Nutrient Management in Rainfed Lowland Rice in the Lao PDR

Bruce Linquist and Pheng Sengxua

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About the cover: Background: farmers grow different rice varieties on their lowland fields. Upper inset: rice husks applied to lowland fields before land preparation. Lower right inset: farmers are using more inorganic fertilizer. Lower left: applying manure to lowland fields.

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Foreword

Rice, grown on more than 700,000 ha, is the single most important crop in Lao PDR. The most important rice production system, in terms of productivity and area, is the lowland system in which rice is grown in bunded, flooded fields. Annually, more than 600,000 ha are devoted to lowland rice production in Laos.

Since 1991, IRRI has been working with the government of Laos to improve the productivity of the country's rice-based systems. This collaboration has been through the Swiss Agency for Development and Cooperation-funded Lao-IRRI Project. Within the last few years, Laos has achieved self-sufficiency in rice as a result of improved productivity in the lowland rice systems. Increased productivity has resulted from an expansion in irrigated area (allowing cropping in both the wet and dry seasons), the introduction of new varieties, and the increased use of fertilizer.

To sustain the productivity and viability of lowland rice systems, balanced, economical, and sustainable nutrient management strategies are required. One of the main objectives of the Lao-IRRI Project has been to develop such strategies. The term "nutrient management" as opposed to "fertilizer management" in the title of this book is important to recognize. Efficient nutrient management includes fertilizer management but also recognizes the importance of efficient nutrient cycling within the farming system.

This book reviews this research and is a resource for those working with lowland rice farmers in research, extension, and development. The book focuses on the rainfed lowland rice system, although considerable reference is made to the lowland irrigated rice system. It summarizes the results of nutrient management research conducted in the lowland rice system in Laos from 1991 to 2000. On the basis of these results, a nutrient management strategy is provided. This strategy could also be valuable for similar environments in Cambodia and northeast Thailand. In addition, this book contains information on the lowland rice production environment, future challenges and opportunities, a list of Lao-IRRI publications relevant to the lowland environment, and a complete list of nutrient management experiments conducted in Laos.

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Nutrient management of rainfed lowland rice in the Lao PDR

B. Linquist and P. Sengxua

Introduction

Rice is the single most important crop in the Lao PDR (hereafter referred to as Laos), providing 67% of the total calorie supply (IRRI 1995) and constituting 60% of the total agricultural production (UNDP 1998). Approximately 737,000 ha of land were under cultivation in 1997, of which 646,000 ha (88%) were planted to rice. Lowland rice is grown on approximately 75% of the area planted to rice.

Increased demand for higher outputs is being placed on the lowland rice ecosystem. This demand is a result of increasing integration into a market economy, increasing population (2.8% growth per annum), and government policy that aims to reduce slash-and-burn agriculture in the uplands. Higher productivity requires increased nutrient inputs. Laos imports all of its inorganic fertilizer and fertilizer imports to Laos are the lowest in Asia (IRRI 1995); however, recently, fertilizer imports have been increasing (Fig. 1) and farmers are applying more to their rice crops. Efficient and sustainable nutrient recommendations are required. We use the phrase "nutrient management" as opposed to "fertilizer management" in this book. Efficient nutrient management strategies involve good fertilizer management but also recognize the importance of efficient nutrient cycling within the farming system. For example, nutrients contained in on-farm residues (manure, straw, etc.) are part of the farming system and have thus been included in the development of the nutrient management strategy presented here.

The International Rice Research Institute (Lao-IRRI Project) and the Lao National Rice Research Program have been collaborating on rice research since 1991. Soil fertility research has been conducted in all provinces of Laos through this effort. The objective of this book is to review the research that has been conducted on nutrient management of lowland rice in Laos from 1991 to 2000 and to present an integrated and sustainable nutrient management approach that is relevant to Lao farmers. We focus on the rainfed lowland rice system as opposed to the irrigated rice system, although references will be made to both. In the first section, an overview of lowland rice trends and practices in Laos will be given. This will be followed by a discussion of the production environment, with emphasis on climate and soils. This will be followed by a presentation of research aimed at identifying nutrient deficiencies and

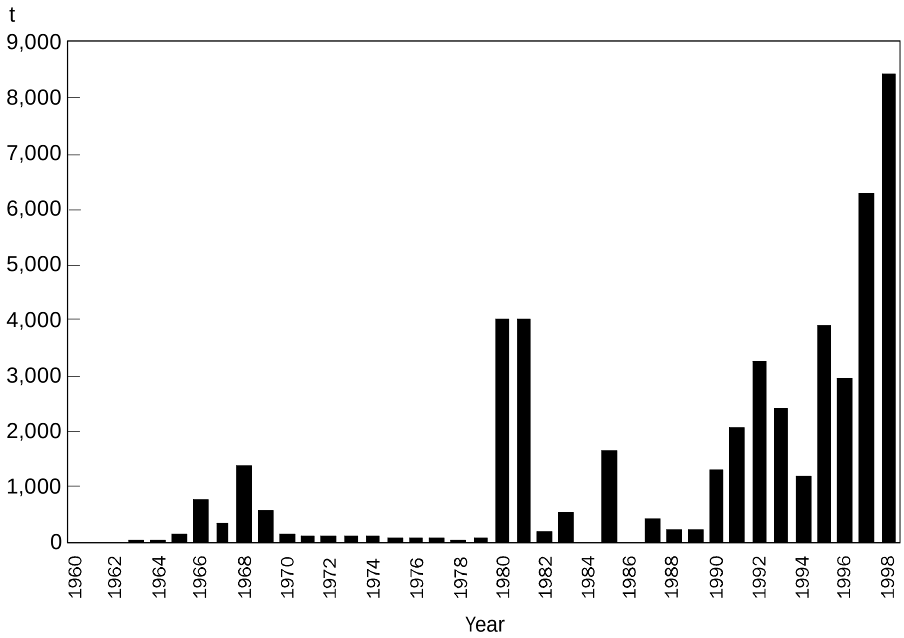


Fig. 1. Lao fertilizer imports from 1961 to 1998. Source: FAO 1998 electronic database.

nutrient management strategies to overcome these deficiencies. Finally, the last section provides an overall summary and recommendation for different soils. In the appendixes at the end, we have provided (1) a list of Lao-IRRI publications relating to rainfed lowland rice, which are available from IRRI, and (2) a list of soil fertility experiments that have been conducted from 1991 to 2000. It is from these experiments that the results of this book have been derived.

Lowland rice

Lowland rice is grown in bunded paddies, which allows the soil to become flooded, as opposed to upland rice, which is grown in fields without bunds. Lowland rice can be classified into three ecosystems: irrigated, rainfed, and flood-prone (deepwater). No deepwater rice is grown in Laos.

Approximately 80% of the lowland rice is grown on the six main plains that are adjacent to the Mekong River. These are commonly referred to by the province these plains are in: Vientiane, Bolikhamsay, Khammouane, Savannakhet, Saravane, and Champassak. In the mountainous north, lowland rice is confined primarily to valley regions.

Area under production

Wet-season rice. In the 2000 wet season, the harvested rice area was 475,600 ha (Table 1). The area under wet-season lowland rice production fluctuates annually, in part because of drought, flooding, and pests. Wet-season lowland rice harvested area averaged 393,000 ha from 1976 to 2000, although there was an increasing trend (especially since 1997), reflecting government policy to expand this area (Fig. 2). The harvested area in the 1999 wet season was the highest at 477,000 ha.

On the basis of 2000 statistics, 77% of the wet-season rice area is on the six main plains in southern Laos. Savannakhet has the largest area, occupying 101,600 ha or 21% of the total area. The Vientiane (includes the area in both the municipality and province) and Champassak plains each have more than 70,000 ha. In the north, Sayaboury has the largest lowland rice area (20,000 ha). The other provinces in the north have from 5,000 to 13,000 ha each. Sekong, in southern Laos, has the smallest lowland area of any province (3,000 ha).

Wet-season rice can be broadly classified into rainfed or irrigated. Rainfed lowland rice is rice that is grown in leveled, bunded fields that are flooded with rainwater. Wet-season irrigated rice can receive supplemental irrigation water (i.e., during times of drought) during the wet season. During the 2000 wet season, approximately 280,000 ha of lowland rice area had access to supplemental irrigation water (almost 60% of the wet-season rice area) and could therefore be classified as irrigated.

Table 1. Lowland harvested rice area for the wet season (2000) and dry season (1995 and 2000).

Province	Wet season 2000 (ha)	Dry season-irrigated		
		1995 (ha)	2000 (ha)	Percent increase 1995 to 2000
Phongsaly	5,400	47	60	28
Luang Namtha	7,900	25	740	2,860
Oudomsay	9,200	173	830	380
Bokeo	10,200	0	220	[a]
Luang Prabang	9,800	748	1,800	141
Houaphanh	11,400	750	980	31
Sayaboury	21,500	546	1,950	257
Xieng Khouang	14,500	0	330	[a]
Saysomboune	4,000	5	80	1,500
Vientiane Municipality	50,600	6,466	19,520	202
Vientiane Province	37,700	1,200	6,970	481
Bolikhamsay	25,000	40	4,310	10,675
Khammouane	34,000	739	7,770	951
Savannakhet	101,600	2,017	21,250	954
Saravane	46,300	143	4,890	3,320
Sekong	3,000	4	420	10,400
Champassak	71,100	398	19,230	4,732
Attopeu	12,400	0	450	[a]
Total	475,600	13,301	91,800	590

[a]Cannot calculate because there was no irrigated area in 1995.

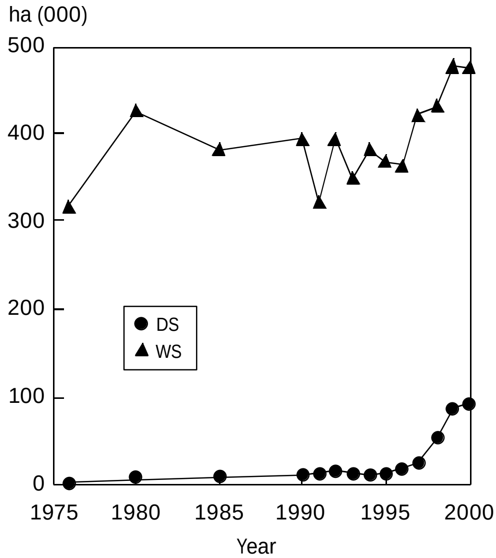


Fig. 2. Harvested lowland rice area during the wet (WS) and dry (DS) seasons from 1976 to 2000. WS rice includes both rainfed and irrigated area, whereas DS rice is only irrigated area.

Dry-season irrigated rice. Because of the lack of rainfall in the dry season, all rice grown during the dry season is irrigated. One of the most striking features of rice production in Laos during the last half of the 1990s was the rapid expansion of the irrigated area, which was about 13,000 ha through the 1995 dry season (Fig. 2). From 1995 to 2000, the area increased by about 600% to 91,800 ha.

In 1995, almost 50% of the irrigated rice area was in Vientiane Municipality and five provinces had 5 ha or less of irrigated rice (Table 1). The expansion of the irrigated rice area occurred in all provinces so that by the 2000 dry season all provinces had at least 60 ha. Most of the expansion has been on the six main rice-growing plains in southern Laos, particularly in Savannakhet and Champassak. By 2000, Vientiane Municipality, Savannakhet, and Champassak all had more than 19,000 ha of dry-season irrigated rice area. In the north, the irrigated area has expanded by more than 200% since 1995. The 2000 dry season had almost 7,000 ha of irrigated rice in the north, or approximately 8% of the total irrigated rice area. Sayaboury and Luang Prabang have the largest irrigated area in the north, with Sayaboury having 1,950 ha and Luang Prabang 1,800 ha.

Production practices

Varieties. Most varieties grown in the lowlands are glutinous. On the basis of survey results from 1995 from some districts in Champassak and Saravane, farmers grow up to nine different varieties in any given year, with the norm being four or five (Pandey and Sanamongkhoun 1998). These varieties are a combination of traditional and improved varieties and they vary in duration and photoperiod sensitivity. Choice of variety is based on available water, labor resources, and quality. Long-duration varieties are typically grown in low-lying areas where the risk of drought is less. Short-duration varieties are grown in higher areas or sandy soils where the risk of drought is higher or close to the house.

The adoption of improved varieties is increasing following the release of several varieties from the National Rice Research Program. These varieties typically perform similarly to the traditional varieties under low-fertility conditions but respond better to applied nutrients. Table 2 lists the currently recommended Lao glutinous varieties and some of their properties (duration does not apply for dry-season rice).

No varieties have been developed specifically for dry-season production in Laos, although work is ongoing. Currently, farmers use varieties that have been developed for the wet season. Although this has proven to be an adequate solution for southern Laos, where temperatures remain warm, in the cooler portions of northern Laos, these varieties have not performed well.

Management. Wet-season rice production typically begins in May at the start of the monsoon rains. In May to early June, following sufficient rains, the nursery is prepared by plowing and puddling using a harrow. If farmers apply manure to the nursery, they do it before plowing; however, most farmers do not use manure or other fertilizers in the nursery. Rice is sown immediately following puddling. The seedlings in the nursery typically grow for about 30 d, although farmers may transplant anytime from 25 to 40 d. Delaying transplanting to 45 d after sowing can reduce yields (Sipaseuth et al 2001). An exception to this is in the north, where upland farmers who have some lowland rice area establish nurseries in the upland fields adjacent to their lowland fields. Having upland instead of lowland nurseries is primarily because of the high labor demand from their upland fields.

The main fields are initially plowed about 2 to 4 wk before transplanting. Just before transplanting and when the soil is flooded, the field is plowed again and puddled

Table 2. Recommended varieties for wet-season production in Laos.

Variety name	Rice type
TDK1	Glutinous
TDK2	Glutinous
TDK3	Glutinous
TDK4	Glutinous
PN1	Glutinous
PN2	Glutinous
TSN1	Glutinous
NTN1	Glutinous
RD10	Glutinous
RD8	Glutinous
RD6	Glutinous
KDML 105	Nonglutinous (jasmine)

using a harrow. In sandy soils, this must be done immediately before transplanting because the soil settles fast and it becomes difficult to transplant. Transplanting is a labor-intensive operation. Seedlings are first pulled from the nursery, bundled, taken to the field, and then transplanted. Farmers typically transplant at a hill density of 16 m^{-2} using about three seedlings per hill. Research in Laos and elsewhere has demonstrated that closer spacing (25 to 44 hills m^{-2}) can increase yields (Sipaseuth et al 2001). However, the potential for higher yields needs to be weighed against the cost of increased labor to transplant and the risk that the crop may be further predisposed to drought in the event of a water shortage.

Fertilizer and pesticide inputs are not used extensively in the rainfed lowlands but are used more in the irrigated environment. Fertilizer use is increasing, however, as is evident from a survey in southern Laos, which indicated that, in 1995, 60% of the farmers using fertilizer had only started using it in the past two years. Given the recent use of fertilizer, farmers do not often know how to manage it. The amount of fertilizer used and when it is applied often depend on the availability of cash. The most common fertilizers imported are 16-20-0 and 46-0-0 (urea), which represented 87% and 73% of the total fertilizer imported in 1996 and 1999, respectively (Table 3).

Weeds are not normally perceived as a big problem in most lowland rice fields. Manual weeding is done up to two times before flowering. Rice starts to mature as early as September and continues until November depending on variety and time of planting. Harvesting is done manually by cutting off the panicle about halfway up the rice plant. The panicles are bundled and left in the field for a few days to dry. The panicles are then moved to a central location for threshing—either mechanical or by hand (details of residue management can be found in the section "Residue management effects on nutrient budgets").

Irrigated rice production during the dry season is a relatively new practice for many farmers, especially outside Vientiane Municipality. Dry-season rice production typically starts in November or December. The timing depends on the availability of water from the irrigation scheme and temperature. In the north, where dry-season irrigated rice production is new, farmers prefer to transplant early, before the cold season sets in. This allows seedlings some time to become established (whether this is a sound management practice remains to be determined). In southern Laos,

Table 3. Lao fertilizer imports in 1996 and 1999.

Fertilizer	1996	1999
	Percent of total fertilizer imports	
46-0-0 (urea)	31	11
16-20-0	56	62
15-15-15	10	13
Total	97	86

Source: Ministry of Agriculture and Forestry, Department of Agriculture.

nurseries are normally established when water is available from the irrigation canal. This varies between years and between irrigation schemes. Although management practices in the irrigated rice system are generally similar to those in wet-season rice production, dry-season production differs in the following areas: more inorganic fertilizer inputs are used, hill spacing is typically closer (25 to 44 hills m^{-2}), and straw management is different. Stubble straw (straw remaining after harvest) is more commonly burned in the irrigated system than in the rainfed system, where animals typically graze it.

The production environment

For our purposes, two broad rice production areas or regions in Laos will be discussed based on differences primarily in topography, which affects the relative importance of the type of rice culture (upland vs lowland) in each area. These regions will be referred to as the north (provinces of Sayaboury, Luang Prabang, Xieng Khouang, Oudomsay, Houaphanh, Phongsaly, Luang Namtha, and Bokeo and the Saysomboune Special Zone) and the south (Vientiane Municipality and the provinces of Vientiane, Bolikhamsay, Khammouane, Savannakhet, Saravane, Champassak, Sekong, and Attopeu) (Fig. 3). The northern region is mountainous and most of the rice is grown in upland fields; lowland rice production is confined to valley areas. In the south, most of the rice is grown in lowland fields on the plains adjacent to the Mekong River. These divisions are general and considerable variability exists within them. Although differences occur between these regions in topography, differences also exist in climate and soils, which will be discussed.

Rainfall

Rainfall is perhaps the most important climatic variable in determining the productivity and potential of rainfed agricultural systems. Rainfall data (1985-98) were analyzed from 11 weather stations in Laos (Vientiane Municipality, Vientiane, Khammouane, Savannakhet, Saravane, and Champassak in the south and Houaphanh, Luang Prabang, Oudomsay, Sayaboury, and Xieng Khouang in the north). Annual rainfall averaged 1,440 mm in the north and 1,920 mm in the south. The north has only two months (July and August) that average more than 200 mm of rainfall compared with five months (May through September) in southern Laos (Fig. 4A). However, within regions, rainfall is highly variable. For example, in the north, all locations received less than 1,470 mm of rainfall annually except Houaphanh (on the eastern side of the Annamite Mountain Chain), which received 1,750 mm. Sayaboury, in the north, was the driest location, averaging only 1,270 mm annually. In the south, Savannakhet was the driest location (1,420 mm) and Vientiane Province and Khammouane were the wettest with more than 2,250 mm of rainfall annually.

In the north, 83% of the precipitation falls during the rainy season (May through October), whereas in the south 92% of the precipitation falls during the same period. Rainfall in all regions increases from May to August, after which it declines rapidly.

Fig. 3. Map of Laos showing the provinces of the north (shaded) and south as used in this publication.

Rainfall varies not so much in absolute amounts but in terms of the time of its onset and cessation and periods of drought or flooding. The average trends shown in Figure 4A mask the erratic nature of rainfall. The standard deviation of average monthly rainfall for three locations in Laos shows that, in general, variation is higher in southern locations (Vientiane and Pakse), which receive more rainfall (Fig. 4B). In Vientiane, the months with the greatest variability are May through July, the early part of the growing season. High variability in May, when average rainfall is relatively low, suggests that the onset of the rainy season and hence the time of planting may vary. High variability in June and July suggests the potential for early season drought. In

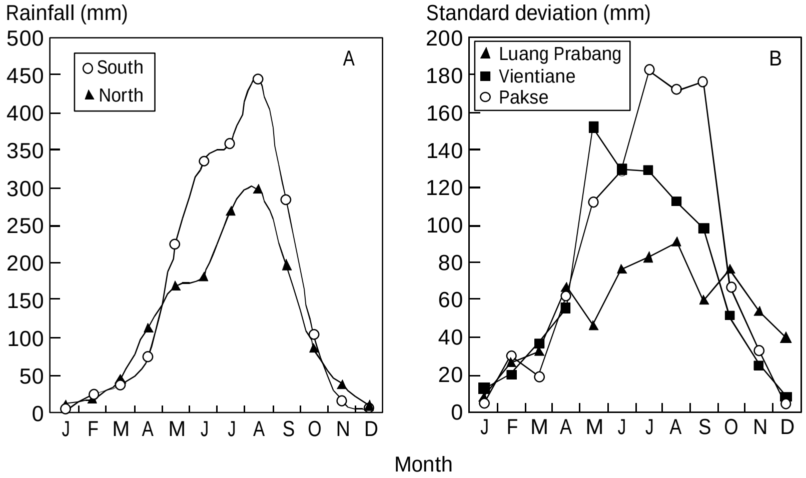


Fig. 4. (A) Mean monthly rainfall (1985-98) for southern and northern Laos. (B) Standard deviation of monthly rainfall (1985-99) for three locations in Laos.

Pakse, rainfall variability is high in July through September. September has low relative rainfall and is the end of the wet season; therefore, late-season drought may be expected to be more prevalent. In Luang Prabang, rainfall variability is high relative to total monthly rainfall from April through June. This suggests the potential for early season drought or a delay in the onset of the wet season.

Temperature

In southern Laos, the mean maximum and minimum temperatures during the wet season (May-October) average 32.2 and 23.7 °C, respectively (Fig. 5A). In the north, temperatures are cooler, with the mean maximum and minimum temperatures averaging 29.7 and 20.3 °C, respectively, during the same period. Dry-season temperatures are cooler throughout Laos. The mean maximum and minimum temperatures for the three coolest months (December to February) are 30.7 and 17.2 °C for southern Laos and 25.3 and 12.0 °C for northern Laos. Temperatures can drop below freezing in some high-elevation areas. This occurred most recently during late December of 1999 when subzero temperatures were recorded in some areas of the north. From February to April, temperatures increase to an annual high, when mean monthly maximum temperatures are 35.1 and 31.1 °C in southern and northern Laos, respectively. Temperatures above 40 °C during late March and April are not uncommon.

Temperature differences between regions can largely be explained by differences in elevation. The elevation of weather stations analyzed varied from 120 m (Pakse, Champassak) to 1,050 m (Phonsavan, Xieng Khouang). There is a close relationship between mean annual high and low temperature and elevation, which indicates that a 100-m change in altitude results in a temperature change of about 0.7 °C (Fig. 5B).

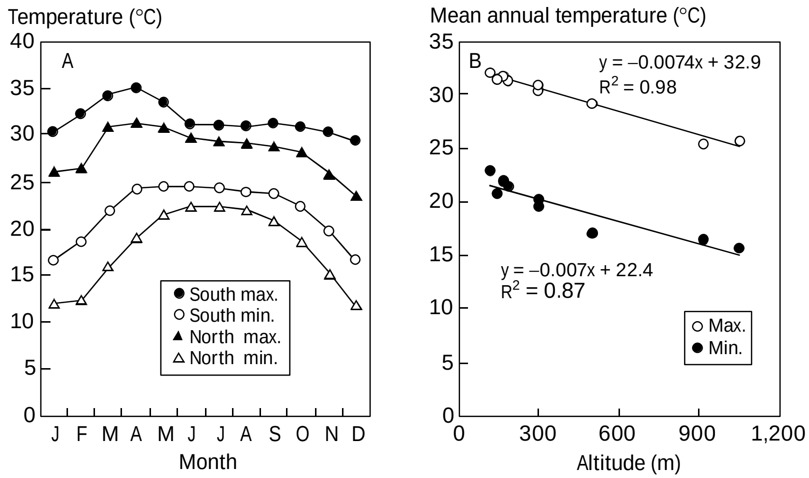


Fig. 5. (A) Monthly mean maximum (max) and minimum (min) temperatures for northern and southern Laos. (B) Mean annual minimum and maximum temperatures as a function of altitude.

