Zentrum für Entwicklungsforschung

Potential of organic manures in rainfed lowland rice-based production systems on sandy soils of Cambodia

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ABSTRACT

Rainfed lowland rice is the dominant food crop in the low-input agricultural systems of Cambodia. The main production area is characterized by sandy soils with low contents in nitrogen, phosphorus and organic matter, as well as low cation exchange capacity. The use efficiency of applied nutrients is reportedly very low, and the outcome of nutrient application strategies is highly variable. This study assesses the potential of organic manures to replace mineral N fertilizers in rainfed lowland rice-based production systems on sandy soils of Cambodia. It comprised field experiments and surveys. Four field experiments were conducted between 2013 and 2014 and differed by district and soil type (shallow vs. deep). Treatments compared the recommended rates of applied mineral N, with farmyard manure and mungbean (*Vigna radiate*) used as a pre-rice leguminous green manure. Legume treatments were further varied including with or without P application to the green manure and different residue management strategies (all residues returned, only grain harvested, all residues removed). The survey investigated farmers' perceptions regarding potentials and constraints to leguminous green manure adoption (here mungbean). The analysis of all manure-amended plots (farmyard and green manure combined) showed that organic manure could replace approximately 50% of the mineral N recommended for sandy soils. In addition, the use of organic amendments entailed significant increases in residual soil C and N after only one cropping cycle, suggesting that soil fertility may be enhanced in the long-term. In the case of mungbean green manure, the N_2 fixation measured by the δ^{15}N natural abundance varied from 9 to 78 kg N ha^{-1} (average of 36 kg N ha^{-1}). Highest N_2 fixation was associated with low rainfall intensity during legume establishment and the absence of soil flooding during the pre-rice period. Only on deep sandy soils, the addition of 10 kg P ha^{-1} to mungbean was able to more than double the amount of N_2 fixation compared to the legume without P amendment. The incorporation of P-amended legume residues (total biomass or after grain harvest) produced in both soil types rice grain yields that were comparable those obtained with the recommended mineral N application rate. Similarly, farmyard manure applied at 60 kg N ha^{-1} produced a rice yield comparable to mineral fertilizer N, however only in the deep soils. The study of farmers' perception and adoption of organic amendments highlights that the use of farmyard manure is widespread but that its efficiency to replace mineral N is highly soil-specific. However, the availability of farmyard manure will be increasingly constrained by declining cattle numbers. While the adoption of legume green manures is potentially high, their actual use is constrained by soil P availability and limited to sites without soil flooding during the pre-rice niche and to systems with sufficient labor availability of biomass incorporation. While organic amendments have the potential to replace mineral fertilizers, such options and use strategies are highly site- and system specific.

Keywords: rainfed lowland rice, green manure, farmyard manure, phosphorus, biological nitrogen fixation

Potenzial organischer Dünger in Reisanbausystemen auf sandigen Böden im Tiefland von Kambodscha

KURZFASSUNG

Regengespeister Nass-Reis ist das vorherrschende angebaute Nahrungsmittel in extensiven Agrarsystemen von Kambodscha. Die überwiegenden Teile des Anbaugebiets sind durch sandige Böden mit geringen Gehalten an Stickstoffgehalt, Phosphor, und organischer Substanz sowie niedriger Kationenaustauschkapazität geprägt. Auch die Nutzungseffizienz extern über mineralische oder organische Düngung zugeführter Nährstoffe ist in der Regel sehr gering und oft extrem variabel. Die vorliegende Studie untersucht das Potenzial der Anwendung organischer Dünger zu Nass-Reis im Regenfeldbau auf sandigen Böden in Kambodscha im Hinblick auf den Ersatz der kaum verfügbaren mineralischen N Dünger. Vier Feldexperimente wurden zwischen 2013 und 2014 durchgeführt. Sie unterschieden sich durch die Lage (Bezirk und Bodentyp – flachgründig vs. tiefgründig), die empfohlene Rate von mineralischem N und die Integrationen von Leguminosen in das Anbausystem (P-Anwendung zu Reis oder der Leguminose, Rückführung der Ernterückstände). Ferner wurde die Akzeptanz, Einschränkung und die Wahrnehmung von Bauern gegenüber Leguminosen als Gründünger im Vergleich zu Stallmist und Mineraldünger untersucht.

Die organische Düngung vermochte im Mittel etwa 50% der empfohlene Mineral-N-Düngergabe für sandige Böden zu ersetzen und gleichzeitig die Gehalte der Böden an organischem C und N bereits nach einem Anbauzyklus signifikant zu erhöhen, was eine Verbesserung der Bodenfruchtbarkeit bei längerfristigen Anwendung vermuten lässt. Im Falle von Gründünger (hier Mungbohne) variierte die N_2-Bindung, die mit Hilfe der natürlichen Abundanz-Methode (δ $^{15}N'$) gemessen wurde, zwischen 9 und 78 kg N ha^{-1} (durchschnittlich 36 kg N ha^{-1}). Hohe Werte der N_2-Bindung durch die Leguminosen waren mit geringem Niederschlag während der Vorfruchtperiode assoziiert, was darauf hinweist, dass die N_2-Bindung von der Bodenhydrologie (hier temporärer Wasserüberstau) beeinfluss wird. Auf tiefgründigen Böden führte die Zugabe von 10 kg P ha^{-1} zu Mungbohne zu einer Verdoppelung der N_2-Bindung verglichen zum Anbau ohne P- Zufuhr. Die Einarbeitung von Ernterückständen der Mungbohne erzielte in beiden Bodentypen vergleichbare Reiserträge wie bei empfohlener mineralischer N-Zufuhr. Eine Stallmistgabe, äquivalent zu 60 kg N ha^{-1}, erzielte ebenfalls einen Reisertrag vergleichbar dem einer empfohlenen Mineral-N-Düngung auf tiefgründigen, jedoch nicht auf flachgründigen Böden.

Die Akzeptanzstudie vermochte zu zeigen, dass die Nutzung von Stallmist in der Region weit verbreitet ist und mineralischen Dünger in Abhängigkeit des Bodentyps effizient zu ersetzen vermag. Allerdings ist die Verfügbarkeit von Mist durch sinkende Viehbestände in der Region zunehmend limitiert. Die Akzeptanz von Leguminosen zur Gründüngung im Regenfeld-Reisanbau ist potentiell hoch, allerdings unter den Voraussetzungen, dass hinreichend verfügbares P vorhanden ist, dass die Flächen während der Zwischenfrucht- Anbauperiode nicht überflutet sind, und dass Arbeitskräfte für die Einarbeitung der Biomasse zur Verfügung stehen. Ich kann gefolgert werden, dass Lösungsansätze und Technologie-Optionen zur organischen Düngung Standort- und System-spezifisch erfolgen müssen.

Schlüsselwörter: Nass-Reis, Gründünger, Stallmist, Phosphor, biologische Stickstoffbindung

LIST OF ACRONYMS AND ABBREVIATIONS

AE	Agronomic N use efficiency
ANOVA	Analysis of variance
BNF	Biological nitrogen fixation
^{0}C	Degree Celsius
C:N	Carbon to nitrogen ratio
Ca	Calcium
CASC	Cambodian agronomic soil classification
CEC	Cation exchange capacity
Cu	Copper
EC	Electrical conductivity
FYM	Farmyard manure
GM	Green manure
ha	Hectare
HI	Harvest index
K	Potassium
KCl	Muriate of potash
kg	Kilogram
kg ha^{-1}	Kilogram per hectare
LSD	Least significance difference
MFE	Mineral fertilizer equivalence
Mg	Magnesium
Mg ha^{-1}	Megagram per hectare
N	Nitrogen
Ndfa	Nitrogen derived from the atmosphere
Ndfs	Nitrogen derived from the soil
NGOs	Non-organisations
NH_4^+	Ammonium
NO_3^{-1}	Nitrate
^{15}N	Stable nitrogen isotope with the atomic mass of 15

P	Phosphorus
pH	Acidity (potential of protons)
SD	Standard deviation
SOM	Soil organic matter
SPSS	Statistical package for the social sciences
$t\ ha^{-1}$	Tonne per hectare
TN	Total nitrogen
TOC	Total organic carbon
TSP	Triple super phosphate
USDA	United states department of agriculture
Zn	Zinc

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1 GENERAL INTRODUCTION

1.1 Background and problem statements

Nutrient-deficient and highly weathered soils are common in most parts of the tropics (Feller and Beare 1997), where combined nitrogen (N) and phosphorus (P) deficiencies are a widespread problem on tropical soils (Smithson and Giller 2002). Mineral fertilizers are generally not affordable by subsistence-oriented farmers, leading to widespread nutrient deficiency in small-holder crop production systems (Glaser et al. 2002). Against this background, nutrient cycling from soil organic matter is a promising way to restore soil fertility (Tiessen et al. 1994). Therefore, organic amendments play a crucial role in both short-term nutrient supply and long-term build-up of organic matter (SOM) and soil quality improvement for small-scale farmers in tropical regions (Giller et al. 2006b; Palm et al. 2001a; Palm et al. 2001b).

Rice production occupies 154 million ha worldwide of which rainfed lowland rice covers 34% or approximately 54 million ha (Maclean et al. 2002). Lowland rice accounts for >70% of the global rice production (Fageria and Santos 2015). Lowland rice-growing areas are mainly found in South and Southeast Asia (Wade et al. 1999b) where rice is the main staple food (Maclean et al. 2002). Rainfed rice production is mainly constrained by irregular water supply (droughts and floods), low soil fertility, pests and weeds (Datta 1981; Maclean et al. 2002). Fertilizers are generally only applied in small doses due to the economic constraints among small-scale farmers. The large diversity between diverse rainfed environments, but also within confined areas and even within the same field, cause a large variability in hydrology and soil fertility situations (Wade et al. 1999b).

Long-term experiments in India and The Philippines showed a decline in soil N availability in lowland rice systems. The main causes are drying and flooding cycles that enhance gaseous N losses, little return of organic matter through crop residues, and a general absence of the use of symbiotic N_2-fixing systems under intensified cropping. As N is the main limiting nutrient for rice production, it must be either supplied by the soil or added in the form of mineral or organic N fertilizers (Kundu and Ladha 1999). However, a relatively low response of the rainfed rice to added mineral fertilizers is commonly reported and generally widespread. Additionally, this response is highly variable, inconsistent across various studies (Boling et al. 2004) and often unreliable (Wade et al. 1999a; Willett 1995), suggesting a need for flexible and condition-specifically adapted management strategies (Haefele et al. 2006). Previous findings show the potential of organic amendments. Thus, a study by Haefele et al. (2006) reported improved response and use efficiency of rice when organic fertilizers were applied to sandy soils in rainfed environments. Site-specific organic amendments have been shown to enhance rice yields, to substitute for inorganic fertilizers (Bi et al. 2009), and to sustain soil productivity by building soil organic matter (Yan et al. 2007). Therefore, the systems' internal resources, particularly locally available organic materials such as farmyard manure (FYM) and N supplied from biological N_2 fixation (BNF), need to be more widely exploited.

Since the mid-1980s, a frequently advocated strategy has been the use of both post-rice and pre-rice leguminous green manures. Besides adding substantial amounts of biologically-fixed N, maintaining soil-N content and generally improving soil physical, chemical and biological properties, green manuring has been shown in around 270 studies to substantially increase paddy rice yields. Kundu and Ladha (1999) showed that the N balance resulting from BNF was as high as 19-38 kg N ha^{-1}, 28-33 N ha^{-1} and 30-52 kg N ha^{-1} in lowland rice-based systems of Japan, Thailand and The Philippines, respectively. Experiments conducted at the International Rice Research Institute (IRRI) showed that BNF from the legume species *Sesbania* (river hemp) and *Azolla* (an aquatic fern) was much higher than in urea-amended treatments (Kundu and Ladha 1999). *Azolla* provided N inputs from 70-110 kg ha^{-1}, while *Sesbania* sp. fixed 55-90 kg ha^{-1} N (Ventura and Watanabe 1993). The use of *Sesbania* and mungbean (*Vigna radiata*) as green manure for rice-wheat cropping systems increased the rice yield up to 0.4 t and 0.3 t ha^{-1}, respectively (Sharma et al. 1995). There is considerable evidence that green manure stands as a good candidate for soil fertility improvement. Becker et al. (1990) revealed that legume species such as *Sesbania rostrata* and *Aeschynomene afraspera* performed well as fertilizers for lowland rice because of their ability to fix N_2 and yield high biomass, resulting in a significant rice yield increase. Soybean *(Glycine max)* also shows a high N contribution from BNF (up to 70% Ndfa), compared to *Phaseolus* beans (23% Ndfa) at flowering (George et al. 1992). The N accumulation by rice was higher following a soybean crop than after non-nodulating groundnut or maize. Soybean also increased the rice dry matter compared to maize as a pre-rice crop (Schulz et al. 1999).

Despite these positive reports, the adoption of green manure technologies remains low and is even declining in many parts of Asia (Ladha and Garrity 1994). Numerous factors have been advanced to explain farmers' reluctance to adopt green manures. The lack of an available time window for a green manure to occupy the field, the lack of appropriate seeds, labor constraints for green manure application, and the absence of immediate economic benefits from a green manure measure are the main culprits for the decline in green manure use. Apart from green manure, manure from livestock is considered as an important component for sustainable crop production because of its N, P and potassium (K) content (Mishima et al. 2012). The positive effect of organic manure on rice crops was attributed to the increase in soil-organic carbon and soil nutrient supplies over a long-term period (Bi et al. 2009; Meng et al. 2005). Bi et al. (2009) further reported that organic manure could substitute 30-70% of the mineral-N fertilizers used for rice production in China.

In summary, both leguminous green manures and farmyard manure are promising potential sources of C and N for lowland rice–based systems. However, adoption at farm-level is often constrained by various factors that need to be site-specifically addressed. This had so far not be done for the case of rainfed rice in Cambodia.

Rainfed lowland rice is the dominant food crop in the low-input agricultural systems of Cambodia. The main production area is characterized by highly weathered sandy soils with low N and organic matter contents (Seng et al. 2001). General low soil fertility, and particularly extremely low soil-available P content (White et al. 1997) severely limit rice growth (Seng et al. 2004a). These soils have a low specific surface area with low activity material dominating the clay fraction, resulting in a low cation exchange capacity (CEC) and concomitantly poor nutrient and water holding capacities. Arguably, if these unfavorable soil traits could be ameliorated, fertilizer and water use efficiencies could be improved, which in turn would contribute to increase rainfed rice yields in Cambodia (Pheav et al. 2005).

The sandy soils in the rainfed lowland area of Cambodia are differentiated into two main categories, i.e. the Prey Khmer (deep sand) and the Prateah Lang (shallow sand fraction overlaying a loam/clay subsoil). The use efficiency of applied nutrients is reportedly very low and the outcome of nutrient application strategies is highly variable (Bell et al. 2006). In addition to unfavourable soil attributes, the reported high variability in rice yields is also influenced by environmental stress, i.e. unreliable rainfall. Mineral fertilizers are also not affordable by many small-scale farmers in Cambodia. The farmers are therefore concerned with the low economic return from mineral fertilizer application (Ros et al. 1997).

Locally-available organic manures to address soil fertility constraints are gaining importance, particularly in areas with high cost and/or low availability of mineral fertilizers. Such organic materials may comprise crop residues, i.e. rice straw and stubble farmyard manure, and green manures either from leaf litter from adjacent areas or from leguminous crops in rotation with rice. In a few cases, compost use is frequently promoted by NGOs, however this option is limited to a few skilled farmers with a high labor availability (pers. observation in Tram Kak district).

