Nutr Cycl Agroecosyst
DOI 10.1007/s10705-007-9095-5

RESEARCH ARTICLE

Benefits of organic residues and chemical fertilizer to productivity of rain-fed lowland rice and to soil nutrient balances

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Received: 20 November 2006 / Accepted: 5 February 2007

Abstract Low yields and high risk characterize many rain-fed lowland rice environments, including those in Laos. Drought and fluctuating soil-water conditions (from aerobic to anaerobic states) can limit productivity and the efficient use of applied nutrients. Although addition of organic matter may improve the efficiency of fertilizer use, on-farm residues, for example farmyard manure (FYM), rice straw and rice hulls, are, currently, poorly utilized in these systems. Single and multi-year experiments were designed to evaluate the effect of these residues on rice productivity and efficiency of fertilizer use at four sites. Rice yield without fertilizer but with addition of residues ranged from 1.1 to 1.7 t ha^{-1} across sites and years. In response to fertilizer, yields increased on average by 1.4 t ha^{-1}. For all sites and years there was a significant response of yield to organic residues applied without fertilizer, with responses ranging from 0.2 to 1.4 t ha^{-1}. In 58% of cases there was no residue×fertilizer interaction (benefits of residues when applied with fertilizer were additive). In 38 and 4% of cases the interaction was negative (no response to residues if fertilizer was already applied) or positive (synergistic), respectively. In the multi-year studies, the type of interaction varied between years, suggesting that seasonal events, rather than soil type, determine the type of interaction. The greatest benefits of applying organic and chemical fertilizers together were observed in years when soil-water conditions were unfavorable (fluctuating anaerobic–aerobic conditions). The long-term effects of these different management strategies on soil nutrient balances suggest that N, P, and K balances were maintained as a result of balanced commercial fertilizer management but that addition of residues further enhanced these balances. All residues, when applied alone, resulted in positive soil Si balances; only with FYM were long-term N, P, and K balances maintained or positive, however. For resource-poor farmers, applying on-farm residues can be a sustainable approach to increasing productivity.

Keywords Fertility management · Interactions · Nitrogen · Nutrient-use efficiency · Organic · Phosphorus · Potassium · Rain-fed lowland rice · Residue · Silica · Synergistic benefits

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Introduction

Rain-fed lowland rice occupies approximately 46 million hectares, or 35% of global rice area (Maclean et al. 2002). It is grown on level to slightly sloping bunded fields with non-continuous flooding of variable depth and duration (Zeigler and Puckridge 1995). Compared with rice farmers in irrigated lowlands, farmers of rain-fed rice usually have fewer resources and limited access to credit (Zeigler and Puckridge 1995), so risk avoidance is of greater importance (Dobermann and White 1999). Large areas of rain-fed lowland rice, including those in Laos, are characterized as having soils with low fertility and high spatial and temporal variability of water availability (Zeigler and Puckridge 1995); this has direct implications for nutrient management. On the basis of NPK omission studies, Linquist et al. (1998) reported that in the primary rice-growing soils of central and southern Laos, N is the most limiting nutrient (in 86% of sites which responded), followed by P (80% of sites which responded), and K (27% of sites which responded).

Maximizing nutrient-use efficiency in rain-fed systems is imperative for resource-poor farmers. High inputs are not the solution, because of the high risk of crop failure. Lao rice farmers apply fertilizers at low rates (Pandey and Sanamongkhoun 1998) and there is the potential for good yield responses if they are applied properly (Linquist et al. 1998; Linquist and Sengxue 2003).

Use of organic residues has been shown to enhance nutrient cycling, improve nutrient use efficiency, and increase productivity in rain-fed lowland rice systems in other Southeast Asian countries (Ragland and Boonpuckdee 1988; Willet 1995; Seng et al. 2004). Available on-farm residues include rice straw, rice hulls, and farmyard manure (FYM). Straw accounts for approximately 60% of aboveground biomass and is probably the most abundant on-farm residue available. In Laos, approximately half of the rice straw remains in the field after the harvest. This stubble is either burned or grazed by livestock during the dry season. The top portion of the straw is cut at harvest and removed from the field. This straw is either burned or fed to livestock after threshing. Because livestock account for 46% of expendable cash income (Pandey and Sanamongkhoun 1998), the most valuable use of straw may be as livestock feed. Livestock graze freely and little effort is made to collect manure. On the basis of survey results, only 11% of farmers use manure, with application rates varying between 35 and 1050 kg ha^{-1} and most of it being applied to rice seedling nurseries (Lao-IRRI 1995). Rice hulls account for approximately 20% of unmilled rice (Juliano and Bechtel 1985), or approximately 10% of aboveground biomass, and are usually left at the rice mills.

The objective of this study was to evaluate the effect of application of on-farm organic residues (FYM, rice straw, and rice hulls) on rice productivity, fertilizer-use efficiency, and soil properties. On the basis of the assessment of residue use discussed earlier, the application rates used in this study were realistic in terms of the amount of residue available to farmers. Some studies have used very high rates, for example Supapoj et al. (1998) reported use of 25 t ha^{-1} of rice straw. It is, however, unlikely that farmers can acquire this amount of residue; if they could, it would result in concentration of these residues in one field at the expense of others.

Materials and methods

Two on-farm experiments were conducted in four locations in rain-fed lowland rice fields of central and southern Laos. The objectives of the experiments were to evaluate the application of on-farm residues and inorganic fertilizers alone or in combination on rice yields, and to evaluate fertilizer-use efficiency. Soils in all locations were typical of the area and were infertile (Table 1). Both P and K were below the critical levels of 5 mg P kg^{-1} and 0.2 cmol$_c$ K kg^{-1}, respectively (Dobberman and Fairhurst 2000). The primary difference between the experiments was that in Experiment 1 the effect of N fertilizer over a single season was evaluated whereas in Experiment 2 the effect of N–P–K fertilizer was evaluated over two to four seasons. Details of each experiment are described below.