For wet-season rice production, temperatures are generally favorable. During the dry season, however, low temperatures at higher elevations prolong growth or have adverse effects on young seedlings (Sihathep et al 2001). At the lower elevations in the south, temperatures above 36 °C during flowering may result in grain sterility (Yoshida 1978). If rice is sown in late December to early January (as is the common practice), flowering will occur during late March and April when temperatures are the hottest.

Daylength

Daylength is important because it determines the potential amount of solar radiation available for crop growth. Also, many rice varieties, particularly traditional ones, are photoperiod-sensitive, meaning that they flower in response to daylength.

The daylength for any location is determined by its latitude. Laos is situated between 13° and 23° north of the equator and experiences noticeable changes in daylength during the year and between locations. Figure 6 gives the number of hours from sunrise to sunset (not including twilight) for Pakse (Champassak), Vientiane, and Luang Namtha (north). On the longest day of the year (21 June), daylength is 12 h 54 min, 13 h 5 min, and 13 h 17 min for Pakse, Vientiane, and Luang Namtha, respectively. On the shortest day of the year (21 Dec.), daylength is 11 h 6 min, 10 h 55 min, and 10 h 43 min, respectively. This represents a change in daylength of 1 h 48 min, 2 h 10 min, and 2 h 34 min, respectively.

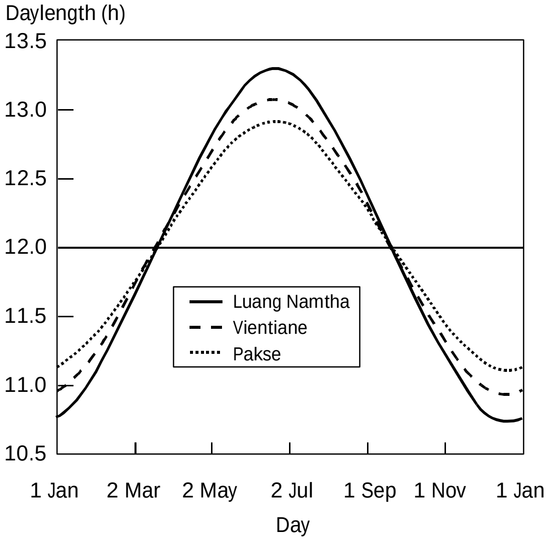


Fig. 6. Calculated daylength (not including twilight) at three locations in Laos.

Sunshine hours and solar radiation

Average monthly sunshine hours for Pakse, Vientiane, and Luang Prabang are shown in Figure 7A. At all locations, sunshine hours were lowest from June to August, corresponding to the peak of the wet season (Fig. 4A). During the dry season, despite the shorter daylength (Fig. 6), the number of sunshine hours was the highest.

Solar radiation determines the potential energy available for crop growth. Solar radiation is not measured directly at any of the weather stations in Laos. Solar radiation is estimated from sunshine hours, daylength, and latitude (Fig. 7B). Maximum solar radiation in Laos occurs during the dry season, from February to May. In Luang Prabang, and to a lesser extent in Vientiane, solar radiation dips in March. This may be due to extensive burning in the uplands during this period, with the smoke blocking out the sun. Solar radiation begins to decline at all sites during May and June (the onset of the rainy season) and is at a minimum in July and August when rainfall is heaviest (Fig. 4A). Solar radiation increases during September, as the wet season ends, then declines through December with the shortening days. On the basis of such data, the yield potential is higher during the dry season than during the wet season because of the greater amount of solar radiation received during this period.

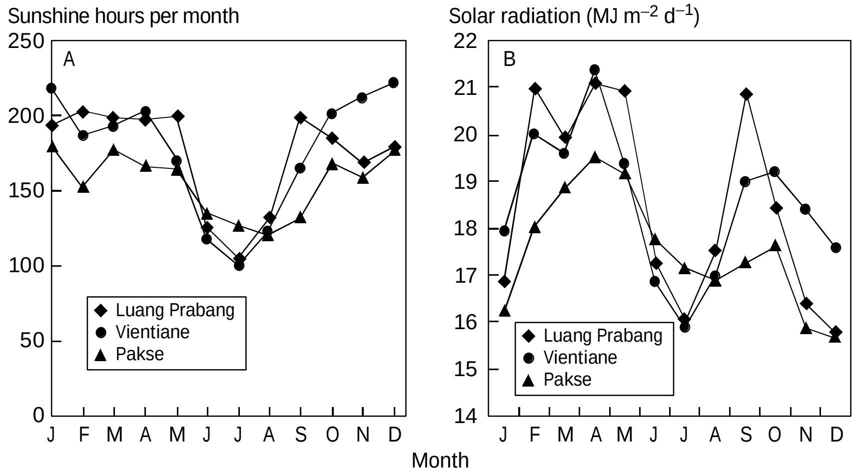


Fig. 7. Sunshine hours (A) and solar radiation (B) at three locations in Laos. Data represent means from 1985 to 1998.

Nutrient deficiencies in lowland rice soils

Soils

The Soil Survey and Land Classification Center (SSLCC) under the National Agriculture and Forestry Research Institute (NAFRI) is in the process of characterizing soils using the FAO/UNESCO Soil Map of the World, Legend (version) 1988.

Although the classification of Lao soils is not yet complete, the data available from the SSLCC indicate that the predominant lowland rice soils in southern Laos are Acrisols. Acrisols are characterized as highly weathered soils with an argic B horizon (a subsurface layer with a higher clay content than the surface soil layer). Acrisols have a low content of primary minerals and a strong dominance of 1:1 clays expressed by a low cation exchange capacity (CEC). By definition, the CEC of clay is <24 meq 100 g^{-1} clay. In addition, Acrisols have a low base saturation (<50%) and the elements Ca, Mg, K, and Na are replaced by H and Al. Thus, a low natural fertility and a low pH occur, usually close to 5.5 or lower. The typical characteristics of the lowland rice Acrisols are their gleyic and/or stagnic properties, which are expressed by mottling (red oxidized iron patches) in a usually gray (reduced) soil matrix. Rice is extensively grown on Cambisols, besides on Acrisols. These Cambisols are younger soils, often river or colluvial deposits, having a cambic subsurface horizon, which is a horizon in the first stages of weathering and soil formation. Being younger soils, they are often more fertile than the Acrisols (of course, depending also on the origin of the parent material), but they contain appreciable amounts of weatherable minerals. What they have in common with the lowland rice Acrisols are the gleyic and/or stagnic conditions.

In northern Laos, on the larger valleys that are not covered by recent deposits, soils are most likely Acrisols. In the smaller valleys and on the footslopes, particularly in the areas where shifting cultivation is practiced (causing erosion), the parent material of the lowland rice soils is colluvium or alluvium and these soils are classified as Cambisols. But, in both cases, gleyic properties will often be present.

Chemical and physical properties used for classification are available and are useful in identifying major soil differences between regions. Analysis of lowland rice soil data (0–20 cm) from the SSLCC indicates that 80% of the soils in the south contain less than 2% organic matter, 68% are coarse-textured (sands, loamy sands, and sandy loams), and 87% have a pH (H_2O) of less than 5.5 (Fig. 8). In contrast, soils in the north are more fertile: 66% of the soils contain more than 2% organic matter, 80% are loams or clay loams, and 48% have a pH of less than 5.5. The prevalence of more fertile soils in the north may be due to less rainfall and lower temperatures than those typically found in the south.

These differences in soil fertility indicators between the north and south are also evident from rice yields where no fertilizer is applied. Average lowland rice yields during the wet season, without fertilizer, are 2.0 t ha^{-1} in the south and 2.6 t ha^{-1} in the north (Fig. 9).

Extent of major nutrient deficiencies

To determine which nutrients (N, P, or K) limit crop productivity, nutrient omission studies were conducted in areas with significant amounts of lowland rice cultivation. The data presented in Tables 4 and 5 show the extent of nutrient deficiencies but are

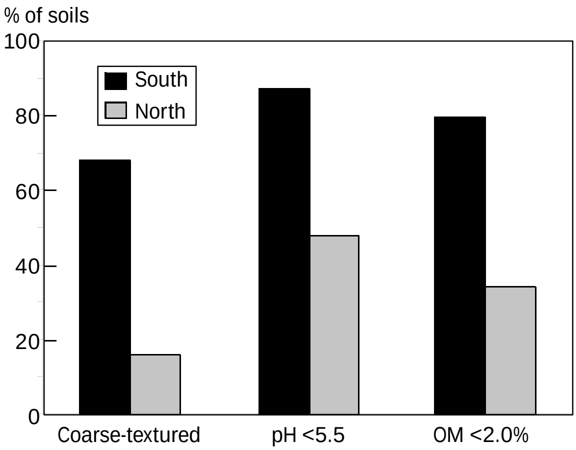


Fig. 8. Comparison of soil texture, pH, and organic matter (OM) content of lowland rice soils (0–20 cm) in southern and northern Laos. Coarse-textured soils include sands, loamy sands, and sandy loams. Source: Soil Survey and Land Classification Center.

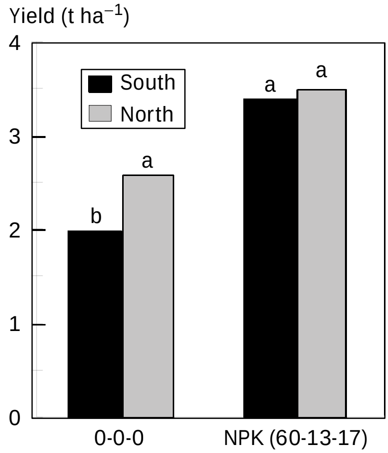


Fig. 9. Wet-season lowland rice yields in the south and north with and without fertilizer. Results are averages from 37 experiments (23 in the south and 14 in the north) conducted from 1992 to 1996. Different letters in the same column group indicate significantly different yields.

not intended to be used as a guide for these deficiencies in a particular district or village. Soils and their fertility vary tremendously even at the village level because of position within the toposequence and farmer management practices.

Nutrient deficiencies were determined using on-farm nutrient omission experiments. There were usually five treatments: (1) no fertilizer, (2) complete fertilizer (N, P, and K applied at 60, 13, and 17 kg ha^{-1}, respectively), (3) complete fertilizer minus N, (4) complete fertilizer minus P, and (5) complete fertilizer minus K. In 1997 and 1998, S was also included in the experiments and rates of all nutrients were increased. Additionally, in 1997, a small and separate S omission study was conducted at seven locations to help determine the extent of S deficiencies.

Rainfed wet season. From 1992 to 1998, a total of 43 such studies were conducted in the rainfed lowland environment (Table 4). All studies showed a significant response to a combined application of N, P, and K, with the exception of Luang Namtha, Sing District. The soils at this site may have been limited by another nutrient besides N, P, or K. It is also noteworthy that a subsequent study in this same area showed a significant response to the combined application of N, P, K, and S.

Nitrogen was deficient at most sites (Fig. 10). In the south, N was limiting at all sites except Savannakhet, Xaybouli District (this study was conducted at a location where farmers routinely apply manure and incorporate straw). In other studies (data not shown), in which N has not been deficient, the soils have recently been cleared and devoted to rice production. In the north, an N response occurred at 69% of the sites.

Table 4. Results from NPK omission studies conducted from 1992 to 1998 during the wet season.

Province	District	Village	Year	Response to			
				NPK	N	P	K
South							
Bolikhamsay	Paksan	B. Phonesawang	1992	Y	Y	N	N
Champassak	Sanasomboune	B. Sapay	1992	Y	[a]	Y	N
Champassak	Phonethong	B. Oupalath	1992	Y	[a]	Y	N
Champassak	Pakse	Phone Ngam Stat	1992	Y	Y	N	Y
Khammouane	Thakhek	B. Thangam	1992	Y	Y	Y	N
Khammouane	Nongbok	B. Song Muang	1992	Y	Y	Y	Y
Savannakhet	Khanthabouly	B. Phonesim	1992	Y	[a]	Y	N
Savannakhet	Champhone	B. Phaleng	1992	Y	Y	N	N
Vientiane P.	Phonehong	B. Phonehene	1992	Y	[a]	Y	Y
Vientiane P.	Phonehong	B. Phonehong	1992	Y	[a]	Y	N
Vientiane P.	Phonehong	B. Phone Kham	1992	Y	Y	Y	Y
Vientiane M.	Naxaythong	B. Namkhiang	1992	Y	Y	N	N
Vientiane M.	Sikhotabong	B. Dongnathong	1992	Y	Y	Y	N
Vientiane M.	Saythany	Km 39	1992	Y	Y	Y	N
Vientiane M.	Saythany	Km 21	1992	Y	Y	Y	N
Vientiane M.	Saythany	Nabong College	1992	Y	Y	N	N
Saravane	Khongsedon	Naphong	1993	Y	Y	Y	N
Saravane	Saravane	Nakhoysaw	1993	Y	Y	Y	N
Saravane	Vapi	Phakha	1993	Y	Y	Y	N
Savannakhet	Xaybouly	Bungsay	1993	Y	N	N	N
Champassak	Soukhouma	S. Neua	1995	Y	Y	Y	Y
Attopeu	Saysetha		1996	Y	Y	Y	Y
Sekong	Lamam	Donechan	1996	Y	Y	N	N
Sekong	Thateng	B. Nyokthong	1998	Y	Y	Y	N
North							
Houaphanh	Samneua	B. Navieng	1992	Y	[a]	Y	N
Houaphanh	Et	B. Sod	1998	Y	Y	Y	N
Oudomsay	Xai	B. Don Geaw	1992	Y	[a]	Y	N
Sayaboury	Phiang	B. Nakaem	1992	Y	Y	N	N
Sayaboury	Phiang	B. Phonhin	1998	Y	Y	N	N
Houaphanh	Xieng Kho	Hab	1993	Y	Y	N	N
Luang Namtha	Sing	Namgeaw Luang	1993	N	N	N	N
Luang Namtha	Namtha	Thongchaineua	1993	Y	N	N	N
Luang Prabang	Xieng Nguen	Houay Khot Stn.	1993	Y	Y	Y	N
Luang Prabang	Nane	Sibounheuang	1993	Y	Y	N	N
Luang Prabang	Nane	Sibounheuang	1997	Y	Y	N	N
Luang Prabang	Xieng Nguen	Houay Khot	1993	Y	Y	N	N
Phongsaly	Bounneua		1993	Y	N	N	Y
Xieng Khouang	Pek	Ngua	1993	Y	Y	Y	N
Xieng Khouang	Kham	Hin	1997	Y	Y	N	N
Luang Namtha	Sing	Xiengchay	1994	Y	Y	N	N
Luang Namtha	Namtha	Thungdee	1994	Y	N	N	N
Bokeo	Thonepheung	Thonepheung	1995	Y	N	Y	N
Bokeo	Houeyxai	Namkhok	1995	Y	Y	Y	Y

[a]In the 1992 studies, it was not always possible to determine whether N was a limiting nutrient because there was no PK treatment to compare with the NPK treatment. There was a treatment in which only N was applied, so, if yield in this treatment was greater than that of the control, an N deficiency was inferred. Also, in some of the studies, an N rate trial was imbedded in the experiment so an N deficiency could be inferred from this.

Table 5. Results from NPK omission studies conducted from 1992 to 1999 during the dry season.

Province	District	Village	Year	Response to			
				NPK	N	P	K
South							
Vientiane M.	Naxaythong	Nakha	1992	Y	Y	Y	N
Vientiane M	Saythany	Namonh	1992	Y	Y	N	N
Vientiane M.	Saythany	Viengkham	1993	Y	Y	Y	N
Vientiane P.	Thurakhom	Chaeng	1994	Y	N	N	N
Vientiane P.	Phonhong	Phonemi	1993	Y	Y	Y	Y
Bolikhamsay	Paksan	B. Thana	1998	Y	Y	Y	N
Khammouane	Gnommalath	Thathot	1994	Y	Y	Y	Y
Khammouane	Thakhek	Jomejaeng	1993	Y	Y	N	N
Savannakhet	Saybouly	Bungxay	1993	Y	Y	Y	Y
Savannakhet	Champhone		1999	Y	Y	Y	N
Saravane	Saravane	Bungxay	1993	Y	Y	Y	Y
Saravane	Vapi		1997	Y	Y	Y	N
Champassak	Champassak	Phaphim	1993	Y	Y	Y	N
Champassak	Pakse	Viunpakvang	1994	Y	Y	Y	N
North							
Sayaboury	Phiang	Nasang	1993	Y	Y	Y	N
Sayaboury	Phiang		1997	Y	Y	Y	Y
Sayaboury	Phiang		1999	Y	Y	Y	Y
Luang Prabang	Xieng Nguen	Houay Khot Stn.	1993	Y	Y	Y	Y
Luang Prabang	Chompetch	Xiengmane	1995	Y	Y	N	N
Luang Prabang	Nane	Sibounheuang	1996	Y	Y	N	Y
Luang Prabang	Nane	Sibounheuang	1998	Y	Y	N	N
Houaphanh	Xieng Kho	Wan	1993	Y	Y	N	N

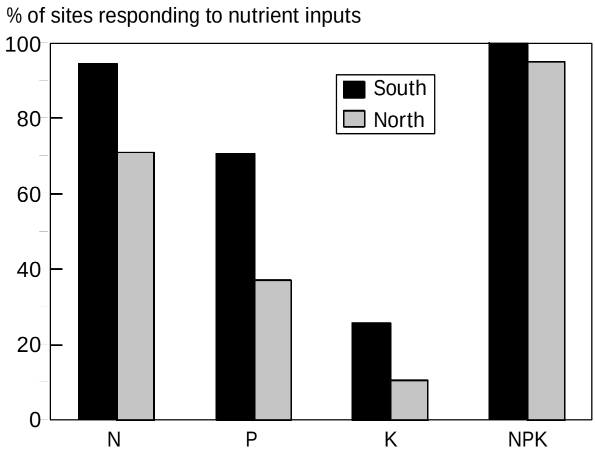


Fig. 10. The percentage of sites in which rice responded to the addition of nutrients. Data represent means of 43 NPK omission trials (24 in the south and 19 in the north) conducted from 1992 to 1998 in the wet season.

Although N deficiencies were widespread, their severity varied considerably. On the basis of an analysis of sites where both yield data in −N plots (but P and K added) and soil organic matter (SOM) data were available, variability in N deficiency severity appears to be related to SOM. Under conditions where P and K are added, it is expected that N would be the most limiting nutrient and yields would be an indicator of indigenous soil N fertility (Dobermann and Fairhurst 2000). For this analysis, 32 sites were available: 11 from the north and 21 from the south. The regression of SOM against grain yields in −N plots shows a significant and positive correlation (Fig. 11). For each additional 1% increase in SOM, yields increase by 0.77 t ha^{-1}. Soils in the south typically have lower organic matter contents than those in the north (Fig. 8), which partially explains why N deficiency is more prevalent in the south and why yields in the south are typically lower than those in the north when no fertilizers are applied.

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). Using grain yield measurements from −N plots, these authors provide the following formula to estimate INS:

$$INS = GY \times 13 \quad (1)$$

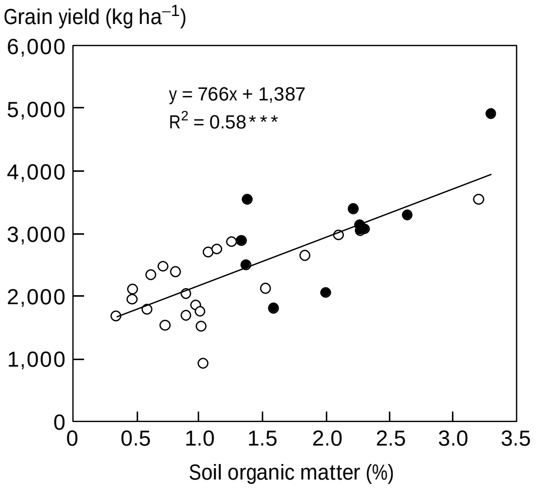


Fig. 11. The relationship between soil organic matter and rice grain yields in –N plots (received P and K fertilizer but no N). Values are means from 11 field experiments in northern Laos (filled circles) and 21 in southern Laos during the wet season. *** indicates significance at $P<0.001$.

where GY is grain yield (t ha^{-1}) in the −N plots and 13 kg is the average amount of N taken up by rice to produce 1 t of grain.

Using the data from the 32 sites above, INS ranged from 12 to 64 kg N ha^{-1} and averaged 28 and 40 kg N ha^{-1} in the south and north, respectively. Regression of INS against soil organic matter (data not shown) indicates that, for every 1% increase in SOM, INS increases by almost 10 kg ha^{-1}.

Phosphorus was the second most limiting nutrient, with 71% of the sites in the south responding to P and 37% in the north (Fig. 10). In the south, at approximately 30% of the sites, the soils were so P-deficient that there was no response to other nutrients unless P was applied first (data not shown). Although P deficiencies may be less prevalent in the north, some areas have severe P deficiencies, the most notable being those in parts of Xieng Khouang Province.

The response to K was much less than for N and P, with significant responses to K in 25% and 11% of the studies in the south and north, respectively (Fig. 10). However, K deficiencies are expected to increase in the future as farmers typically apply N and P fertilizer but not K fertilizer to their fields (this will be discussed in greater detail later).

Sulfur is another major plant nutrient that is limiting in some soils, although the extent of S deficiencies has not been examined in the same detail as N, P, and K. Severe S deficiencies have been observed in Sekong (Thateng District) and small responses to S in Luang Namtha (both Namtha and Sing districts) and Bolikhamsay. Approximately 25% of the sites evaluated showed some response to S, although most responses were small.

For all of the major plant nutrients, the extent of deficiencies was much greater in the south than in the north. Soils in the north are generally less weathered because of lower temperatures and less rainfall than in the south. This is reflected in the higher soil pH and organic matter contents of soils in the north (Fig. 8). Higher organic matter contents can be maintained in these soils because of lower temperatures and less rainfall. Finally, the soils in the north typically contain more clay, which allows for improved nutrient retention.

Irrigated dry season. From the 1992 to 1999 dry seasons, 22 NPK omission trials were conducted (Table 5). Yields without fertilizer were only 1.5 and 1.7 t ha^{-1} for the south and north, respectively (Fig. 12). This is significantly lower than yields in minus fertilizer plots during the wet season, in which yields averaged 2.0 and 2.6 t ha^{-1} in the south and north, respectively (Fig. 9). In all cases, there was a significant response to the combined application of N, P, and K (Fig. 13).