Among diverse organic materials, FYM is the organic source most commonly utilized by small-scale farmers. This is due to the fact that cattle is primarily used for draught power (Serey et al. 2014), and thus also provides manure for crop production as an additional benefit. Ly et al. (2012) reported that FYM was one of the factors determining rice yields in Southern Cambodia. However, the number of cattle varied from farmer to farmer and location to location, resulting diverse availability. For instance, Ly et al. (2012) and Serey et al. (2014) reported that farmers own 2 to 3 heads per household, while Pen et al. (2009) reported 4 to 5 per household. As the availability of FYM is very limited, application is generally prioritized to plots near to the homesteads (Ly et al. 2012). For the small-scale farmers who own few or no cattle, availing of sufficient amounts of FYM is a key challenge. Often application rates are too low to satisfy the nutrient demand of rice for more than low to moderate yields (Kho 2000). Furthermore, it was reported that there was a decline in small-scale cattle raising in Cambodia by 11% (MAFF 2015). Therefore, there is a need to explore alternative options that are site- and system-specific rather than to rely solely on FYM. Another option is to explore the contribution of additional N from biological fixation by short-duration legumes as green manure. Green manure (particularly from grain legumes) has been reported as a more promising option to address the soil fertility constraints and to contribute to yield increases. Seeds are available and can be broadcasted at the onset of the rains, and the biomass (after harvesting green pods) can be incorporated directly into the soil during land preparation. Benefits of such measures comprise soil fertility management (Wortmann et al. 2000), building of soil organic matter (Toomsan et al. 2000), substitution of mineral fertilizer, and potential savings of native soil N (George et al. 1992).

However, the adoption of green manure is also tied to the multi-purpose character of a crop, and the sole use as green manure will not be acceptable in most situations. Forage legumes are of little interest in Cambodia due to the low number of heads of cattle per household. Thus, only potential grain legumes are seen fit to be used in the rainfed systems on the sandy soils there. Non-grain, forage legumes and woody multipurpose plants are thus not of interest. Soil texture also needs to be taken into account when introducing green manure in the system. Ladha and Garrity (1994) compared the effect of green manure and mineral N. When the sand content increased, the N use efficiency decreased. However, the N-use efficiency of legume N was higher than that of urea N under sandy soils. This finding indicates that it could be of interest to include legumes in the rice cropping system in Cambodia, where sandy soils are predominant.

Several fast-growing grain legumes may fit during the fallow period between two rice crops. Here, mungbean is the most promising species (Kundu and Ladha 1999). It has a growth duration from seed to seed of <70 days, and can thus easily fit into the pre-rice niche of rainfed environments. This legume can be grown with the onset of the first rain in April (or May in a few cases), and possibly harvested for grain, and/or incorporated as green manure in the process of land preparation prior to rice cultivation. Sharma et al. (1995) found that mungbean residue incorporation had positive effects similar to those of *Sesbania* on grain and straw yield, which were more pronounced than those of pre-rice fallow. Mandal et al. (2003) showed that mungbean also improved soil organic matter resulting in better soil aggregation, reduced bulk density and better water flow. Senarane and Ratnasinghe (1993) reported that some grain legumes, including mungbean, have a potential as biofertilizer for rice and could be well-adapted to rainfed lowland rice. Consequently, mungbean could be suitable for use as a green manure crop in Cambodia. However, being an upland legume, mungbean will not tolerate prolonged periods of anoxic soil conditions and flooding may well become a key production constraint for mungbean growth during the pre-rice niche, in years when the rains start early. Furthermore, a deficiency of soil-available P will restrict legume BNF. This was evident by the response of legumes to P application as reported by Gunawardena et al. (1992) and Hayat et al. (2008). Thus, the low soil-available P in the sandy soils in Cambodia (Seng et al. 2001) may entail low N_2 fixation by legume crops. Conversely, if P is applied to the legume instead of to rice, the enhanced BNF by the legume may stimulate directly the performance of the legume and indirectly that of rice upon green manure incorporation.

1.2 Hypothesis, goals and objectives

Reportedly, N and P deficiencies are widespread constraints in rainfed lowland rice production systems of Cambodia, whereby N is the most limiting nutrient element for rice. Mineral fertilizer sources are often unaffordable to small-scale producers (Blair and Blair 2014; Morris et al. 1986). In addition, the efficiency and profitability of the recommended application rates is highly variable and often low (Seng et al. 2001). There is a need for differentiated, system-specific adapted solutions using locally available organic materials.

Besides serving as draught power, cattle provide manure as an organic source (Serey et al. 2014). Farmyard manure is widely used, but the number of farm animals increasingly limits FYM availability in Cambodia. Since the time span between the onset of the first rains and the transplanting of wet-season rice ranges from 50-75 days, it appears possible to include a short-duration legume in the pre-rice niche. Such niches where green manures can be competitive with mineral fertilizer application have been defined and are reportedly characterized by (1) rainfed conditions (low N-use efficiency of mineral N sources due to alternate drying and wetting cycles), (2) sandy soils (high mineral N losses, mainly by nitrate leaching) and (3) a sufficient supply of P (usually >5ppm available P required for legume BNF) (Becker et al., 1994; Carsky et al. 1998). In addition, the use of green manures with multiple uses (feed stuff and grain in addition to fertility improvement) has been shown to enhance adoption rates. Such conditions (rainfed agriculture combined with sandy soils) prevail in Cambodia (provided that P can be supplemented), making the country an ideal candidate for future green manure use in rice.

It is hypothesized that green manuring with a short-cycled grain legume (mungbean) during the pre-rice niche may be a suitable technology to address the prevailing soil fertility constraints and to enhance rice productivity, provided that P is available. The main goal of the study is to assess the potential and the adoptability of green and other organic manures in combination with P-fertilizer strategies on different sandy soils of Cambodia. The following objectives will be addressed:

- Assess mineral N fertilizer equivalence of organic manures in rainfed lowland rice systems.
- Assess P-application strategies on performance and biological N_2 fixation of mungbean

- Assess rice yield response to different mineral and organic fertilizer management options
- Assess adoption, constraints and farmers' perceptions of leguminous green manure.

1.3 Thesis outline

This thesis consists of seven chapters. The first chapter elaborates the research background and reviews relevant aspects of rainfed rice and the use of organic amendments. Chapter 2 provides an overview of the general methodology applied in this study. Chapter 3 assesses the possibility of mungbean residues and farmyard manure as alternatives to mineral fertilizer. Chapter 4 investigates the effect of P-application strategies on the performance and biological N_2 fixation of mungbean as a green manure. Chapter 5 compares the rice yield response to different fertilizer management options. Chapter 6 assesses adoption, constraints and farmers' perceptions of leguminous green manure. Finally, Chapter 7 presents the general discussion, conclusions and research outlook.

2 GENERAL METHODOLOGY

2.1 Study region

Cambodia covers an area of 181.035 km^2 and borders on Thailand, Lao and Vietnam. In the main rice-growing Takeo province in southern Cambodia, the districts Tram Kak (90 km from the capital city Phnom Penh) and Prey Kabas (65 km from Phnom Penh) were selected for this study. Sandy soils, which are the most common soil types for rice production in Cambodia, dominate in these districts.

According to the Köppen-Geiger classification (Peel et al. 2007), the climate in the study areas belongs to the Tropical Rainforest type (Af) and is characterized by one distinct wet season between May and October and a dry season between November and April. Annual rainfall ranges from 1, 250 to 1,750 mm (White et al. 1997) with highest precipitation occurring in October. The temperatures vary from 21°C in November-January to 35°C in April-May.

Table 2.1 Selected biophysical and socio-economic attributes of the study districts in Cambodia

Parameter	**Districts**	
	Tram Kak	**Prey Kabas**
Total land area	54,694 ha	26,910 ha
Cultivated area	35,677 ha	20,737 ha
Area under wet-season rainfed rice (%)	32,322 ha (86)	10,419 ha (88)
Population	171,532	103,294
Total number of families	34,629	20,916
Number of families engaged in agriculture (%)	33,445 (97)	19,206 (92)
Families engaged in rice farming (%)	33,415 (96)	19, 179 (92)

Source: National Committee for Sub-National Democratic Development (NCDD): Prey Kabas and Tram Kak districts data book of Takeo province, Cambodia 2009. Data of year 2008.

Most lowland areas in the study districts are under paddy rice cultivation. One single crop of wet-season rice is mostly cultivated, but two crops per year are also possible in some parts. Most of the fields are left to bare fallow during the dry season, while crops may be grown during the short dry-to-wet season transition period in the pre-rice niche before the onset of the main rainy season, or in the post-rice niche using the residual soil moisture after the rice harvest. Such crops comprise vegetables (e.g. cucumber, radish, mustard, etc.), mungbean, soybean, maize and groundnut. In both study districts, the most common diversification option in the rice cultivation systems is mungbean, both during the early wet season (pre-rice niche) as well as in the early dry season (post-rice niche) provided that irrigation is available. Fields and farmers were selected in the Tram Kak and Prey Kabas districts (Figure 1), which represent the dominant rice cropping areas. Selected physical and chemical properties of the experimental soils are provided in Table 2.9.

2.2 Soil groups

The Cambodian Agronomic Soil Classification (CASC) system differentiates 11 soil groups for rice production. Most common among those are the groups Prey Khmer (PK) and the Prateah Lang (PL), which occupy 39% of the total rice-growing area (Bell and Seng 2003) and represent generally phosphorus-(P)-deficient soils with a sandy surface horizon. The main difference between the two soil groups is the thickness of the topsoil and the texture of the subsoil. While the Prateah Lang group has a shallow sandy topsoil of 10-25 cm overlaying a loamy clay subsoil, the Prey Khmer has a deep sandy topsoil of 40-100 cm overlaying a sandy subsoil (Bell and Seng 2003). Both soil groups have been formed on pleistocene alluvial/colluvial and lacustrine sediments that have developed by the weathering of mesozoic sandstone parent material (White et al. 1997). The deep sandy Prey Khmer group occupies 10-12% and the shallow Prateah Lang group 25-30% of the total lowland rice growing area (White et al. 2000; White et al. 1997). Both soils are classified as Fluvisol (some also as Luvisols, Acrisols or Planosols, White et al. 1997) according to the World Reference Base (FAO, 1996). According to USDA, deep sandy soils are classified as Entisol or Ultisol, while the shallow Prateah Lang soil is classified as Alfisol.

2.3 Field experiments

2.3.1 Experimental sites

A total of four field experiments was conducted in farmers´ fields in 2013 and 2014. Their location in southern Cambodia is depicted in Figure 2.1.

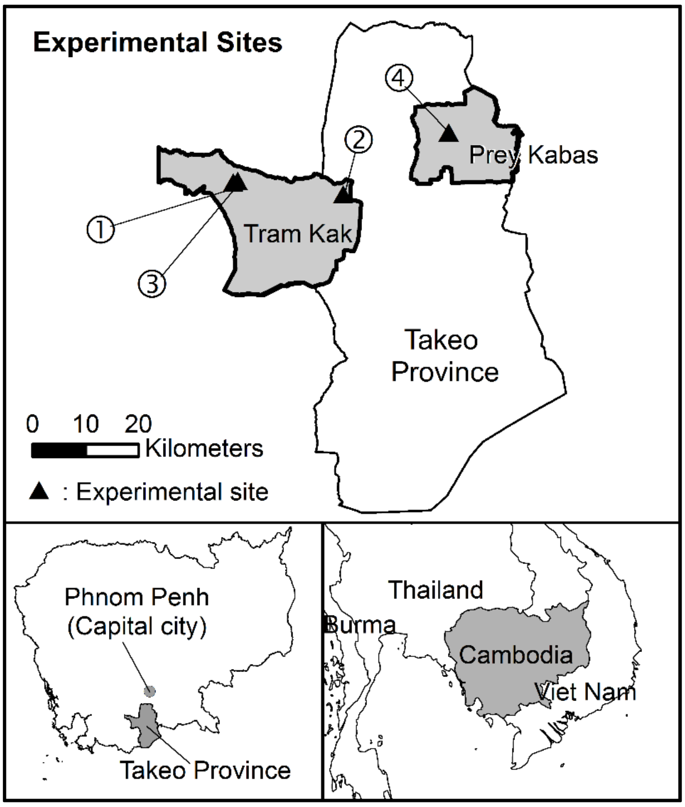


Figure 2.1 Locations of the experimental sites in Cambodia

2.3.2 Experimental design and treatment application

The four field experiments differed by site (district) and soil type (shallow vs. deep), and treatments compared the soil-specific recommended rates of applied mineral N with farmyard manure (FYM) and pre-rice mungbean green manure, whereby the mungbean grew either with or without added P, and crop residues were either all retained (green manure legume use), grains were harvested (grain legume use) or all residues were removed (forage legume use) application, residue management). All plots were surrounded by field bunds reinforced by dug-out grass plagges obtained from neighboring fields. The native weed germination was allowed to occur in the bare fallow plots during the dry-to-wet season transition period. In all other plots, weeds were removed manually and pests controlled as required. Plots were randomly arranged and replicated 4 times with plot sizes varying between 16 and 25 m^2. All fields were fenced to prevent trespassing of grazing animals. Details to the four field experiments are presented thereafter.

Field experiment 1, 2013: In the first experiment, the recommended mineral fertilizer-N application to rice following a period of bare fallow was compared with the use of pre-rice mungbean green manure (CMB3 variety) both in the absence and presence of applied mineral P. The experiment was conducted in the Tram Kak district (11^{0}04’36.3’’N, 104^{0}32’13.2’’E) on the deep Prey Khmer sandy soil using a randomized complete block design with four replications and a plot size of 4 m x 4 m. Because of the poor performance of mungbean, the rice crop received a basal application consisting of farmyard manure at a rate equivalent to 60 kg N ha^{-1}, and 4 kg and 30 kg ha^{-1} P and potassium (K), respectively. The treatments comprised three-split mineral-N applications (0, 14, and 28 kg urea-N ha^{-1}) to the rainfed lowland rice following a period of bare fallow during the dry season and the dry-to-wet season transition period, and two organic manure treatments. Here mungbean was cultivated for a period of around 8 weeks during the dry-to-wet season transition period prior to wetland rice, either in the absence or the presence of mineral P (10 kg ha^{-1}) applied as triple super phosphate (TSP). In case of no P amendment to the green manure, the equivalent P fertilizer was applied to the rice. The nutrient application schedule and rates are presented in Table 2.2.

Field experiment 2, **2013**: In the second experiment, the recommended mineral fertilizer applications were compared with application of farmyard manure in the Tram Kak district (11^{0}03’23.5’’N, 104^{0}43’25.2’’E) on the shallow Prateah Lang sandy soil in a randomized complete block design. Accordingly, the recommended mineral fertilizer application rates were higher than in experiment 1 (Table 2.3), and the plot size was increased to 4 m x 5 m.