Table 1 Soil properties (0–20 cm) for all locations

Year and site	Soil texture	pH (H_20)	Organic C (%)	Kjeldahl N (%)	Olsen P (mg kg^{-1})	Exch. K (cmol kg^{-1})
1998						
Vientiane	Loam	4.6	0.68	0.096	1.7	0.082
Saravan	Silty loam	5.7	0.11	0.007	1.1	0.077
1999						
Champassak	Sandy loam	4.4	0.13	0.028	1.1	0.035
Saravan	Silty loam	5.0	0.31	0.070	1.1	0.085

Experiment 1

This experiment was conducted during the 1998 wet season in Vientiane (central Laos) and Saravan (southern Laos) to evaluate the efficiency of fertilizer N use with or without addition of organic matter. The experimental design was a split-plot design with three replicates. Main plots were 0 and 60 kg N ha^{-1} and the four subplots were on-farm organic residues: none, farmyard manure (FYM) at two rates, and rice hulls. On a dry-weight basis, the FYM was applied at 2.6 (Manure-1) and 5.2 t ha^{-1} (Manure-2) and rice hulls at 1.3 t ha^{-1}. The source of the residues was the same for both sites. The N, P, and K composition of the residues is shown in Table 2. Each subplot (3 m × 6 m) was separated by bunds. Nitrogen fertilizer (urea) was applied in three equal splits as basal, and at active tilling, and panicle initiation. A basal application of 13, 71, and 30 kg ha^{-1} P, K and S, respectively, was made to all plots, using triple-super-phosphate and potassium sulfate. The N and P fertilizer rate is the current recommendation provided to farmers; the recommended rate of K and S is 30 kg ha^{-1}. Potassium sulfate was the only fertilizer available so 30 kg S ha^{-1} was applied and thus more K than necessary was applied.

Basal fertilizers and residues were applied just before transplanting, and were incorporated with a hoe. Thirty-day-old seedlings of rice (improved glutinous variety-TDK1) were transplanted at a hill spacing of 20 cm × 20 cm and 4–6 seedlings per hill. TDK1 is a high-yielding, nutrient-responsive variety and is the most popular rice variety in Laos. Under low-input conditions TDK1 yields are, furthermore, higher than the traditional varieties commonly used (Linquist et al. 1998). Furidan (33 kg ha^{-1}) was applied at 25 and 45 DAT to control gall midge and stem borer. Weeding was performed as necessary. At maturity, border rows were removed from around each plot and the remaining hills harvested by cutting off the panicles. After threshing, grain weights and moisture content (Kett (Japan) grain-moisture meter) were determined and grain yields reported after adjusting to 14% moisture.

Agronomic N-use efficiency (AE) is used as the measure of the efficiency of N-use. This incremental efficiency from applied N is proportional to the

Table 2 Concentrations of N, P, and K and total amounts of the nutrients applied in the manure and rice hull treatments (Experiment 1)

Nutrient	Manure-1	Manure-2	Rice hulls
	Nutrient concentration (%)		
N	1.94	1.94	0.31
P	0.28	0.28	0.08
K	1.41	1.41	0.36
	Amount of nutrient applied from residues (kg ha^{-1})[a]		
N	50	101	4.1
P	7	15	1.1
K	37	73	4.7

[a] On a dry-weight basis, 2.6 t ha^{-1} Manure-1, 5.2 t ha^{-1} Manure-2, and 1.3 t ha^{-1} rice hulls were applied. Manure-1 and manure-2 were the from the same source

cost-benefit ratio from investment in N inputs (Cassman et al. 1996) and is calculated as:

$$\mathrm{AE\ (kg\ grain/kg\ N)} = \frac{\mathrm{+N\ treatment\ yield\ (kg)} - \mathrm{0N\ treatment\ yield\ (kg)}}{\mathrm{amount\ of\ N\ applied\ (kg).}}$$

Experiment 2

This experiment was conducted at two sites in southern Laos (in the provinces of Champassak and Saravan) to evaluate rice-yield responses to the application of on-farm residues and inorganic fertilizers alone or in combination with each other. The location of the 1999 experiment in Saravan was not the same as in 1998. The experiment was initiated at both sites in 1999 and continued until 2000 in Saravan and 2002 in Champassak. The experiment was set up as a split-plot design with three replicates. Plot size was 16 m^2 (4 m × 4 m). Main plot treatments were plus and minus chemical fertilizer (60, 13, and 18 kg ha^{-1} of N, P and K, respectively) and sub-plot treatments were different—residues, none; FYM, rice straw, or rice hulls applied at a rate of 2 t ha^{-1} dry weight (Table 3 shows the nutrient concentration of each residue). Treatment plots were maintained for the duration of the experiment with fertilizers and residues being applied annually. The same residues were used at both sites from 1999 to 2001 and a separate set of residues was used in 2002. All fertilizer P (as triple-super-phosphate) and K (as potassium sulfate) and one-third of the N (as urea) was applied just before transplanting and incorporated into the soil. The remaining N (urea) was applied in equal splits 30 and 55 days after transplanting, and corresponded to maximum tilling and panicle initiation.

Residues were broadcast and incorporated into the soil with a hoe, just before rice seedlings (variety TDK1) were transplanted. Important cropping events at Champassak are listed in Table 4.

Seedlings were transplanted when they were approximately 30 days old. Hill density was 25 hills m^{-2} with 4–6 seedlings per hill. At Champassak the soil-water level in each plot was monitored throughout the season. Weeds were controlled by hand as necessary. At harvest, 7.8 m^2 was sampled from the middle of each plot, to determine grain yield, by cutting and removing the top half of the plant and then threshing outside the plot. The grain moisture content was determined (Kett (Japan) grain-moisture meter) after threshing and grain yields are reported after adjusting to 14% moisture. From within this harvest area, 12 rice hills were sampled by cutting the rice at ground level for determination of straw yield, harvest index, and nutrient (N, P, K, and Si) analysis.

Percentage fertilizer N recovery (FNR) was calculated as:

$$\mathrm{FNR\ (\%)} = \frac{\mathrm{(N\ uptake\ in\ +N\ treatment)} - \mathrm{(N\ uptake\ in\ 0N\ treatment)}}{\mathrm{amount\ of\ N\ applied}}$$

Nutrient balance calculations were based on removal of all grain and half of the straw

Table 3 Concentrations of N, P, and K in residues, and amounts of N, P and K applied in each treatment at a rate of 2 t ha^{-1} (Experiment 2)[a]

Nutrient	Manure	Rice hulls	Straw
	Nutrient concentration (%)		
N	2.01/1.82	0.36/0.48	0.88/0.52
P	0.28/0.22	0.03/0.02	0.09/0.06
K	1.49/1.50	0.31/0.39	1.50/1.60
Si	18.7/11.5	6.75/6.72	5.28/3.65
	Amount of nutrient applied from residues (kg ha^{-1})		
N	40/36	7/10	18/10
P	5.5/4.3	0.6/0.4	1.7/1.2
K	30/30	6/8	30/31
Si	374/230	135/134	106/73

[a] The first number is for the residues used from 1999 to 2001; the second number is for residues used in 2002

and inputs from residues and fertilizers. The calculations do not account for losses that may have occurred because of leaching and run-off. Soil samples (five soil cores taken at 0–20 cm) were taken from every plot in each season before land preparation. Soil samples were dried in air, ground to pass a 2-mm sieve, and analyzed for total N and C, extractable P and K, and pH (1:1 H_2O).