All sites showed a response to the application of N, with the exception of the site in Vientiane (Thurakhom District), although there was a response to the combined application of all nutrients at this site. Phosphorus was deficient at 79% of the sites in the south and at 50% of the sites in the north. Potassium was deficient at 29% of the sites in the south and at 50% of the sites in the north, considerably higher than what was observed during the wet season (25% and 11%, respectively).

Unlike what was observed during the wet season, deficiency problems between northern and southern Laos were similar in the dry season; however, these data need

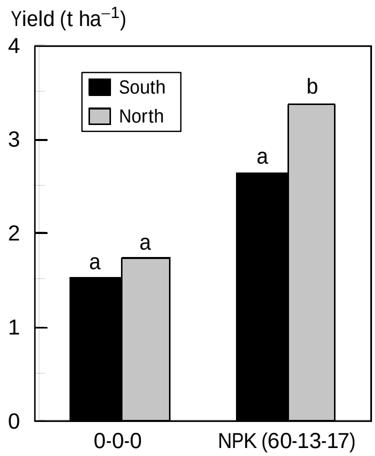


Fig. 12. Dry-season rice yields in the south and north with and without fertilizer. Results are averages from 18 experiments (12 in the south and 6 in the north) conducted from 1992 to 1996. Different letters in the same column group indicate significantly different yields.

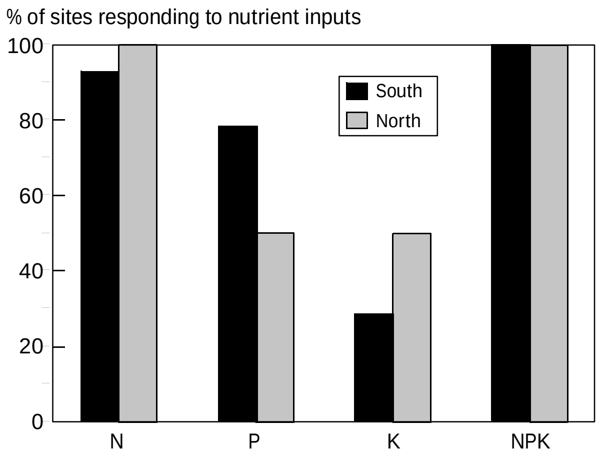


Fig. 13. The percentage of sites in which rice responded to the addition of nutrients. Data represent means of 22 NPK omission trials (14 in the south and 8 in the north) conducted from 1992 to 1998.

to be interpreted with caution as a much smaller number of sites were evaluated. Most of the experiments were conducted in Sayaboury and Luang Prabang as these are the major areas of dry-season rice production in the north. However, with the expansion of the irrigated area, further testing is required.

Nutrient budgets

Nutrient budgets indicate the nutrient inputs and losses in a field or farming system. These budgets are helpful in developing nutrient recommendations, identifying potential nutrient problems, and understanding the effect of management practices on nutrient availability. Nutrient inputs into the system include those from fertilizer, biological N_2 fixation, rainfall, and irrigation water. Nutrient losses include those nutrients removed by the crop when grain and straw are removed, leaching, losses to the atmosphere (i.e., denitrification), runoff, and erosion. It is not possible to estimate and measure all inputs and losses with precision but good estimates are possible in most cases.

Nutrient inputs. Nutrient inputs include nutrients in rainfall, irrigation water, biological N_2 fixation, and fertilizers. Inputs from biological N_2 fixation are significant. By adding legumes to the system, N inputs from biological N_2 fixation can be enhanced, as will be discussed later in the section on green manures.

Data on nutrient inputs from rainfall were gathered over a 2-year period from seven locations in Laos. Rainwater contains very little N, in most cases less than 1 kg N ha^{-1} is deposited annually (Table 6). Sulfur is supplied in rainfall at about 5 kg ha^{-1} annually, slightly higher than that reported for northeast Thailand, which receives about 4 kg S ha^{-1} annually in rainfall (Blair 1990).

Irrigation water was sampled during the dry season from 12 irrigation schemes in Laos. Table 7 shows the nutrient concentration of water. The amount of nutrient added to the crop depends on the amount of irrigation water added. The amount of irrigation water required depends on the season and soil type. During the dry season,

Table 6. Annual nitrogen and sulfur inputs from rainfall water[a].

Province	Nitrogen (kg ha^{-1})	Sulfur (kg ha^{-1})
Vientiane Municipality	0.18	5.27
Vientiane Province	0.23	5.58
Savannakhet	0.48	5.67
Champassak	0.17	6.58
Sayaboury	0.19	4.93
Luang Prabang	0.21	4.64
Luang Namtha	0.28	5.49
Mean	0.25	5.45

[a]Data collected from March 1999 to February 2001.

Table 7. Nutrient concentration in and nutrient input from irrigation water in Laos.

Province	District	Water source	Tot N	P	K	S	Ca	Mg	Mn	B	Fe	Cu	Zn	Na	Al
									(mg L^{-1})						
Nutrient concentration in irrigation water															
Vientiane	Naysaythong	Nam Houm Res.	nd[a]	0.006	1.42	0.000	5.25	0.91	0.057	0.007	0.041	0.002	0.013	0.49	0.000
Vientiane	Naysaythong	Huay Son	nd	0.022	1.46	0.030	8.66	1.96	0.033	0.010	0.074	0.007	0.005	1.52	0.001
Vientiane	Naysaythong	Huay Son	nd	0.020	1.28	0.049	8.99	1.71	0.017	0.007	0.046	0.001	0.003	0.83	0.000
Vientiane	Saythany	Ngam Ngum	nd	0.047	1.11	1.265	16.75	3.21	0.002	0.018	0.011	0.000	0.002	6.53	0.009
Savannakhet	Champhone	Resevoir	nd	0.017	1.26	0.779	3.95	3.28	0.012	0.025	0.381	0.006	0.008	52.85	0.843
Saravane	Saravane	Seseck	nd	0.205	2.51	0.388	8.82	6.29	0.014	0.012	0.055	0.003	0.013	6.74	0.057
Champassak	Sanasomboune	Xedon	nd	0.024	1.06	0.205	8.25	4.77	0.007	0.006	0.121	0.002	0.005	3.66	0.227
Champassak	Soukouma	Mekong	nd	0.029	1.80	5.890	34.85	5.96	0.002	0.027	0.023	0.004	0.001	10.95	0.021
Sekong	Thateng	Sekong tributary	nd	0.054	1.46	0.459	7.77	4.84	0.024	0.011	0.038	0.005	0.013	4.85	0.055
Sayaboury	Phiang	Nam Than	nd	0.011	0.53	0.924	33.65	3.07	0.003	0.007	0.047	0.002	0.001	3.75	0.098
Sayaboury	Phiang	Nam Phiang #2	nd	0.022	0.60	0.611	33.10	3.54	0.003	0.006	0.035	0.002	0.002	4.14	0.034
L. Prabang	Nane		nd	0.034	2.05	1.140	58.25	6.34	0.004	0.031	0.028	0.004	0.003	7.60	0.027
									(kg ha^{-1})						
Nutrient input per 1,000 mm irrigation water															
Vientiane	Naysaythong	Nam Houm Res.	0	0.06	14.2	0.0	53	9	0.57	0.07	0.41	0.02	0.13	5	0.00
Vientiane	Naysaythong	Huay Son	0	0.22	14.6	0.3	87	20	0.33	0.10	0.74	0.07	0.05	15	0.01
Vientiane	Naysaythong	Huay Son	0	0.20	12.8	0.5	90	17	0.17	0.07	0.46	0.01	0.03	8	0.00
Vientiane	Saythany	Ngam Ngum	0	0.47	11.1	12.7	168	32	0.02	0.18	0.11	0.00	0.02	65	0.09
Savannakhet	Champhone	Reservoir	0	0.17	12.6	7.8	40	33	0.12	0.25	3.81	0.06	0.08	529	8.43
Saravane	Saravane	Seseck	0	2.05	25.1	3.9	88	63	0.14	0.12	0.55	0.03	0.13	67	0.57
Champassak	Sanasomboune	Xedon	0	0.24	10.6	2.0	83	48	0.07	0.06	1.21	0.02	0.05	37	2.27
Champassak	Soukouma	Mekong	0	0.29	18.0	58.9	349	60	0.02	0.27	0.23	0.04	0.01	110	0.21
Sekong	Thateng	Sekong tributary	0	0.54	14.6	4.6	78	48	0.24	0.11	0.38	0.05	0.13	48	0.55
Sayaboury	Phiang	Nam Than	0	0.11	5.3	9.2	337	31	0.03	0.07	0.47	0.02	0.01	38	0.98
Sayaboury	Phiang	Nam Phiang #2	0	0.22	6.0	6.1	331	35	0.03	0.06	0.35	0.02	0.02	41	0.34
L. Prabang	Nane		0	0.34	20.5	11.4	583	63	0.04	0.31	0.28	0.04	0.03	76	0.27

[a]nd = not detectable.

more irrigation water is applied than during the wet season. Soils with high hydraulic conductivity (usually sandy soils) require more water than soils with a low hydraulic conductivity (usually clay soils). In the dry season, the amount of irrigation water added ranges from approximately 1,000 mm in a clay soil to 2,500 mm in a sandy soil. Similarly, in the wet season, the amount required ranges from approximately 300 mm in a clay soil to 1,200 mm for a sandy soil. The amount of nutrient added per ha in Table 7 is based on an application rate of 1,000 mm of water. The data show that the quantity of N and P is either low or not detectable in most water. Inputs of K and S are variable but generally low to moderate. It is interesting to note that in Sayaboury (Phiang District), where K deficiencies are the most, K concentrations are the lowest. Other nutrients such as Ca and Mg are relatively high.

Inputs from fertilizer vary among regions and farmers. A 1996 survey conducted in Champassak and Saravane of rainfed lowland rice farmers suggests that fertilizer use is recent, with 60% of the farmers starting to use fertilizer in 1995 or after (Pandey and Sanamongkhoun 1998). The survey also reports that the amount of fertilizer used is low. Of those farmers using fertilizer, they applied on average about 30 kg of nutrient per ha (equivalent to about 1.5 bags of fertilizer per ha). However, fertilizer import data suggest that fertilizer use is increasing. Of the fertilizer imported, about 90% is either 16-20-0 or urea (46-0-0) (Table 3), indicating that the primary fertilizer inputs are N and P.

Nutrient losses. Nutrient losses from the soil are caused by crop removal or leaching, runoff, erosion, or losses to the atmosphere as ions are converted to gases. Some of these losses are not important in lowland rice fields (i.e., erosion) and others are difficult to quantify. Of the two major nutrients that are most commonly applied, both are lost via crop removal, but P is not very susceptible to other losses, whereas N is highly susceptible to leaching, runoff, and gaseous N losses (denitrification and NH_3 volatilization), which are difficult to quantify. Leaching is a potential problem in sandy soils that have high water percolation rates and low nutrient retention capacity. Runoff can be a problem on poorly drained soils with low sorption capacity because a sizable fraction of the fertilizer N remains in the floodwater following application. Runoff could then be an important mechanism of nutrient loss in areas with high probability for inundation following intense rainfall (Satrusajang et al 1991). Denitrification occurs when soil becomes anaerobic and soil nitrate is lost to the atmosphere as N gas (N_2O and N_2). In rainfed lowland systems, it is common for soils to cycle between flooded (anaerobic) and aerobic states, resulting in N losses via denitrification. NH_3 volatilization is favored by naturally high soil pH (not a problem in most Lao soils) or by reactions that temporarily raise pH (such as when urea is added). These losses are difficult to quantify, however, in a well-managed system, in which 50% or more of the N applied as fertilizer may be lost (to leaching, runoff, NH_3 volatilization, or denitrification), with the end result being that the crop actually takes up only 50% of the N applied.

Potentially, the greatest nutrient loss results from nutrient uptake by the rice crop and subsequent removal at harvest. Table 8 provides the approximate amount of various nutrients in the rice plant at harvest. An examination of the primary nutrients

Table 8. Macro- and micronutrients in the rice grain and straw at harvest. Data are from experiments conducted in Laos.

Item	N	P	K	S	Ca	Mg	Mn	Zn	Cu
					Nutrient concentration				
	%	%	%	%	%	%	µg g^{-1}	µg g^{-1}	µg g^{-1}
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
					Nutrient per ton of grain yield (kg t^{-1})[a]				
Grain	7.9	1.9	2.8	0.9	0.4	1.0	0.1	0.02	0.04
Straw	4.8	0.6	11.8	1.4	5.9	2.6	1.3	0.04	0.04
Total	12.7	2.5	14.6	2.3	6.3	3.6	1.4	0.06	0.08
					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

[a]Assumes a harvest index of 0.4. Therefore, if rice grain yield is 1 t ha^{-1}, the straw yield would be 1.5 t ha^{-1}.

shows that N and K are taken up in the largest quantities (13–15 kg t^{-1} of grain yield). Phosphorus is taken up in much smaller quantities, averaging about 2.5 kg t^{-1} of grain yield. Of interest is where the nutrient is in the rice crop at maturity. At harvest, most of the N and P is in the grain and is thus removed then. The straw contains 50% or more of the other nutrients, thus indicating the importance of straw management for maintaining soil fertility, which will be discussed in more detail in the following section.

Residue management effects on nutrient budgets. Current residue management practices can be generally described as follows. At harvest, farmers cut off the panicle, leaving about half (depending on variety and farmer) of the rice straw in the field. This stubble straw is most commonly grazed by livestock during the dry season, but it may also be burned. The panicle straw, which is removed with the grain, is moved to a central location, which depends on how the rice will be threshed. Large mechanical threshers mounted on trucks are becoming more common and, in this case, the straw will be moved near the road. Following threshing, the straw is usually burned in a ditch beside the road. If the panicles are to be hand-threshed, the straw is moved near the house for threshing. In this case, the panicle straw will often be stored for livestock feed. There is a trade-off between the amount of straw potentially available and the number of ruminant livestock. Although rice straw may be important for soil fertility, it is also an important livestock feed during the dry season when little other forage is available. Livestock account for a significant portion of expendable cash income (50% in southern Laos, Pandey and Sanamongkhoun 1998); therefore, the most valuable use of straw may be as livestock feed. Livestock graze freely and little effort is made to collect and use manure. Data from southern Laos indicate that only 11% of farmers use manure, with application rates (mostly to nurseries) varying from 35 to 1,050 kg ha^{-1} (Lao-IRRI 1995). The rice husk and bran are usually removed at a rice mill. The cost of milling is the bran from the rice, which the mill sells for animal feed. The rice husks are usually left at the mill, although some farmers return the husks to their fields.

The amount of residue available annually can be estimated relatively accurately for straw and rice husks. Straw accounts for approximately 60% of aboveground biomass and is probably the most abundant on-farm residue. Rice husks account for about 20% of unmilled rice. Therefore, if farm grain yields average 3.5 t ha^{-1}, there will be 5.3 t ha^{-1} of straw and about 0.7 t ha^{-1} of rice husks. Accurate estimates of the amount of available manure are much more difficult to make. If the average farmer has five cows and/or buffaloes (Lao-IRRI 1995), and assuming that each animal produces 1.5 t of manure y^{-1}, 7.5 t of manure are produced per farm.

Table 9 gives the nutrient concentrations of some residues. The nutrient concentration estimates for plant residues are relatively accurate, whereas nutrient concentrations of animal wastes can vary widely.

Straw management in particular has a large effect on the nutrient balance because many nutrients are present in larger quantities in the straw than in the grain. Table 8 shows the percentage of other nutrients that are in the straw compared with the grain. With the exception of N, P, and Cu, more than 50% of the nutrients are in the straw at harvest. Therefore, removing the grain harvest removes most of the N and P, but straw management has a greater effect on the nutrient balance of the other nutrients. Potassium (K) is of critical concern because of the amount required by the crop. If straw is continually removed from the field, K deficiencies will probably occur. This process is accelerated if farmers apply N and P without K, as N and P inputs will initially increase yields; however, this also results in greater K uptake, which will lead to K deficiencies in the long term. The process is further accelerated in the irrigated rice system, in which farmers apply more nutrients (N and P) and crop twice a year. As noted previously, this may be the reason K deficiencies are more common in the irrigated rice areas than in the rainfed areas (Figs. 10 and 13).

Nitrogen and P are the primary limiting nutrients in most soils; however, most residues are low in N and P (Tables 8 and 9). Therefore, to increase productivity, nutrient inputs, particularly N and P, are required. The role of residues in the rice system will be discussed in greater detail later (see "Nutrient management" section).

Table 9. Nutrient concentration of some on-farm residues.

Residue	Nutrient						
	N (%)	P (%)	K (%)	S (%)	Ca (%)	Mg (%)	Mn ($\mu g\ g^{-1}$)
Rice straw	0.32	0.04	0.79	0.10	0.39	0.17	884
Rice husks[a]	0.43–0.55	0.03–0.08	0.17–0.87	0.05	0.07–0.15	0.03	116–337
FYM[b]	0.5–1.0	0.12–0.17	0.22–0.26	na[c]	na	na	na
Cattle dung[b]	0.35	0.11	0.09	na	na	na	na
Cattle urine[b]	0.80	0.02	0.26	na	na	na	na

[a]Juliano and Bechtel (1985). [b]Uexkull and Mutert (1992). [c]na = not available.

Nutrient budget for lowland systems. Simple nutrient budgets were developed for both the rainfed and irrigated lowland rice systems using assumptions based on current fertilizer and residue management practices. The assumptions are: In the rainfed lowlands, yields are 2.4 t ha^{-1}; the harvest index is 0.4; fertilizer inputs are 18.5, 8.1, and 0.9 kg ha^{-1} for N, P, and K, respectively (based on data from Pandey and Sanamongkhoung 1998); and all the grain and straw are removed (because of harvest operations, grazing, or burning). In the irrigated environment, yields are 3.5 t ha^{-1}; the harvest index is 0.4; fertilizer inputs for each crop (both wet and dry season) are 78, 8.6, and 0 kg ha^{-1} for N, P and K, respectively (approximate amount used based on informal surveys); and all the grain and half of the straw are removed and the remaining stubble is burned, resulting in a loss of all the N, although the P and K remain in the ash. The grain and straw nutrient concentration was in each case based on data in Table 8. There was no estimate of losses apart from those removed by the crop. As indicated above, N losses are usually as high as 50%.

In the rainfed lowland system, N and K are both negative, suggesting a nonsustainable system. Potassium is of special concern as almost 34 kg K ha^{-1} are removed annually (Table 10). In coarse-textured soils that are prevalent in Laos, K deficiencies are likely to increase, especially with the increased use of N and P fertilizers that have increased yields (and K uptake) in the short term. The P balance is positive, as farmers tend to overapply 16-20-0 because it is the cheapest fertilizer available. Research examining the fate of residual P in these soils indicates that, at the application rates typically used by farmers, soil P will likely build up (see the section on "Long-term P management").

In the irrigated rice system, N and P are both positive (Table 10). However, if a loss of 50% of the N by leaching, denitrification, NH_3 volatilization, etc., is accounted for, then the actual N balance is close to zero. The major concern for the irrigated environment is K. Assuming that two crops of rice are grown annually, there will be a net removal of more than 60 kg K ha^{-1}. On the basis of Table 7, approximately 14 kg K ha^{-1} are applied in the irrigation water during the dry season (assuming an application of 1,000 mm of water). Assuming that half of this amount is during the

Table 10. Annual N, P, and K nutrient balances for rainfed and irrigated (two crops per year) lowland rice systems in Laos (for assumptions[a] used, see below).

Ecosystem	Inputs (kg ha^{-1})			Losses (kg ha^{-1})			Balance (kg ha^{-1})		
	N	P	K	N	P	K	N	P	K
Rainfed lowland	18.5	8.1	0.9	29.8	5.9	34.4	–11.3	2.2	–33.5
Irrigated lowland	156	17.2	0[b]	89	15.4	61	67	1.8	61

[a]Assumptions: The grain and straw nutrient concentrations were in each case based on data in Table 8. *Rainfed lowland system:* yields are 2.4 t ha^{-1}; harvest index is 0.4; fertilizer inputs are 18.5, 8.1, and 0.9 kg ha^{-1} for N, P, and K, respectively; all the grain and straw are removed. *Irrigated lowland system:* yields are 3.5 t ha^{-1}; harvest index is 0.4; fertilizer inputs for each crop (both wet and dry season) are 78, 8.6, and 0 kg ha^{-1} for N, P, and K; all the grain and half of the straw are removed and the remaining stubble is burned, resulting in a loss of all the N, although the P and K remain in the ash. [b]K is available in irrigation water at varying amounts: see Table 7 and discussion related to Table 10.

wet season (when less irrigation water is applied), a total of 21 kg K ha^{-1} are applied annually in irrigation water. This still represents a negative balance of about 40 kg K ha^{-1}. Given the current nutrient and residue management practices and the recent increase in irrigation area and N and P fertilizer use and the low nutrient reserves in these primarily coarse-textured soils, K deficiencies will probably become a greater problem in the irrigated systems.

Nutrient management

Nutrient management will focus on the rainfed rice system as this has been the focus of most of the research. From a nutrient management perspective, the irrigated and rainfed systems are managed differently because of higher risk in the rainfed environment, especially from drought. Therefore, nutrients are usually applied at suboptimal levels since farmers aim to increase yields without undue risk. The objective is not to achieve optimum yield as may be the case in the irrigated environment.

Nursery management

Transplanted rice is the predominant method of crop establishment in Laos in both the rainfed and irrigated environments. Good nutrient management starts in the nursery or seedbed. The objective of nutrition management in the nursery is to obtain healthy and vigorous seedlings for transplanting. Such seedlings will withstand transplant shock better, be better able to withstand initial drought following transplanting, and produce a higher yield at harvest.

Research has been limited on rice nursery management in Laos; however, on the basis of research conducted elsewhere (CIAP 1995) and the limited work in Laos, a good recommendation can be made. The nursery should receive 50 kg of manure plus 1 kg of 16-20-0 per 100 m^2. The manure should be applied and incorporated during seedbed preparation. The 16-20-0 fertilizer should be applied and incorporated with the manure or broadcast 10 to 15 d after sowing the seed when there is standing water in the nursery. It is not advisable to apply N within 1 wk of when the seedlings will be pulled for transplanting. This causes rapid growth, resulting in weak stems that break when they are pulled from the soil.

Residues

Efficient and sustainable farming systems require efficient nutrient cycling, including nutrients stored in on-farm residues such as rice straw, rice husks, and manure. The current management and nutrient content of on-farm residues have already been discussed (under “Nutrient budgets”). Recycling residues has several potential advantages. First, residues contain nutrients commonly not found in inorganic fertilizers such as micronutrients. Second, the efficiency of inorganic fertilizers may be improved with the combined use of inorganic and organic amendments such as residues. Third, continual use of residues may lead to a gradual increase in soil organic matter. Since 1998, several experiments have evaluated the role of residues in lowland rice farming systems. These are summarized below.