Table 2.2 Treatments, seasonal management and nutrient application in field experiment 1 on the deep Prey Khmer Fluvisol, Tram Kak district, Cambodia, 2013

Treatment	**Pre-rice period**	**Wet season**	**NPK (kg ha^{-1})**
1. Urea 0	Bare fallow	No N + PK	00/04/30[1]
2. Urea 14	Bare fallow	14 kg N + PK	14/04/30
3. Urea 28	Bare fallow	28 kg N + PK	28/04/30
4. Grain legume –P/FYM + P	Mungbean	BNF[2]-N+FYM+10 kg P+K	61/19/79
5. Grain legume +P/FYM - P	Mungbean + 10 kg P	BNF-N+FYM + K	70/9/79

FYM = farmyard manure applied basally at a rate equivalent to 60:09:49 kg NPK ha^{-1}; BNF = biologically-fixed nitrogen

[1] *K and P rate consists of a basal mineral application of 4 and 30 kg ha^{-1} as muriate of potash (KCl) and TSP respectively.* [2] *The amount of N derived from biological nitrogen fixation by the mungbean was estimated at 1 kg N ha^{-1} for treatment 4 and at 10 kg N was for treatment 5.*

Table 2.3 Treatments, seasonal management and nutrient application schedule and rates in field experiment 2 on the shallow Prateah Lang Fluvisol, Tram Kak district, Cambodia, 2013

Treatment	Pre-rice period	Wet season	NPK (kg ha^{-1})
1. Urea 0	Bare fallow	No N + PK	0/10/25[1]
2. Urea 25	Bare fallow	25 kg N + PK	25/10/25
3. Urea 50	Bare fallow	50 kg N + PK	50/10/25
4. Farmyard manure -P	Bare fallow	FYM + K	60/17/89
5. Farmyard manure +P	Bare fallow	FYM + PK	60/7/89

FYM = farmyard manure applied basally at the rate equivalent to 60:07:64 kg NPK ha^{-1}.
[1] P and K rate consist of a basal mineral application of 10 kg P ha^{-1} and 25 kg K ha^{-1} as TSP and KCl, respectively

Field experiment 3, 2014: In the third experiment, the recommended mineral fertilizer N rate was compared with the use of pre-rice mungbean (CMB3 variety) with and without applied mineral P. In this study, however, the type of residue management of the mungbean was modified, including (1) the green manure treatment or “all residues returned” as in experiment 1, with (2) only grains removed and stover returned as with a food grain legume, and (3) all residues removed as with a forage legume. The experiment was conducted in 2014 in Tram Kak district (11^{0}04’36.3’’N, 104^{0}32’13.2’’E) on the deep Prey Khmer sandy soil. The 9 treatments were laid out in a randomized block design with four replications and a 5 m x 5 m plot size. The treatments and nutrient application schedules and rates are presented in Table 2.4.

Table 2.4 Treatments, residue management and nutrient application schedule and rates in field experiment 3 on the deep Prey Khmer Fluvisol, Tram Kak district, Cambodia, 2014

Treatment	**Pre-rice period**	**Wet season**	**NPK (kg ha^{-1})**
1. Urea 0	Bare fallow	No N + PK	0/04/30[1]
2. Urea 14	Bare fallow	14 kg N + PK	14/04/30
3. Urea 28	Bare fallow	28 kg N + PK	28/04/30
4. Green manure - P	Mungbean	BNF-N[2] + 10 kg P + K	09/10/30
5. Green manure + P	Mungbean + 10 kg P	BNF-N + K	21/00/30
6. Grain legume – P	Mungbean	BNF-N + 10 kg P + K	09/10/30
7. Grain legume + P	Mungbean + 10 kg P	BNF-N (stover) + K	21/00/30
8. Forage legume – P	Mungbean	10 kg P + K	00/10/30
9. Forage legume + P	Mungbean + 10 kg P	+ K	00/00/30

BNF = biological nitrogen fixation

[1] *P and K rate consists of a basal mineral application of 04 kg P and 30 kg K ha^{-1} as KCl and TSP, respectively.*

[2] *The amount of N derived from biological nitrogen fixation by the mungbean was estimated at 21 (in case +P) and 09 (in case –P) kg N ha^{-1} in the green manure and grain legume residue management treatment. In the forage legume treatment, all biologically fixed N was removed with grains and stover.*

Field experiment 4, 2014: In the fourth experiment, different residue management of pre-rice mungbean (CARDI Chey genotype) was compared, comprising incorporation of mungbean residues after grain harvest as with grain legume production with “all residues removed” as with a forage legume. The experiment was conducted on the shallow Prateah Lang soil in Prey Kabas district, Takeo province (11°09’42.7”N, 104°54´10.7”E). The three treatments involved residual management of legume with and without mineral fertilizer N applied to wet-season rice (Table 2.5). The experiment was laid out in a randomized complete block design.

Table 2.5 Treatments, and nutrient application schedule and rates in field experiment 4 on the shallow Prateah Lang Fluvisol, Prey Kabas district, Cambodia, 2013

Treatment	Pre-rice period	Wet season	NPK (kg ha^{-1})
1. Forage legume + Urea 50	Mungbean + FYM[1]	BNF-N[2] + 50 kg N + PK	50/10/25
2. Green manure – Urea	Mungbean + FYM	BNF-N + PK	78/10/25
3. Green manure + Urea 50	Mungbean + FYM	BNF-N + 50 kg N + PK	128/10/25

[1] Farmyard manure applied basally in pre-rice legume at a rate equivalent to 78/09/83 (N/P/K kg ha^{-1})
[2] The amount of N derived from biological nitrogen fixation by the mungbean was estimated at 78 kg ha^{-1}. In the forage legume treatment, all biologically fixed N was removed with grains and stover.

2.4 Plant material

Mungbean *(Vigna radiata)* was chosen as pre-rice legume due to its short growth duration, the wide availability of seeds officially released by research institutions in the country, and its popularity, together with a general and wide adoption and local acceptance of the crop in prevailing production systems. Depending on the district and the soil type, two mungbean varieties obtained from the Cambodian Agricultural Research and Development Institute were selected. Their main attributes are presented in Table 6. Mungbean seeds were established at a 20 cm x 20 cm spacing (one seed per hill) after manual land preparation in the paddy fields and left to grow for a periods of 55-56 days. The establishment of the crops varied by site and the onset of the first rains between 11 April (experiment 3 in 2014) and 26 April (experiment 4 in 2014) and harvested/incorporated between 15 and 23 June. In experiment 1, the mungbean was planted in 15 May 2013 and harvested/incorporated 13 July 2013.

The lowland rice (*Oryza sativa* L.) used in the study was the semi-traditional rainfed lowland genotype Phkar Rumdoul (Kamoshita et al. 2009). Certified seeds were obtained from the Cambodian Agricultural Research and Development Institute. Selected varietal attributes are presented in Table 7. Seeds were seeded at a rate of 6 g m^{-2} into a nursery and transplanted at an age of 21 days at a 20 cm x 20 cm spacing into the puddled paddy field plots. Depending on the site and the year, the rice was seeded between 25 July and 1 August, transplanted between 21 and 26 August, and harvested between 24 November and 2 December.

Table 2.6 Selected attributes of the mungbean (*Vigna radiata L.)* varieties used in the field experiments (Cambodia 2013-2014)

Characteristic	**Mungbean varieties**	
	CMB3	**CARDI Chey**
Year of release	2009	2001
Line origin	ATF 3944 (Australia)	VC1973A (AVRDC)
Plant height (cm)	50-100	50-73
Days to flowering (day)	30	35
First pod harvest (day)	50	55
Average yield (t ha^{-1})	0.853	0.61
Achievable yield (t ha^{-1})	1.9	1.9

Source: Cambodian Agricultural Research and Development Institute, 2005 and 2009

2.5 Farmyard manure source and application

Farmyard manure was applied in form of cow dung, which was locally collected. It was applied on a fresh weight basis to each plot as basal at the beginning of the rice growth in the wet season. It was then incorporated into the soil during the first land preparation 15-20 days before rice establishment using a spade at a depth of approximately 20 cm. The amount of manure needed was calculated based on its N-percentage content regardless of moisture content, because the total N was analyzed on a wet basis at site-specific moisture. To estimate the 60 N kg ha^{-1} derived from the manure, the percentage of total N, P and K was analyzed at the National Agriculture Laboratory of Ministry of Agriculture, Forestry and Fishery. The site-specific total N, P and K content of the soils is shown in Table 2.8

Table 2.7 Selected attributes of the rainfed lowland rice variety Phkar Rumduol used in all field experiments

Characteristic	**Value**
Released year	1999
Variety type	Medium-period
Flowering period	Mid-October
Photoperiod type	Photoperiod-sensitive
Plant Height (cm)	110-170
Productive tillers per plant	5-10
No. of grain per grain	110-150
Panicle length (cm)	18-28
Average yield (t ha^{-1})	3.5
Potential yield (t ha^{-1})	5.5

Source: Cambodian Agricultural Research and Development Institute, 2002

Table 2.8 Total nitrogen, phosphorus and potassium content in farmyard manure (FYM) used in experiments

Content/experiment	**Experiment 1**		**Experiment 2 and 4**	
	Content (%)	**Nutrient (kg ha^{-1})**	**Content (%)**	**Nutrient (kg ha^{-1})**
Nitrogen (N)	1.22	60	0.78	60
Phosphorus(P)	0.19	09	0.09	07
Potassium (K)	1.00	49	0.83	64
FYM application rate (t ha^{-1})	4.92		7.69	

1) *Total N, P and K analysis was done using Kjeldahl's sulfuric acid, Spectro Molybdovanadophospate and Flame Photometer methods, respectively.*
2) *The FYM was analyzed at the National Agricultural Laboratory, Ministry of Agriculture, Fishery and Forestry, Cambodia.*

2.6 Mineral fertilizers

Urea was applied to the rice as a source of N while the site-specific fertilizer P and K were applied as basal through triple super phosphate (TSP) and muriate of potash, respectively, whereas 30% of N was applied as basal, 40% at tillering (30 days after transplanting) and the remaining 30% at panicle initiation. The rate of fertilizer in each treatment was converted to the equivalent amount per plot. Triple-Superphosphate (TSP), which is not commonly used in Cambodia, was used as the P source. TSP contained 46% P_2O_5 (20% P), and was analyzed to confirm the P contents at the National Agricultural Laboratory, Ministry of Agriculture, Fishery and Forestry, Cambodia in 2014. The recommended fertilizer rates for the two sites with their different sand profile depths are 50:10:25 NPK for the shallow-sandy soil (Prateah Lang) and 28:4:30 NPK for the deep-sandy soil (Prey Khmer) (Cambodia Agricultural Research and Development Institute, 2010).

2.7 Climatic data

In general, in the two study years rain did not fall frequently during the main wet season at the study sites, especially at the early stage of rice growth. Thus, supplementary irrigation was done. Only occasional supplementary irrigation was necessary at the Prateah Lang site as the soil could retain water well and the standing water remained in the plots, while frequent irrigation was necessary for the very deep sandy soil at the Prey Khmer site. Simple atmospheric and temperature gadgets were installed at each site, except for the experimental site in Prey Kabas. Measurements were taken three times a day at 8:00 am, 12:00 pm and 17:00 pm. The values were averaged to represent data for each day. For measuring daily rainfall, a plastic beaker with 10 cm diameter and 14 cm height was installed, and rainfall recorded immediately after the rain had stopped. At the Prey Kabas site, no meteorological data were recorded and the provincial data were used.

2.8 Soil sampling and analysis

Soils were sampled twice. The first samples were taken prior to the commencement of each experiment and the second after the end of the experiments. All samplings were done on composited bases by collecting samples at five points and mixed for one sampling unit. The soil was sampled at 20 cm depth. The soil was sampled at 20 cm depth. Fresh samples were air-dried for 5-7 days and sieved at 2 mm. All samples were transported to Germany and analyzed at the Institute of Crop Science and Resource Conservation, Department of Plant Nutrition, University of Bonn, for CEC, total N, total organic C, available P (Olsen), and available K; pH, EC and texture were determined at the Faculty of Agronomy, Royal University of Agriculture, Cambodia. The pH and electrical conductivity (EC) of the soil were measured using the ratio 1:5 with respective portable meters (Vernier LabQuest reference Guide, version 1.1). Total N and total organic C were determined using an automatic elemental analyzer (Euro EA Elemental Analyzer series 3000). The cation exchange capacity (CEC) of the soil was analyzed using the BaCl$_2$-TEA pH 8.2 method. The Olsen method (soil extraction NHCO$_3$, pH 8.5) was used for available P and K analyses. Texture was determined using the Pipet method.

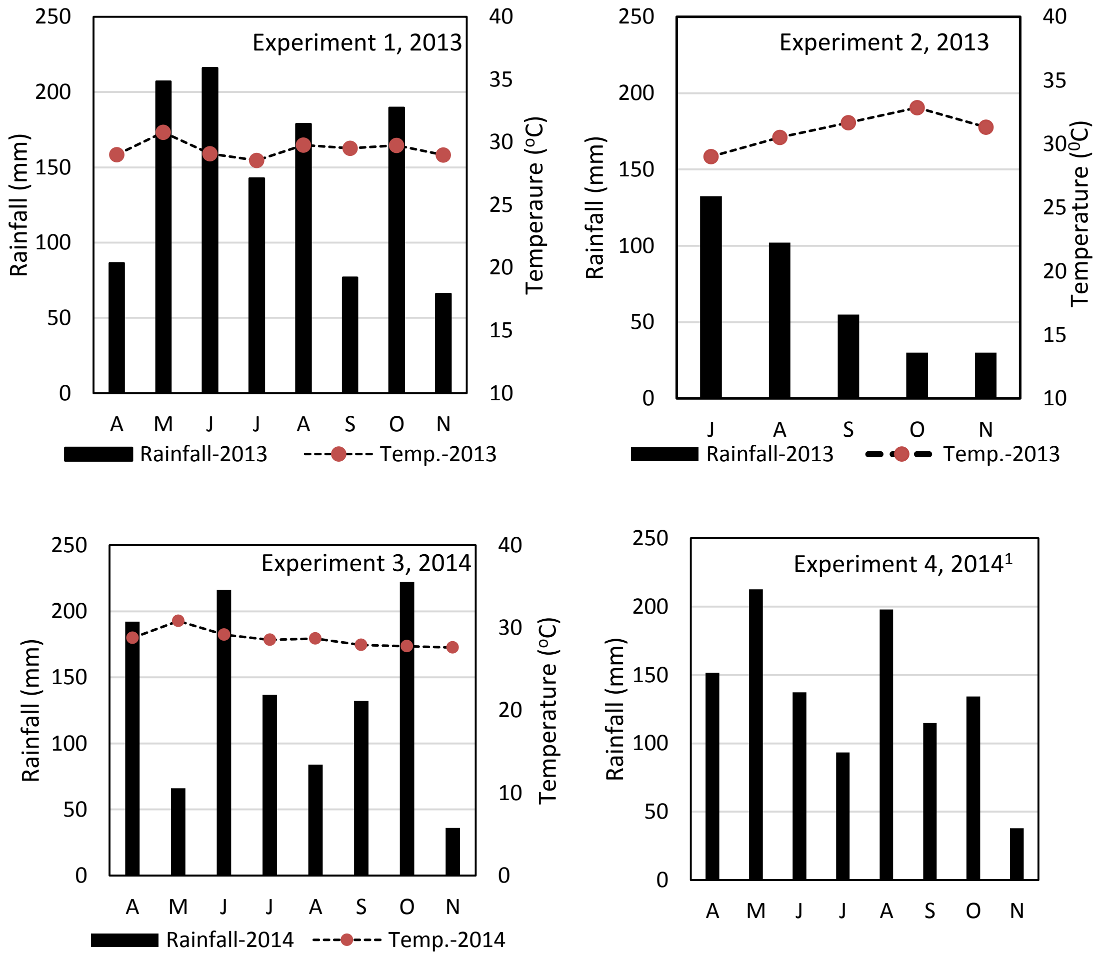


Figure 2.2 Rainfall and cumulative rainfall in the four experimental sites.

[1] *Takeo provincial data; temperature data was not available.*

2.9 Statistical analyses

All data were checked for normality of distribution, statistically analyzed by ANOVA for significance, and mean values separated by least significant difference (LSD). Both ANOVA and mean comparison were assessed using Stastitix 8 (Version 8.0, Analytical Software, 1985-2003). The data sets 'with and 'without P' were compared using a "t-test".