Statistical analysis

All plant (yield and nutrient) and soil (soil C, N, P, K and pH) data were tested for normality (Shapiro and Wilk 1965) and homogeneity of variance using a χ^2 test (Gomez and Gomez, 1984). Data that did not conform with these assumptions for analysis of variance (ANOVA) were transformed for analysis. For each site and year the effects of fertilizer and residue were analyzed by subjecting the data to an ANOVA for a split-plot design. Data for each year from Experiment 2 were also combined for analysis with each year being a repeated measure. When there was a significant fertilizer×residue interaction, an additional ANOVA was conducted for each residue to identify the source and type of interaction. A non-significant interaction from these individual ANOVAs indicates additive benefits when residues and fertilizer are applied together (the benefits from residues and fertilizers applied together was equal to the sum of the benefits when they were applied separately). Significant interactions can be either negative or positive. A negative interaction indicates that the benefit of applying residues and fertilizer together is less than additive. A positive interaction indicates a synergistic benefit.

Results

Experiment 1

In Vientiane, the yield without fertilizer N and residues was 2.1 t ha^{-1} (Fig. 1). Addition of N fertilizer increased yields by 0.9 t ha^{-1}—an AE of 15 kg kg^{-1}. There was a significant yield response to all residues but the interaction between N and residues was not significant (Fig. 1 and Table 5), suggesting additive benefits from the combined application of residues and fertilizer N. Average yields across N treatments increased by 0.9, 0.6,

Table 4 Management and flowering dates for each year in the Champassak experiment

Operation or growth stage	1999	2000	2001	2002
Seeds sowed in nursery	May 30	June 3	June 13	July 7
Transplanting	June 22	June 28	July 10	July 29
Flowering[a]	Sept. 15	Sept. 5	Oct. 1	Oct. 16
Harvest	Oct. 15	Oct. 3	Oct. 26	Nov. 14

[a] Approximate flowering date, because actual flowering times varied with treatment

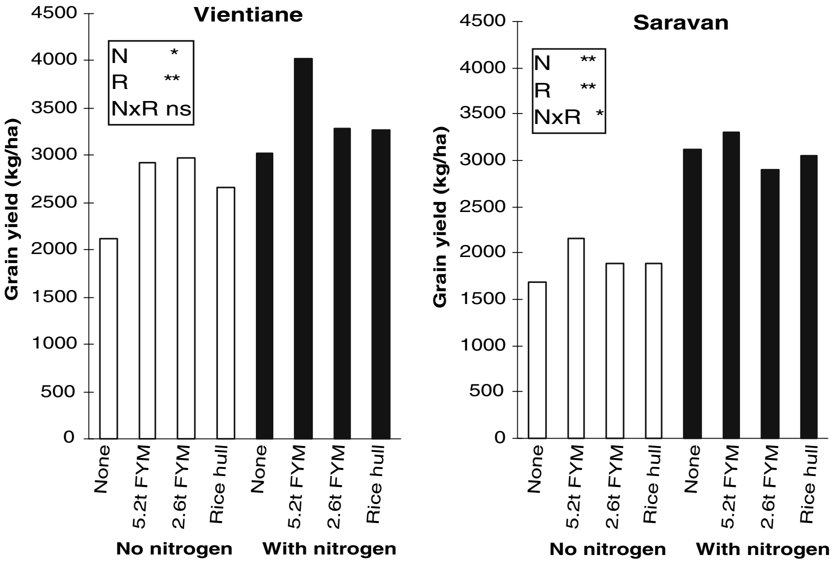


Fig. 1 Rice-yield response to application of chemical fertilizer N (60 kg N ha^{-1}) and residue (none, farmyard manure (*FYM*), or rice hulls). Experiments were conducted in 1998 in Vientiane and Saravan provinces of the Lao PDR. Yields are adjusted to 14% moisture.* and ** indicate a significant difference at $P = 0.05$ and 0.01, respectively. LSD$_{(0.05)}$ for comparison of residue treatments are 140 kg ha^{-1} (Saravan) and 395 kg ha^{-1} (Vientiane)

and 0.4 t ha^{-1} in response to 5.2 and 2.6 t ha^{-1} of FYM and rice hulls, respectively (yield increases of 15–35%). Despite large differences between the amount of nutrients applied in the residues (Table 2), the yield response was similar for all residues.

In Saravan, yield without N fertilizer and residues was 1.7 t ha^{-1} and increased by 1.4 t ha^{-1} in response to urea-N alone—an AE of 23 kg kg^{-1} (Fig. 1). There was a significant yield response to residues. In the treatments that did not receive N, yields increased by about 0.2 t ha^{-1} in response to rice hulls and 2.6 t FYM ha^{-1} and by 0.5 t ha^{-1} in response to 5.6 t FYM ha^{-1} (a yield increase of 12–28%). The interaction between N fertilizer and residues was significant but negative (Fig. 1 and Table 5), indicating no yield benefit from residues if N fertilizer had already been applied.

Experiment 2

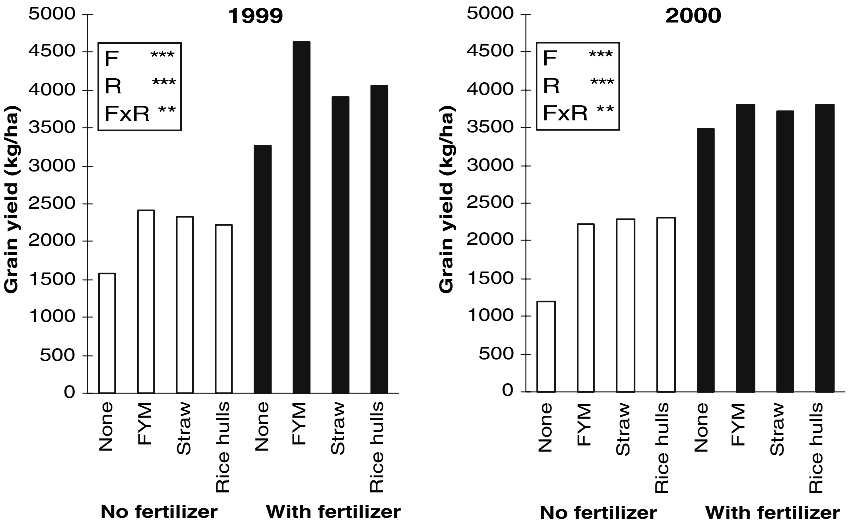
In Saravan, when no fertilizers or residues were applied yields were 1.6 t ha^{-1} in 1999 and 1.2 t ha^{-1} in 2000 (Fig. 2). In response to fertilizer alone yields increased by 1.7 t ha^{-1} (107%

