the time of the last N application, relative yield (relative to the highest yield at each site) was plotted versus the time of the last N application (Figure 3). Applying N from 20 d before to 7 d after panicle initiation gave similar yields. Delaying the application by more than one week after panicle initiation resulted in lower yields and AE.

Discussion

The significant and positive relationship between SOM and INS reported here ($R^2=0.58$ – Figure 2) is in contrast to the poor correlation reported by Cassman et al. (1996a) for irrigated rice. They attributed the poor correlation to N inputs from other sources besides SOM, such as: degree of congruence between N supply and crop demand (affected by crop rotation, fallow length, soil moisture and residue management), and differences in SOM quality. Rainfed lowland rice fields are more homogeneous in some respects than irrigated fields. For example, only one rice crop is grown and fields are fallow during the dry season. At the onset of the wet season, all residues have been removed from a combination of harvesting, grazing and burning of rice straw. Also, there is no variation caused by differing amounts of N supplied from irrigation water. On the other hand, fields differ in the duration and number of wetting and drying cycles in any given growing season. Wetting and drying cycles vary regionally because of differences in rainfall patterns, but also on-farm because of differences in field position along a toposequence (Wade et al. 1998). Such differences could affect N mineralization, N loss and subsequently N uptake (Buresh and De Datta 1991).

The lower SOM in southern Laos, reported here and elsewhere (Linquist et al. 1998), may be due to warmer temperatures and higher rainfall in the south, which leads to greater biological activity and faster decomposition of organic matter. Low SOM (and INS – see Figure 2) may be the reason that rice yields are lower in southern Laos in the absence of N fertilizer as reported here and by Linquist and Sengxua (2001). However, the coarser texture and lower pH of soils in the south, as discussed earlier, may also affect yields.

Rice normally takes up less than 40% of applied N in flooded systems. Low efficiency results from NH_3 volatilization, denitrification, leaching and runoff (Schnier 1995). In the rainfed lowland environment, the duration of the flooded and non-flooded periods and the transition from aerobic to anaerobic phases have a large effect on the accumulation and dissipation of soil mineral N (Buresh and De Datta 1991;

Table 5. Effect of timing of the first N application for soils differing in organic matter on grain yield response of rice. Yields are averages from 15 locations and represent the increase in yields (kg/ha) relative to a minus-N control. In all cases 60 kg N/ha was applied in three equal splits (20 kg N/ha each).

Time of first N application (days after transplanting)	All sites (n = 15)	Soil organic matter	
		< 0.8% (n = 6)	> 1.0% (n = 9)
	Increase in grain yield (kg/ha)		
0*	1348	1450	1291
1	1353	1320	1376
10	1326	1308	1337
20	1395	1350	1425
30	1530	1452	1573
	ns	ns	ns

* applied and incorporated before transplanting. ns = not significant.

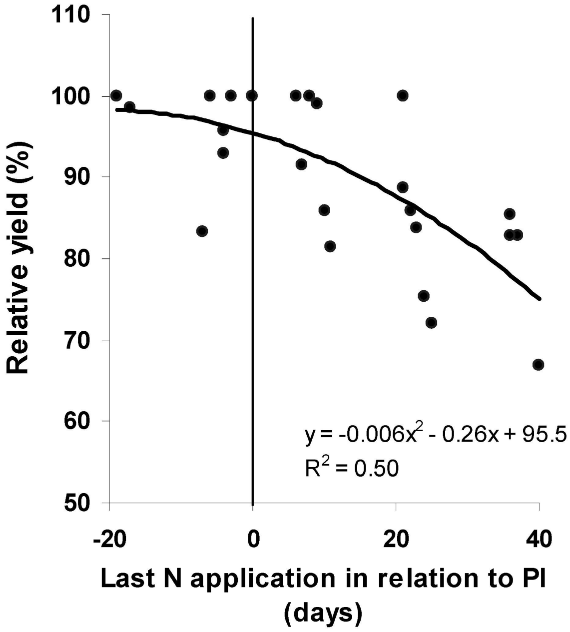

Figure 3. Relative yield (relative to the highest yield at each site) in relation to the timing of the last N application. The X axis is the timing of the last N application relative to panicle initiation (PI) (i.e., PI is day 0).

Wade et al. 1999). Losses from denitrification occur because NO_3 that accumulates during the aerobic phase is lost in the transition to the anaerobic phase (Wade et al. 1998). In coarse-textured soils with high infiltration rates (typical of many Lao soils), the frequency of aerobic and anaerobic phases is higher than that for soils with low infiltration rates. In order to reduce such sequential denitrification losses, N needs to be applied to soils when they are flooded. Strategies exist that allow farmers to maintain floodwater (i.e. on-farm water storage – Bhuiyan 1994) in rainfed environments. However, in Laos most farmers have no water control and are totally dependent on rainfall to maintain flood water. Therefore strategies are needed which provide flexibility in N timing whilst still maintaining efficiency.