Table 2.9 Selected attributes of the experimental soils analyzed prior to each experiment

Property	**Deep Fluvisol (Expt. 1)**	**Shallow Fluvisol (Expt. 2)**	**Deep Fluvisol (Expt. 3)**	**Shallow Fluvisol (Expt. 4)**
pH (water, 1:5)	5.67	5.74	5.68	5.7
EC (dS/m)	0.03	0.03	0.06	0.05
CEC (cmolc /kg)	1.10	0.44	0.08	-
Total N (g kg^{-1})	0.14	0.14	0.15	0.20
Total organic C (g kg^{-1})	1.22	1.75	1.74	1.74
Available P (mg kg^{-1})	<1	2.00	2.70	2.30
Available K (mg kg^{-1})	0.02	0.05	0.03	-
Sand (%)	92.7	86.3	88.7	80.3
Silt (%)	2.6	8.4	4.6	14.5
Clay (%)	4.7	5.3	6.7	5.2
Texture class[1]	Loamy sand	Loamy sand	Loamy sand	Sandy loam

[1] *Texture was determined for the upper 20 cm of the soil.*

3 ASSESSING ORGANIC MATERIALS AS ALTERNATIVE TO MINERAL FERTILIZER

3.1 Introduction

Rice (*Oryza sativa*) is globally the most important food crop. As the world is demanding more rice and an expansion of production areas in Asia is no longer possible, the productivity of rice needs to be increased (Wade et al. 1999b). In Cambodia, rainfed lowland cropping systems dominate the rice production sector, whereby one single crop of wet-season rice is followed by an extended period when the land is left to fallow during the dry season (Seng et al. 2008).

Besides an unreliable water supply, the poor fertility of most rainfed lowland soils is the main constraint limiting rice production in Cambodia (Seng et al. 2004a). Some 39% of the rice-growing areas are characterized by sandy Fluvisols belonging to the Prey Khmer (deep sand profile) and Prateah Lang soil groups (shallow sandy topsoils overlaying a clay layer), according to the national soil classification system for rice production. With >80% sand fractions, both soil types are typically associated with low organic C and available P, and widespread deficiencies in micro-nutrients (Bell and Seng 2003). The most limiting nutrient element, however, is nitrogen (N). The required increases in rice production can only be achieved by application of large quantities of both mineral and organic fertilizers (Seng et al. 2001). However, the recommended rates of farmyard manure (FYM) and mineral fertilizers are rarely applied. On the one hand, the number of farm animals limits FYM availability and on the other hand, mineral fertilizers are often unaffordable for small-scale producers (Blair and Blair 2014; Morris et al. 1986). In addition, the efficiency and profitability of the recommendations is highly variable and often low (Seng et al. 2001). There is a need for differentiated, system-specific adapted solutions, including the use of locally available organic materials. Site specific organic amendments to substitute inorganic fertilizers (Bi et al. 2009) have been shown to enhance rice yields (Jeon et al. 2011) and to sustain soil productivity by building soil organic matter (Yan et al. 2007). In the case of the small-scale, low-input rainfed systems of Cambodia, the use of mineral fertilizers at affordable rates (lower than recommended levels), combined with locally available FYM and the addition of biologically fixed N from site-specifically adapted legume green manures may present an alternative to current blanket recommendations (Seng et al. 2001).

Green manures are used for the purpose of soil fertility improvement (Olesen et al. 2009) and as a source of N for the subsequent crops (Cherr et al. 2006). In addition, they can have phytosanitary effects and reduce native N losses from soils (Becker et al. 2007). Their use is reportedly more efficient in rainfed than in irrigated production systems (Becker et al. 1995), provided that the niche for growing the legume is sufficiently long (Garrity and Becker 1992), that seeds are available (Ali et al., 1995) and that the legume performance is not constrained by P deficiency (Engels et al. 1995).

In the case of the rainfed systems in Cambodia, there is sufficient time between the onset of the monsoon rains and the transplanting of rice (pre-rice niche) to cultivate a short-duration legume. Mungbean (*Vigna radiata* L.) is fast-growing, widely used, and locally adapted genotypes are available. Possible P limitations may be overcome by applying the mineral P destined to rice already to the pre-rice green manure. Further limiting nutrients may be added via farmyard manure and complemented by supplementary mineral N applications. Rates and combinations need to reflect the soil-specific differences and crop demand, as well as the mineral fertilizer equivalence values of the organic amendments (Kai et al. 2008; Abrol et al. 2012). Most importantly, the technology options or combinations need not only to be adoptable by farmers but also need to consider farmer’s perception and expectations.

The main goals in this research are (1) to assess available organic amendments (FYM and green manure) as supplemental nutrient sources and/or as alternatives to mineral fertilizer under rainfed lowland conditions on sandy soils in Cambodia, and (2) to assess the perception, the expectations and the aspirations of farmers related to the use of organic materials (FYM and green manure) and mineral fertilizer in the main rainfed production systems.

3.2 Materials and methods

The study area, the origin and attributes of the plant material, the experimental design and treatment applications, and the applied field management are described in Chapter 2. One of the main objectives described in this chapter was to explore the fertilizer substitution value of organic resources in comparison with mineral N fertilizer. We comparatively analyzed organic and mineral fertilizer sources and treatments in four experiments (91 experimental plots). The experiments were conducted in 2013 and 2014 and replicated 4 times on farmers´ fields. The treatments and applied mineral or organic NPK rates are summarizes in Table 3.1

Table 3.1 Organic and mineral fertilizer treatments and nutrient inputs

	Treatment	**N (kg ha^{-1})**			**NPK[1] (kg ha^{-1})**
		Green manure	**FYM**	**Urea**	
Organic resources	Grain legume -P/FYM +P	01	60	-	61/19/79
	Grain legume + P/FYM -P	10	60	-	70/09/79
	FYM – P	-	60	-	60/17/89
	FYM + P	-	60	-	60/07/89
	Green manure - P	09	-	-	09/10/30
	Green manure + P	21	-	-	21/00/30
	Grain legume - P	09	-	-	09/10/30
	Grain legume + P	21	-	-	21/00/30
	Green manure	78	-	-	78/10/25
Mineral fertilizer	Urea 0 (control)	-	-	-	00/04/30
	Urea 14	-	-	14	14/04/30
	Urea 28	-	-	28	28/04/30
	Urea 0 (control)	-	-	-	00/10/25
	Urea 25	-	-	25	25/10/25
	Urea 50	-	-	50	50/10/25

FYM = farmyard manure applied to rice

[1] *P and K were applied in the form of triple superphosphate (TSP, 20% P) and muriate of potash (KCl, 60% K), respectively. In case FYM was used, additional P and K were derived from the manure. Green legume: residue was incorporated after grain harvesting. Green manure: residue was incorporated during podding stage.*

3.2.1 Mineral fertilizer equivalence

Mineral fertilizer equivalence (MFE) is the amount of mineral fertilizer-N (kg) required to obtain the same yield as organic amendments and is expressed either as kg urea-N or as percent of an N amount equivalent to 100 kg manure-N. In this study, we define the mineral N equivalence in the following ways: 1) MFE (kg ha^{-1}) refers to the amount of mineral fertilizer that is equivalent to or can be replaced by organic materials. 2) MFE (%) refers to the equivalence of 100 kg N from the organic materials to mineral fertilizer N or the relative efficiency. Farmyard manure (FYM) and mungbean green manure (GM) were used as organic sources.

The calculation was adapted and modified from Kai et al. 2008:

$$\text{MFE (kg ha}^{-1}\text{)} = \frac{Y_{FYM\ and/or\ GM} - b}{a}, \tag{3.1}$$

where MEF is the fertilizer-N equivalent of FYM and/or GM-plots (kg ha^{-1}). “a” and “b” were obtained from the equation of the linear regression Y = aX + b, where “a” is the slope and “b” is the intercept of the regression. Y is the grain yield (kg ha^{-1}) while X is the added amount of N (kg ha^{-1})

$$\text{MFE (\%)} = \frac{E}{N_{FYM\ and/or\ GM}} \text{ X } 100, \tag{3.2}$$

E = MEF (kg ha^{-1}) and $N_{\text{FYM and/or GM}}$ = N Kg input from manure per ha.

Table 3.2 Values of the slope (a) and intercept (b) of the regression from a linear model (Y = a + bX), plotting grain yield as a function of applied mineral fertilizer N.

Field experiment (Exp.)	**Soil group/year**	**a**	**b**
Exp. 1	PK/2013	31.6	2956
Exp. 2	PL/2013	25.1	4139
Exp. 3	PK/2014	33.0	2575
Exp. 4[1]	PL/2014	25.1	4139

[1] In experiment 4, there was no mineral fertilizer application. We used the slope (a) and the intercept (b) value from experiment 2 (same soil and similar agronomic management for rice cultivation).
PL= Prateah Lang, PK= Prey Khmer soil groups

In cases where grain yield obtained from organic sources application was higher than the response curve of mineral fertilizer, the mineral N fertilizer equivalence could not be calculated.

3.2.2 Performance attributes

The grain yield was measured from 2 m x 3 m areas in the center of each plot. Harvested plants were threshed by hand, and the weight of the rice grain was adjusted to 14 %

moisture. At the end of each experiment, total soil N (TN) and organic C (TOC) from each plot were analyzed at the Institute of Crop Science and Resource Conservation, Department of Plant Nutrition, University of Bonn, Germany, using an automated elemental analyzer (Euro EA Elemental Analyzer series 3000). The agronomic N-use efficiency (AE) was calculated as increase in grain yield per unit of applied N as follows (Peng et al. 2006):

$$\text{AE (kg kg}^{-1}\text{)} = \frac{\boldsymbol{Grain\ yield\ in\ N\ fertilized\ plot}\ (\boldsymbol{kg\ ha^{-1}}) - \boldsymbol{Grain\ yield\ in\ 0\ N\ \ plot}\ (\boldsymbol{kg\ ha^{-1}})}{\boldsymbol{N\ input}\ (\boldsymbol{kg\ ha^{-1}})} \qquad (3.3)$$

3.2.3 Farmers’ perception of fertilizer uses

Farmers‘ perception of fertilizer uses was assessed through structured questionnaires administered during individual interviews with 100 rice farmers in 10 out of the 15 communes in Prey Kabas district of Takeo province (10 farmers per commune). The study sites cover both shallow and deep sandy soils (Table 3.3). The draft questionnaire was pre-tested with 6 farmers prior to the interview.

3.2.4 Statistical analyses

Linear regressions and Pearson´s correlation coefficients were determined using Microsoft Excel. Mean comparisons were done by least significance difference (LSD) test at $P < 0.05$ using Statistix 8 (Version 8.0, Analytical Software, 1985-2003). The values for the dependent variable were the mean of 4 replications in each treatment. The data entry and analyses from the farmers’ survey were done using Statistical Package for the Social Science (SPSS, version 22).

Table 3.3 Farm and household attributes in the Prey Kabas district of Cambodia (n=100)

Variable	Description	%
Gender	Female	61
	Male	39
Age of household head (years)	25-39	15
	40-60	45
	>60	40
Household size (total family members)	1-3	0
	4-6	27
	>7	73
Education level	Illiterate	9
	Primary	49
	Secondary and upper secondary	42
Number of fields	1-3	91
	4-6	9
Average field area (ha)	<0.5 ha	54
	0.5-1 ha	29
	>1 ha	17
Soil texture[1]	Sandy	29
	Loamy sand	71
Rice ecosystem	Only wet season	54
	Early-wet and wet season	30
	Wet season and dry season	16

N = 100 farmers

[1] Assessed by the farmers, based on the top soils

3.3 Results

3.3.1 Mineral nitrogen fertilizer equivalence of applied organic manure

In general, organic amendments (green manure and/or FYM) were able to substitute between 10 and 30 kg of mineral fertilizer N ha^{-1} with corresponding relative efficiencies ranging from 25 to 139 % (Table 3.4).

Table 3.4 Mineral N fertilizer equivalence of organic amendments used in Tram Kak and Prey Kabas district of Cambodia

Organic amendment	Additional treatment	Rice yield (Mg ha^{-1})	N input (kg ha^{-1})	MFE[1] (kg ha^{-1})	(%)	Soil group
Grain legume	+P/FYM	4.21	70	48[2]	69	Deep sandy
Grain legume	-P/FYM	3.53	61	22	37	
Green manure	+ P	3.14	21	13	63	
Green manure	- P	3.11	9	12	139	
Grain legume	+ P	3.42	21	26	124	
Grain legume	– P	3.06	9	10	114	
	Mean	**3.41**	**32**	**17**	**95**	
FYM	+ P	4.86	60	30	51	Shallow sandy
FYM	- P	4.71	60	24	39	
Green manure	none	4.61	78	19	25	
	Mean	**4.73**	**66**	**24**	**38**	

[1] MFE = mineral N fertilizer equivalence; FYM = farmyard manure applied to rice

[2] Estimation as grain yield exceeded the mineral N fertilizer response curve

The mean mineral N fertilizer equivalence of organic sources tended to be lower on the deep than on the shallow sandy soils (17 vs. 24 kg ha^{-1}, respectively), but corresponded in both cases to about 50 % of the recommended mineral N rate (28 and 50 kg N ha^{-1} for deep and shallow sandy soil, respectively). When expressing the mineral fertilizer N equivalence on a percentage basis (kg mineral fertilizer N equivalent per 100 kg N from organic sources), the relative efficiency of the N applied by organic amendments was higher in the deep than in the shallow sandy soil (average of 95 vs. 38 kg N). However, the N input from organic amendments was not correlated with the mineral N fertilizer equivalence (r = 0.61 ns).

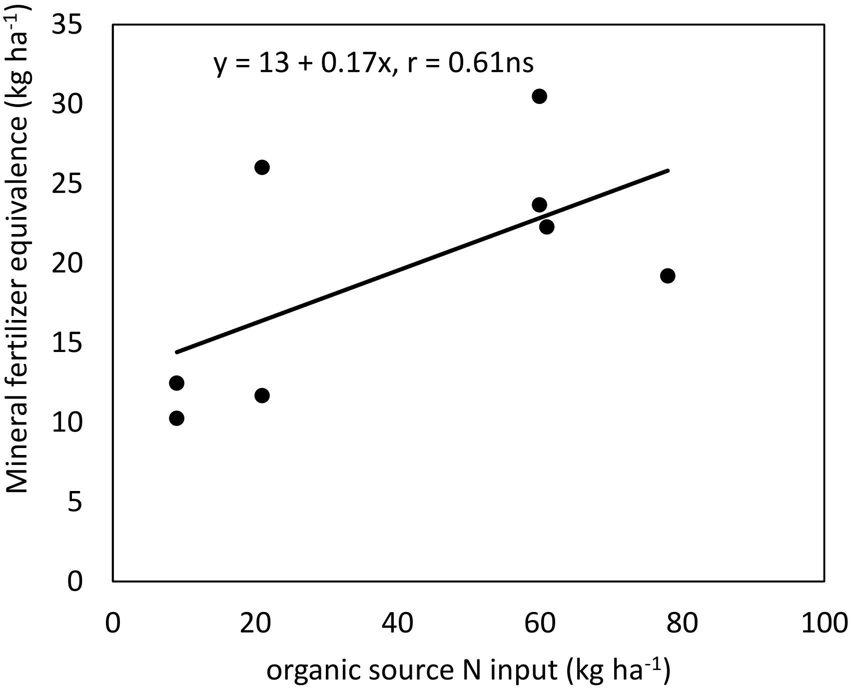


Figure 3.1 Relationship between N input from organic sources and mineral N fertilizer equivalence (kg ha^{-1}). *Each point represents average of 4 replications.*

3.3.2 Grain yield responses and agronomic-use efficiency

The grain yield obtained from the plots with mineral N fertilizer (urea) treatment ranged from 3.2 to 5.1 Mg ha^{-1} while that obtained applying organic sources ranged from 2.8 to 4.9 Mg ha^{-1} (Figure 3.2a). The grain yield of rice responded significantly to the amount of added N, irrespective of whether this N was from mineral or organic sources ($r_{mineral}$ = 0.78** ; $r_{organic}$ = 0.84**). The agronomic N use efficiency (kg grain per kg of N input) tended to be lower with increasing N application from both organic manure and mineral fertilizers, but the relationship was not significant (Figure 3.2b). While mineral N sources tended to out-yield the organic amendments, the yield variability was higher with mineral than with organic sources, and was lowest in the no-amendments control (Figure 3.3a). The addition of urea-N increased the rice yield over the control (no N applied) by 0.98 Mg ha^{-1}, which was not significantly different from the yield obtained with organic amendments. While rice yields were generally higher on the shallow than on the deep sandy soils, no differences between mineral and organic amendments were apparent (Figure 3.2).