Table 5 Grain yield responses to fertilizer and residues applied alone, and the fertilizer×residue interaction[a] ANOVA results for each residue analyzed separately

Site	Year	Response to fertilizer alone	Response to residue alone	Fertilizer×residue interaction		
Experiment 1		kg ha^{-1}	kg ha^{-1}	FYM-5.2	FYM-2.6	Hulls
Vientiane	1998	893	730	0	0	0
Saravan	1998	1429	296	–	–	–
Experiment 2				FYM	Straw	Hulls
Saravan	1999	1691	748	+	0	0
	2000	2285	1077	–	–	–
Champassak	1999	1517	559	0	–	–
	2000	1462	582	0	–	0
	2001	680	1230	0	0	0
	2002	1549	1065	0	0	0
Average		1438	786			

[a] A "0" indicates no interaction (benefits are additive), a "–" indicates a negative interaction and a "+" indicates a positive interaction (synergistic benefits)

Fig. 2 Grain yields (14% moisture) in response to organic residue (none, farmyard manure (*FYM*), rice straw, and rice hulls) and fertilizer (60, 13, and 18 kg ha^{-1} of N, P and K, respectively) applications in Saravan province in 1999 and 2000. *, **, and *** indicate a significant difference at $P = 0.05$, 0.01, and 0.001, respectively. LSD$_{(0.05)}$ for comparison of residue treatments are 179 kg ha^{-1} (1999) and 196 kg ha^{-1} (2000)

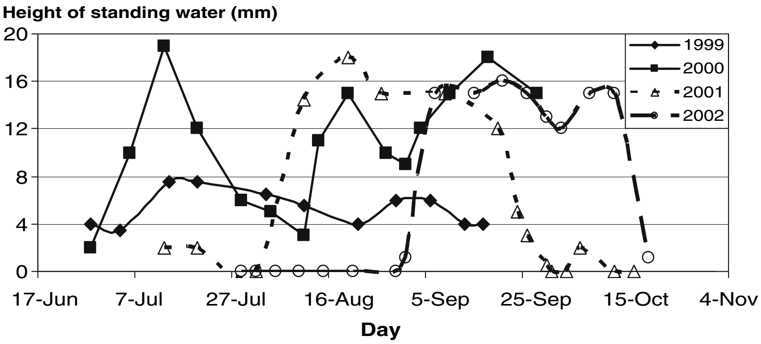


increase) and 2.3 t ha^{-1} (192% increase) in 1999 and 2000, respectively. In response to residues alone there was little difference between residues with yields increasing by 0.7 t ha^{-1} (47% increase) in 1999 and 1.1 t ha^{-1} (90% increase) in 2000. In both years there was a significant fertilizer×residue interaction. In 1999 there was a positive interaction because of the synergistic benefit of applying FYM with fertilizer (the only synergistic benefit observed in either experiment) (Table 5). There were additive benefits when straw and rice hulls were applied with fertilizer. In 2000 a negative interaction was observed for all residues (Fig. 2 and Table 5).

At Champassak in 1999 and 2000 the soils remained flooded for the entire season (Fig. 3); in 2001 and 2002, however, the soils were unflooded early in the season and in 2001 late in the season. Early and late season drought (or periods when rice fields are unflooded and aerobic) as shown here are typical of rain-fed lowland rice systems in Laos (Fukai et al. 1998). During these unflooded periods the crop did not experience drought stress, on the basis of visual observations and the fact that yields were comparable with or higher than those in other years.

When no fertilizers or residues were applied, rice yields at Champassak ranged from 1.1 to 1.6 t ha^{-1} (Fig. 4). Applying only chemical fertilizer increased yields significantly in all years by 1.5 t ha^{-1} (126% increase) in the first two years, 0.7 t ha^{-1} (43% increase) in 2001, and 1.5 t ha^{-1} in 2002 (98% increase). When only residues were applied, rice yields increased on average, by 0.6 t ha^{-1} (48% increase) in the first two years, 1.2 t ha^{-1} (78%) in 2001, and 1.1 t ha^{-1} (68% increase) in 2002. In 2001 there was no fertilizer×residue interaction (additive

Fig. 3 The height of standing water in the field from transplanting through flowering at the Champassak site. Different starting times and ending times represent differences in when the crop was transplanted and harvested



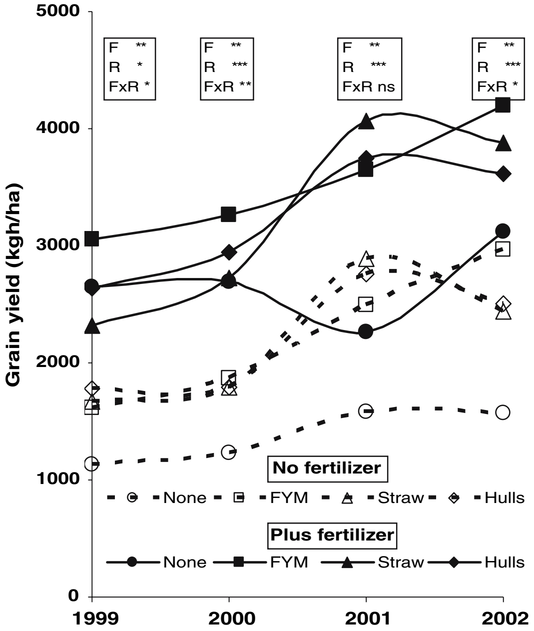


Fig. 4 Grain yields of rice at Champassak from 1999 to 2002 as affected by fertilizer (*F*) and residue (*R*) applications. Residues were none, farmyard manure (*FYM*), rice straw, and rice hulls. Chemical fertilizers were applied at levels of 60, 13, and 18 kg ha^{-1} of N, P and K, respectively. LSD$_{(0.05)}$ for comparison of residue treatments are 288 kg ha^{-1} (1999), 117 kg ha^{-1} (2000), 339 kg ha^{-1} (2001), and 319 kg ha^{-1} (2002)

benefits). In contrast, there were significant fertilizer×residue interactions in the other years. Further examination of these interactions shows no interaction for FYM (additive benefits) in all years but negative interactions for straw and rice hulls in 1999 and 2000 (Table 5). The benefits from residues when applied with fertilizer were generally better in 2001 and 2002 (Table 5) when soil conditions were less favorable (Fig. 3).