Optimizing efficiency

Increasing the congruence between crop N demand and N supply improves N use efficiency in lowland rice (Cassman et al. 1996b, 1998). In our studies, splitting the N requirement three times gave higher yields and increased AE than when N was applied in a single application at transplanting when demand is low. These results are consistent with reports from elsewhere (i.e. De Datta et al. 1988; Ohnishi et al. 1999), which have formed the basis for the recommendation of splitting the N requirement for both irrigated and rainfed lowland rice. Congruence was further enhanced and AE increased (from 19 to 28 kg/kg N) by applying a greater portion of the N requirement during active tillering and panicle initiation (Table 3), when crop growth is rapid and N demand is high (Cassman et al. 1998).

An N application at transplanting may not be necessary because transplanted rice suffers from physiological transplanting shock for 10 to 14 d following transplanting, so N demand is low (Schnier et al. 1987). Furthermore, N available from the mineralization of organic matter is greatest during this phase (Dei and Yamasaki 1979) and should be adequate to meet crop needs during the early growth stage. Our results confirmed this hypothesis for rainfed lowland rice (Table 5), and this is discussed in greater detail below.

Risk avoidance and flexibility

Flexible N management strategies allow farmers to reduce risk and make decisions based on the progress of the season. Splitting the N rate is often recommended to improve efficiency; however, it also helps reduce risk associated with a poor early season. If the N is applied as a single application at transplanting, then a crop failure following this application also results in the loss of a large fertilizer investment. By applying the N in splits, farmers can adjust N inputs, if needed, based on the season.

Farmers often cannot apply fertilizer at the 'recommended' time because of soil-water conditions or fertilizer availability. Research conducted here identifies windows of opportunity during which N can be applied, with a focus on the first and last N applications.

It has been recommended that the first N application be broadcast and incorporated prior to transplanting to avoid losses from ammonia volatilization (De Datta et al. 1987); however, farmers in Asia are reluctant to do this (Fujisaka 1993). Based on arguments discussed earlier, the recommendation for irrigated rice has changed. For soils with a high INS, the first N application should be made at 10–14 DAT, whereas an N application at transplanting is recommended for soils with a low INS (Schnier 1995; Dobermann and Fairhurst 2000). For rainfed lowland rice under suboptimal N supply, our studies indicate that there was no effect on rice yields if the first N application was or was not incorporated. Furthermore, the first N could be applied up to 30 DAT (corresponding to active tillering for the medium duration variety used here) without compromising yields, regardless of the N status of the soil (assuming SOM is an indicator of INS – Figure 2). Despite visual N deficiencies early during crop growth, the crop was able to compensate when N was applied later. The window for the first N application may vary for different duration varieties or if seedlings are planted at a different age. In this study, a medium duration variety (145 d from seed to maturity) was used and seedlings were transplanted 30 d after sowing.

The window of opportunity for the last N application was a period from two weeks before to one week after panicle initiation. Nitrogen applications after this had little benefit. This is in contrast to the irrigated environment where, under conditions of high yield potential, an N application at flowering is recommended (Dobermann and Fairhurst 2000).

Applying N in splits as discussed here requires additional labor. Currently in Laos, about 50% of farmers that apply fertilizer, apply it in two splits (at transplanting and active tillering) and 6% in three splits (Shrestha 2002). This suggests that farmers may be willing to apply N in splits if positive benefits in terms of risk avoidance and rice productivity are realized.

Summary and Conclusions

The research reported here forms the basis for an efficient (AE ranges from 20 to 25 kg/kg N), yet flexible N management strategy for rainfed lowland rice when N is supplied at suboptimal rates. This strategy can be applied across a wide range of soils and is summarized as follows: where farmers grow both traditional and improved varieties, limited N resources should be applied to improved varieties that utilize N more efficiently (Linquist and Sengxua 2001). Nitrogen should be applied in three splits between transplanting and one week after panicle initiation and should always be applied to flood water. About 20% of the N requirement should be applied in the first application and 40% in each of the last two applications. The first N application can be made anytime during a 30-day period following transplanting (timing may vary depending on variety duration and age of transplanted seedlings). The last N application can be made from two weeks before to one week after panicle initiation. Within these windows of opportunity, N should be applied as soon as conditions are favorable for application.

This strategy provides flexibility and efficiency where soil moisture status varies but physiological drought does not occur. Further research is required on nutrient management following physiological drought.

Acknowledgements

The authors would like to thank the Lao Ministry of Agriculture and the Swiss Agency for Development and Cooperation for the support of this research.

References

Bhuiyan S.I. (ed.) 1994. On-Farm Reservoir Systems for Rainfed Rice Lands. International Rice Research Institute, Los Baños, Philippines, 164 pp.