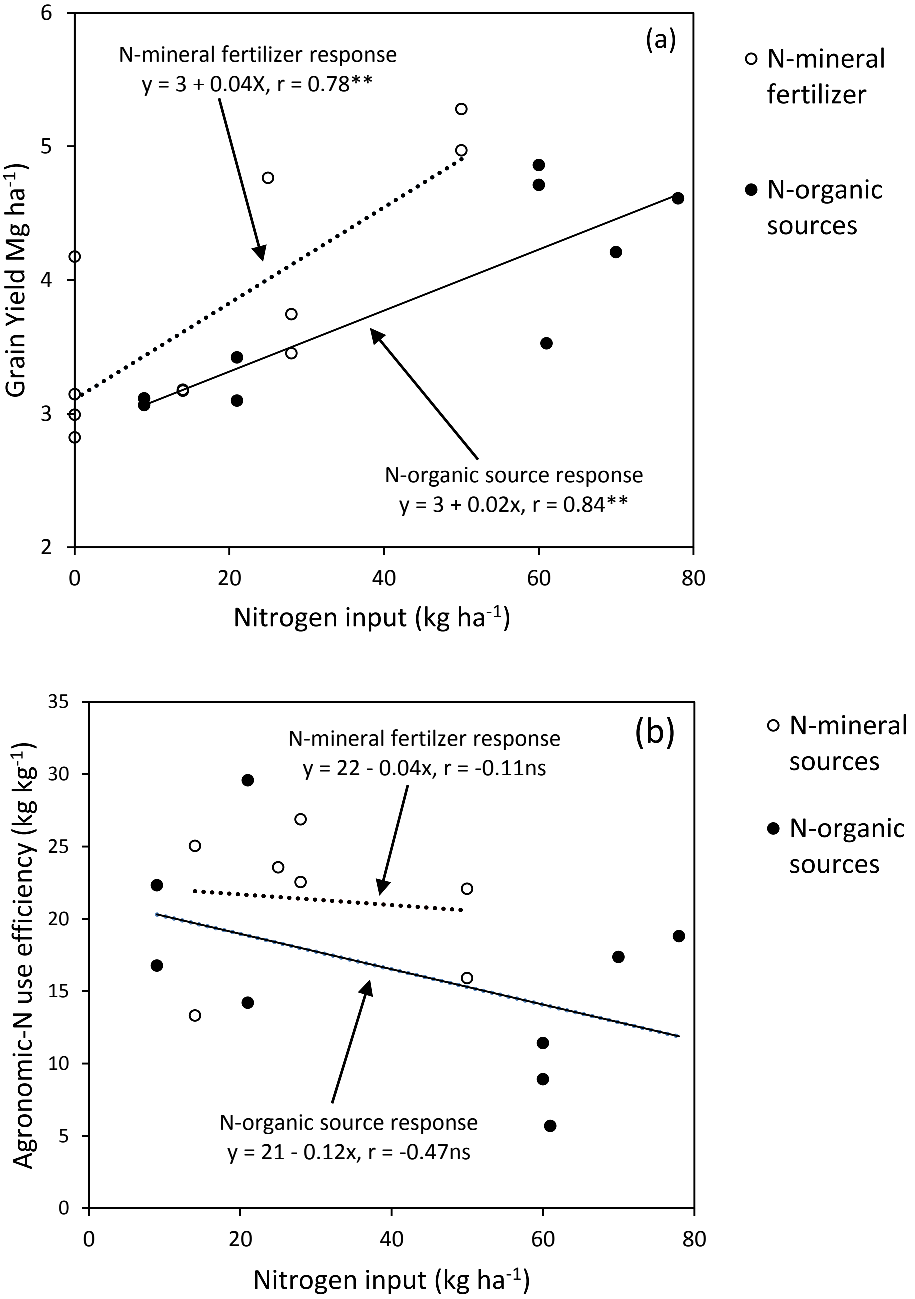


Figure 3.2 Relationship between mineral and organic N inputs and rice yield (a) and agronomic-N use efficiency (b). Each point represents average of 4 replications.

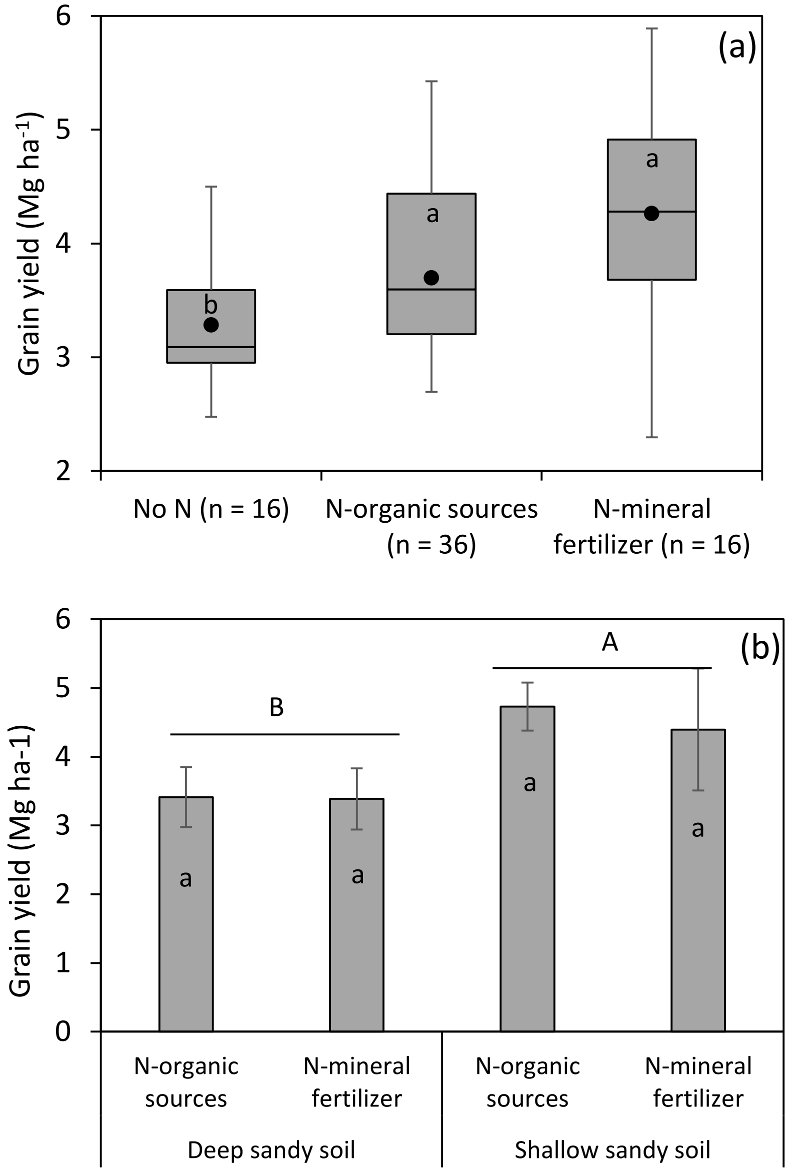


Figure 3.3. (a) Grain yield obtained without N application and with organic and mineral N fertilizer sources. *The solid line inside boxes is the median and the black dot represents the overall average across soil groups and sites. The upper box boundary shows that 75% of the grain yield falls below the upper quartile and the lower box boundary indicates that 25% of the grain yield falls below the lower quartile.* (b) Grain yield by types of N sources and soil groups. *The error bars represent standard deviation. Small letters indicate significance of both N-sources in each soil group ($p < 0.05$) while capital letters show the significance between the two soil groups. The same letters are not significantly different at 5% as determined by Least Significant Difference (LSD).*

3.3.3 Total N and total organic C

The total N (TN) and total organic C (TOC) contents of the soils after two crop cycles increased significantly with applied organic amendments ($r = 0.63$, $P<0.05$), ranging from 1.57 to 5.76 g C kg^{-1} and from 0.13 to 0.55 g N kg^{-1}. Despite these positive trends, the values are still to be classified as “extremely low”. With mineral N sources, no change trends in soil C and N were apparent (Figure 3.4).

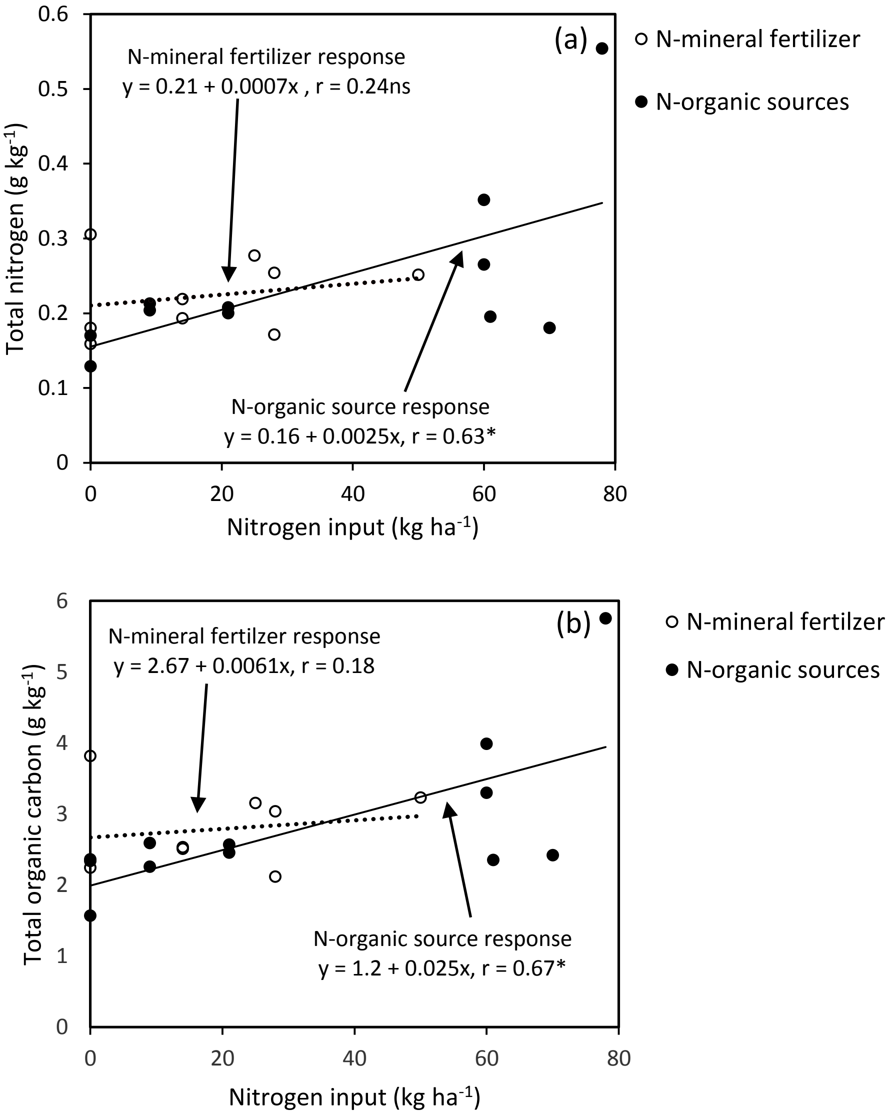


Figure 3.4 Relationship between N input from mineral and organic sources and total soil nitrogen (a) and carbon (b) contents

Each point represents mean of 4 replications.

3.3.4 Farmers‘ perception toward fertilizers

Most farmers in the study region use both animal manure and mineral N fertilizer. On the other hand, the adoption of green manure is restricted to only 21% of the farmers.

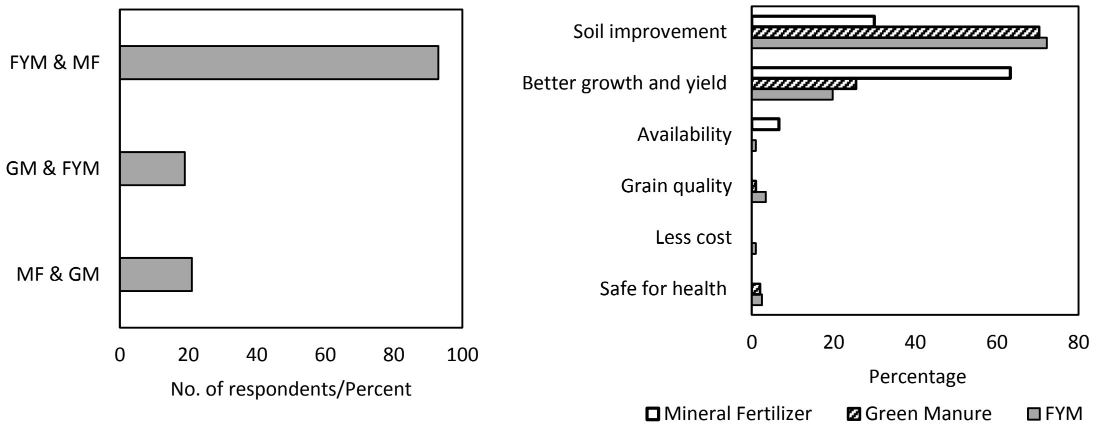
Table 3.5 Farmers´ judgement of the three types of fertilizers and main perceived constraints limiting use/adoption (multiple responses were possible)

Fertilizer type	Use (%)	Ranking Quality Mean (±SD)	 Preference Mean (±SD)	Main constraints
FYM[1]	96	1.3 (±0.50)	1.2 (±0.5)	Insufficient manure
Green manure	21	2.0 (±0.89)	2.0 (±0.9)	Labor shortage
Mineral fertilizer	98	2.5 (±0.9)	2.5 (±0.9)	Cannot afford

The farmers were asked to rank the fertilizer type from 1 (top) to 3 (least). [1]FYM = farmyard manure. SD = standard deviation.

Farmyard manure is the preferred (quality ranking 1.3) and also most widely adopted (96%) fertilizer use in the sample (Table 3.5). Farmers indicated that they would like to use more manure but are constrained by the poor availability linked to the low number of farm animals. The perceived value of green manures is also very high (quality ranking 2); however, only 21% of the farmers in the study area apply it. Key constraints to adoption are labor shortage, which restrains green manure establishment, and it is only incorporated on parts of the fields. The least preferred but most widely used fertilizer is urea with a quality and preference ranking of 2.5 but an adoption rate of nearly 100%. However, despite its wide use, the applied rates are very low, which is related to the perceived high price of urea and its unaffordability by small-scale subsistence farmers.

The relatively high quality and preference rating of both green and animal manures are related to perceived benefits such as ʹʹsoil improvementʹʹ and ʹʹyield increasesʹʹ. The majority of the farmers (93%) use a combination of FYM and mineral fertilizer rather than only one type, while around 20% of the respondents combine green manure with FYM.



(a) (b)

Figure 3.5 (a) Combined uses of fertilizers; (b) main positive perception of each fertilizer (multiple respondents). *MF=mineral fertilizer and GM=green manure.*

3.4 Discussion

3.4.1 Mineral fertilizer equivalence and efficiency of organic sources

Grain yields increased with applied N from both mineral and organic sources (r = 0.78** and r = 0.84**, respectively). However, with the same amount of applied N, the grain yield responded more to mineral fertilizer applications than to organic amendments, and yields were always higher on the shallow than on the deep sandy soils. This general trend may be attributed to a generally higher fertilizer use on shallow soils. Thus, the recommended fertilizer rate on soils of the shallow sandy group is 50:10:25 (N:P:K kg ha^{-1}), while it is only 28:05:33 (N:P:K kg ha^{-1}) on soils of the deep sandy group. The strong and positive grain yield response to applied fertilizer N is neither new nor unexpected (Yadav et al. 2000). However, the differential response of the two soil groups was surprising. Consequently, the deep sandy soils of the Prey Khmer group must be classified and considered as being less productive than the shallow sandy soils of the Prey Khmer group as has been previously suggested by White et al. (1997).