Nitrogen fertilizer recovery (FNR) by the crop when no residues were applied averaged 29% in 1999, 2000, and 2002, but was only 5% in 2001 (Table 6). Poor FNR in 2001 was most probably because of fluctuating soil-water conditions at the beginning of the season (Fig. 3), which may have resulted in denitrification losses (Buresh and De Datta 1991). In 1999, 2000, and 2002 (when FNR was high) residues had little effect on FNR. In 2001, however, the application of residues significantly increased FNR from 5% to 19%.

Table 6 Fertilizer N recovery efficiency in each year of the Champassak study

	1999	2000	2001	2002
No residue	40 a	21	5 c	27
Residue-FYM	41 a	14	13 bc	19
Residue-Straw	18 b	13	20 ab	32
Residue-Hulls	30 ab	12	24 a	19
$P > 0.05$	0.049	ns	0.015	ns
Residue average	30	13	19	23

Average annual aboveground nutrient uptake in the control (no fertilizer or residues) was 18, 2, 17, and 75 kg ha^{-1} for N, P, K, and Si, respectively, and increased with addition of residue and fertilizer (Fig. 5). The increase in N, P, K, and Si uptake as a result of residue application was higher for the unfertilized treatment than for the fertilized treatment. For both the fertilized and unfertilized treatments, application of FYM, the residue with the highest concentrations of nutrients, resulted in greater uptake of N, P, K, and Si than application of the other residues.

The critical concentration of Si in mature rice straw is 5% (Dobberman and Fairhurst 2000) but is 3–4% in rain-fed systems (Chabalier 1987). The Si concentration in mature rice straw in all treatments ranged from 2.5% to 3.5%, but application of residues usually increased the Si content by 0.2–0.3% (data not shown) and kept soil Si budgets positive (Fig. 6).

The nutrient balance over the four-year period at the Champassak site, not accounting for losses because of surface runoff (probably negligible) and leaching, reveals negative balances of N, P, K, and Si when no residue or fertilizer was applied (Fig. 6). Application of FYM in the absence of fertilizer resulted in positive balances whereas applying straw resulted in negative N and P balances but positive K and Si balances. Application of only rice hulls resulted in negative N, P, and K balances but a positive Si balance. Fertilizer applications kept N, P, and K balances positive, except the K balance was slightly negative (–9 kg ha^{-1}) when no residues were applied. After four years, soil-available K was lowest when no residues were applied (data not shown). There was no change in soil pH, but increasing trends (not significant) of organic matter, soil N, and P in relation to inputs from residues and fertilizers.

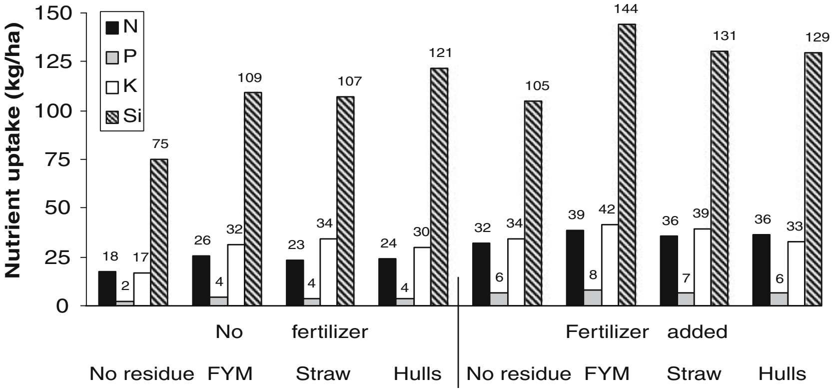


Fig. 5 Average annual aboveground uptake of N, P, and K by the rice crop at Champassak after different treatments with organic residues (none, farmyard manure (FYM), rice straw, and rice hulls) and fertilizer-amended (60, 13, and 18 kg ha^{-1} of N, P, and K, respectively) treatments. Except for effect of fertilizer on K uptake there were always significant differences between nutrient uptake as a result of fertilizer and residue applications. Only for P uptake was there a significant fertilizer×residue interaction. LSD$_{(0.05)}$ for comparison of residue treatments are 2.5 kg ha^{-1} (N), 0.5 kg ha^{-1} (P), 7.4 kg ha^{-1} (K), and 16.7 kg ha^{-1} (Si)

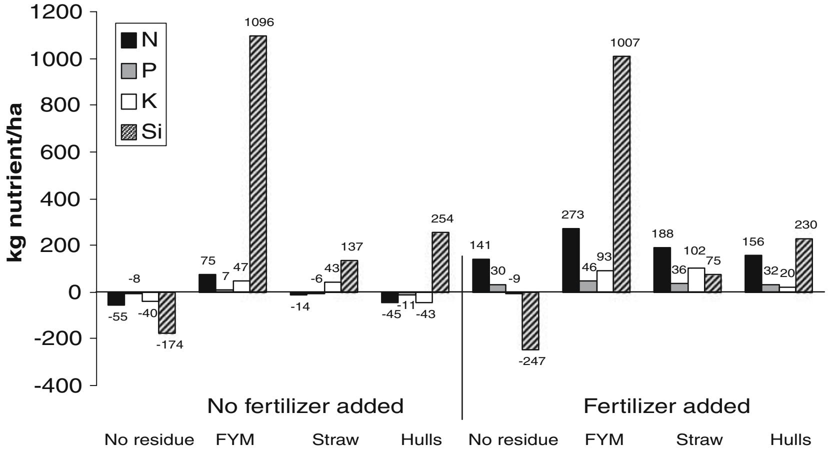


Fig. 6 Balances of N, P, K, and Si after four years at the Champassak site. The balance assumes removal of all grain and half of the straw biomass. Nutrient balances are based on inputs from residues and fertilizers. Outputs were from removal of all grain and half of the straw biomass. There were always significant differences between nutrient balances as a result of fertilizer and residue applications. Only for P was there a significant fertilizer×residue interaction. LSD$_{(0.05)}$ for comparison of residue treatments are 6.8 kg ha^{-1} (N), 1.5 kg ha^{-1} (P), 14.8 kg ha^{-1} (K), and 33.9 kg ha^{-1} (Si)