Rice response to residues. To evaluate whether residues improve fertilizer-use efficiency, two studies were conducted at each of two locations during the 1998 and 1999 wet seasons. The residues evaluated were rice straw, rice hulls, and farmyard manure (FYM). The objective of the 1998 study was to determine whether or not residues in combination with N improve fertilizer N-use efficiency. The experiment was conducted in Vientiane and Saravane (Khongsedon District) provinces. The experiment had four residue treatments (no residue control, manure at 2.6 and 5.2 t ha^{-1}, and rice husks at 1.3 t ha^{-1}—all weights on a dry weight basis) with and without 60 kg N ha^{-1}. Phosphorus and K were applied to all treatments to ensure that these nutrients were not limiting. In 1999, a similar study was conducted in Champassak and Saravane (Saravane District) to evaluate the effect of residues on fertilizer-use efficiency (as opposed to N-use efficiency). The experiment had four residue treatments (manure, rice husks and straw, each at 2.0 t ha^{-1} on a dry weight basis, and a control) with and without fertilizer (60, 13, and 18 kg ha^{-1} of N, P, and K, respectively). Soils at the three sites in the south (Saravane and Champassak) were low in organic C and N and available P and K, whereas the soil in Vientiane was more fertile (Table 11). Fertilizer- or N-use efficiency was evaluated on the basis of agronomic efficiency (AE), which is calculated as follows:

$$\text{AE} = \frac{\text{Yield increase in response to fertilizer or N (kg ha}^{-1}\text{)}}{\text{Amount of fertilizer or N applied (kg ha}^{-1}\text{)}} \quad (2)$$

In the 1998 study, yields increased by 0.9 (AE = 15 kg kg^{-1}) and 1.4 t ha^{-1} (AE = 23 kg kg^{-1}) in Vientiane and Saravane, respectively, in response to fertilizer N alone (Fig. 14). Yield increases from residues alone ranged from 12% to 35%, with the response to residues being greater in Vientiane than in Saravane. On average, yields increased by 0.3, 0.4, and 0.7 t ha^{-1} in response to rice husks and 2.6 and 5.2 t ha^{-1} of FYM, respectively. In Vientiane, the interaction between residues and N was not significant, suggesting that the benefits of residues and N fertilizer were additive. However, Saravane showed a significant but negative interaction. In this case, there was no benefit of residues for grain yield if N fertilizer was already applied.

Table 11. Soil properties from on-farm residue experiments conducted in 1998 and 1999 wet seasons.

Location	Year	Soil texture	Olsen P ($mg\ kg^{-1}$)	Exch K ($cmol\ kg^{-1}$)
Vientiane	1998	Loam	1.7	0.082
Saravane	1998	Silty loam	1.1	0.077
Champassak	1999	Sandy loam	1.1	0.035
Saravane	1999	Silty loam	1.1	0.085

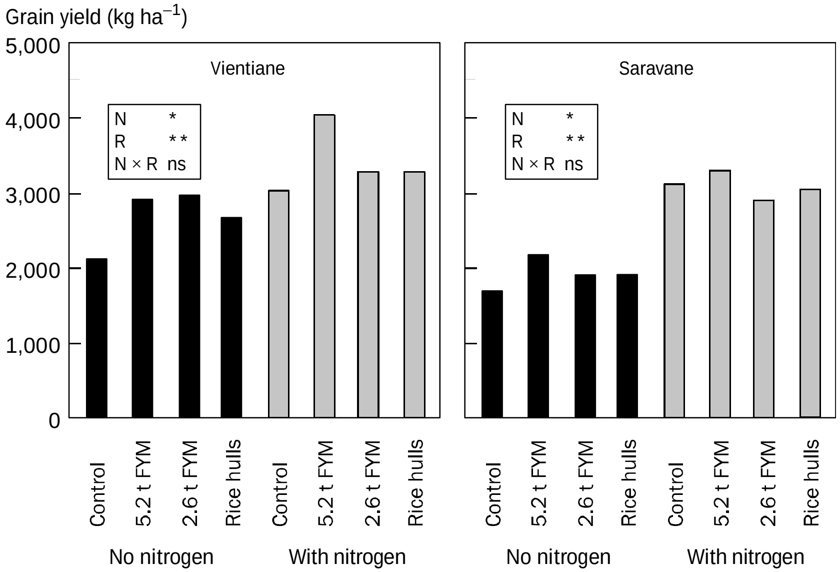


Fig. 14. Rice grain yield response to the application of inorganic N (60 kg N ha^{-1}) and residue (rice husks and farmyard manure, FYM). * and ** indicate a significant difference at P = 0.05 and 0.01, respectively. N = nitrogen, R = residue.

In the 1999 study, the application of fertilizer alone increased yields at both sites by 134% and 107% in Champassak and Saravane, respectively, whereas additions of residues alone increased yields by approximately 50% at both sites (Fig. 15). The greater response to fertilizer and residues in 1999 versus 1998 is probably because the response is due to a combination of N, P, and K as opposed to only N in 1998. Champassak showed a significant but negative interaction between residues and fertilizer treatments, similar to that observed in the 1998 Saravane study. The 1999 Saravane study showed a positive interaction between fertilizer and residue treatments. In this case, manure, applied with inorganic fertilizers, increased yields by 1.4 t ha^{-1}, suggesting a synergistic benefit from manure and inorganic fertilizer.

Results of these studies showed that commonly available on-farm residues applied alone and at realistic rates can increase yields by up to 50% and that modest rates of inorganic fertilizer applied alone can increase yields by more than 100%. There was limited evidence that residues improved fertilizer-use efficiency in the first year, as only one case showed a positive interaction between residues and fertilizer applications (Fig. 15-Saravane). In fact, two of the sites (Fig. 14-Saravane and Fig. 15-Champassak) showed a significant negative interaction, indicating that the benefits of residues are not apparent when they are applied with inorganic fertilizer. These data are in contrast to what has been observed on soils in northeast Thailand.

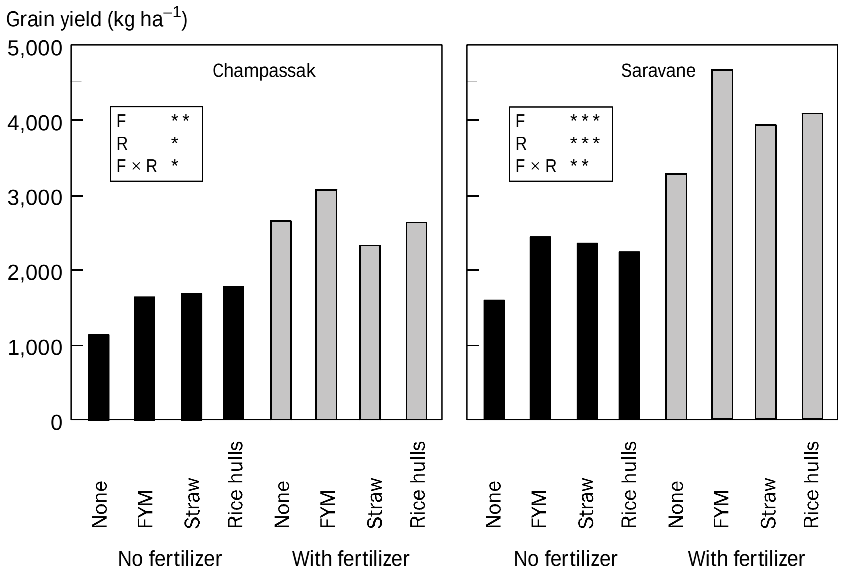


Fig. 15. Grain yield response to on-farm residues (2 t ha^{-1} on a dry weight basis) with and without inorganic fertilizer. The inorganic fertilizer was applied at 60-13-17 kg ha^{-1} of N, P, and K, respectively. *, **, and *** indicate a significant difference at $P = 0.05$, 0.01, and 0.001, respectively. F = fertilizer, R = residue.

Willett (1995) and Ragland and Boonpuckdee (1988) reported that there is no response to inorganic fertilizers without also applying organic amendments and vice versa. The Lao soils we evaluated usually showed a good response to both residues and inorganic fertilizers applied alone.

The role of residues in lowland rice farming systems. Improved and sustained rice productivity in cash-poor economies requires a balanced nutrient management program that involves the efficient use of inorganic fertilizers and recycling of on-farm residues. As noted above, realistic residue application rates can increase yields by up to 50%. Since on-farm residues are low in N and P, the most limiting plant nutrients, large yield gains will not be possible with residues alone. For poor farmers, however, residue applications may be a viable alternative that provides moderate yield increases.

Furthermore, these experiments have evaluated only the immediate effect of residues on rice yields. Based on the nutrient budget calculations (see section on "Nutrient budgets"), the role of residue management in these systems will be to maintain the inherent soil fertility and return nutrients that are not available in the commercial fertilizers currently available. Farmers now use primarily N- and P-containing fertilizers because K-containing fertilizers are either not available or are expensive and little on-farm residue is returned to the field. Although such nutrient management practices may result in some short-term yield gains, there will be a net negative effect on the soil nutrient balance, which will lower the productivity of these systems in the long term. The situation is exacerbated by the fact that most soils are coarse- textured and low in nutrient reserves.

Despite the benefits of using residues, farmers often raise concerns regarding their use. First, collecting residues is difficult. Some are bulky (i.e., straw) and require extra effort to move them around. Rice hulls are usually easy to obtain and transport but they are also bulky. Manure is difficult to collect because animals are free-grazing. Penning animals near the house or tying them in the fields would help but this requires additional labor.

Second, residues are difficult to incorporate. This is particularly true of rice straw. Farmers typically say that the straw clogs up farm implements, thus making land preparation more tedious. Applying straw early, before the first land preparation, will allow the first rains to break down the straw, making it easier to incorporate.

Finally, crop yellowing is commonly observed during the first few weeks following transplanting when straw is incorporated. This is due to N immobilization, causing N deficiencies early during crop growth. This N is usually available later during crop growth and, in systems in which suboptimal N rates are applied, this early season N deficiency has not been shown to reduce final yields. In fact, the experiments evaluated above indicate that final yields are higher when straw is applied.

Green manures

Crop demand is higher for N than for any other nutrients. Green manure (GM) technology has often been proposed as a means for farmers to meet their crop N demands. Green manures are usually legumes that can obtain their N requirement from atmospheric N (the air we breathe is 80% N) by the process of biological nitrogen fixation. Biological N_2 fixation is possible because of the symbiotic relationship between the legume and a soil bacterium (*Rhizobium*, or rhizobia). The rhizobia provide the plant with N while the plant provides carbohydrates for the rhizobia. Rhizobia are usually located in nodules on the roots; however, in some legumes the nodules are on the stem. The N accumulated by the legume can be available to the following crop and help provide some or all of the crop's N requirement. The potential of various GM species and their management have been evaluated since 1991.

Potential green manure crops. Potential prerice GM crops were assessed from 1991 to 1997 in Vientiane. From 1991 to 1993, *Sesbania rostrata*, Sunn hemp (*Crotalaria juncea*), mungbean (*Vigna radiata*), grain cowpea (blackbean, *V. unguiculata*), and vegetable cowpea (*V. unguiculata*) were evaluated. The studies continued in 1994 through 1997, but Sunn hemp and cowpea were replaced by *S. aculeata* and *Aeschynomene afraspera* (Fig. 16).

Susceptibility to saturated soil conditions was the primary factor determining the performance of these potential GMs. The performance of the grain legumes (cowpea, mungbean, and blackbean) and Sunn hemp was good in years when the soil did not become saturated with water. *Sesbania rostrata*, *S. aculeata*, and *A. afraspera* (stem-nodulating legumes), on the other hand, performed well under both saturated and

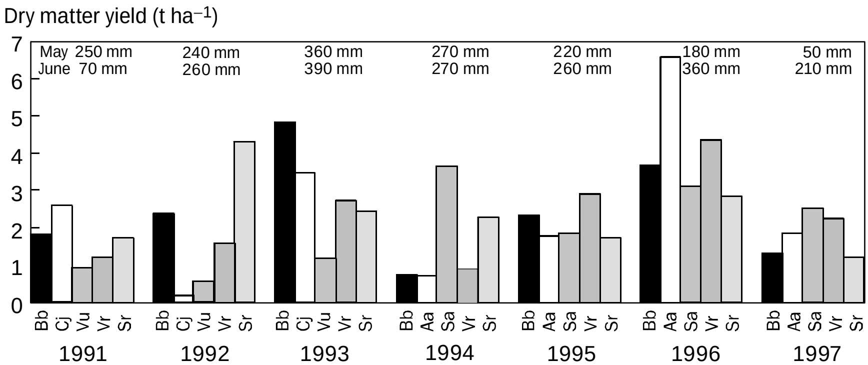


Fig. 16. Dry matter yield of various green manures [*Sesbania rostrata* = Sr, Sunn hemp (*Crotalaria juncea* = Cj), mungbean (*Vigna radiata* = Vr), blackbean (Bb), cowpea (*V. unguiculata* = Vu), *S. aculeata* (Sa), and *Aeschynomene afraspera* = Aa] grown in Vientiane Municipality from 1991 to 1997 in the wet season. Rainfall for May and June is given above the corresponding year.

nonsaturated soil water conditions. Potential GMs need to be tolerant of saturated soil to be effective in this system. Of the two grain legumes that were kept in the experiment (on account of being more tolerant of saturated soil conditions), blackbean generally outperformed mungbean. One of the potential benefits of using grain legumes as a GM is the possibility of an economic harvest of vegetable pods before the crop is incorporated into the soil. However, the duration of varieties used in these studies was too long to achieve such a harvest. Also, if such a harvest were possible, the N contribution to the following crop would be reduced because much of the N stored within a plant is in the developing pods or grain.

Green manure management. Green manures need to be sown approximately 2 mo before the expected date of transplanting. This usually coincides with the start of the first rains in late April to early May. The soil needs to be tilled and a smooth seedbed prepared. The seed is broadcast along with fertilizer and then the seeds are raked into the soil surface. After 50 to 60 d and at least 1 wk before transplanting, the GM should be cut and tilled into the soil.

GM legumes are highly dependent on an adequate P supply. Most of the GM research in Laos has been conducted in southern Laos, where soils are P-deficient. An application of P is usually required to obtain good GM growth and nitrogen fixation. Typical responses to P on these soils are shown in Figure 17. The P requirement of GM on sandy soils is usually about 19 to 26 kg P ha^{-1} (45 to 60 kg P_2O_5 ha^{-1}). When no P is applied, *S. rostrata* dry weight biomass is less than 0.5 t ha^{-1} and the N content is less than 10 kg ha^{-1}. With adequate P, the dry weight biomass is typically from 1.5 to 2 t ha^{-1} and the N content is from 30 to 40 kg ha^{-1}. Higher green manure biomass and N content are possible; however, because of the erratic nature of the

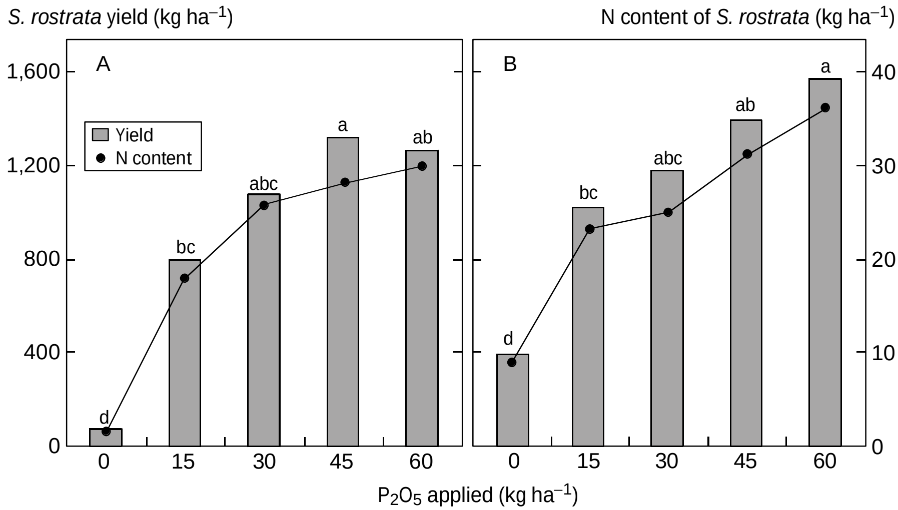


Fig. 17. The yield response and N content in the aboveground biomass (kg ha^{-1}) of *Sesbania rostrata* at various applications of P_2O_5 (P = P_2O_5 × 0.43) at sowing in Champone District, Savannakhet Province (left) and Phonethong District, Champassak (right).

early season rains, drought often limits productivity. Becker et al (1990) reported biomass yields exceeding 8 t ha^{-1} that contained more than 150 kg N ha^{-1} under optimal conditions.

Rice response to GM. Several studies have evaluated the response of rice to GM. However, these will not be dealt with in detail. A typical response of rice to GM can be seen from a study conducted in Vientiane Municipality during the 1997 wet season on a deep sandy soil (Fig. 18). In response to urea-N, rice grain yield increased almost linearly from 0 to 90 kg urea-N ha^{-1}. Maximum yields of 3.7 t ha^{-1} were obtained in response to 90 kg urea-N ha^{-1}. *S. rostrata* and *A. afraspera* alone increased rice yields by 1.3 and 0.6 t ha^{-1}, respectively, which was roughly equivalent to 30 to 60 kg urea-N ha^{-1}. Adding rice straw (1.5 t ha^{-1}) to *A. afraspera* increased rice yields by 0.7 t ha^{-1} but had no effect when applied to *S. rostrata*. These results are similar to those reported elsewhere, in which straw added to GM residues slowed N mineralization, reduced N losses, and improved N-use efficiency. The difference in results between the two green manures is most likely because of the higher C:N ratio of *S. rostrata*. In our study, *S. rostrata* biomass N concentration (1.86%) was lower than that of *A. afraspera* (2.13%), suggesting a higher C:N ratio. Becker et al (1990) also found that *S. rostrata* had a higher C:N ratio than *A. afraspera*. The higher C:N ratio results in slower N mineralization and an N supply that is more synchronous with crop demand.

Considerations. It is often suggested that GMs will increase soil organic matter. Although the Lao studies have not investigated this, other studies from Thailand sug-

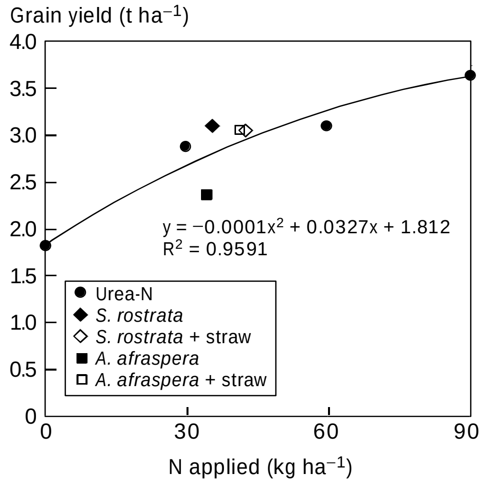


Fig. 18. The grain yield response of rice to urea-N and N supplied by the green manure crops *Sesbania rostrata* and *Aeschynomene afraspera*. Both green manure crops were evaluated with and without rice straw.

gest that incorporation of residue with fast breakdown rates (such as the stem-nodulating legumes investigated here) has not led to increases in soil carbon (Naklang et al 1999). The C:N ratio of these green manures is low and most of the N and C is mineralized in the first season. Other residues with higher C:N ratios such as straw, rice hulls, leaves, and more woody legumes have led to soil organic matter increases over time. However, the immediate benefits of GMs are that they can lead to increases in rice yield because of the additional N input. Despite these benefits, farmers are often reluctant to adopt the technology for several reasons:

- Seeds are difficult to produce or purchase.
- Land preparation is difficult, especially using buffalo.
- Crop establishment can be difficult.
- Cutting the GMs and incorporating them are difficult and time-consuming and this occurs at transplanting time when labor demand is especially high.
- The P requirement of GMs is typically higher than for rice. So, although there may be savings in terms of the N economy, this benefit may be lost because of having to add additional P fertilizer. In most soils in the south, the P requirement for GMs is from 19 to 26 kg P ha^{-1} (45 to 60 kg P_2O_5 ha^{-1}), in contrast to rice, which requires only 6 to 13 kg P ha^{-1} (15 to 30 kg P_2O_5 ha^{-1}) on similar soils (Fig. 19). In fact, on some soils, rice does not respond to P additions but the GMs do. At least two factors cause the higher P requirement of GMs. First, P is less available under aerobic conditions, which are common during

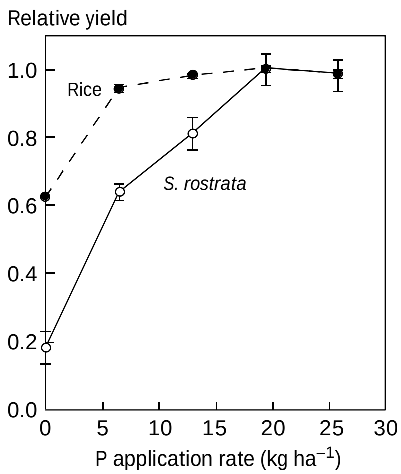


Fig. 19. Relative yield (relative to maximum yield) of *Sesbania rostrata* and rice in response to P on coarse-textured soils. Error bars represent one standard deviation.

the GM growth period, than under anaerobic conditions, which prevail during most of the rice-growing season. Second, legumes tend to have a higher P requirement than other crops because of the energy requirement of biological nitrogen fixation.

Green manure technology should not be broadly recommended on the P-deficient soils of southern Laos where fertilizers are readily available. In the north, where N deficiencies are common, P deficiencies are less, and fertilizers are less available, GM technology may be feasible and economical; however, this has not been evaluated.

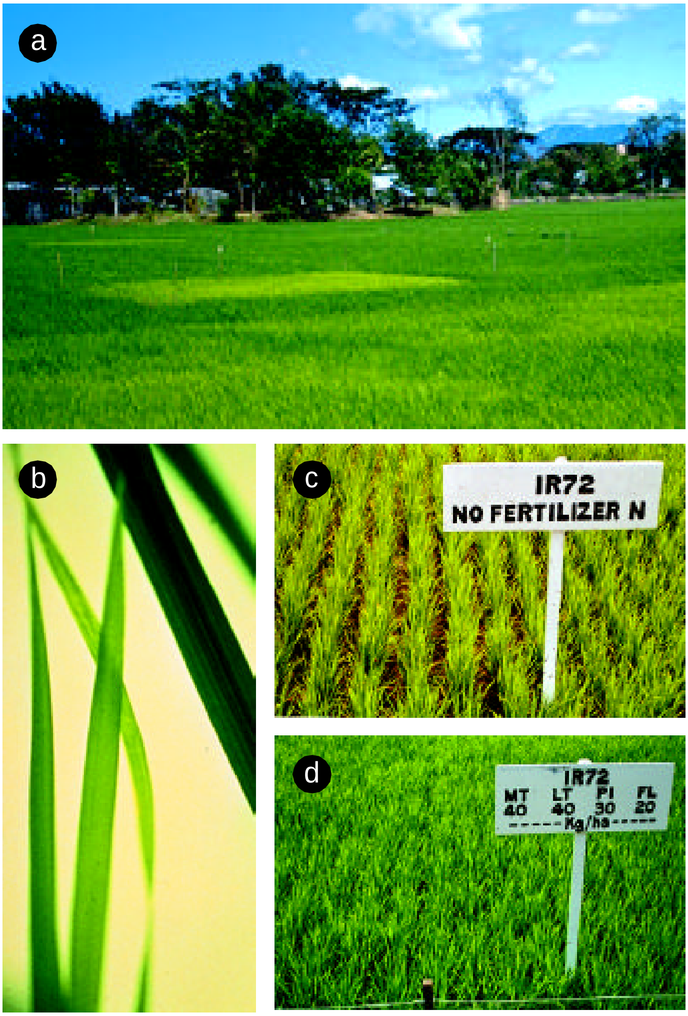
Inorganic fertilizers

Improved productivity will usually require the addition of N and P to lowland rice soils. As discussed earlier, organic fertilizers and residues are usually low in these nutrients and, although GMs may be high in N, they usually require P to obtain high biomass. Therefore, inorganic fertilizers are required for increased productivity.