The mineral N fertilizer equivalence allows comparing the applied treatments by calculating the amount of mineral N that can be substituted for by organic amendments or the relative efficiency of applied organic relative to applied mineral N sources. Compared to the recommend N standard for both soil groups, the averaged value of mineral fertilizer equivalence for both soil groups showed that organic sources can replace about 50% of the mineral N recommended to be applied to each soil group. The mean mineral fertilizer equivalence (kg N ha^{-1}) of organic sources applied on the shallow sandy soil group was higher than on the deep sandy soils.

In some cases, the value of mineral fertilizer equivalent (as percent) exceeded 100%, especially in the deep sandy soil group in the case of green manure amendment. The high mineral fertilizer equivalence > 100% was also reported by Tran et al. (2012). In another words, the efficiency of N from green manure in this soil was higher than that of the mineral N fertilizer. Green manure generally has a lower C:N ratio of about 15 (Das et al. 1993) than FYM with about 18 (Mariaselvam et al. 2014). Consequently, the decomposition of incorporated green manure was likely to be faster (Aulakh et al. 2001) than that of FYM. However, this pattern was not consistent on the shallow sandy soil where a high atmospheric N_2 fixation was associated with a low relative mineral N fertilizer equivalence. It is possible that the relatively high N input rates led to a lower agronomic N use efficiency, which was evident from the negative trends between N inputs from organic sources (r = -0.47) and agronomic N use efficiency (Figure 3.2, b). The agronomic N use efficiency in this study ranged from 6 to 30 kg ha^{-1} and from 13 to 27 kg ha^{-1} in the case of N from organic sources and mineral fertilizers, respectively. This range is comparable with those reported before (Peng et al. 1996; Peng et al. 2006). In another words, increasing the amount of N inputs will decrease the agronomic N use efficiency. This suggests that the low native soil N supply from the prevailing sandy materials requires higher N application. Alternatively, it may be possible that N absorbed by the rice crop during the early growth stages simply enhanced biomass growth, but reduced the harvest index or the C and N partitioning towards reproductive organs (Peng et al. 2006). It can also not be excluded that high N losses from the sandy soil may have occurred before the plant could take this N up. While Peng et al. (2006) reported that agronomic N use efficiency decreased with increasing N application rates, such trends differ between organic and mineral sources and the dominant soil type. Thus, Becker et al. (1995) reported that the N use efficiency is higher with urea in irrigated systems on clay soils and with green manure in rainfed systems on sandy soils. In the present study, the agronomic N use efficiency tended to be higher with mineral N fertilizer than with organic amendments. A plausible explanation could be that the N derived from organic manures was available to the rice crop at the later stage (Ventura and Watanabe 1993) while the urea dose was split in triple applications for a crop cycle of rice, making it more efficient for rice production. However, these differences were not significant.

3.4.2 Residual total N and organic C

In contrast to urea, total soil N and organic C increased with applied organic amendments already within one or two seasons. In another words, the changes in total soil N and organic C correlated linearly with the amount of N contributed by organic sources. Such trends will be enhanced in the longer term as has been reported before (Lv et al. 2011; Tong et al. 2009; Cassman et al. 1996; Zhang and He 2004; Liu et al. 2013; Singh et al. 2007) or in at least three to four crop cycles as reported by Mandal et al. 2003 and Yaduvanshi 2003. Short-term changes as reported here are unlikely to occur (Haynes 2005) or will only concern certain fractions of soil C and N (Yang et al. 2005; Raun et al. 1998). However, Zia et al. (1992) reported changes in total N in the case of green manure and FYM application in one crop cycle of lowland rice in Pakistan. The specific soil conditions in Cambodia may have contributed to the observed significant short-term changes with organic addition despite the high rates of nutrient leaching in the sandy soils.

The residual total N after the growing season in this study was mainly related to the N derived from green manure (Roger and Ladha 1992; Zia et al. 1992) and FYM (Zia et al. 1992), whereas organic C was probably due to C input through crop stubble, root exudates and N fixation (Tong et al. 2009). The residual soil organic C in this short-term study may have been largely contributed by the root-derived C of the green manure (Puget and Drinkwater 2001). Nitrogen from green manure is less susceptible to loss mechanisms (Becker 2001), maybe contributing to this residual total N accumulation. Panda et al. (1994) and Aulakh et al. (2000) also reported that less nitrate leached with green manure amendment than with mineral N application.

In contrast, the increase in total N and organic C due to applied urea was small and the relationship was insignificant. It was due to the fact that urea application released available N (NH_4^+) rapidly (Singh et al. 1981) that was taken up by the rice within a crop cycle. This phenomenon caused rapid rice yield response. On the other hand, the applied inorganic N may have also been lost or decreased (Cao et al. 1984; Singh et al. 1981) either by volatilization or denitrification (Datta and Buresh 1989) within one crop cycle.

3.4.3 Farmers' perception of fertilizers and implications

The farmers in the study areas like elsewhere in Cambodia were generally considered as small-scale famers. According to the interviews, they had contrasting perceptions between mineral fertilizers and organic manures. The farmers tended to appreciate the quality and prefer organic manures (particularly FYM) to mineral fertilizers, which was related to their perception that organic manures provided long-term benefits as soil fertility improvement. However, they also perceived that rice growth and yield responded rapidly and efficiently to mineral fertilizers. Considering the high cost of mineral fertilizers (Blair and Blair 2014) and probably high variability in efficiency and profitability (Seng et al. 2001), the farmers are reluctant to apply mineral fertilizers as recommended. Thus, although the application rate of mineral fertilizers in rice production is already relatively low, the farmers generally apply even lower amounts (Blair and Blair 2014). Nevertheless, almost all the farmers in the interviews applied mineral fertilizers. The use of mineral fertilizers is inevitable because of the limited organic sources. Therefore, most of the farmers normally use a combination of FYM and mineral fertilizers. Green manure, on the other hand, received high appreciation in terms of quality and quantity but it was applied by only a small number of farmers. Green manure was mainly constrained by labor shortage.

3.5 Conclusions

The objective of this study was to provide an overview of alterative N-mineral sources. The mineral fertilizer N equivalence and grain yield obtained from organic sources was compared to the use of mineral fertilizer based on the pooled data analyses of four field experiments covering a wide range of treatments (91 plots). This study is limited to differentiation of organic source types and one crop cycle and focused on two main organic sources.

The application of organic sources (green manure and FYM) was equivalent to around 50% of the national recommended N rate for both soil groups, but led to residual total N and organic C after one crop cycle. This suggests that N may not have been fully available in the organic sources, which probably had a limiting effect on rice yield and did not enhance the N use efficiency over the short-term study period. But N could potentially build up in a long-term application. Rapid response of rice yield to N-mineral fertilizer is associated with the readily available N within one crop cycle. Therefore mineral N fertilizer had a small effect on fertility build up.

Organic manures were preferred and appreciated by the farmers. However, the increase in FYM application beyond that actually applied in this study (4 to 7 t ha^{-1}) is not likely to be possible for most small-scale famers. Alternatively, it is important to maximize the benefits from green manure through improving N fixation of the manure taking into account the less labor-intensive technology. The adoption of organic materials to replace mineral N could be possible provided that the supply of FYM is sufficient and the agronomic and social-economic constraints of growing green manure can be solved.

Therefore, organic manure application could play a very crucial role in enhancing both organic C and N in rainfed lowland rice, but may not be able to achieve an optimal rice yield in a short-term application.

4 EFFECT OF PHOSPHORUS APPLICATION ON MUNGBEAN PERFORMANCE

4.1 Introduction

Nitrogen (N) and phosphorus (P) deficiencies, common in most tropical soils, are key constraints to increased crop productivity in low-input production systems (Ankomah et al. 1996). Rainfed lowland rice is the dominant food crop in the low-input agricultural systems of Cambodia, where infertile soils cover more than half of the area under rainfed lowland rice (White et al. 1997), severely limiting rice production (Seng et al. 2004a). These soils are highly weathered sands (Pheav et al. 2005) with low N and extremely low available P contents and with low-activity material dominating the clay fraction (White et al. 1997). Their low specific surface area results in a low cation exchange capacity (CEC) and, concomitantly, poor nutrient holding capacities.

As N is the main limiting nutrient for rice production, it must be either supplied by the soil or added in the form of mineral or organic N fertilizers. The recommended rates of farmyard manure (FYM) are rarely applied due to the limited number of farm animals, while mineral fertilizer sources are often unaffordable to small-scale producers (Blair and Blair 2014; Morris et al. 1986). In addition, the efficiency of the recommendations is highly variable and their profitability is often low (Seng et al. 2001).

Green manures can be integrated into rice farming systems either in the pre-rice or in the post-rice cropping niches, whereby the use of the pre-rice niche has been suggested to be more applicable in the case of rainfed rice systems in South East Asia (Ladha and Garrity 1994). However, the adoption of green manures is limited by a number of constraints, such as the availability of seeds and of labor for biomass incorporation (Ali 1999). The adoption of green manure technologies has been hypothesized to be substantially increased by using multi-purpose legumes, which provide additional benefits such as feed stuff and grain in addition to fertility improvement (Becker 2003). Such multiple-use legumes are particularly suited for rainfed rice systems (McDonagh et al. 1995), where they show reportedly higher N use efficiencies than in irrigated systems or compared to mineral N fertilizers, particularly on sandy-textured soils (Becker et al. 1995). The N balances resulting from legume-based BNF contributions can be improved by as much as 19-38 kg N ha^{-1}, 28-33 N ha^{-1}

and 30 to 52 kg N ha^{-1} in lowland rice-based systems of Japan, Thailand and The Philippines, respectively (Kundu and Ladha 1999).

However sufficient available P is a crucial component for legume establishment (Walley et al. 2005), growth and biomass accumulation, and particularly N_2-fixation (Israel 1987; Niemi et al. 1997). In the sandy soils prevailing the lowland rice production of Cambodia, P deficiency is a major production constraint, potentially affecting the N_2 fixation by legume (Araújo et al. 1997). Concomitant to the positive effect of P on N_2 fixation, increases in legume biomass and grain yield have been reported (Hayat et al. 2008; Bhuiyan et al. 2008). Besides the ability of legumes to fix N_2 and contribute N to the subsequent rice crop, the legume-absorbed and returned P can significantly benefit the rice crop, often even more than direct P application to rice.

Rainfed-based rice production on sandy soils make Cambodia thus an ideal candidate for future pre-rice green manure or grain legume uses provided that P can be supplemented. The objectives of this study were 1) to determine N_2 fixation of pre-rice multi-purpose crop of mungbean crop, and 2) to comparatively assess the effect of P application strategies on the performance of both the legume and the subsequent rainfed rice.

4.2 Materials and methods

4.2.1 Experimental design and treatment application

A detailed description of the study sites, the experimental design and the plant materials used are provided in Chapter 2. In brief, the experiments were conducted in farmers´ fields in the Tram Kak district of Takeo province in Cambodia in 2013 and 2014, where the experiments were located on a deep “Prey Khmer” sandy Fluvisol. The treatments are part of experiments 1 and 3 presented in Chapter 2. In 2013, mungbean was grown as a green manure in the pre-rice niche, either with or without the application of mineral P. During the wet season, FYM was applied, providing 60 kg N ha^{-1} before rice transplanting. Rice received an equivalent amount of P when no P had been applied to the legume. The experiment was conducted with a plot size of 4 m x 4 m using four replications. In 2014, pre-rice mungbean with and without applied mineral P was grown, but the management of the mungbean residues was modified, including (1) the green manure treatment or “all residues returned”, (2) grains removed as with a food grain legume or “only stover returned”, and (3) the total above-ground biomass harvested as with a forage legume or “all residues removed” The experiment was conducted with a plot size of 5 m x 5 m using four replications and a randomized block design. Phosphorus was applied basally at a rate of 10 kg ha^{-1} as triple superphosphate (TSP, 20% P). In 2013, 9 kg P ha^{-1} were additionally supplied from the FYM to the rice. The treatments and nutrient application schedules and rates are presented in Table 4.1.

Table 4.1 Treatments, seasonal management and nutrient application schedule and rates in the field experiments on deep Prey Khmer Fluvisol, Tram Kak district, Cambodia, 2013

Treatment	**Pre-rice period**	**Wet season**	**NPK (kg ha^{-1})**
	2013		
Green manure + FYM -P	Mungbean	BNF[2]-N+FYM+10 kg P	61/19/79[1]
Green manure +FYM +P	Mungbean + 10 kg P	BNF-N+FYM	70/9/79
	2014		
Green manure-P	Mungbean	BNF-N + 10 kg P	09/10/30
Green manure +P	Mungbean + 10 kg P	BNF-N	21[2]/00/30
Grain legume -P	Mungbean	BNF-N + 10 kg P	09/10/30
Grain legume +P	Mungbean + 10 kg P	BNF-N (stover)	21[2]/00/30
Forage legume -P	Mungbean	10 kg P	00[3]/10/30
Forage legume +P	Mungbean + 10 kg P	none	00/00/30

BNF = biological nitrogen fixation

[1] *K rate consists of a basal mineral application of 30 kg ha^{-1} as muriate of potash (KCl). In the case of FYM, additional 49 kg K ha^{-1} was from FYM.*

[2] *The amount of N derived from biological N fixation by the mungbean was estimated at 09 kg N ha^{-1} with pre-legume-P, and at 21 kg ha^{-1} with pre-legume + P in the green-manure and grain-legume-residue-management treatments. In the forage-legume treatment, all biologically fixed N was removed with grains and stover.*

4.2.2 Measurements and data collection

The plant height of the mungbean was recorded prior to harvesting based on three neighboring plants. The dry weight of both aboveground and root biomass was determined from subplots 25 cm x 25 cm randomly selected from each plot after uprooting the whole plants and oven-drying at 70 °C for 48 h. The grain yield was based on 2 m x 3 m sampling areas and adjusted to 12% moisture content. The 100-grain weight was based on random samples from the harvested legume grain.

The rice grain yield was measured from 2 m x 3 m harvest areas in the center of each plot. The harvested plants were threshed manually and the grain weight was assessed to 14% moisture.

To determine the N fixation, maize was used as a reference plant (Senaratne and Ratnasinghe 1995) planted in a 2 m x 1 m micro-plot located within each mungbean plot. The experiment was replicated 4 times. The reference plant was harvested separately at the same day as the legumes using a 0.6 m x 1.0 m sampling frame.

Only aboveground plant parts were used for ^{15}N natural abundance analysis. All samples were oven-dried at 70°C for 48 hours, milled at <0.1 mm, and analyzed for N isotope ratios in duplicates at the Institute of Crop Science and Resource Conservation, Department of Plant Nutrition, University of Bonn, Germany, using an ANCA-SL 2020 mass spectrometer. The share of N derived from the atmosphere (%Ndfa) was calculated as follows:

$$\%\text{Ndfa} = \frac{\delta 15N\ of\ reference\ plant - \delta 15N\ of\ N_2\ fixing\ legume}{\delta 15N\ of\ reference\ plant - B}\ \boldsymbol{X\ 100}$$

(Unkovich 2008) (4.1)

$$\text{N fixed} = \frac{\%Ndf}{100}\ \text{X}\ legume\ N\ (kg\ ha^{-1})$$ (Amanuel et al. 2000) (4.2)

A "B-value" of 3.5 (natural isotopic discrimination) was applied for the mungbean. The belowground N contribution was estimated by multiplying the aboveground N with a factor of 1.5 as suggested by People et al. (1989). Soil samples (0-20 cm) were collected at the end of each experiment and analyzed after bicarbonate extraction ($NaHCO_3$, pH 8.5) for soil available P by the Olsen method. All samples represented composites from 5 sampling points per plot. Fresh samples were air-dried for 5-7 days, sieved through a 2 mm-sieve and analyzed in duplicates at the Institute of

Crop Science and Resource Conservation, Department of Plant Nutrition, University of Bonn. Determined parameters and methods used are presented in Chapter 2.