Discussion

Yield response to chemical fertilizer alone

The yields observed in these studies without inputs ranged from 1.1 to 1.7 t ha^{-1} and are typical of yields on soils of central and southern Laos (Linquist et al. 1998). Four-year data from Champassak show that such yields can be sustained without fertilizer or residue inputs (Fig. 4). Linquist and Sengxua (2003) reported that the AE of applied N to these soils was usually 20–25 kg grain kg^{-1} N. Good yield responses to fertilizer N (Experiment 1) and combined fertilizer application (Experiment 2) support these findings. Average yields across all sites and years increased by 1.4 t ha^{-1} in response to chemical fertilizer (only N in 1998). The exception to these good responses was in 2001 at Champassak. The 2001 season was unique, because at the beginning of the season (when the fertilizer had recently been applied) the soil was flooded, and then a one-week unflooded period was experienced (Fig. 3). Reasons for poor fertilizer responses during soil flooding and drying cycles include drought stress to rice (Wade et al. 1999), water stresses interacting with nutrient supply (Haefele et al. 2006), reduced availability of nutrients (especially P), increased acidity and Al toxicity (Seng et al. 2004), and losses of N via denitrification (Buresh and De Datta 1991). In this instance it is likely that denitrification resulted in N loss and a poor N response. The one-week unflooded period would have resulted in nitrification followed by subsequent losses of N as a result of denitrification when the soil reflooded. This hypothesis is supported by the low FNR (5%) that year compared with an average of 29% for the other years (Table 6).

Yield response to organic residues alone

For all sites and years there were significant yield responses to organic residues alone. There was little difference between residues, and yield response to residues ranged from 0.3 to 1.4 t ha^{-1}. Similarly, Wade et al. (1999) reported positive (but varying in magnitude) yield responses to FYM across Asia. Results from long-term irrigated rice management studies in the tropics (Witt et al. 1998, 2000; Bellakki et al. 1998; Surekha et al. 2003), the Sahel (van Asten et al. 2005), and temperate climates (Bird et al. 2001; Linquist et al. 2006) show yield increases when straw is returned. Where measured, these increases were related to improved soil N supply and uptake. Rice straw, which commonly has a high C:N ratio, can immobilize N temporarily; N immobilization is less of a problem in flooded anaerobic soils than in aerobic soils, however (Williams et al. 1968; Broadbent and Nakashima 1970). Rao and Mikkelsen (1976) reported that incorporation of rice straw into soil for 15–30 days before planting reduced N immobilization and promoted plant growth. In transplanted rice systems, seedlings experience transplant shock for approximately two weeks after transplanting during which time N demand is low (Schneir et al. 1987). Thus, when the crop N demand is high after transplanting shock, N immobilization may not be a factor limiting N uptake. Other evidence that N immobilization did not limit N uptake in this study is that yields did not decrease after treatment in which only residues were applied (i.e. because of immobilization of native soil N) and FNR was usually not significantly reduced when residues and fertilizer were applied together (Table 6).

Many studies have shown the positive residual effect of straw incorporation on the K fertility status of upland and lowland rice systems (Cox and Uribe 1992; Wihardjaka et al. 1999; Prasad et al. 1999; Dierolf and Yost 2000). Rice straw contains approximately 80% of the above ground plant K and can amount to over 150 kg K ha^{-1} (Dobermann et al. 1996, 1998; Dobbermann and Fairhurst 2000). Straw removal therefore exacerbates K deficiency problems and has been cited as the major cause of K deficiencies in irrigated rice fields throughout Asia (De Datta 1981; Gill and Kamprath 1990; Dobermann et al. 1998).

The nutrient concentration in residues varied substantially, and the N, P, and K input from FYM was 4–25 times more than for rice hulls (Tables 2 and 3). Because N and P are the nutrients that most limit rice productivity (Linquist et al. 1998), and there was a good response to chemical fertilizer, it is unclear why there was a similar yield response to the different residues. There are some possibilities and, given the complexity of these systems, the reason is likely to be a combination of these. First, Si has been shown to improve fertilizer use efficiency and improve the ability of crops to resist or tolerate biotic (insects and diseases) and abiotic (toxicity of Al and Fe) stresses (Savant et al. 1997). At Champassak, the concentration of Si in the mature rice straw was at or below the critical limit, suggesting Si deficiency. The residues all contained high concentrations of Si (Table 3), and this may have increased yields. Second, yield declines in continuously cropped soils have been attributed to micronutrient deficiencies (Heathcote 1970). Residues contain micro-nutrients not available in commercial fertilizers. For example, in rice, with the exception of N, P, and Cu, over 60% of the nutrients are in the straw at harvest (Table 7). If, however, the yield response to residues was because of one of the above mentioned possibilities, it does not explain why there was such a good response to the application of only chemical fertilizer, which is presumably low in Si and micro-nutrients. A third possibility is that residues increase the availability of soil nutrients. Seng et al. (2004) found that when there was a temporary loss of water in flooded rice systems, straw incorporation increased P availability and uptake, increased soil pH, reduced Al toxicity, and increased rice growth. Temporary losses of floodwater are common in rain-fed rice soils (Fukai et al. 1998) and were observed in two of the four years at Champassak (Fig. 3). Although, in this study, rice hulls added 6–8 kg K ha^{-1} annually, average annual K uptake at Champassak increased by 13 kg K ha^{-1} when only rice hulls were applied. This was not observed for other nutrients or residues, however. Finally, residues may help reduce N losses because of denitrification, thus conserving native soil N or applied chemical N. This is shown in 2001 at Champassak, where the FNR significantly increased when residues were applied (Table 6). None of these possibilities is entirely satisfactory on its own. The reason is likely a combination of these and merits further research.

Benefits from combined applications of organic residues and chemical fertilizer

The combined application of organic residues and fertilizer can result in negative, positive (synergistic benefits), or no (additive benefits) interactions. In this study, 24 seperate observations are possible when each residue is examined individually across sites and years. In fourteen instances there was no interaction, in nine the interaction was negative, and in only instance was the interaction positive (Table 5). Additive or synergistic benefits from the combined application of organic and chemical fertilizers were more likely in seasons where soil-water conditions were less favorable (alternate flooding and drying). Loss of flood water does not necessarily result in drought stress (Seng et al. 2004) but the flooding (anaerobic) and drying (aerobic) cycles affect the soil oxidation–reduction state and have large effect on the availability of several nutrients, as reviewed by Ponnamperuma (1972) and Kirk (2004). The resulting fluctuations in nutrient availability are greater in sandy soils, which often have low soil organic matter content and cation-exchange capacity, and hence poor buffering capacities against the pH changes caused by changes in the redox potential. As soils become oxidized during a drying period, the pH drops rapidly, because of poor buffering capacity; this can result in Al toxicity and poor crop responses to fertilizers (Ragland and Boonpuckdee 1988; Willet 1995; Seng et al. 2004). Management of organic matter in these soils is therefore essential to maintain cation-exchange capacity, especially when there are flooding and drying cycles. Data from the multi-year experiments confirm this. At these sites the interactions between residues and fertilizer varied among years, suggesting that seasonal events, rather than soil type, affect the interaction. At Champassak, where field water conditions were monitored, the soils were unflooded for parts of the 2001 and 2002 seasons (Fig. 3) and no negative interactions were observed. In contrast, in 1999 and 2000, when soil-water conditions were favorable (flooded all season), negative interactions occurred in half of the cases (Table 5). One example of residues improving fertilizer use efficiency was in 2001, when the soil-water conditions were favorable for