The most common commercially available inorganic fertilizers in Laos are urea (46-0-0) and 16-20-0. These two fertilizers made up approximately 75% of the 1999 fertilizer imports (Table 3). The compound fertilizer 15-15-15 accounted for an additional 13% but few rice farmers use this on rice as it is 10% to 15% more expensive than 16-20-0.

Fertilizers are an expensive investment but, with good management, they can give good returns. Results averaged across 37 sites show that yields in the south were

Nitrogen deficiency

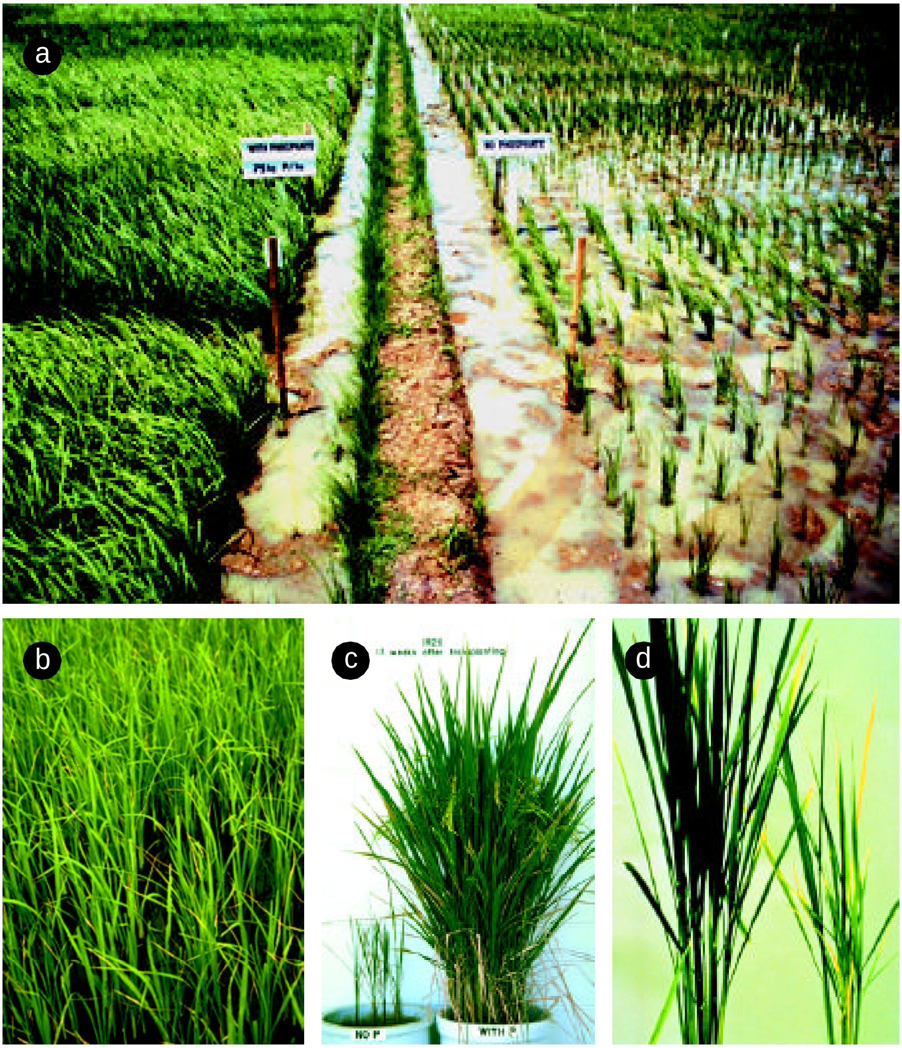


(a) In the omission plot where N has not been applied, leaves are yellowish green. (b) In N-deficient plants, leaves are smaller. (c) Tillering is reduced where N is deficient. (d) Tillering is greater where N fertilizer has been applied.

B. Linquist

An experiment in Sayaboury examining the response of different varieties to N fertilizer.

Phosphorus deficiency



(a) Tillering is reduced where P is deficient. (b) Even under less pronounced P deficiency, stems are thin and spindly and plant development is retarded. (c), (d) Plants are stunted, small, and erect compared with normal plants.

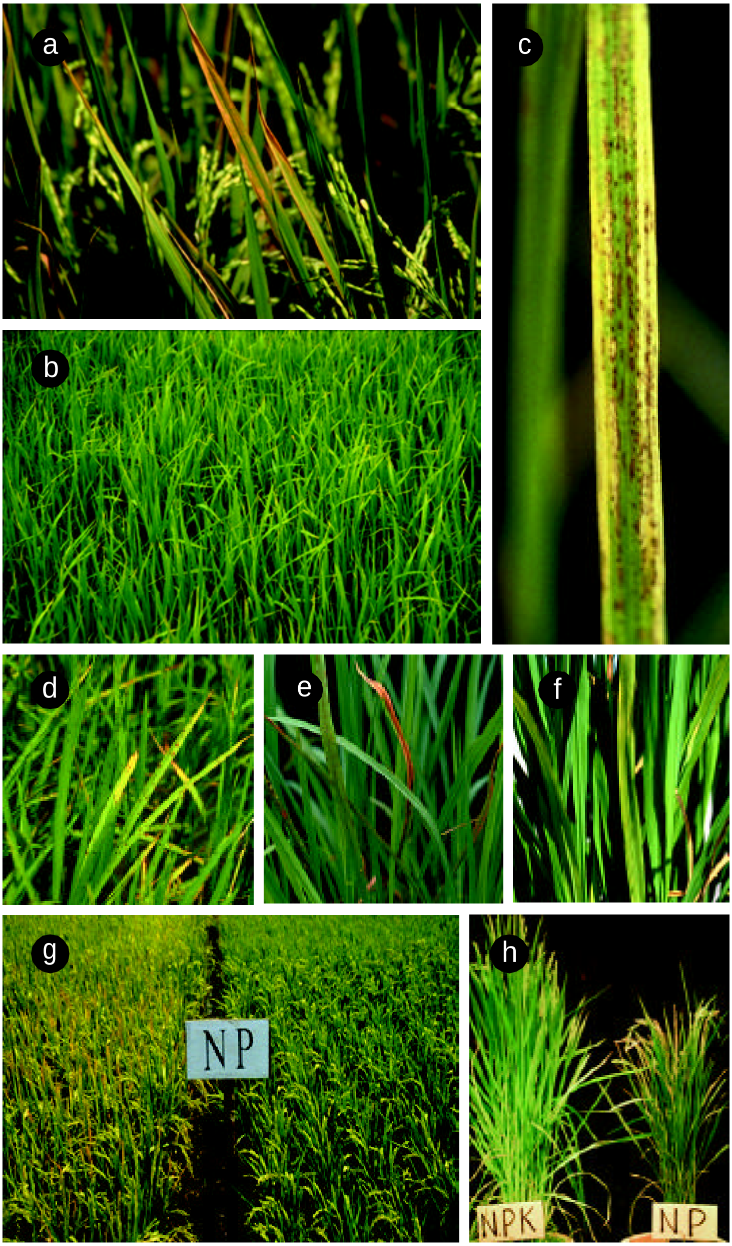
B. Linquist

Sesbania rostrata with (foreground right) and without (foreground left) P fertilizer.

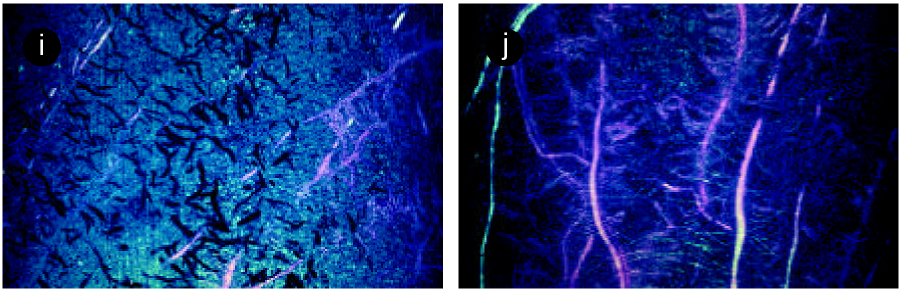
B. Linquist

Phosphorus deficiency is a common problem in many soils. Rice that received P is on the left and on the right the rice received no P.

Potassium deficiency



(a), (b), (c) Leaf margins become yellowish brown. (d), (e) Dark brown spots appear on the leaf surface. (f) Leaf bronzing is also a characteristic of K deficiency. (g) K-deficiency symptoms are more likely to occur in hybrid rice (on the left) than in modern inbred varieties (on the right). (h) Rice yields are often constrained by unbalanced fertilization where the response to N and P is constrained by insufficient K. (i) K-deficient rice plant roots may be covered with black iron sulfide. (j) In comparison, healthy rice roots are covered with red-brown iron oxide.

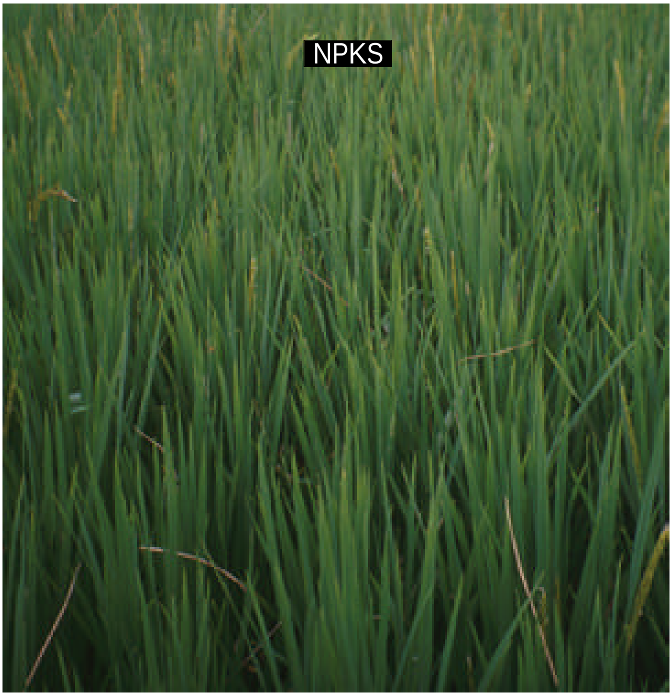


In Sayaboury, K deficiency is a problem. K-deficiency symptoms are shown in the foreground.

B. Linquist

Sulfur deficiency

(a), (b) The leaf canopy appears pale yellow because of yellowing of the youngest leaves, and plant height and tillering are reduced. (c), (d) Chlorosis is more pronounced in young leaves, where the leaf tips may become necrotic.



Sulfur deficiency in Sekong (Thateng District). Note the yellower color and fewer tillers in the "–S" plot.

Iron toxicity

(a) Tiny brown spots developed on the leaf tip and spread toward the leaf base. (b) Symptoms first appear on the older leaves. (a), (c) Under severe Fe toxicity, the whole leaf surface is affected. (d) Leaf bronzing occurs in K-deficient rice plants, which are unable to maintain sufficient root oxidation power (left).

B. Linquist

Typical lowland rice area in southern Lao PDR.

J. Schiller

Typical lowland rice area in northern Lao PDR.

Nursery and transplanting

B. Linquist

Rice nursery in foreground with fields ready for transplanting in the background.

B. Linquist

Transplanting rice.

J. Schiller

Farmers grow several different varieties on their farms that may mature at different times.

J. Schiller

At harvest, farmers cut the rice panicles off the main stem and let them dry in the field for a couple of days before threshing.

B. Linquist

Harvesting rice.

B. Linquist

Mechanical threshers are becoming more popular. Rice panicles are moved near the road for threshing. The remaining straw is often burned in the ditch beside the road.

B. Linquist

Rice hulls applied to lowland rice fields before land preparation.

B. Linquist

Farmer applying fertilizer to his field.

J. Schiller

During the dry season, animals graze rainfed lowland rice fields.

B. Linquist

Straw saved to feed livestock.

Experiments

B. Linquist

Nutrient deficiencies are first identified using nutrient omission experiments such as the one shown here.

B. Linquist

An experiment in Savannakhet examining the effects of residual P.

B. Linquist

Evaluation of *Sesbania rostrata* and *Aeschynomene afraspera* as potential green manures.

B. Linquist

Evaluation of postrice legume crops.

B. Linquist

Comparing inorganic and organic fertilizers.

only 2.0 t ha^{-1} without fertilizer, but, with modest fertilizer applications (60, 13, and 17 kg ha^{-1} of N, P, and K, respectively), yields increased to 3.5 t ha^{-1} (Fig. 9), a 75% increase. In the north, yields without fertilizer were 2.6 t ha^{-1} and increased to 3.5 t ha^{-1} with the same fertilizer additions (a 40% increase).

Good returns on fertilizer investments require that nutrient recommendations be balanced and that the fertilizer be applied properly and at the right time, and require the use of improved varieties and good crop management (i.e., controlling pests, weeds, and diseases). The role of improved varieties is discussed briefly in the section on N. Crop management is not discussed in detail (see the last section, "Nutrient management recommendations," for some discussion), but, if weeds and pests are not controlled, rice yields may be reduced or the crop completely destroyed, resulting in poor nutrient-use efficiency.

In the following sections, the primary limiting nutrients and how to correct the deficiencies and improve fertilizer efficiency will be discussed separately. The primary focus is on N and P, the two most limiting nutrients, but K and S are also discussed. In a later section ("Nutrient management recommendations"), an integrated nutrient management recommendation is provided for various soils on the basis of fertilizer availability. This section brings together what has been discussed in relation to nutrient balances, on-farm residues, and inorganic fertilizers.

Most rainfed lowland rice farmers are poor and risk-averse. Therefore, the research conducted on nutrient management has focused on improving the efficiency of fertilizer. There are many ways to evaluate efficiency but, for the purposes of this book, we will use AE (see equation 2). As an example, if a farmer applies 60 kg N ha^{-1} to rice and this results in a yield increase of 1 t ha^{-1}, the AE of applied N is 16.7 kg kg^{-1} (1,000 kg grain 60 kg^{-1} N). This incremental efficiency from applied fertilizer is proportional to the cost-benefit ratio from investment in fertilizer inputs (Cassman et al 1996).

Nitrogen

Nitrogen, limiting on most lowland rice soils in Laos, is required in higher quantities than any other nutrient. For every 1,000 kg of yield, the required crop uptake is about 15 kg (Table 8). Of the main plant nutrients, it is also the most prone to losses. Leaching, runoff, denitrification, and volatilization can all result in significant losses of N. Therefore, the primary focus of N management research conducted in Laos has been to improve N-use efficiency.

The current N recommendation for improved varieties in the rainfed lowland environment (see the section on "Nutrient management recommendations" for details) is 60 kg N ha^{-1} applied in three splits at transplanting, active tillering (AT), and panicle initiation (PI). The N rate is based on N response experiments and it accounts for farmer risk. To evaluate the response of rice to N, experiments were conducted at 20 sites around Laos (12 in southern Laos and 8 in northern Laos) from 1993 to 1998. Nitrogen rates ranged from 0 to 90 kg N ha^{-1} or, in some cases, 0 to 120 kg N ha^{-1}. The N-responsive variety TDK1 was used in all studies. In both the north and the south, there was a good response to N up to 60 kg N ha^{-1} (Fig. 20). In the north, there

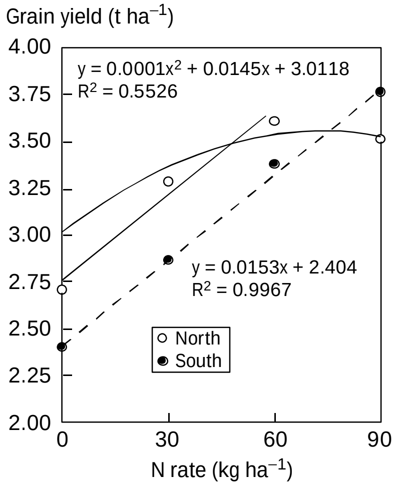


Fig. 20. The grain yield response of TDK1 to added N fertilizer in southern and northern Laos. The data represent means of 20 experiments (12 in the south and 8 in the north). The linear straight line for the northern points (0 to 60 kg N ha^{-1}) is added to illustrate that the responses to N in the north and south are parallel up to 60 kg N ha^{-1}.

was no further increase in yields with N inputs higher than 60 kg N ha^{-1}. In the south, on the other hand, the yield response was linear from 0 to 90 kg N ha^{-1} (in some studies that included a 120 kg ha^{-1} N rate, the response continued to be linear) and yields increased from 2.4 to 3.8 t ha^{-1}. Therefore, the recommendation of 60 kg N ha^{-1} provides insufficient N for optimal or maximum rice yields in most cases. Although higher yields may result from increased N inputs, the additional cost of inputs needs to be evaluated against the risks of crop loss from environmental factors or pests.

The AE of N applied using this recommendation (60 kg N ha^{-1} applied in three equal splits) was determined from 107 experiments conducted in Laos from 1991 to 1999 (32 in the north and 75 in the south). In all cases, improved varieties were used and P and K were applied at transplanting to ensure that these nutrients were not limiting. Sites adversely affected by drought, flooding, or insect damage were not removed from the analysis; therefore, a lack of response to N at a site may be due to an N deficiency or damage caused by pests or climatic factors. There was a significant N response ($P<0.05$) at 77% of the sites. The average AE across all sites in response to 60 kg N ha^{-1} was 14.9 kg kg^{-1} and ranged from 0 to 38 kg kg^{-1} (Table 12). If the experiments with crop failures are omitted from the analysis, AE in excess of 20 kg kg^{-1} is common, as will be seen in the following discussion.

Table 12. Agronomic efficiency of applied N fertilizer (AE = grain yield increase per unit applied N) averaged across 107 experiments conducted from 1991 to 1999.

Site division	Division description	Number of sites	AE (kg grain kg^{-1} N)
All		107	14.9
Location	North	32	14.5
	South	75	15.1
Yield in –N treatment	<1	5	13.8
(t ha^{-1})	1–2	43	15.4
	2–3	36	14.1
	>3	23	15.4

Further analysis of this data set indicated no difference in AE between northern (14.5 kg kg^{-1}) and southern (15.1 kg kg^{-1}) Laos. Analysis of a subset of these data (those sites that showed a significant response to applied fertilizer N and where soil data were available, 31 sites) indicated no relationship between AE and either clay or organic matter content (data not shown). A prominent feature of Lao soils is that they are coarse-textured (Fig. 8) and as such tend to have higher percolation rates than finer textured soils. In such cases, N is more susceptible to leaching losses and denitrification (because of the high probability of wetting and drying cycles in the rainfed environment) and lower AE would be expected. However, under the conditions in which the N was applied (three splits), differences in soil properties such as soil texture, organic matter, or indigenous N supply did not have an effect on AE. It is possible that, if all the N fertilizer had been applied at one time only, these differences in soil properties might have had a significant effect.

Research aimed at maximizing N-use efficiency has focused on identifying N-responsive varieties, application timing, and crop density effects.

Variety effect on N-use efficiency. Until recently, most of the rainfed lowland rice area was planted to traditional rice varieties. In a survey conducted in 1996 in southern Laos (Saravane and Champassak), Pandey and Sanamongkhoun (1998) reported that 79% of the rice area was planted to traditional varieties. However, the situation is changing rapidly, as in recent years there has been an increasing amount of improved varieties grown. Despite this shift, many farmers still grow traditional varieties on a portion of their land, perhaps because of preferences in taste or other grain qualities or to spread risk and labor demand. Given limited capital to purchase N, the efficiency of N applied to traditional and improved varieties needs to be investigated.

Results from nine studies conducted during the 1995 and 1996 wet seasons compared the response of traditional and improved varieties to fertilizer N. Five of the sites were in the south and four in the north. When no N was applied, traditional variety yields were similar to those of improved varieties (Fig. 21). In all cases, there was a positive yield response to N up to 60 kg N ha^{-1}; however, only in the south with the use of improved varieties was there a continued response to additional N inputs. The N response between traditional and improved varieties also varied, with a better

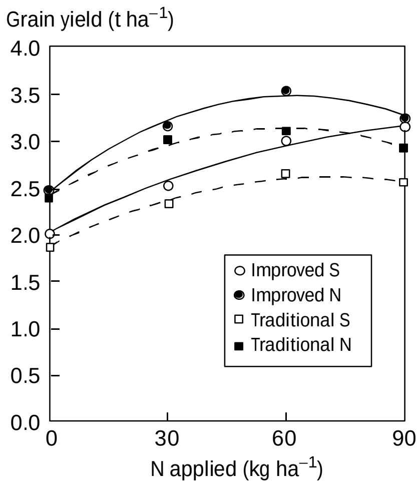


Fig. 21. The response of improved and traditional varieties to added fertilizer N in southern and northern Laos. The data represent means of 18 experiments (10 in the south and 8 in the north) conducted during the 1995 and 1996 wet seasons.

N response from the improved varieties. The AE of N at rates of up to 60 kg N ha^{-1} averaged 18.3 kg grain kg^{-1} N for improved varieties versus 15.0 kg grain kg^{-1} N for traditional varieties. Similar responses have been observed elsewhere and for different crops. These results suggest that, for resource-poor farmers, limited N resources should be applied to improved varieties rather than as a blanket application across all fields to maximize N-use efficiency.