Buresh R.J. and De Datta S.K. 1991. Nitrogen dynamics and management in rice–legume cropping systems. Adv. Agron. 45: 1–59.

Cassman K.G., Dobermann A., Sta Cruz P.C., Gines G.C., Samson M.I., Descalsota J.P. et al. 1996a. Soil organic matter and the indigenous nitrogen supply of intensive irrigated rice systems in the tropics. Plant Soil 182: 267–278.

Cassman K.G., Gines G.C., Dizon M.A., Samson M.I. and Alcantara J.M. 1996b. Nitrogen-use efficiency in tropical lowland rice systems: contributions from indigenous and applied nitrogen. Field Crops Res. 47: 1–12.

Cassman K.G., Peng S., Olk D.C., Ladha J.K., Reichardt W., Dobermann A. et al. 1998. Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated systems. Field Crops Res. 56: 7–39.

De Datta S.K. 1981. Principles and Practices of Rice Production. John Wiley, New York, 618 pp.

De Datta S.K., Obcemea W.N., Chen Ry., Calabio J.C. and Evangelista R.C. 1987. Effect of water depth on nitrogen use efficiency and nitrogen-15 balance in lowland rice. Agron. J. 79: 210–216.

De Datta S.K., Buresh R.J., Samson M.I. and Kai-Rong W. 1988. Nitrogen use efficiency and nitrogen-15 balances in broadcast flooded and transplanted rice. Soil Sci. Soc. Am. J. 52: 849–855.

Dei Y. and Yamasaki S. 1979. Effect of water and crop management on the nitrogen-supplying capacity of paddy soils. In: Nitrogen and Rice. International Rice Research Institute, Los Baños, Philippines, pp. 451–463.

Dobermann A. and White P.F. 1999. Strategies for nutrient management in irrigated and rainfed lowland rice systems. Nutr. Cycl. Agroecosyst. 53: 1–18.

Dobermann A. and Fairhurst T. 2000. Rice: Nutrient Disorders and Nutrient Management. Potash & Phosphate Institute (PPI), Potash & Phosphate Institute of Canada (PPIC), and International Rice Research Institute (IRRI), 191 pp.

Fujisaka S. 1993. Were farmers wrong in rejecting a recommendation? The case of nitrogen at transplanting for irrigated rice. Agricult. Syst. 43: 271–286.

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 Prod. Sci. 1: 75–82.

Maclean J.L., Dawe D.C., Hardy B. and Hettel G.P. (eds) 2002. Rice Almanac. 3rd edn. International Rice Research Institute, Los Baños, Philippines, West Africa Rice Development Association, Bouake, Ivory Coast, International Center for Tropical Agriculture, Cali, Colombia, and Food and Agriculture Organization, Rome, Italy, 253 pp.

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

Linquist B. and Sengxua P. 2001. Nitrogen management in rainfed lowland rice systems of Laos. In: Fukai S. and Basnayake J. (eds), Increased Lowland Rice Production in the Mekong Region. Proceedings of an International Workshop, Vientiane, Laos. ACIAR Proceedings No. 101., pp. 179–190.

Ohnishi M., Horie T., Homma K., Supapoj N., Takano H. and Yamamoto S. 1999. Nitrogen management and cultivar effects on rice yield and nitrogen use efficiency in Northeast Thailand. Field Crops Res. 64: 109–120.

Peng S., Garcia F.V., Laza R.C., Sanico A.L., Visperas R.M. and Cassman K.G. 1996. Increased N-use efficiency using a chlorophyll meter on high-yielding irrigated rice. Field Crops Res. 47: 243–252.

Schnier H.F. 1995. Significance of timing and method of N fertilizer application for the N-use efficiency in flooded tropical rice. Fert. Res. 42: 129–138.

Schnier H.F., De Datta S.K. and Mengel K. 1987. Dynamics of ^{15}N labeled ammonium sulfate in various inorganic and organic soil fractions of wetland rice soils. Biol. Fert. Soils 4: 171–177.

Shrestha S. 2002. Lao-IRRI Project: Impact assessment of research and technology development. International Rice Research Institute, Los Baños, Philippines.

Tyurin I.V. 1931. A new modification of the volumetric method of determining soil organic matter by means of chromic acid. Pochvovedenie 26: 36–47.

Wade L.J., George T., Ladha J.K., Singh U., Bhuiyan S.I. and Pandey S. 1998. Opportunities to manipulate nutrient-by-water interactions in rainfed lowland rice systems. Field Crops Res. 56: 93–112.

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 Res. 64: 3–12.

Zeigler R.S. and Puckridge D.W. 1995. Improving sustainable productivity in rice-based rainfed lowland systems of South and Southeast Asia. Feeding 4 billion people. The challenge for rice research in the 21st century. GeoJournal 35: 307–324.