Table 7 Concentrations and distribution of macronutrients and micronutrients in the rice grain and straw at harvest

	N (%)	P (%)	K (%)	S (%)	Ca (%)	Mg (%)	Mn (μg g^{-1})	Zn (μg g^{-1})	Cu (μg g^{-1})
	Nutrient concentration								
Grain	0.79	0.19	0.28	0.10	0.04	0.10	103	23	39
Straw	0.32	0.04	0.79	0.10	0.39	0.17	884	25	25
	Percent of nutrient in grain or straw at harvest								
Grain	62	76	19	41	7	28	7	38	51
Straw	38	24	81	59	93	72	93	62	49

Source: Linquist and Sengxua (2001)

denitrification; residues significantly increased FNR, however, as discussed earlier (Table 6). Positive interactions have been reported across the border in northeast Thailand (Willet 1995; Ragland and Boonpuckdee 1988). The rice soils in northeast Thailand are, in general, coarser textured and have higher percolation rates. This, combined with lower rainfall, results in more frequent flooding and drying cycles during the growing season (Bell and Seng 2004). Thus, on the basis of the above hypothesis, one would expect to see greater benefits from the combined application of residues and chemical fertilizer there.

Long-term effects of using organic residues and chemical fertilizers

In the four-year Champassak study yields for all treatments were maintained or increased over the study period. The long-term effects of the different nutrient management strategies on soil nutrient balances indicate that balanced N, P, and K fertilizer management maintains or improves N, P, and K balances and that addition of residues further enhanced nutrient balances. The fertilizer industry is turning to the production of high-analysis fertilizers which are usually devoid of micronutrients (Friesen 1991). Application of fertilizers can therefore increase yields in the short-term but may deplete the soil of micronutrients in the long-term, because of removal in grain and residues. The depletion of soil nutrients is likely to occur more rapidly from coarse-textured soils. Straw and other organic amendments can therefore be important in maintaining soil fertility, even when chemical fertilizers are used. The residues used in this study resulted in similar yield responses but had different effects on soil nutrient balances, This suggests that mixing residues, but still using low rates (2 t ha^{-1}), may increase yields while maintaining soil nutrient balances.

Conclusion

In this study good yield responses were observed when organic residues and chemical fertilizers were applied separately. On average, across sites and years, the yield response to fertilizer (1.4 t ha^{-1}) was higher than that to residues (0.8 t ha^{-1}). Combined application of residues and fertilizer did not usually result in positive interactions, but rather in no interaction or negative interactions. In years when soil-water conditions were unfavorable the benefit of applying residues and fertilizer together was greater. The response to the different residues was similar, despite different concentrations of N, P, and K in the residues. The reason for this response is not clear and merits further investigation. Application of fertilizer or FYM alone ensured positive soil N, P, and K balances whereas application of straw resulted in nutrient balances being approximately even and application of rice hulls alone resulted in negative balances. It is possible that mixing straw or rice hulls with FYM would result in good yield responses while maintaining soil nutrient balances. For resource-poor farmers, such application of residues could be a sustainable means of increasing productivity.

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

References

Bell RW, Seng V (2004) Rain-fed lowland rice-growing soils of Cambodia, Laos and Northeast Thailand. In: Seng V, Craswell E, Fukai S, Fisher K (eds) Water in agriculture, pp 161–173. ACIAR Proceedings 116

Bellakki MA, Badanur VP, Setty RA (1998) Effect of long-term integrated nutrient management on important properties of a vertisol. J Indian Soc Soil Sci 46:176–180

Bird JA, Horwath WR, Eagle AJ, van Kessel C (2001) Immobilization of fertilizer nitrogen in rice: effects of straw management practices. Soil Sci Soc Am J 65:1143–1152

Broadbent FE, Nakashima T (1970) Nitrogen immobilization in flooded soils. Soil Sci Soc Amer Proc 34:218–221

Buresh RJ, De Datta SK (1991) Nitrogen dynamics and management in rice-legume cropping systems. Adv Agron 45:1–59

Cassman KG, Gines GC, Dizon MA, Samson MI, Alcantara JM (1996) Nitrogen-use efficiency in tropical lowland rice systems: contributions from indigenous and applied nitrogen. Field Crops Res 47:1–12

Chabalier P (1987) Rice. In: Martin-Prevel P, Gagnard J, Gautier P (eds) Plant analysis as a guide to the nutrient requirements of temperate and tropical crops. Lavoisier Publishing Inc., New York, pp 526–530

Cox FR, Uribe E (1992) Management and dynamics of potassium in a humid tropical ultisol under a rice-cowpea rotation. Agron. J. 84:655–660

De Datta SK (1981) Principles and practices of rice production. John Wiley, New York, pp 618

Dierolf TS, Yost RS (2000) Stover and potassium management in an upland rice-soybean rotation on an Indonesian ultisol. Agron J 92:106–114

Dobermann A, Sta Cruz PC, Cassman KG (1996) Fertilizer inputs, nutrient balance, and soil nutrient-supplying power in intensive, irrigated rice systems. I. Potassium uptake and K balance. Nutr Cycling Agroeco 46:1–10

Dobermann A, Cassman KG, Mamaril CP, Sheehy JE (1998) Management of phosphorus, potassium, and sulfur in intensive irrigated lowland rice. Field Crops Res 56:113–138

Dobermann A, Fairhurst T (2000) Rice: nutrient disorders and nutrient management. Singapore and Los Baños, Potash & Phosphate Institute (PPI), Potash & Phosphate Institute of Canada (PPIC), and International Rice Research Institute (IRRI), 191 pp

Dobermann A, White PF (1999) Strategies for nutrient management in irrigated and rain-fed lowland rice systems. Nutr Cycl Agroecosyst 53: 1–18

Friesen DK (1991) Fate and efficiency of sulfur fertilizer applied to food crops in West Africa. Fert Res 29:35–44