Evaluation of improved varieties indicates that TDK1 is the variety most responsive to N. As an example, during the 1998 dry season, three experiments were conducted in southern Laos to compare the response of four recommended Lao glutinous varieties (TDK1, RD10, TDK3, and NTN1) to N (Fig. 22). N rates at all sites ranged from 0 to 120 kg N ha^{-1}. Combined analysis across sites in the south indicated significant variety and N effects and variety by site interactions. The average yield of TDK1 was significantly higher than that of the other varieties. When no N was applied, the yield of TDK1, averaged across sites, was 0.4 t ha^{-1} greater than the combined average of all the other varieties (2.6 vs 2.2 t ha^{-1}). At all three sites, TDK1 had the highest yields. Maximum yields for TDK1 averaged 0.7 t ha^{-1} more than the combined average of all the other varieties (5.1 vs 4.4 t ha^{-1}). The performance of the other varieties varied among sites. These observations are similar to those of the wet season, which indicates that TDK1 is generally superior to other varieties in productivity and N-use efficiency in the southern rice-growing regions of Laos under both low and high N conditions. Results from 10 N-by-variety trials conducted during the

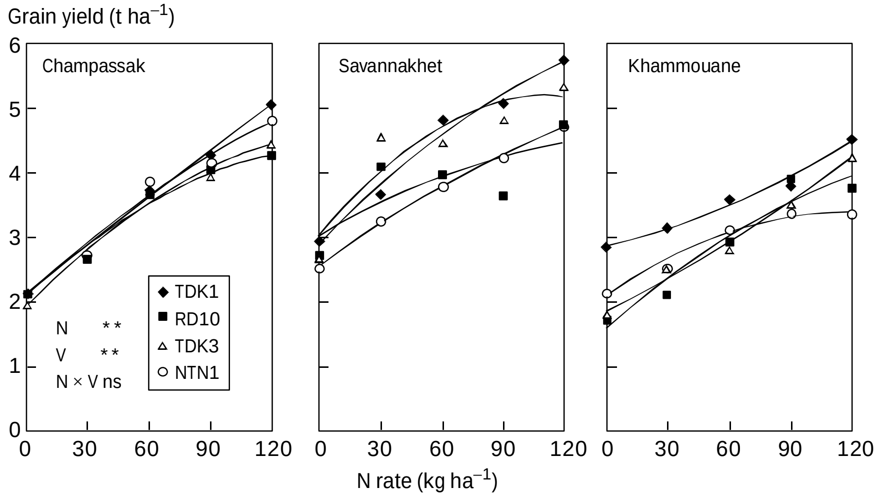


Fig. 22. The response of improved glutinous varieties to N at three sites during the 1998 dry season. * and ** indicate a significant difference at P = 0.05 and 0.01, respectively; ns = not significant.

wet season from 1994 to 1998 in southern Laos indicate that TDK1 performed better than or as good as the other varieties tested in nine of the studies (data not shown).

Fewer data are available for northern Laos. Although the data available suggest that TDK1 performs adequately during the wet season, local varieties have been shown to perform just as well. For dry-season production, temperatures are typically lower in the north (because of higher elevation) and suitable varieties are still needed.

Although we have indicated that TDK1 is a superior variety in response to N, variety selection for any location should consider other problems such as pests or diseases. For example, TDK1 is highly susceptible to gall midge attack and should not be used in areas where this insect is a problem.

Management (splitting the N recommendation). Improving the congruence of N supply and N demand should increase N-use efficiency by reducing N losses (Cassman et al 1996). This can be done by splitting the N requirement and applying N when crop demand for it is high. The effect of applying the entire N recommendation at once compared with applying it in splits was evaluated in 26 on-farm studies. There were four treatments: (1) all N applied at transplanting, (2) N requirement split equally between transplanting and 50 d after transplanting (DAT), (3) N requirement split equally among transplanting and 35 and 55 DAT, and (4) N requirement split equally among transplanting and 20, 40, and 60 DAT. In all cases, improved varieties were used. Results indicate that applying the N recommendation in three or more splits was superior to one or two splits (Table 13). Splitting the N recommendation three times, as opposed to applying all the N at transplanting, increased yields significantly by 0.37 t ha^{-1}. This corresponds to a 12% increase in yield and an improvement in AE

Table 13. Effect on grain yield of splitting the N rate. In all cases, 60 kg N ha^{-1} were applied. When the application was split, the doses were equal. Grain yields are averages from 26 experiments.

Number of splits	Timing of N applications	Grain yield (kg ha^{-1})
1	Transplanting	3,130 c
2	Transplanting and 50 DAT[a]	3,312 b
3	Transplanting and 35 and 55 DAT	3,496 a
4	Transplanting and 20, 40 and 60 DAT	3,405 ab

[a]DAT = days after transplanting. Grain yield means followed by the same letter do not differ significantly (P<0.05).

of 4.1 kg grain kg^{-1} N. These results are consistent with reports from elsewhere (Prasad and De Datta 1979, De Datta et al 1988) and form the basis for splitting the N requirement. Furthermore, for high-risk low-input systems, splitting the N requirement helps minimize risk in cases of crop failure during early vegetative growth because a large initial purchase of fertilizer is avoided.

Management (timing of the first N application). The recommended times for N application are at transplanting, AT, and PI; however, N application at these times may not be possible because of temporary flooding, no standing water, or no cash to purchase fertilizer. Therefore, it is important to define windows of opportunity during which N can be applied without a loss in efficiency. Several experiments have been conducted with the primary objective of determining these windows of opportunity for the first and last N application.

Recommendations typically call for the first N application to be incorporated into the soil just before transplanting. This puts the fertilizer N into a reduced soil layer and minimizes losses from denitrification. Farmers in general have not adopted this practice and prefer to make the first N application after crop establishment. Therefore, to determine whether such a recommendation is necessary, we compared the effect of incorporating N just before transplanting with applying N 1 d after transplanting in six replicated experiments. There was a good response to applied N at all sites, with yields increasing by 63% on average. However, there was no yield difference between the different methods of N incorporation (Table 14). Therefore, the current farmer practice of applying N following crop establishment seems reasonable.

Some researchers question the need for a basal application since transplanted rice suffers from physiological transplanting shock for 10 to 14 d after transplanting, during which time crop N demand is low. Fertilizer N applied at this time would not be readily taken up and would be prone to losses. Furthermore, N available from the mineralization of organic matter is greatest during the crop establishment phase and should be adequate to meet crop needs during the early growth stage, at least for soils with a high N status. However, Lao soils are inherently low in organic matter (Fig. 8) and the necessity of an early N application needed to be evaluated under such conditions. The timing of the first N application was evaluated in Laos across 15 sites (each site being a single replication). The first N application was made before transplanting or 1, 10, 20, or 30 DAT. In all cases, 60 kg N ha^{-1} were applied in three equal splits (20 kg N ha^{-1} each) the first time and then at 30 and 50 DAT. The exception was the treatment in which the first N application was made at 30 DAT. In this treatment, the N was applied in two equal splits (30 kg N ha^{-1} each) at 30 and 50 DAT. In all cases, the popular improved variety TDK1 was used. Analysis across sites and treatments shows that yields increased by 1.39 t ha^{-1} in response to N, corresponding to an AE of 23 kg grain kg^{-1} N (Table 15). There was no significant effect of the timing of the first N application on rice yields. Furthermore, there was no effect of soil organic matter or soil texture. These results suggest that either adequate N is available from N mineralization to provide N needs early during crop growth even at low organic matter or the crop is able to compensate for temporary N deficiencies early in crop growth. The latter case seems more probable since the rice crop displayed visual N-deficiency symptoms during early growth at most sites when the N was applied late.

Table 14. Comparison of incorporating the first N application before transplanting or applying the N after transplanting and not incorporating (based on results of six replicated experiments).

N treatment	Grain yield[a] (kg ha^{-1})
No N	2,451 b
N incorporated before transplanting	3,880 a
N applied 1 day after transplanting	4,120 a
Site	***
N treatment	***
Site × N	ns

[a]Grain yield means followed by the same letter do not differ significantly (P<0.05); *** indicates significance at P<0.001; ns indicates not significant.

Table 15. Effect of timing of the first N application on rice grain yields. Separate analysis was also conducted after separating the sites based on organic matter and clay content. Data represent the increase in yield (kg ha^{-1}) relative to a –N control.

Timing of first N application (DAT)[a]	All sites (n=15)	Organic matter <0.8% (n=6)	Organic matter >1.0% (n=9)	Clay content <12% (n=4)	Clay content >15% (n=11)
	Increase in grain yield (kg ha^{-1})				
0[b]	1,348	1,450	1,291	1,610	1,276
1	1,353	1,320	1,376	1,293	1,375
10	1,326	1,308	1,337	1,519	1,274
20	1,395	1,350	1,425	1,287	1,434
30	1,530	1,452	1,573	1,406	1,564
	ns	ns	ns	ns	ns

[a]DAT = days after transplanting. [b]Applied and incorporated before transplanting. [c]ns = not significant.

Under conditions of suboptimal N supply, these data suggest that early season N deficiencies can be compensated for by applying the N later.

These results indicate considerable flexibility in the timing of the first N application—any time between transplanting and 30 DAT. However, it is generally recommended that P fertilizer be applied early (Diamond 1985). Since P fertilizer in Laos is available only in compound fertilizers with N, N would need to be applied early as well.

Management (timing of the last N application). The timing of the last N application should ideally be at PI; however, late-season drought often forces farmers to delay this application. To evaluate the window in which the last N application is most efficiently used, seven replicated studies were conducted in the wet and dry seasons. In these experiments, we attempted to make the last N application at 50, 65, and 80 DAT (in the dry-season experiments, we also included 40 DAT). During the wet season, 60 kg N ha^{-1} were applied, whereas 90 kg ha^{-1} were applied during the dry season. In both cases, the N was applied in three equal splits. TDK1 was used in all studies and PI for TDK1 is roughly at 50 DAT; however, this can vary with location. Therefore, to standardize the timing across sites for analysis, we assumed PI to be 25 d before flowering (De Datta 1981). All of the application times were then made relative to PI rather than to the time of transplanting. To evaluate the data across sites, relative yield (relative to the highest yield at each site) was plotted against the time of the last N application (Fig. 23). The data indicate that delaying the last N application by more than 1 wk after PI results in yield declines. There does not appear to be a

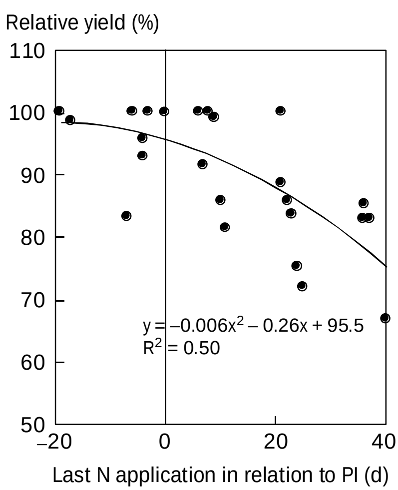


Fig. 23. Relative yield (relative to the highest yield at each site) in relation to the timing of the last N application. The X axis is the timing of the last N application relative to panicle initiation (day 0 is the day panicle initiation occurs).

negative effect of applying the N up to 20 d before PI. Therefore, farmers should not wait until PI to apply N, if conditions are favorable, but can apply it 2 wk before PI. If conditions are not favorable, the application can wait up to 1 wk after PI.

Ratio of N in each split. N-use efficiency can be increased by increasing the congruence between crop N supply and crop demand. As noted above, N demand is low during the early vegetative growth following transplanting and N from the mineralization of organic matter may be sufficient to meet early crop demand. Furthermore, crop demand is high during AT and PI, suggesting that more N is required during this period. Therefore, a study was conducted to compare the effectiveness of N applied in three equal splits (the current recommendation) with applying most of the N at AT and PI. The two treatments were N (60 kg ha^{-1}) applied in three equal splits at transplanting, AT, and PI or applied at 10, 25, and 25 kg ha^{-1} at transplanting, AT, and PI, respectively. The replicated experiment was conducted at six locations during the 1998 and 1999 wet seasons.

There was a good response to N in both treatments, with yields increasing by 1.42 t ha^{-1}, on average, in response to 60 kg N ha^{-1} (AE = 24 kg grain kg^{-1} N) (Table 16). When 83% of the N requirement was applied at AT or PI, yields were higher (0.53 t ha^{-1}) than when N was applied in equal splits. On average, AE increased by approximately 9 kg grain kg^{-1} N (from 19.3 to 28.1 kg kg^{-1}). Further examination of the significant interaction between N treatment and site indicated that at half of the sites the response to applying a greater portion of the N later during crop growth was greater than 0.4 t ha^{-1}, whereas, at the remaining sites, yields were similar for the two N management strategies. Importantly, no site had a negative effect of applying a greater portion of the N later during crop growth.

Hill spacing. Hill density is important in optimizing yields and N-use efficiency. Farmers typically transplant at about 16 hills m^{-2} (25 × 25 cm) during the wet season. Closer hill spacing is used during the dry season (25 to 44 hills m^{-2}, corresponding to hill spacing of 20 × 20 to 15 × 15 cm, respectively). Research conducted in both the wet and dry seasons indicates that higher hill density results in higher yields under

Table 16. The effect on grain yield of applying 60 kg N ha^{-1} in three equal splits (20 kg N ha^{-1} each) at transplanting (TP), active tillering (AT), and panicle initiation (PI) versus applying 10, 25, and 25 kg N at TP, AT, and PI, respectively. Data are the results of seven experiments conducted over two wet seasons.

Treatment: N applied (kg ha^{-1}) at TP-AT-PI	Yield (kg ha^{-1})	Agronomic efficiency (kg grain kg^{-1} N)
0-0-0	2,458 c	–
20-20-20	3,615 b	19.3
10-25-25	4,141 a	28.1
Site	***[a]	
N	***	
Site × N	***	

[a]*** indicates significance at *P*<0.001.

conditions in which N is not applied and in which N is applied (Fig. 24). Although increasing hill density results in higher yields, it may also predispose the crop to drought during a dry spell. Therefore, closer spacing should not be recommended on soils that are highly susceptible to drought, such as sandy soils on the upper terraces.

Phosphorus

Response to P. About 71% and 37% of the soils evaluated were P-deficient in southern and northern Laos, respectively (Fig. 10). In the south, P deficiencies can be so severe that there is no response to other nutrients unless P is applied. The severity of P deficiencies can vary from season to season depending on soil moisture. Where the soil remains flooded or saturated (anaerobic), P is more available than where the soil is aerobic (Ponnamperuma 1965).

Soil tests provide one method of identifying whether a soil is potentially P-deficient. The critical level of Olsen P was estimated using soil and crop response data from 29 sites. Soils with an Olsen P level above 5 mg kg^{-1} showed little or no response to added P fertilizer, whereas those below 3.5 mg kg^{-1} usually responded to P additions (Fig. 25). However, the use of soil tests is a difficult if not impossible option for most farmers in Laos as only one laboratory can do such an analysis (Soil Survey and Land Classification Center) and the cost is relatively high.

Because P deficiencies are widespread (especially in the south), P fertilizer is broadly recommended. The amount of P required to correct a P deficiency typically depends on the soil texture. Soils with higher clay contents require more P because of

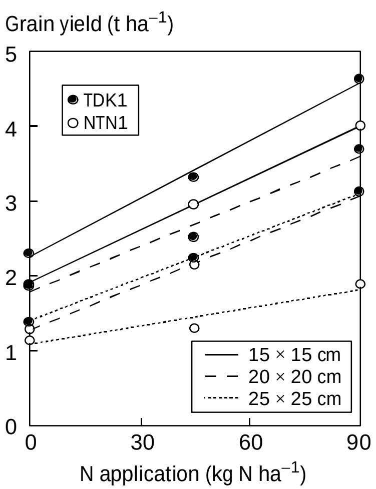


Fig. 24. Effect of hill spacing and N fertilizer regime on rice yields of TDK1 and NTN1. Experiments were conducted during the dry season in Vientiane Municipality.

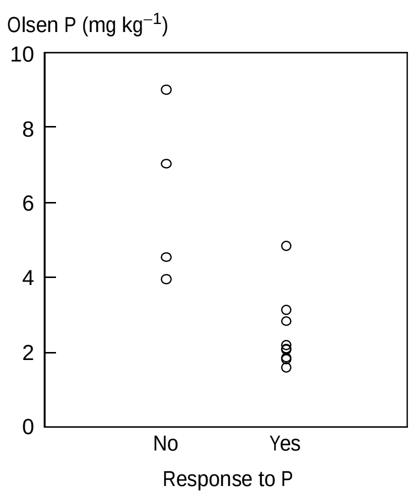


Fig. 25. Rice response to P in relation to soil Olsen P levels.

the higher P-fixation capacity associated with the clays present in these soils. On sandy soils, an application of 6 to 13 kg P ha^{-1} (15 to 30 kg P_2O_5 ha^{-1}) is normally adequate to correct a P deficiency, whereas loam soils need about 13 to 19 kg P ha^{-1} (30 to 45 kg P_2O_5 ha^{-1}) and clay loams and clays up to 26 kg P ha^{-1} (60 kg P_2O_5 ha^{-1}). The P should be applied before land preparation before transplanting to ensure that it is adequately incorporated into the soil.

Long-term P management. About 20% to 40% of freshly applied P is taken up by the rice crop in a season. The fate and availability of the P that remains in the soil (residual P) is of importance in developing efficient long-term P management strategies. To evaluate the effectiveness and availability of residual P, experiments were conducted over two seasons at three sites with varying soil texture [Bolikhamsay (sandy loam), Saravane (loam), and Savannakhet (loamy sand)]. In the first season, P was applied at rates ranging from 0 to 26 kg P ha^{-1} (60 kg P_2O_5 ha^{-1}). N, K, and S were applied to all plots to ensure that these nutrients were not limiting. At harvest, plant samples were taken to estimate yield, aboveground biomass, and P uptake. Residual P (P remaining in the soil) was calculated using the following equation:

$$\text{Residual P} = \text{fertilizer P added} - (\text{P uptake with P fertilizer} - \text{P uptake without P fertilizer}) \quad (3)$$

In the second year, fresh P was applied to a plot with no previous P applications. Plots receiving P in the first year did not receive additional P. In addition, some plots in Saravane received fresh P (residual + fresh). The effectiveness (EFF) of fresh and residual P was calculated using the following equation:

$$\text{EFF} = (\text{yield with P fertilizer} - \text{yield without P fertilizer})/\text{residual or fresh P} \quad (4)$$

In the first season, there was a significant response to P fertilizer at all sites. The residual P following the first season ranged from 69% to 85% of the P added (Table 17). In the second year, there was a significant response to residual and fresh P at all sites (Fig. 26). At the Saravane site, the EFF of residual P and "residual + fresh" P was similar to that of fresh P and averaged 132 kg grain kg^{-1} P. In both Savannakhet and Bolikhamsay, the yield response to residual P was less than to fresh P. Soils at both sites were coarse-textured and would be expected to have low P-fixation capacities and high water percolation rates. The lower EFF of residual P may be due to P

Table 17. Soil characteristics (0–20 cm), response to P in the first season, and the percent fertilizer P remaining after the first crop (equation 3) for three experimental sites.

Site	Soil texture	pH	Organic C (%)	Yield range (t ha^{-1})	Yield increase (%)	Fertilizer P remaining (%)
Bolikhamsay	Sandy loam	4.9	0.25	1.6–2.5	56	85
Saravane	Loam	5.1	0.29	2.3–5.4	139	69
Savannakhet	Loamy sand	5.5	0.21	1.4–3.4	138	73

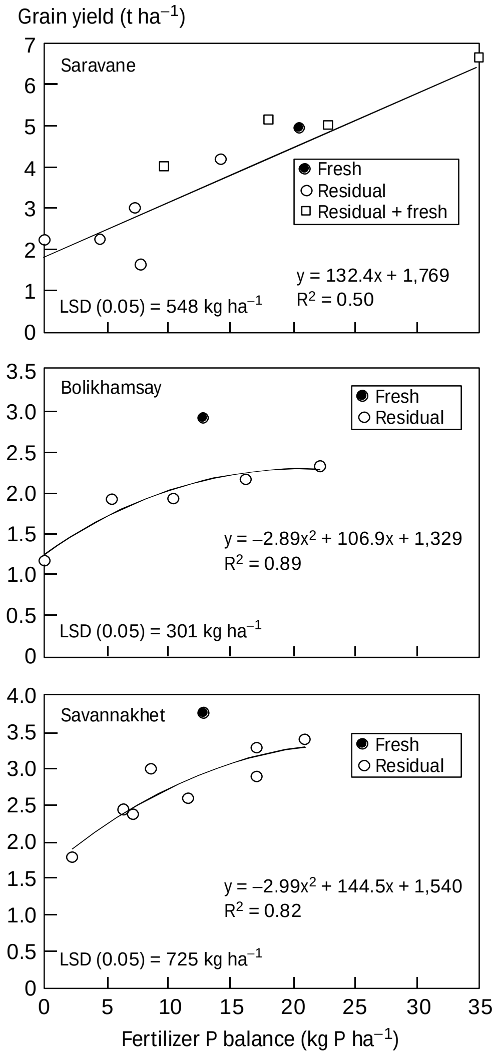


Fig. 26. Grain yield response to fresh and residual P. Fertilizer P balance is either the residual P from the previous crop (equation 3) or the amount of fresh P applied. The line or curves are fitted to the residual points.

losses via leaching. This hypothesis is supported by the curve linear response to residual P at both sites (Fig. 26) and the differences in EFF with increasing levels of residual P (Table 18). At low residual P levels, the EFF of residual P was similar to that of fresh P, whereas, at higher residual P levels (where P leaching would be more prevalent), the EFF was less.

Table 18. Effectiveness of residual and fresh P (equation 4) at two sites with coarse-textured soils.

Type of P	Amount of P ($kg\ ha^{-1}$)	Effectiveness ($kg\ kg^{-1}$)	
		Savannakhet	Bolikhamsay
Fresh	12.9	169	150
Residual	0–9	127	150
Residual	11–21	88	67

In summary, if P is applied initially at the recommended rate, the residual P in the following season will have an EFF similar to that of fresh P. However, at higher application rates to sandy soils, the EFF of residual P is reduced. A similar long-term P management strategy is recommended for all soil types. In the first year, apply an initial dose to meet the P requirement. In subsequent years, make maintenance applications, replacing the P removed by the crop. This is approximately 2.5 kg P ha^{-1} (6 kg P_2O_5) per ton of grain yield (Table 8).

Rock phosphate. Rock phosphate (RP) is not mined in Laos; however, it is available from China and Thailand. RP is lower priced than acidulated phosphates (i.e., triple superphosphate [0-46-0]) and may represent a means of reducing fertilizer cost where transport costs are not too great. Furthermore, most RP also contains "impurities" of other nutrients (i.e., S) that are beneficial to crop growth. However, the quality of RP varies significantly depending on its source and the degree to which it has been ground. Thus, the effectiveness of RP can vary. The RP used in these studies was considered to be of fairly high quality. It originated from southern China (Kunming) and contained 32.8% P_2O_5, 17.4% of which was citrate-soluble.

Several studies have begun in Laos to evaluate the potential of RP on lowland rice soils, but the results are inconclusive. Applications of RP in the first year show little response to P. In the experiments, RP was applied just before transplanting. Under these conditions, the soil pH is near neutral because the soil is flooded and anaerobic. RP requires acid soils to solubilize. It is hypothesized that, if the RP had been applied early (i.e., before the first plowing about 1 mo before transplanting), the soil would not have been saturated and the pH would have been lower, possibly allowing for the solubilization of the RP. It is also possible that in the year following RP application the P will have had time to solubilize and would be available. However, this has yet to be tested.