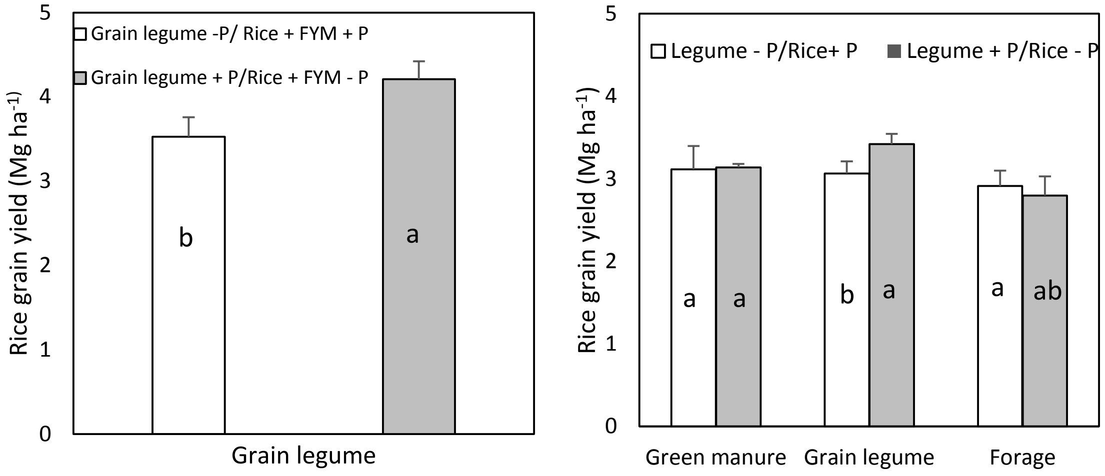
4.3 Results

4.3.1 Mungbean performance

The application of P had a significant effect on legume performance (Table 4.2). The biomass of mungbean amended with P was 0.6 (2013) and 1.1 (2014) Mg ha^{-1} compared to 2.2 (2013) and 0.8 (2014) Mg ha^{-1} without added P. The total N accumulation and the shares and amounts of N derived from biological N_2 fixation also strongly responded to applied P in both years (Table 3). Thus, 10 kg P ha^{-1} increased the N_2 fixation from 17 % to 36 % Ndfa compared to the non-amended green manure. However, the total amount of N_2 fixed from the atmosphere was only 21 and 9 kg ha^{-1} for P-treated and non-P treated mungbean. In the absence of P application, mungbean yielded no grain in 2013 and only 0.27 Mg ha^{-1} in 2014. With P, grain yields ranged from 2.7 (2013) to 4.0 (2014) Mg ha^{-1}.

4.3.2 Rice performance

The rice grain yields were around 4.0 Mg ha^{-1} in 2013 and 3.0 Mg ha^{-1} in 2014, irrespective of whether mineral P was supplied to the green manure or directly to the rice (Figure 1). Phosphate strategies have significant effects on rice grain yields. The subsequent rice yield was higher when P was applied to the pre-rice grain legume where which residues were incorporated after grain harvesting. However, when all residues were removed (forage treatment), application of P to the legume slightly decreased the rice yield. Furthermore, the residue management (legume biomass returned or partially removed) showed no significant effects in 2014 (3.2 Mg ha^{-1}), except in treatments where all residues were removed (2.8 Mg ha^{-1}).



(2013) (2014)

Figure 4.1 Rice yield with phosphorus (P) applied to legume (only indirect contribution to rice upon residue incorporation) or directly to the succeeding rice crop

Table 4.2 Performance of mungbean and its nitrogen fixation in two locations

Parameter	**(2013)**		**Sig.**	**(2014)**		**Sig.**
	-P	**+P**		**-P**	**+P**	
1000-grain weight	n.a	n.a	n.a	67	65	n.s
Dry biomass^1 (kg ha^{-1})	160	621	*	781	1090	**
Plant height (cm)	n.a	18	n.a	25	25	n.s
Grain yield (kg ha^{-1})	0	273	n.a	266	404	**

*Sig. = significant difference by Least Significant Difference (LSD), with P < 0.01 as *, and 0.01 < P < 0.05 as **.* ^{1}*both root and aboveground biomass*

The available P in the soil after rice harvest varied from 0.10 to 2.32 mg kg^{-1}. The combined use of green manure and FYM under both P strategies (green manure + FYM – P and green manure + FYM +P) did not show a significant difference in available P (Table 4.4). In 2014, the available residual soil P was higher when P had been applied to rice rather than to mungbean. Residue management yielded no significant differences whether legume was cultivated as green manure, grain legume or forage.

Table 4.3 Biological nitrogen fixation (%Nfda) of mungbean with mineral P and without mineral P in 2013 and 2014

Year	Fertilizer application	N in mungbean (kg ha^{-1})	%N from N_2 fixation (%Nfda)	Total N fixed (kg ha^{-1})
2013	+ P	-	-	*10*[1] ± 3.90
	-P	-	-	*1*[1] ± 0.95
2014	+ P	34 ± 4.8	36 ± 2.6	*21* ± 2.60
	- P	*23* ± 2.2	*17* ± 1.7	*9* ± 0.04

[1] *Estimation of total N fixed is based on N in mungbean and %Nfda measured in the experiment 2014*
Value is the mean ± standard deviation (SD)

Table 4.4 Effect of legume residue management and P fertilizer on soil-available P after rice growing season

Treatment		**Avail P (mg kg^{-1})**
2013	Green manure + FYM + P	1.09
	Green manure + FYM - P	1.74
	Significance	n.s
2014	Green manure + P	0.62 cd
	Grain legume + P	0.10 cd
	Forage legume + P	0.41 d
	Green manure - P	2.32 abc
	Grain legume -P	2.26 abc
	Forage - P	1.88 bcd
	Significance:	**
	P application	**
	Residue management	n.s

FYM = farmyard manure; Avail. P: Olsen

4.4 Discussion

4.4.1 Mungbean performance

The significant effect of P on dried green manure biomass and grain yield was observed for both years. Similar effects of applied P on total biomass and grain yield of mungbean were reported by Malik et al. (2003) and Chaudhary and Fujita (1998). Hayat et al. (2008) found that with the P amendment, the nodulation, shoot dry matter, grain yield and N concentration of mungbean was higher compared to non-P fertilization. Similarly, Bhuiyan et al. 2008 reported increasing stover and grain yield of mungbean with P application. Grain yield response to P application was also reported (Sharma and Prasad 2011). There are also reports on the effect of P on grain yield and other parameters of mungbean (Ahmad et al. 2015; Jan et al. 2012; Sharar et al. 1999) . A positive response of shoot biomass to the application of P was also reported by Pereira and Bliss 1987. With P amendment, grain and biomass yields of 3.4 and 0.7 t ha^{-1}, respectively, were reported (Jan et al. 2012).

It is known that P is a part of the plant components like nucleic acids, phospholipids and ATP (Schachtman et al. 1998). Higher biomass amount with P application was probably the result of photosynthetic activity caused by P application. Compared with other legumes such as mashbean and soybean, mungbean responded with an increase in crop P uptake even at much lower P application rates of 12.5 kg P ha^{-1} (Chaudhary and Fujita 1998). Such strong responses to applied P were hypothesized to be related to an exceptionally high root exudation rate in mungbean (Singh and Pandey 2003). Likewise, Gunawardena et al. (1992) reported that mungbean strongly increased P uptake at increasing P application rates and translocated most of the absorbed P into the leaves. There, P contributes to an enhanced leaf area, thus further stimulating the photosynthetic activity (Chaudhary and Fujita 1998). The increase in N accumulation with P amendment (Chaudhary and Fujita 1998) is yet another factor contributing to the reported enhanced photosynthetic activity of mungbean. Naeem et al. (2006) reported that the application of P enhances the P content in the seed, which in turn may increase seed weight and early vigor.

The grain yield obtained in the experiments was comparable to that in other studies in Cambodia. Bunna et al. (2011) conducted an experiment on the use of mulch on post-rice mungbean producing the grain yields ranging from 182 to 638 kg ha^{-1}. Cheth (2011) obtained an average mungbean yield of 425 kg ha^{-1}. The average yield of up to 1.6 Mg ha^{-1} of mungbean as pre-rice crop was reported by Polthanee et al. (2012) on sandy soil in Thailand, which was higher than obtained in Cambodia. This may be due to the better soil characteristics because, compared to the soil in this study, their soil had higher available P at 6.7 mg kg^{-1} and also higher total N at 0.038%. The use of farmyard manure in their experiment may also have contributed to the higher yield.

Fukai et al. (2013) reported that grain yield of post-rice mungbean varied between 47 and 1160 kg ha^{-1} on the shallow Prateah Lang sandy soil, and 216-1340 kg ha^{-1} on the deep Prey Khmer sandy soil. The range was similar with 202-1485 kg ha^{-1} in the experiment conducted by De Costa et al. (1999). Webber et al. (2006) obtained yield and aboveground biomass of 0.5-1.0 Mg ha^{-1} and 2.1-5.6 Mg ha^{-1}, respectively. Pannu and Singh (1993) reported a variation of mungbean grain yield and aboveground biomass in the range of 0.8 to 1.6 Mg ha^{-1} and 2.5 to 4.9 Mg ha^{-1}, respectively. Low yields of mungbean grown under lowland rice conditions have frequently been reported. The establishment of mungbean under such conditions is restricted by the soil physical and chemical conditions. For example, it is difficult for the mungbean roots to penetrate the soil due to hard pan (Bunna et al. 2011), soil fertility is low (Fukai and Ouk 2012).

4.4.2 Biological nitrogen fixation (BNF)

The application of P at rates as low as 10 kg ha^{-1} significantly stimulated the biological N_2 fixation (%Nfda). This %Nfda in the deep sandy soil was however very low, with a stimulation of only 26 % compared to no-P application. Phosphorus is one of the most limiting nutrients for crops in many low-input agricultural systems (Ramaekers et al. 2010), and many studies have pinpointed the role of P on N_2 fixation of leguminous plants (Israel 1987). Thus, the response of mungbean to applied P has been widely reported (Bhuiyan et al. 2008; Chaudhary and Fujita 1998; Hayat et al. 2008; Malik et al. 2003). The differences in N_2 fixation (%) could be attributed to the application of P to low-P soil. Available P in the experimental deep sandy soil was low. Under P-deficient soils, Gunawardena et al. (1992) reported that N_2 fixed (Ndfa) of mungbean increased with P application by the range of 46 to 66 %, which was higher than observed in this study. Hayat et al. (2008) also reported an increase in N_2 fixed (%) affected by P fertilization at 80 kg ha^{-1}, ranging from 32 to 57 %, equivalent to 17 to 58 kg ha^{-1} of N_2 fixed. The finding suggests the importance of P amendment for improved N_2 fixation. The results indicate that P deficiency is a limiting nutrient not only for mungbean grain yield, but also for N_2 fixation. The increase in shoot biomass corresponded with both percent of N_2 fixed and total N_2 fixed (Ankomah et al. 1996). The higher N_2 fixation was the main factor affecting the increase in grain yield.

4.4.3 Rice response

In both years, the higher rice yield when P was applied to the pre-rice grain legume (legume biomass partially removed) compared to the yield when P was applied directly to the rice may be the result of additional N from the biological fixation by the P-amended grain legume even though P was not applied to the rice in this case. The mungbean with applied P generally performed better and fixed higher amounts of N compared to the mung bean not treated with P. In the experiment in 2013, the 9 kg P ha^{-1} derived from FYM applied on wet-season rice may be sufficient to replace the recommended P (4 kg P ha^{-1}). Nuruzzaman et al. (2005a) reported that the legume (green manure) used P for its growth. In addition to this, P applied to mungbean may have a residual effect on the receding rice crop (Pheav et al. 2003). The incorporated biomass of mungbean may also have been able to enhance soil-available P for plant uptake (Randhawa et al. 2005) either from the P stored in the soil or from the residual P. Nuruzzaman et al. (2005 a&b) reported that the subsequent crop had a better P uptake with the receding legume crop. Zhang et al. (1994) also reported an increase in the organic P faction with green manure amendment. Also, residual P from the green manure period may have been available to the following rice crop (Pheav et al. 2003).

4.4.4 Residual available soil P

The P application directly to rice was higher compared to the application to green manure. However, statistically there was no significant difference in the experiment in 2013, while there was in the experiment in 2014. Even though a residual effect of P was reported by Pheav et al. (2003), the large amount of P applied to the first crop was most likely used by the mungbean crop as shown by the response of green manure to P amendment in this study (Table 4.2). This agrees with findings of Malik et al. (2003), Chaudhary and Fujita (1998), and Hayat et al. (2008). Nuruzzaman et al. (2005a) reported that legumes may mobilize P through root exudates for their own growth, and this P is stored in the aboveground biomass (Braum and Helmke 1995) and then in organic P pools (Friesen et al. 1997). This organic P fraction was not detected by Olsen extraction as used in this study, but it may be mineralized over longer periods of time.

4.5 Conclusions

The results of this study show that there was a clear effect of P in both legume green manure performance and N_2 fixation. Even though only a low amount of N_2 was fixed by the legume, it maintained its ability to fix N_2. Therefore, legume in this study was restricted by soil-P deficiency. To cope with this, the supply of P enhances legume growth, yield and N_2 fixation compared to non-P legumes. Under deep sandy soil conditions and amendment with P at 10 kg ha^{-1}, N_2 fixation (36 %Nfda) was more than twice that of non-P legumes (17 %Nfda), i.e., 21 kg N_2 ha^{-1} and 9 kg N_2 ha^{-1}. Although the performance and grain yield of the legume on the deep sandy soil was low, values are in the range reported in Cambodia. The low N_2 fixation under these conditions suggests there are some restrictions. Application of P improved the pre-rice legume and the atmospheric N_2 fixation. Thus, application of P to the first pre-rice legume may be a better option, rather than direct application of P to the subsequent rice crop. Both P strategies produced comparable rice yields. Furthermore, the rice yield was even higher when the legume biomass was partially removed (grain legume). Application of P to the pre-rice legume offers enhanced grain yields as an economical bonus.

5 RICE YIELD RESPONSE TO DIFFERENT FERTILIZER MANAGEMENT OPTIONS

5.1 Introduction

Paddy rice (*Oryza sativa L.)* occupies around 90 % of the global rice-growing area (Buresh and Haefele 2010). Rice cultivation is one of the main agricultural activities in Cambodia and rice is also a vital export commodity. Rice farming systems in Cambodia can be differentiated by elevation, soil type and hydrology. Predominating, however, is the cultivation of one single crop of rainfed rice during the wet season (August-December) on sandy soils in the lowland areas of the country. In some areas, however, the duration of the wet season is long enough or the water availability is sufficient to permit the growth of another crop directly before or after rice (Fukai and Ouk 2012). The yield of rainfed lowland rice is generally low, which is partially related to the low soil fertility. Thus, both the deep and the shallow sandy Fluvisols (Prey Khmer and Prateah Lang soils, respectively, according to the local soil classification for rice) have low nutrient reserves (mainly N and P), low levels of organic matter and low CEC (Seng et al. 2001). The use efficiency of applied nutrients to rice is reportedly very low, and the outcome of nutrient application strategies is highly variable (Bell et al. 2006). In addition, both soil types are moderately to highly acidic. There is a need to tackle the complex fertility problems in a comprehensive way that addresses the problems related to low soil-organic carbon and low CEC in addition to supplying N and P.