Fukai S, Sittisuang P, Chanphengsay M (1998) Increasing production of rain-fed lowland rice in drought prone environments—a case study of Thailand and Laos. Plant Prod Sci 1:75–82

Gill DW, Kamprath EJ (1990) Potassium uptake and recovery by an upland rice-soybean rotation on an Oxisol. Agron J 82:329–333

Gomez KA, Gomez AA (1984) Statistical procedures for agricultural research. John Wiley & Sons, New York

Heathcote RG (1970) Soil fertility under continuous cultivation in northern Nigeria. II. Response to fertilizer in the absence of organic manures. Exp Agric 6:345–350

Heefele SM, Naklang K, Harnpichitvitaya D, Jearakongman S, Skulkhu E, Romyen P, Phasopa S, Tabtim S, Suriya-arunroj D, Khunthasuvon S, Kraisorakul D, Youngsuk P, Amarante ST, Wade LJ (2006) Factors affecting rice yield and fertilizer response in rain-fed lowlands of northeast Thailand. Field Crops Res 98:39–51

Juliano BO, Bechtel DB (1985) The rice grain and its gross composition. In: Juliano B.O. (ed) Rice: Chemistry and technology, 2nd edn. St. Paul, Minnesota. American Association of Cereal Chemists. AACC monograph series, 774 p

Kirk GJD (2004) The biogeochemistry of submerged soils. Wiley Science, Chichester, UK

Lao-IRRI. (1995) Annual Technical Report, 296 p

Linquist BA, Sengxua P, Whitbread A, Schiller J, 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, Piggin C. (eds) Rain-fed lowland rice: advances in nutrient management research. Proceedings of the international workshop on nutrient research in rain-fed Lowlands, 12–15 Oct. 1998, Ubon Ratchathani, Thailand

Linquist BA, Sengxua P (2001) Nutrient management in rain-fed lowland rice in the Lao PDR. Los Banos, Philippines, International Rice Research Institute, p 88

Linquist BA, Sengxua P (2003) Efficient and flexible management of nitrogen for rain-fed lowland rice. Nutr Cycling Agroecosyst 67:107–115

Linquist BA, Brouder SM, Hill JE (2006) Winter straw and water management effects on soil nitrogen dynamics in California rice systems. Agron J 98: 1050–1059

Maclean JL, Dawe DC, Hardy B, Hettel GP (eds) (2002) Rice Almanac, 3rd edn. Los Banos (Philippines): International Rice Research Institute, Bouake (Cote d'Ivoire): West Africa Rice Development Association, Cali (Colombia): International Center for Tropical Agriculture, Rome (Italy): Food and Agriculture Organization, 253 pp

Pandey S, Sanamongkhoun M (1998) rain-fed lowland rice in Laos: a socio-economic benchmark study. International Rice Research Institute, Los Banos, Philippines

Ponnamperuma F (1972) The chemistry of submerged soils. Adv Agron 24:29–97

Prasad R, Gangaiah B, Aipe KC (1999) Effect of rice crop residue management in a rice-wheat cropping system on growth and yield of crops and on soil. Exp Agric 35:427–435

Ragland J, Boonpuckdee L (1988) Fertilizer responses in NE Thailand. 3. Nitrogen use and soil acidity. Thai J Soils Fert 10:67–76

Rao DN, Mikkelsen DS (1976) Effect of rice straw incorporation on rice plant growth and nutrition. Agron J 6:752–755

Savant NK, Snyder GH, Datnoff LE (1997) Silicon management and sustainable rice production. Adv Agron 58:151–199

Seng V, Bell RW, Willet IR (2004) Amelioration of growth reduction of lowland rice caused by a temporary loss of soil-water saturation. Plant Soil 265:1–16

Schnier HF, De Datta SK, Mengel K (1987) Dynamics of ^{15}N labeled ammonium sulfate in various inorganic and organic soil fractions of wetland rice soils. Biol Fertil Soils 4:171–177

Shapiro SS, Wilk M (1965) An analysis of variance test for normality. Biometrika 52:591–611

Supapoj N, Naklang K, Konboon Y (1998) Using organic material to improve soil productivity in rainfed lowland rice in Northeast Thailand. In: Ladha JK, Wade LJ, Dobermann A, Reichardt W, Kirk GJD, Piggin C (eds) rain-fed lowland rice: advances in nutrient management research. Proceedings of the international workshop on nutrient research in rain-fed Lowlands, 12–15 Oct. 1998, Ubon Ratchathani, Thailand

Surekha K, Padma Kumari AP, Narayana Reddy M, Satyanarayana K, Sta Cruz PC (2003) Crop residue management to sustain soil fertility and irrigated rice yields. Nutr Cycling Agroecosyst 67:145–1544

Van Asten PJA, van Bodegom PM, Mulder LM, Kropff MJ (2005) Effect of straw application on rice yields and nutrient availability on an alkaline and a pH-neutral soil in a Sahlian irrigation scheme. Nutr Cycling Agroecosyst 72:255–266

Wade LJ, Amarante ST, Olea A, Harnpichitvitaya D, Naklang K, Wihardjaka A, Sengar SS, Mazid MA, Singh G, McLaren CG (1999) Nutrient requirements in rain-fed lowland rice. Field Crops Res 64:91–107

Willet IR (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, Craswell E.T. (eds) Soil organic matter management for sustainable agriculture: a workshop held in Ubon, Thailand, 24–26 August 1994. ACIAR Proceedings No. 56, 163 p

Wihardjaka A, Kirk GJD, Abdulrachman S, Mamaril CP (1999) Potassium balances in rain-fed lowland rice on a light-textured soil. Field Crops Res 64:237–247

Williams WA, Mikkelsen DS, Mueller KE, Ruckman JE (1968) Nitrogen immobilization by rice straw incorporated in lowland rice production. Plant Soil 28:49–60

Witt C, Cassman KG, Ottow JCG, Biker U (1998) Soil microbial biomass and nitrogen supply in an irrigated lowland rice soil as affected by crop rotation and residue management. Biol Fertil Soils 28:71–80

Witt C, Cassman KG, Olk DC, Biker U, Liboon SP, Samson MI, Ottow JCG (2000) Initial effects of crop rotation and residue management on carbon sequestration, nitrogen cycling, and productivity of irrigated rice systems. Plant Soil 225:263–278

Zeigler RS, Puckridge DW (1995) Improving sustainable productivity in rice-based rain-fed lowland systems of South and Southeast Asia. Feeding 4 billion people. The challenge for rice research in the 21st century. GeoJournal 35:307–324