Potassium

Potassium responses are observed only on a relatively small number of soils compared with N or P. In Sayaboury (Phiang District), K deficiencies are prevalent and severe. This area has been irrigated since the mid-1970s and has been double-cropped for much of that time. Furthermore, the K content of the irrigation water is particularly low (Table 7). Responses to K are observed in both the wet and dry seasons

(Figs. 27A and 28) although greater responses are usually observed in the wet season, perhaps because less irrigation water is used and hence less K from the irrigation water is applied. The yield response to K in this area is almost linear up to 50 to 70 kg K ha^{-1} (60 to 80 kg K_2O ha^{-1}).

These studies also show a close relationship between K deficiency and brown spot disease incidence. Brown spot incidence decreases as K is added, from a score of 5 (severe brown spot) when no K is applied to about 1.5 when higher rates of K are applied (Fig. 27B). Figure 27A also illustrates that, when only N, P, and S are added (no K), yields are lower than when no fertilizers are added. When no fertilizers were applied, yields were 1.7 t ha^{-1}, whereas, when N, P, and S were applied (without K), yields were only 0.9 t ha^{-1}. Adding fertilizer without K appears to exacerbate brown spot disease. Brown spot incidence in the "no fertilizer" treatment had a brown spot score of 4 compared with 5 in the treatment that received N, P, and S fertilizer but no K (Fig. 27B).

K deficiencies are expected to increase in the future because of the increased use of N and P fertilizers and current straw management practices. About 80% of the K is in the straw at harvest (Table 8) and therefore straw management is critical for long-term K management. A crop yielding 3.5 t ha^{-1} takes up about 50 kg K ha^{-1}, of which 40 kg K ha^{-1} are in the straw. Farmers typically remove about half the straw when they harvest; the remaining straw is either burned or grazed by animals. The net result is that most of the K is removed and no or little K is being returned (even when straw

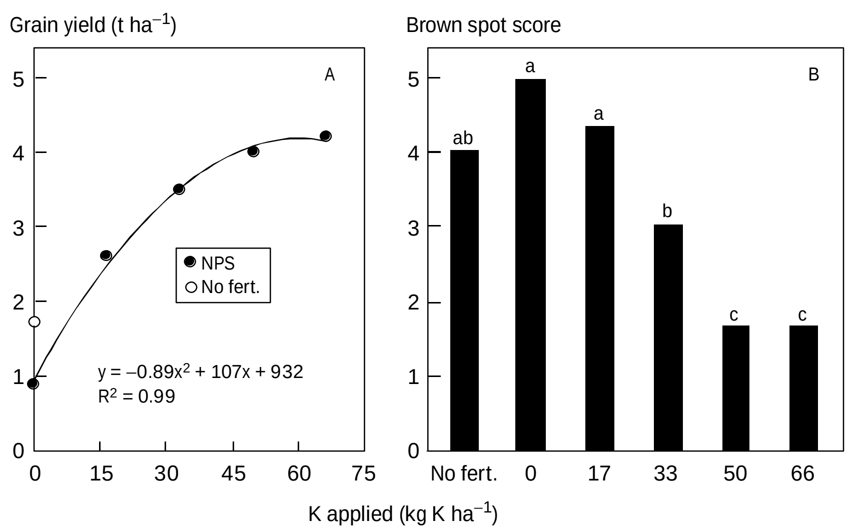


Fig. 27. (A) Grain yield response to K in Sayaboury Province (Phiang District) during the wet season. All treatments received N, P, and S (NPS) with varying rates of K except one that received no fertilizer. (B) Brown spot scores in relation to K application, where 0 and 5 represent no brown spot and severe brown spot, respectively.

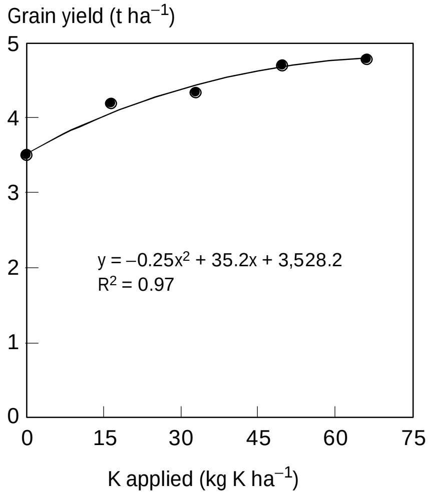


Fig. 28. Grain yield response to K during the dry season in Sayaboury Province (Phiang District).

is burned, much of the ash, which contains K, is blown out of the field by winds). The recommended nutrient management strategy is to apply on-farm residues such as straw, rice husks, and manure and apply low amounts of K fertilizer to replace the K that is removed by the crop. As a maintenance recommendation, 25 kg K ha^{-1} (30 kg K_2O ha^{-1}) should be applied with each crop, although this can vary depending on farmer residue management.

To evaluate the effect of applying only N and P fertilizers without K, an experiment was conducted at 17 lowland irrigated sites during the 1999 dry season. There were three treatments with only one replication per site. The treatments were (1) a control with no fertilizer, (2) 16-20-0 as a basal fertilizer, and (3) 15-15-15 as a basal fertilizer. In the two treatments that received fertilizer, N was applied at 90 kg N ha^{-1} in both cases. The N was split between an application at transplanting and at 30 and 50 DAT. The compound fertilizer supplied all the N in the first application, whereas urea was the N source for the two topdressings. The total P and K for each was 16 and 0 kg ha^{-1}, respectively, for the 16-20-0 compound fertilizer and 13 and 25 kg ha^{-1} for the 15-15-15 compound fertilizer. These plots (50 m^2 each) were maintained for four seasons to examine the long-term effects of each fertilizer management strategy.

Across all sites and seasons there was a significant response to both fertilizer treatments. Yields in the no-fertilizer control averaged 1.9 t ha^{-1} versus 3.5 t ha^{-1} for the plus-fertilizer treatments. In the first season, the K-containing fertilizer (15-15-15) produced higher yields than the 16-20-0 fertilizer at only 13% of the sites (Fig. 29). However, after four seasons, this had increased to 40% of the sites. For the yield trends, yields remained relatively stable (averaging 3.5 t ha^{-1}) across all four seasons

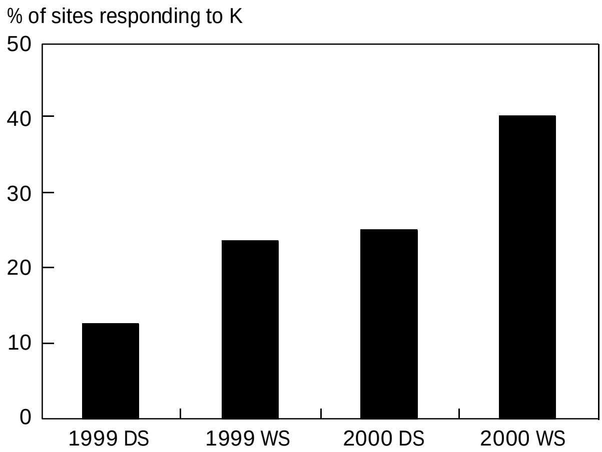


Fig. 29. Results of four seasons (DS and WS = dry and wet season, respectively) comparing the use of 16-20-0 and 15-15-15 as a basal fertilizer for rice. Graph presents the percentage of sites at which the 15-15-15 fertilizer (contains K) produced yields that were at least 0.4 t ha^{-1} greater than that from 16-20-0 fertilizer (contains no K).

when 15-15-15 was applied. However, in the 16-20-0 plots, yields during the first three seasons averaged 3.6 t ha^{-1} but in the last season dropped to 3.1 t ha^{-1}. In all cases in which farmers were asked about their straw management practices, the straw remaining after harvest was either burned or grazed by animals. These data highlight that K deficiencies will become more prevalent if farmers apply only N- and P-containing fertilizers and remove straw. Although this study was conducted in the irrigated environment, K deficiencies may become a greater problem over time in the rainfed environment, albeit at a slower rate because only one crop is grown per year and lower rates of N and P fertilizer are used.

Sulfur

On the basis of limited evidence, sulfur deficiencies are not widespread and are usually not severe. Of the few sites that have been evaluated, about 25% have been S-deficient. At most sites where S was deficient, there was a weak to moderate yield response to S additions. Only one site (Sekong Province, Thateng District) had severe S deficiencies. At this site, yields increased from 3.4 to 4.7 t ha^{-1} with the addition of 30 kg S ha^{-1}.

Sulfur is available in small quantities in rainfall with about 5 kg S ha^{-1} deposited annually (Table 6). At the irrigated sites, S is available in the irrigation water although its concentration varies widely (Table 7). No rate studies have been conducted in Laos to determine the appropriate amount of S to alleviate the constraints, although work conducted in Thailand suggests that 20 to 30 kg S ha^{-1} are adequate. If

S deficiencies are suspected, it is recommended that the commonly available fertilizer (16-20-0) be used as it contains up to 12% S.

Future challenges and opportunities

We have presented nutrient management strategies that can be applied to and modified for a wide variety of soils in Laos. If these nutrient recommendations are practiced with good agronomic management practices (using improved varieties, IPM measures, close spacing, etc.), fertilizer use can be efficient. However, considerable on-farm variability exists. Differences in previous crop management or positions along the toposequence correspond to changes in soil properties. This affects soil-water relations, root growth, and nutrient availability, all of which require greater understanding to develop site-specific nutrient management strategies. Furthermore, fields within any given farm differ in the risk associated with production. For example, fields high in a toposequence may be more drought-prone, whereas those low in the toposequence may be more prone to flooding. A better understanding is required of how farmers perceive risk and how this affects decision making and farm management.

While considerable research has focused on P management in the rainfed lowlands, little work has been done to examine differences in variety response to P. Inthapanya et al (2000) have shown differences among Lao rice breeding lines and varieties in their ability to acquire and use P. Also, in parts of Xieng Kouang Province, P deficiencies are very severe. In studies conducted in this area using improved varieties, there was no yield if P fertilizer was not applied; in contrast, however, traditional varieties growing around the experiments produced some yield, although it was low.

Research presented here indicates that there is considerable flexibility in when the first N application can be made. However, P-containing fertilizers in Laos are only readily available in compound fertilizers with N. It is generally recommended that P fertilizer be applied early during crop growth and therefore N would need to be applied early as well. However, there has been relatively little research on the timing of P fertilizer applications and results are inconclusive. Where fertilizer availability is limited, it would be worthwhile to investigate this issue further.

Leaf-bronzing is a common symptom of disease in rice plants in Laos that has not been examined closely. The causes of the symptoms are not clear but they may be associated with K deficiency, Fe toxicity, or infection with a fungus. The severity of these symptoms varies depending on soil, water management, fertilizer management, and rice variety. Research needs to quantify the effect of leaf-bronzing on productivity, identify the cause, and develop management strategies to address the problem.

Although transplanting rice is by far the most common method of crop establishment, direct seeding is becoming more popular. Currently, there is research on direct seeding in the area of variety requirement and weed management; however, nutrient management practices will need to be developed for direct-seeded rice.

Laos has recently reached self-sufficiency in rice. As the lowlands begin to reach their productivity potential, excess production will need to be exported. However, the market for glutinous rice is small. Opportunities need to be identified for diversification in the lowlands. The most opportunities for diversification are in the irrigated environment with alternative crops grown during the dry season. This presents new challenges for not only identifying alternative crops but also developing nutrient recommendations for the system. Such changes in the farming system would affect the amount of time a soil remains submerged during the year, the amount of residues recycled, the residual effects of a nutrient applied in one season on the following season, and disease and pest cycles. Understanding these changes will be necessary to develop efficient nutrient management strategies.

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Nutrient management recommendations

On the basis of the research provided in the preceding sections, a general nutrient management strategy for rice grown during the wet season under rainfed conditions is provided here. This does not necessarily apply to the irrigated environment.

General nutrient management considerations

Nutrient management needs to be viewed within the context of the whole-farm system. This includes taking into account differences in soils and variety responsiveness. Research has clearly shown that the adoption of nutrient management practices alone, ignoring variety and other management considerations, leads to poor nutrient-use efficiency.

Balanced recommendation. To achieve optimal nutrient-use efficiency, nutrient recommendations need to be balanced. A balanced recommendation is one that calls for the nutrients needed in the correct proportions. For example, if N, P, and K are deficient but only N and P are applied, the N and P will not be used efficiently because K limits rice growth.

Inputs and losses. A sustainable nutrient recommendation accounts for all inputs and losses from the system. Nutrient inputs include those from fertilizers, residues, and rainfall (N, P, and K are minimal in rainfall) and irrigation water, whereas losses include those removed at harvest (see Box 1), leaching, runoff, NH_3 volatilization, and denitrification (N lost to the atmosphere). For example, repeated application of N and P fertilizer may increase yields in the short term. However, if K is not added and the straw is continually removed (most of the K at harvest is in the straw, see Box 1), there will be a net annual loss of K from the system. This system is not sustainable and with time yields will decline because of K deficiency.

Farmer risk. The rainfed lowland environment is risky for crop production. Any given year may have yield

Box 1. Nutrients removed in the rice crop.

Nutrient	Grain (%)	Straw (%)	Total removed[a] in kg t^{-1} yield
N	0.8	0.35	13
P	0.2	0.04	2.5
K	0.3	0.80	15

$\%P_2O_5 = \%P \times 2.29$

$\%K_2O = \%K \times 1.2$

[a]Assumes that all straw is removed.

losses from drought, flooding, pests, or disease. Obtaining maximum yields is not the objective of a nutrient management program for this environment. To get maximum yield requires a high fertilizer investment, the risk of which is too high for most farmers. The objective is to provide a recommendation with relatively low investment cost and in which nutrients will be used with maximum efficiency.

Variety. Farmers typically grow a mix of both traditional and improved varieties. Traditional varieties may perform better in high-risk parts of the farm such as those susceptible to drought or flooding, or they may be preferred for other reasons such as grain quality. The nutrient recommendations provided here are for use with improved varieties, which are generally more responsive to inputs than traditional varieties.

Soil variation. Lao farmers are aware of the subtle differences on their farms, which they manage accordingly to avoid risk of crop failure. Paddy soils higher in the toposequence are usually more sandy, less fertile, and more drought-prone than those lower in the toposequence, which have higher clay and organic matter contents but which may also be susceptible to flooding. Farmers with limited capital should invest inputs in areas least subject to risk rather than trying to spread limited inputs across the whole farm. This may mean limiting nutrient inputs to only a few paddies.

Crop management. Management practices that need to be considered to obtain maximum nutrient-use efficiency include close spacing of hills during transplanting. Farmers often transplant using a wide hill spacing (25 × 25 cm). Although this results in some labor and seed savings, higher yields and increased nutrient efficiency are possible when seedling hills are spaced at 20 × 20 cm with about 4 to 6 seedlings per hill. Good weed management and appropriate pest control measures are also essential.

Lowland rice in Laos is usually transplanted; therefore, nutrient management strategies are provided for both the seedlings in the nursery and the transplanted rice.

The seedlings

The objective of nutrient management in the seedling nursery is to grow strong and vigorous seedlings for transplanting. Such seedlings will better withstand transplant shock as well as other possible stresses such as early season drought. Phosphorus nutrition is especially important in obtaining good seedling vigor but modest amounts of N are also necessary. High N rates are not recommended as they may produce weak stems that break when the seedlings are pulled for transplanting.

The nutrient management recommendation for the nursery is to apply 50 kg of manure 100 m^{-2} (air-dried cow or buffalo manure) before land preparation. At 10 to 15 d after sowing the seed and when there is standing water in the nursery, apply 16-20-0 fertilizer at 1 kg 100 m^{-2}. Seedlings are normally grown in the nursery for 25 to 30 d.

Transplanted rice

Efficient on-farm recycling of residues. A good nutrient recommendation is balanced, uses nutrients efficiently, and is sustainable. Nutrient inputs can be from either organic or inorganic sources. Farmers should use all available on-farm nutrients, especially those contained in residues (rice straw, rice husks, and manure). These are usually readily available and free, although there are application costs. These residues provide K and micronutrients that are not in most of the inorganic fertilizers available to Lao farmers. Furthermore, they add organic matter to the soil, which increases its ability to hold and provide nutrients. Residues, however, are low in N and P. N and P are the two nutrients that are most limiting in Lao soils; therefore, inorganic fertilizers are generally required for high yields.

Recycling available on-farm residues is recommended for all nutrient management regimes. Even if inorganic fertilizers are not used, applying residues is recommended. Applying residues alone (rice straw, rice husks, or manure) at 2 t ha^{-1} can increase rice yields by 0.5 t ha^{-1}. Applying residues is also important when only N- and P-containing fertilizers are used because residues are often high in K.

Developing fertilizer recommendations. In Laos, three fertilizers are widely and readily available: 16-20-0, 15-15-15, and 46-0-0 (urea). Although we have discussed the "ideal" fertilizer recommendations, it may not be possible to apply the exact amount of each nutrient given the limited choice of fertilizers. Some nutrients will be supplied in excess and other nutrients may be applied in lower than desired quantities. The recommendations provided in Table 19 are for the first year a farmer starts to apply nutrients (or if no fertilizers were applied the previous year). Table 20 provides recommendations for subsequent years. These are different as they account for residual P.

Table 19. Fertilizer recommendations for the first year. Calculations are based on soil type and basal fertilizer availability (15-15-15, 16-20-0, or 18-46-0). Only urea is applied at active tillering and panicle initiation.

Soil texture	Fertilizer recommendation (kg N-P_2O_5-K_2O ha^{-1})	Basal (B)	Active tillering (AT) (kg fertilizer ha^{-1})	Panicle initiation (PI)	Actual amount of nutrient applied (kg N-P_2O_5-K_2O ha^{-1})	N applied at each time (B-AT-PI) (kg N ha^{-1})
		15-15-15	urea (46-0-0)	urea (46-0-0)		
Sand	60-20-30	133	43	43	60-20-20	20+20+20
Sandy loam	60-30-30	200	33	33	60-30-30	30+15+15
Loam	60-45-30[a]	300	0	33	60-45-45	45+ 0+15
Clay loam	60-60-30[a]	400	0	0	60-60-60	60+ 0+ 0
		16-20-0[b]	urea (46-0-0)	urea (46-0-0)		
Sand	60-20-30	100	48	48	60-20-0	16+22+22
Sandy loam	60-30-30	150	39	39	60-30-0	24+18+18
Loam	60-45-30[a]	225	26	26	60-45-0	36+12+12
Clay loam	60-60-30[a]	300	0	26	60-60-0	48+ 0+12
		18-46-0[b]	urea (46-0-0)	urea (46-0-0)		
Sand	60-20-30	43	57	57	60-20-0	8+26+26
Sandy loam	60-30-30	65	52	52	60-30-0	12+24+24
Loam	60-45-30	98	46	46	60-45-0	18+21+21
Clay loam	60-60-30	130	40	40	60-60-0	23+19+19

[a]Recommended last option. First option is to use 18-46-0 or triple superphosphate (0-46-0); second option is to use a short-duration variety (i.e., PN-1 or SK-12) with two application times: a basal application and one at PI. [b]K-containing residues (i.e., rice straw, rice husks, and manure) should always be applied, but especially if 16-20-0 is used instead of 15-15-15.

Table 20. Fertilizer recommendations for the second and subsequent years for all soils. Calculations are based on crop yields and basal fertilizer availability (either 15-15-15 or 16-20-0) and account for residual P availability (P remaining from the previous year's application).

Yield in previous year ($t\ ha^{-1}$)	Fertilizer recommendation ($kg\ N\text{-}P_2O_5\text{-}K_2O\ ha^{-1}$)	Basal (B)	Active tillering (AT) (kg fertilizer ha^{-1})	Panicle initiation (PI)	Actual amount applied ($kg\ N\text{-}P_2O_5\text{-}K_2O\ ha^{-1}$)	N applied at each time (B-AT-PI) ($kg\ N\ ha^{-1}$)
		15-15-15	urea (46-0-0)	urea (46-0-0)		
2	60-12-30	80	52	52	60-12-12	12+24+24
3	60-18-30	120	46	46	60-18-18	18+21+21
4	60-24-30	160	39	39	60-24-24	24+18+18
5	60-30-30	200	33	33	60-30-30	30+15+15
		16-20-0[a]	urea (46-0-0)	urea (46-0-0)		
2	60-12-30	60	54	54	60-12-0	10+25+25
3	60-18-30	90	50	50	60-18-0	14+23+23
4	60-24-30	120	43	43	60-24-0	20+20+20
5	60-30-30	150	39	39	60-30-0	24+18+18

[a]K-containing residues (i.e., rice straw, rice husks, and manure) should always be applied, but especially if 16-20-0 is used instead of 15-15-15.

Inorganic fertilizer recommendations (first year). The first-year recommendation is to apply 60-?-25 kg NPK, respectively (60-?-30 kg $N\text{-}P_2O_5\text{-}K_2O\ ha^{-1}$, respectively). The P rate varies according to soil texture (see "Phosphorus" below). The N is split into three applications, with the first application to be incorporated into the soil just before transplanting in combination with all of the recommended P and K.

Nitrogen. Ideally, 20% of the N should be applied at transplanting, with the remaining 80% being split equally between active tillering and panicle initiation (Table 21). Split N applications ensure that N is available during the most rapid growth stages. More information on N timing is provided later (see "Timing" later in this same section). The rate of N recommended here is lower than that required for maximum yields and reflects farmer risk in this rainfed environment. Higher rates (i.e., 90 to 120 kg N ha^{-1}) will usually result in higher yields under good growing conditions in southern Laos.

Phosphorus. Most soils in Laos are P-deficient. The amount of P required to alleviate this deficiency is closely related to soil texture. The recommended rate in sandy soils is 8.5 kg P ha^{-1} (20 kg P_2O_5 ha^{-1}), and 13 kg P ha^{-1} (30 kg P_2O_5 ha^{-1}) in sandy loam soils, and 19 to 26 kg P ha^{-1} (45 to 60 kg P_2O_5 ha^{-1}) in loams and clay loams.

Potassium. Most soils in Laos are not K-deficient. However, the use of N and P fertilizers without K will most likely lead to K deficiencies over time. This is especially the case for sandy soils, which typically have low K reserves. Therefore, applying K and/or returning crop residues is recommended for sustainable systems. For each 1 t of rice grain yield, about 15 kg of K (18 kg K_2O) are stored in the crop (see Box 1). About 80% of crop K is in the straw at the time of harvest (12 kg K t^{-1} of straw). In most cases, straw is removed from the field during harvest and by grazing.

Table 21. Active tillering and panicle initiation times for some improved varieties used in Laos.

Duration	Sowing to maturity (d)	Variety	Active tillering (DAT)[a]	Panicle initiation (DAT)
Medium late	140–150	TDK1, TDK2	30	55
Medium	130–140	TDK3, RD10, NTN1	25	45
Medium early	120–130	PN1, SK12	20	35

[a]DAT = days after transplanting and assumes that seedlings were transplanted 30 d after sowing.

It is recommended that farmers return rice husks (about 0.5% K) as well as straw (if it is not fed to animals) to the field. If straw is fed to animals, the animal manure should be returned to the field; however, animal manure is usually lower in K than straw. The recommended K rate is 25 kg K ha^{-1} (30 kg K_2O ha^{-1}) (Tables 19 and 20) but this depends on residue management. If residues are managed as recommended here, the inorganic fertilizer K requirement may be reduced.

Inorganic fertilizer recommendations (second and subsequent years). In the second and subsequent years (Table 20), the recommendation is modified to account for P added in the first season that was not removed by the crop (less than 50% of the P applied in the first year is removed by the crop). This residual P is available to the plant in the following season. Therefore, only the amount of P that was removed by the previous crop needs to be applied. The amount of P removed by the crop is determined by the yield and is approximately 2.5 kg P t^{-1} of grain yield (6 kg P_2O_5) depending on straw management. For example, if yields are 3 t ha^{-1} on a sandy loam soil, 7.5 kg P ha^{-1} need to be applied the following year.

What fertilizers to use. As seen in Tables 19 and 20, it is difficult to apply the "ideal" fertilizer recommendation given the limited choice of fertilizers (16-20-0, 15-15-15, and 46-0-0). The difficulties in formulating appropriate recommendations are primarily for soils with a high P requirement (loam and clay soils) in the first year. As P is available only in compound fertilizers, a lot of basal fertilizer needs to be applied early on these soils. This results in higher than optimum rates of N being applied early, when it is not used efficiently. If possible, 18-46-0 is recommended as the basal fertilizer for these soils. Another option, if 18-46-0 is not available, is to grow an early maturing variety (i.e., PN1 or SK12) that requires only two N applications rather than the usual three. In the second and subsequent years, this is not a problem as the P requirement is reduced (Table 20).

Box 2. Numbers on fertilizer bags. What do they mean?

Fertilizer bags contain three numbers that correspond to the percentage of N, P, and K in the fertilizer. The P and K contents of fertilizers are expressed as the oxide (P_2O_5 and K_2O) rather than elemental P and K. Therefore, a bag of 16-20-0 contains 16% N, 20% P_2O_5, and 0% K_2O. To convert to elemental P and K, use the following formulas:

$$\%P = \%P_2O_5 \times 0.43$$
$$\%K = \%K_2O \times 0.83$$

Because of the K content of the fertilizer, 15-15-15 is recommended over 16-20-0 as a basal fertilizer. This is especially the case for sandy soils (loam and clay soils typically have higher K reserves) or when residues are not applied. If 16-20-0 is the only form of fertilizer available, on-farm residues should be returned to the system.

Timing. Nitrogen fertilizer should be applied only when there is standing water in the field. It should not be applied when it is raining or about to rain or when there is water movement across the field.

The first application of N can be made up to 30 DAT (for medium-maturing varieties). However, since P and K are only readily available in compound fertilizer containing N, the first N application will be made with the P and K. The P and K should be applied around transplanting. Therefore, the initial basal fertilizer application containing all of the P and K and a portion of the N should be made at transplanting.

The remaining N requirement should be split equally at active tillering and panicle initiation. For early maturing varieties such as PN1 or SK12, if three applications are not possible, two are adequate: a basal application and one at PI. However, in such situations, it is better to apply more of the N in the basal application (i.e., 30–40% rather than 20%). Table 21 provides times for active tillering and PI for some of the recommended varieties used in Laos. These estimates are approximate and are influenced by environmental conditions (the dry-season growing calendar may be considerably different). For the N applications at active tillering and PI, the N can be applied with no reduction in efficiency 5 d before or after these times. Therefore, if conditions are good for applying fertilizer to TDK1, for example, at 25 DAT, the farmer should apply it then rather than wait until 30 DAT and risk poor conditions for fertilizer application. If the last N application is 2 wk or more after PI, there may be little benefit from the application.

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List of experiments

This list contains soil fertility studies conducted during the wet season from 1991 to 2000. More information can be obtained from each of these studies by referring to the Lao-IRRI Annual Technical Report for that year. Note: An * indicates that the experiment was also conducted during the dry season.

Province	District	Year	Primary nutrient studied	Objective
Attopeu	Saysetha	1996	NPK	Determine limiting nutrients
Attopeu	Saysetha	1999	N	Timing of first N application
Attopeu	Saysetha	1999	N	Timing of last N application
Bokeo	Houeyxai	1995	NPK	Determine limiting nutrients
Bokeo	Houeyxai	1996	NPKS	Compare compound and organic fertilizers
Bokeo	Houeyxai	1996	P	Identify appropriate rate
Bokeo	Houeyxai	1999	N	Timing of first N application
Bokeo	Houeyxai	1998-2000	P	Residual value of TSP[a]
Bokeo	Thonepheung	1995	NPK	Determine limiting nutrients
Bokeo	Thonepheung	1996	P	Identify appropriate rate
Bokeo	Thonepheung	1997	P	Identify appropriate rate
Bokeo	Thonepheung	1999	N	Timing of first N application
Bolikhamsay	Paksan	1992	NPK	Determine limiting nutrients
Bolikhamsay	Paksan	1999	Organic fert.	Compare organic and inorganic fertilizers
Bolikhamsay	Paksan	1998-2000	P	Residual value of TSP
Bolikhamsay	Paksan	1991	N	Identify appropriate rate
Bolikhamsay	Paksan	1993	N	Identify appropriate rate
Bolikhamsay	Paksan	1994	N	Interaction between variety and N
Bolikhamsay	Paksan	1995	N	Interaction between variety and N
Bolikhamsay	Paksan	1996	N	Timing of N applications
Champassak	Khong	1999-2000*	K	Compare 16-20-0 and 15-15-15
Champassak	Pakse	1991	K	Identify appropriate rate
Champassak	Pakse	1991	N	Identify appropriate rate
Champassak	Pakse	1991	P	Identify appropriate rate
Champassak	Pakse	1992	NPK	Determine limiting nutrients
Champassak	Pakse	1993	K	Identify appropriate rate
Champassak	Pakse	1993	N	Identify appropriate rate
Champassak	Pakse	1993	P	Identify appropriate rate

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List of experiments continued.

Province	District	Year	Primary nutrient studied	Objective
Champassak	Pakse	1994	N	Interaction between variety and N
Champassak	Pakse	1995	N	Interaction between variety and N
Champassak	Pakse	1992-95	N	Evaluate green manure
Champassak	Phonethong	1992	NPK	Determine limiting nutrients
Champassak	Phonethong	1993	N	Identify appropriate rate
Champassak	Phonethong	1993	P	Identify appropriate rate
Champassak	Phonethong	1994	N,P	Evaluate green manure
Champassak	Phonethong	1994	P	Identify appropriate rate
Champassak	Phonethong	1995	N	Timing of N applications
Champassak	Phonethong	1996	P	Evaluate green manure
Champassak	Phonethong	1996	N	Timing of N applications
Champassak	Phonethong	1997	N	Interaction between variety and N
Champassak	Phonethong	1999	N	Timing of first N application
Champassak	Phonethong	1999-2000	NPK	Interaction between residue and fertilizer management
Champassak	Phonethong	1992-93	N	Evaluate green manure
Champassak	Phonethong	1996	N	Evaluate green manure
Champassak	Phonethong	1997	S	Determine limiting nutrients
Champassak	Phonethong	1997-98	P	Evaluate green manure
Champassak	Sanasomboune	1992	NPK	Determine limiting nutrients
Champassak	Sanasomboune	1993	K	Identify appropriate rate
Champassak	Sanasomboune	1993	N	Identify appropriate rate
Champassak	Sanasomboune	1993	P	Identify appropriate rate
Champassak	Sanasomboune	1999-2000*	K	Compare 16-20-0 and 15-15-15
Champassak	Soukhouma	1995	NPK	Determine limiting nutrients
Champassak	Soukhouma	1996	K	Identify appropriate rate
Champassak	Soukhouma	1996	P	Identify appropriate rate
Champassak	Soukhouma	1998	P	Evaluate split P applications
Champassak	Soukhouma	1999	Organic fert.	Compare organic and inorganic fertilizers
Champassak	Soukhouma	1999	N	Timing of first N application
Champassak	Soukhouma	1999-2000*	K	Compare 16-20-0 and 15-15-15
Champassak	Soukhouma	1999-2000*	K	Compare 16-20-0 and 15-15-15
Houaphanh	Et	1998	NPKS	Determine limiting nutrients
Houaphanh	Et	1999-2000*	K	Compare 16-20-0 and 15-15-15
Houaphanh	Samneua	1992	NPK	Determine limiting nutrients
Houaphanh	Samneua	1993	P	Identify appropriate rate
Houaphanh	Samneua	1994	P	Identify appropriate rate
Houaphanh	Samneua	1995	P	Identify appropriate rate
Houaphanh	Samneua	1997	S	Determine limiting nutrients
Houaphanh	Samneua	1998	N	Timing of N applications
Houaphanh	Samneua	1999-2000	P	Residual value of TSP and RP[a]
Houaphanh	Sopbao	1999	N	Timing of first N application
Houaphanh	Sopbao	1999	N	Timing of last N application
Houaphanh	Xieng Kho	1993	NPK	Determine limiting nutrients
Houaphanh	Xieng Kho	1995	N	Interaction between variety and N
Houaphanh	Xieng Kho	1996	N	Interaction between variety and N
Khammouane	Gnommalath	1993	NPK	Determine limiting nutrients
Khammouane	Gnommalath	1994	P	Identify appropriate rate
Khammouane	Gnommalath	1995	P	Identify appropriate rate
Khammouane	Gnommalath	1996	N,P	Evaluate green manure

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List of experiments continued.

Province	District	Year	Primary nutrient studied	Objective
Khammouane	Gnommalath	1999	N	Timing of last N application
Khammouane	Gnommalath	1999-2000*	K	Compare 16-20-0 and 15-15-15
Khammouane	Nongbok	1992	NPK	Determine limiting nutrients
Khammouane	Nongbok	1993	K	Identify appropriate rate
Khammouane	Nongbok	1993	N	Identify appropriate rate
Khammouane	Nongbok	1993	P	Identify appropriate rate
Khammouane	Nongbok	1996	N	Interaction between variety and N
Khammouane	Thakhek	1992	NPK	Determine limiting nutrients
Khammouane	Thakhek	1993	N	Identify appropriate rate
Khammouane	Thakhek	1993	P	Identify appropriate rate
Khammouane	Thakhek	1994	P	Identify appropriate rate
Khammouane	Thakhek	1995	N	Interaction between variety and N
Khammouane	Thakhek	1998	N	Timing of N applications
Khammouane	Thakhek	1999	P	Identify appropriate rate
Khammouane	Thakhek	1999	N	Timing of first N application
Khammouane	Thakhek	1999-2000*	K	Compare 16-20-0 and 15-15-15
Luang Namtha	Namtha	1993	NPK	Determine limiting nutrients
Luang Namtha	Namtha	1994	NPK	Determine limiting nutrients
Luang Namtha	Namtha	1995	N	Timing of N applications
Luang Namtha	Namtha	1997	S	Determine limiting nutrients
Luang Namtha	Namtha	1998	N	Timing of N applications
Luang Namtha	Namtha	1999	N	Timing of first N application
Luang Namtha	Namtha	1999-2000*	K	Compare 16-20-0 and 15-15-15
Luang Namtha	Sing	1993	NPK	Determine limiting nutrients
Luang Namtha	Sing	1994	NPK	Determine limiting nutrients
Luang Namtha	Sing	1995	N	Interaction between variety and N
Luang Namtha	Sing	1997	S	Determine limiting nutrients
Luang Namtha	Sing	1999	N	Timing of first N application
Luang Prabang	Chomphet	1995	NPK	Determine limiting nutrients
Luang Prabang	Chomphet	1996	N	Timing of N applications
Luang Prabang	Nane	1993	NPK	Determine limiting nutrients
Luang Prabang	Nane	1996	N	Timing of N applications
Luang Prabang	Nane	1997	NPKS	Determine limiting nutrients
Luang Prabang	Nane	1998	K	Identify appropriate rate
Luang Prabang	Nane	1999	N	Timing of first N application
Luang Prabang	Xieng Nguen	1992	NPK	Determine limiting nutrients
Luang Prabang	Xieng Nguen	1993	NPK	Determine limiting nutrients
Luang Prabang	Xieng Nguen	1993	NPK	Determine limiting nutrients
Luang Prabang	Xieng Nguen	1994	P	Identify appropriate rate
Oudomsay	Xai	1992	NPK	Determine limiting nutrients
Oudomsay	Xai	1993	N	Identify appropriate rate
Oudomsay	Xai	1993	P	Identify appropriate rate
Oudomsay	Xai	1994	P	Identify appropriate rate
Oudomsay	Xai	1996	N	Timing of N applications
Oudomsay	Xai	1999	N	Timing of first N application
Phongsaly	Bounneua	1993	NPK	Determine limiting nutrients
Phongsaly	Bounneua	1994	K	Identify appropriate rate
Phongsaly	Bounneua	1995	K	Identify appropriate rate
Phongsaly	Bounneua	1996	N	Interaction between variety and N
Phongsaly	Bounneua	1997	N	Interaction between variety and N
Saravane	Khongsedon	1993	NPK	Determine limiting nutrients

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List of experiments continued.

Province	District	Year	Primary nutrient studied	Objective
Saravane	Khongsedon	1998	N	Interaction between residue and fertilizer management
Saravane	Khongsedon	1999	P	Identify appropriate rate
Saravane	Saravane	1993	NPK	Determine limiting nutrients
Saravane	Saravane	1994	P	Identify appropriate rate
Saravane	Saravane	1995	P	Identify appropriate rate
Saravane	Saravane	1996	N,P	Evaluate green manure
Saravane	Saravane	1998	N	Timing of N applications
Saravane	Saravane	1999-2000	NPK	Interaction between residue and fertilizer management
Saravane	Saravane	1999-2000*	K	Compare 16-20-0 and 15-15-15
Saravane	Vapi	1993	NPK	Determine limiting nutrients
Saravane	Vapi	1994	P	Identify appropriate rate
Saravane	Vapi	1995	P	Identify appropriate rate
Saravane	Vapi	1996	N	Interaction between variety and N
Saravane	Vapi	1996	P	Nursery P management
Saravane	Vapi	1999	N	Timing of first N application
Saravane	Vapi	1997-98*	P	Residual value of TSP
Saravane	Vapi	1999-2000*	K	Compare 16-20-0 and 15-15-15
Savannakhet	Champhone	1991	N	Identify appropriate rate
Savannakhet	Champhone	1991	P	Identify appropriate rate
Savannakhet	Champhone	1992	NPK	Determine limiting nutrients
Savannakhet	Champhone	1992	N	Evaluate green manure
Savannakhet	Champhone	1993	N	Evaluate green manure
Savannakhet	Champhone	1993	N	Identify appropriate rate
Savannakhet	Champhone	1993	P	Identify appropriate rate
Savannakhet	Champhone	1994	N,P	Evaluate green manure
Savannakhet	Champhone	1994	P	Identify appropriate rate
Savannakhet	Champhone	1995	N,P	Evaluate green manure
Savannakhet	Champhone	1995	N	Timing of N applications
Savannakhet	Champhone	1996	N	Evaluate green manure
Savannakhet	Champhone	1996	P	Evaluate green manure
Savannakhet	Champhone	1999	N	Timing of first N application
Savannakhet	Champhone	1997-98	P	Evaluate green manure
Savannakhet	Champhone	1999-2000*	K	Compare 16-20-0 and 15-15-15
Savannakhet	Khanthabouly	1996	N	Interaction between variety and N
Savannakhet	Khanthabouly	1991	N	Identify appropriate rate
Savannakhet	Khanthabouly	1991	P	Identify appropriate rate
Savannakhet	Khanthabouly	1992	NPK	Determine limiting nutrients
Savannakhet	Khanthabouly	1992	N	Evaluate green manure
Savannakhet	Khanthabouly	1993	N	Evaluate green manure
Savannakhet	Khanthabouly	1993	N	Identify appropriate rate
Savannakhet	Khanthabouly	1993	P	Identify appropriate rate
Savannakhet	Khanthabouly	1994	P	Identify appropriate rate
Savannakhet	Outoumphan	1998	P	Evaluate split P applications
Savannakhet	Xaybouly	1993	NPK	Determine limiting nutrients
Savannakhet	Xaybouly	1995	N	Timing of N applications
Savannakhet	Xaybouly	1996	N	Timing of N applications
Savannakhet	Xaybouly	1998	N	Interaction between residue and fertilizer management
Savannakhet	Xaybouly	1998	N	Interaction between variety and N

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List of experiments continued.

Province	District	Year	Primary nutrient studied	Objective
Savannakhet	Xaybouly	1999-2000*	K	Compare 16-20-0 and 15-15-15
Sayaboury	Phiang	1992	NPK	Determine limiting nutrients
Sayaboury	Phiang	1993	N	Identify appropriate rate
Sayaboury	Phiang	1994	N	Interaction between variety and N
Sayaboury	Phiang	1995	N	Interaction between variety and N
Sayaboury	Phiang	1996	N	Interaction between variety and N
Sayaboury	Phiang	1997	S	Determine limiting nutrients
Sayaboury	Phiang	1997	N	Interaction between variety and N
Sayaboury	Phiang	1998	NPKS	Determine limiting nutrients
Sayaboury	Phiang	1999	NPK	Interaction of nutrients
Sayaboury	Phiang	1999-2000*	K	Compare 16-20-0 and 15-15-15
Sayaboury	Phiang	1996	NPKS	Compare compound and organic fertilizers
Sayaboury	Phiang	1998	K	Identify appropriate rate
Sekong	Lamam	1996	NPK	Determine limiting nutrients
Sekong	Lamam	1998	N	Timing of N applications
Sekong	Lamam	1999	N	Timing of first N application
Sekong	Thateng	1998	NPKS	Determine limiting nutrients
Sekong	Thateng	1999	N	Timing of last N application
Sekong	Thateng	1999-2000*	K	Compare 16-20-0 and 15-15-15
Vientiane	Phonehong	1992	NPK	Determine limiting nutrients
Vientiane	Phonehong	1992	NPK	Determine limiting nutrients
Vientiane	Phonehong	1992	NPK	Determine limiting nutrients
Vientiane	Phonehong	1993	K	Identify appropriate rate
Vientiane	Phonehong	1993	N	Identify appropriate rate
Vientiane	Phonehong	1993	P	Identify appropriate rate
Vientiane	Phonehong	1993	K	Identify appropriate rate
Vientiane	Phonehong	1993	N	Identify appropriate rate
Vientiane	Phonehong	1993	P	Identify appropriate rate
Vientiane	Phonehong	1994	K	Identify appropriate rate
Vientiane	Phonehong	1994	P	Identify appropriate rate
Vientiane	Phonehong	1996	N	Evaluate green manure
Vientiane	Phonehong	1996	P	Evaluate green manure
Vientiane	Phonehong	1998	N	Interaction between residue and fertilizer management
Vientiane	Phonehong	1999-2000*	K	Compare 16-20-0 and 15-15-15
Vientiane	Phonehene	1997	P	Nursery P management
Vientiane	Thurakhom	1993	K	Identify appropriate rate
Vientiane	Thurakhom	1993	N	Identify appropriate rate
Vientiane	Thurakhom	1993	P	Identify appropriate rate
Vientiane	Thurakhom	1994	P	Identify appropriate rate
Vientiane	Thurakhom	1997	S	Determine limiting nutrients
Vientiane	Thurakhom	1997	P	Identify appropriate rate
Vientiane	Thurakhom	1999	P	Identify appropriate rate
Vientiane	Thurakhom	1996	NPKS	Compare compound and organic fertilizers
Vientiane	Thurakhom	1996	N	Interaction between variety and N
Vientiane	Thurakhom	1998	Lime	Response to lime
Vientiane M.	Naxaythong	1992	NPK	Determine limiting nutrients
Vientiane M.	Naxaythong	1993	N	Identify appropriate rate
Vientiane M.	Naxaythong	1993	P	Identify appropriate rate

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List of experiments continued.

Province	District	Year	Primary nutrient studied	Objective
Vientiane M.	Naxaythong	1994	N,P	Evaluate green manure
Vientiane M.	Naxaythong	1998	Lime	Response to lime
Vientiane M.	Naxaythong	1992-93	N	Evaluate green manure
Vientiane M.	Naxaythong	1999-2000*	K	Compare 16-20-0 and 15-15-15
Vientiane M.	Naxaythong	1999-2000*	Organic fert.	Compare organic and inorganic fertilizers
Vientiane M.	Saythany	1991	N	Evaluate green manure
Vientiane M.	Saythany	1991	N	Identify appropriate rate
Vientiane M.	Saythany	1991	P	Identify appropriate rate
Vientiane M.	Saythany	1991	N	Identify appropriate rate
Vientiane M.	Saythany	1991	P	Identify appropriate rate
Vientiane M.	Saythany	1992	NPK	Determine limiting nutrients
Vientiane M.	Saythany	1992	NPK	Determine limiting nutrients
Vientiane M.	Saythany	1992	NPK	Determine limiting nutrients
Vientiane M.	Saythany	1994	N	Interaction between variety and N
Vientiane M.	Saythany	1998	P	Nursery P management
Vientiane M.	Saythany	1998	N	Timing of N applications
Vientiane M.	Saythany	1999	N	Timing of first N application
Vientiane M.	Saythany	1999	N	Timing of first N application
Vientiane M.	Saythany	1992-97	N	Evaluate green manure
Vientiane M.	Saythany	1998-2000	P	Residual value of TSP and RP
Vientiane M.	Saythany	1999-2000*	K	Compare 16-20-0 and 15-15-15
Vientiane M.	Saythany	1999-2000*	Organic fert.	Compare organic and inorganic fertilizers
Vientiane M.	Sikhotabong	1991	N	Identify appropriate rate
Vientiane M.	Sikhotabong	1991	P	Identify appropriate rate
Vientiane M.	Sikhotabong	1991	N	Identify appropriate rate
Vientiane M.	Sikhotabong	1991	P	Identify appropriate rate
Vientiane M.	Sikhotabong	1992	NPK	Determine limiting nutrients
Vientiane M.	Sikhotabong	1997	N	Evaluate green manure
Vientiane M.	Sisantanak	1991	N	Evaluate green manure
Vientiane M.	Sisantanak	1991	P	Identify appropriate rate
Vientiane M.	Sisantanak	1991	N	Identify appropriate rate
Vientiane M.	Sisantanak	1991	P	Identify appropriate rate
Xieng Khouang	Kham	1997	NPKS	Determine limiting nutrients
Xieng Khouang	Kham	1999	N	Timing of first N application
Xieng Khouang	Pek	1993	NPK	Determine limiting nutrients
Xieng Khouang	Phaxay	1994	P	Identify appropriate rate
Xieng Khouang	Phaxay	1995	P	Identify appropriate rate
Xieng Khouang	Phaxay	1996	P	Identify appropriate rate
Xieng Khouang	Phaxay	1998	P	Identify appropriate rate and evaluate RP
Xieng Khouang	Phaxay	1999	N	Timing of first N application
Xieng Khouang	Phaxay	1999-2000	P	Residual value of TSP and RP

[a]TSP = triple superphosphate, RP = rock phosphate.