While several technologies have been developed to counteract soil fertility decline and to increase rice yields, smallholder farmers often do not adopt these innovations, as performance fails to meet their expectations or the technology requirements do not match the resource endowment of the farmers (limitations of land and capital, availability of labor). Blair and Blair (2014) stated that although fertilizer recommendations have been made, the environmental diversity and uncertainty existing in rainfed rice growing areas in Cambodia make it difficult to predict optimum fertilizer uses for respective environments. On the other hand, (Wade et al. 1999b) reported that grain yield variation is generally high under rainfed lowland conditions. Thus, recommended applications of N or NP fertilizers are unlikely to provide a significant yield increase in some cases, and farmers are reluctant or simply unable to follow the recommendation. Inaccessibility of the inputs and unavailability of capital and sometimes also of labor are important factors affecting technology adoption, which differs between farmers and locations.

It appears crucial to develop fertilizer management options that are adapted to the site and systems and specifically targeting the adoption of appropriate technology options as a basis for improved N management strategies. Under such production conditions, the factors availability of green manure (particularly residues of grain legumes) and farmyard manure (FYM) appear to be promising and adoptable options to address soil fertility constraints and to contribute to yield increases. Groundnut, soybean and mungbean are adapted to lowland conditions on both shallow and deep sandy soils (Seng et al. 2008). However, soybean is often affected by insect pests and groundnut exceeds the available growth duration. Mungbean, on the other hand, is less affected by pests than soybean, has a shorter growth duration than groundnut, and hence fits the pre-rice niche in most lowland environments. Farmyard manure is another alternative nutrient source, and may be more beneficial compared to mineral fertilizer under sandy soil conditions (Hanviriyanpant and Fukai 1997).

The fact that (a) the P demand of legumes is generally much higher than that of cereals, and that (b) the sandy Fluvisols of Cambodia are often P deficient may restrict legume performance. This may be overcome by applying the P destined to rice already to the legume. Thus, the biological N_2 fixation may be stimulated, and the fixed N and absorbed P returned with legume residues may benefit the subsequent crop of rice with potential longer-term residual effects. The extent of such carry-over effects are likely to differ depending on residue management. In this study, we compared a range of mineral and organic fertilizer strategies in rainfed rice systems on both deep and shallow sandy soils. Treatments consisted of the recommended mineral N rate, FYM application and pre-rice mungbean with or without P application and different legume residue management options.

The study assessed P fertilizer management options affecting rice productivity in both deep and shallow sandy soils, addressing the following objectives:

1) Investigate the effect of legume (residual management and P application strategies) and FYM on growth and yield of rainfed lowland rice in Cambodia.
2) Provide implications of fertilizer management options under low and high rainfall intensity in legume establishment.

Table 5.1 Treatments and nutrient application in the field experiment (deep sand)

Treatment	**Pre-rice period**	**Wet season**	**NPK (kg ha^{-1})**
Year 2013			
Control	Bare fallow	No N + PK	00/04/30[2]
Urea 14	Bare fallow	14 kg N + PK	14/04/30
Urea 28[1]	Bare fallow	28 kg N + PK	28/04/30
Grain legume-P/FYM+P	Mungbean	BNF-N[2]+FYM+10 kg P	61/19/79
Grain legume+P/FYM-P	Mungbean + 10 kg P	BNF-N+FYM	70/9/79
Year 2014			
Control	Bare fallow	No N + PK	00/04/30
Urea 14	Bare fallow	14 kg N + PK	14/04/30
Urea 28[1]	Bare fallow	28 kg N + PK	28/04/30
Green manure – P	Mungbean	BNF-N[3] + 10 kg P	09/10/30
Green manure + P	Mungbean + 10 kg P	BNF-N	21/10/30
Grain legume – P	Mungbean	BNF-N + 10 kg P	09/10/30
Grain legume + P	Mungbean + 10 kg P	BNF-N (stover)	21/10/30
Forge legume – P	Mungbean	10 kg P	00/10/30
Forage legume + P	Mungbean + 10 kg P	None	00/00/30

FYM = farmyard manure applied basally at a rate equivalent to 60:09:49 kg NPK ha^{-1}; BNF = biologically-fixed nitrogen

[1] *Urea 28 is the recommended N application for deep sandy soils*

[2] *The K and P rate comprised a basal mineral application of 30 and 04 kg ha^{-1} as KCl and TSP, respectively*

[3] *The amount of N derived from biological N_2 fixation by the mungbean was estimated at 10 kg N ha^{-1} for treatment 5, and at 1 kg N ha^{-1} for treatment 4 in 2013, and at 21 kg N ha^{-1} (with mineral P) and 9 kg N ha^{-1} (no P) in the green manure and grain legume residue management treatments in 2014. In the forage legume treatment, all biologically fixed N_2 was been removed with grains and stover (only 2014).*

5.2 Material and methods

The study area, experimental design, treatment applications and field management are described in Chapter 2. In summary, grain yield and yield components affected by different fertilizer management options were studied. Options comprised the recommended mineral N rate, FYM application and pre-rice mungbean with and without P application and different legume residue management. Four field experiments were conducted and differed by site (district and sandy soil type – shallow vs. deep) in 2013 and 2014 in the Tram Kak and Prey Kabas districts in Takeo province of Cambodia (Table 5.1 and 5.2). Early wet-season rainfall varied between years and sites, where extreme rainfall during legume establishment was observed in 2013 affecting legume growth. Therefore, the fertilizer management options applied in each experiment were flexible and adjusted to available-resources.

Table 5.2 Treatments and nutrient application in the field experiment on the shallow sandy soil

Treatment	**Pre-rice period**	**Wet season**	**NPK (kg ha^{-1})**
Year 2013			
1. Control	Bare fallow	No N + PK	0/10/25[2]
2. Urea 25	Bare fallow	25 kg N + PK	25/10/25
3. Urea 50[1]	Bare fallow	50 kg N + PK	50/10/25
4. FYM -P	Bare fallow	FYM[3] – P + K	60/17/89
5. FYM +P	Bare fallow	FYM + PK	60/7/89
Year 2014			
2. Forage legume + Urea 50[1]	Mungbean + FYM[4]	BNF-N[5] + 50 kg N + PK	50/10/25
3. Grain legume – Urea	Mungbean + FYM	BNF-N + PK	78/10/25
4. Grain legume + Urea 50	Mungbean + FYM	BNF-N + 50 kg N + PK	128/10/25

[1] *Urea 25 is the recommended N application for shallow sandy soils*

[2] *The P and K rate consists of a basal mineral application of 10 kg P ha^{-1} and 25 kg K ha^{-1} as TSP and KCl, respectively.*

[3] *FYM (2013) = farmyard manure applied basally at the rate equivalent to 60:07:64 kg NPK ha^{-1}.*

[4] *FYM = farmyard manure applied basally to pre-rice legume at the rate equivalent to 78/09/83 kg NPK ha^{-1}*

[5] *BNF-N = amount of N derived from biological N_2 fixation by mungbean was estimated at 78 kg N ha^{-1}. In the forage legume treatment, all biologically fixed N_2 was removed with grains and stover.*

5.2.1 Rice data collection

Rice yield and harvest index (HI) are based on plots measuring 2 m x 2 m in the center of the fields. After threshing and weighing, straw samples were weighed and biomass determined after oven drying at 70 ˚C for 48 h (Pheav et al. 2003). Grain yield was adjusted to 14% moisture and the weight of straw and grain expressed on a per hectare basis. The HI was calculated as:

$$\text{HI} = \frac{Grain\ Yield}{Grain\ Yield + Straw\ Yield} \tag{5.1}$$

The number of panicles is based on 25 hills per plot converted to number of panicles per 1 m^2, and the number of grains per panicle is based on 25 random panicle samples. The 1000-grain weight is based on three random samples of the grain yield from each plot.

5.2.2 Statistical analyzes

All data were subjected to ANOVA and mean separation was done by Least Significant Difference (LSD) test using Statistix (Analytical Software, version 8.0).

5.3 Results

This chapter presents grain yield and yield components as affected by different fertilizer management options. The experiments were conducted in 2013 and 2014 in Tram Kak and Prey Kabas district of Takeo province, Cambodia. The rainfall during legume growth was higher in 2013 than in 2014, reflecting high and low rainfall scenarios for mungbean production.

Grain yield and yield components responded to different fertilizer management options for deep sandy soil and shallow sandy soil (Table 5.3 and 5.4). In general, the grain yields of rice ranged from 2.8 to 4.2 Mg ha^{-1} on the deep and from 4.4 to 5.4 Mg ha^{-1} on the shallow soil. On average, the grain yield obtained from the shallow sandy soil was higher than that obtained from the deep sandy soil. The analysis of variance for grain yield showed that the treatments (applied mineral N, pre-rice leguminous crops either under P application or not and residue managements) showed significant differences ($P < 0.05$). In both soil types, highest yields were obtained with the urea treatment, closely followed by treatments with mineral and organic amendment combinations. Yields in all treatments were mainly determined by the number of panicles per unit area. Harvest index and other yield components (grains per panicle and 1000-grain weight) did not show any significant variation due to treatment apart from the experiment on the shallow sandy soil (2014), where variations of grains per panicle appeared to have determined the grain yield.

Across years and soil types, there was significant difference among mineral fertilizers where application of N at the recommended rates produced higher rice yields than the reduced N rates, indicating that N was a limiting element for both soil types.

In the deep sandy soil, irrespective of P application and residue management, the pre-rice legume did enhance rice yield above the non-amended control but not above the recommended mineral N application rate of 28 kg ha^{-1} (Table 5.3, 2014). If P was applied to mungbean instead of the subsequent rice, the legume residue incorporation produced higher rice yield than when P was applied directly to rice. The rice yield obtained from the ”grain legume + P” treatment was comparable to that with N application at the recommended rate. In the ”green manure” treatment, there was no significant difference in rice yield whether P was applied to the pre-rice legume or directly to wet-season rice. Both treatments showed lower rice yields than with the recommended mineral N rate. This shows it is more important to apply P to the grain legume (residue incorporation after grain collection) than to the green manure (incorporation at podding stage). The lowest rice yield was observed in the ”forage legume” treatment (residues removed after grain collection), and was statistically comparable to that of the control treatment.

While in the case of FYM application with incorporation of the P-amended legume (grain legume+P/FYM-P) the rice yield was significantly the highest, it was statistically comparable to that of the recommended N application (Table 5.3, 2014).

In summary, rice grain yields in deep sandy soils responded to organic N when this was applied in combination with urea compared to the no-urea treatment. Among the organic treatments (FYM vs. legume), when P was applied to legumes in the ”grain legume” and ”grain legume + FYM” treatments, the grain yield was comparable to that with the recommended N application.

Table 5.3 Effect of fertilizer treatments on grain yield and yield components of rice in the deep sandy soils

Treatment	**Yield ($Mg\ ha^{-1}$)**	**Harvest index**	**Panicles # m^{-2}**	**Grains per panicle**	**TGW (g)**
2013					
Control	2.99 c	0.47	179 c	88	29.6
Urea 14	3.18 bc	0.51	219 b	94	29.6
Urea 28	3.74 ab	0.49	253 ab	93	28.3
Grain legume-P/FYM + P	3.53 bc	0.48	238 b	91	30.2
Grain legume+P/FYM - P	4.21 a	0.51	325 a	93	30.1
Significance	*	n.s	**	n.s	n.s
2014					
Control	2.82 ef	0.53	226 ef	81	30.7
Urea 14	3.17 bc	0.53	263 b	79	30.9
Urea 28	3.45 a	0.48	271 a	81	30.8
Green manure – P	3.11 cd	0.55	234 cd	83	30.3
Green manure + P	3.14 cd	0.55	255 c	79	30.0
Grain legume – P	3.06 cde	0.54	223 f	86	30.8
Grain legume + P	3.42 ab	0.55	269 ab	74	30.8
Forge legume – P	2.91 def	0.55	223 f	89	30.3
Forage legume + P	2.80 f	0.55	232 de	79	30.1
Overall significance	****	*n.s*	****	*n.s*	*n.s*
Residual managements (Sig.)	****	*n.s*	****	*n.s*	*n.s*
P (Sig.)	*n.s*	*n.s*	*n.s*	*n.s*	*n.s*
Residual managements X P	*n.s*	*n.s*	*n.s*	*n.s*	*n.s*

TGW: Thousand grain weight in grams
Different letters in a column denote significant differences at $P < 0.05$ by Least Significant Different (LSD).
*** and * indicates significance at $P < 0.01$ and $0.01 < P < 0.05$, respectively.*

Table 5.4 Effect of fertilizer treatments on grain yield and yield components of rice in the shallow sandy soil

Treatment	**Yield ($Mg\ ha^{-1}$)**	**Harvest index**	**Panicles # m^{-2}**	**Grains per panicle**	**TGW (g)**
2013					
Control	4.18 c	0.55	214 c	95	30.40 c
Urea 25	4.70 b	0.49	238 b	89	31.28 ab
Urea 50	5.43 a	0.51	289 a	94	31.43 a
FYM -P	4.71 b	0.50	243 b	89	30.65 bc
FYM+P	4.86 b	0.49	239 b	100	30.75 bc
Significance	**	n.s	**	n.s	*
2014					
Forage + urea 50	5.10 a	0.47	310 a	107 a	30.45 a
Grain legume - urea 50	4.61 bc	0.47	267 b	100 bc	30.58 a
Grain legume + urea 50	4.83 ab	0.47	283 ab	97 c	30.35 a
Significance	*	n.s	**	**	n.s

TGW: Thousand grain weight in grams
*The same letters in each column are not significantly different at $P < 0.05$ as determined by Least Significant Different (LSD). ** and * indicates significance at $P < 0.01$ and $0.01 < P < 0.05$ respectively.*

On shallow sandy soils, the application of mineral N as recommended (50 kg N ha^{-1}) yielded more rice than organic treatments (FYM) (Table 5.4, 2013). There were no significant effects whether FYM was applied to rice, or whether P was applied or not (”FYM-P” or ”FYM+P”). In 2014, growing pre-rice mungbean combined with an application of recommended mineral N to rice produced the highest grain yield (Table 5.4, 2014). Yield effects were mainly associated with the number of of grains per panicle rather than the number of panicles per unit area.

5.4 Discussion

In some cases, the treatments in the experiments differed within soil type. The fertilizer treatments were modified and adapted to the site- and system-specific target of the adoption of appropriate technology options. For instance, in 2013 rainfall intensity was high during legume establishment. Farmyard manure was used as a main source of N because leguminous green manure (mungbean) could not be established on the shallow sandy soil. On the deep sandy soil, crop performance was poor. On this soil, in 2014 mungbean was applied as green manure, grain and/or forage crop, both with P and without P. Due to the different locations, soil types and treatments, the statistical analyses focused on the individual case and the general trend for each fertilizer management option.

5.4.1 FYM application

The use of FYM significantly increased the rice yield compared to the control treatment (no urea). When the effect of FYM is compared with that of the recommended N application, the response of rice yield to FYM was dependent on soil type. In general, the rice yield responded better to FYM on the deep sandy soil than on the shallow sandy soil.

On the deep sandy soil, P-amended green manure combined with FYM (green manure+P/FYM-P) tended to produce highest rice yield compared to the recommended N ”urea 28”. This was due to the highest panicle number per unit area. Combination of FYM and green manure (under both P strategies) showed a statistically comparable rice yield to that with the recommended N rate. It was observed that the contribution of N from green manure was small due to poor performance (1 kg and 10 kg N_2 fixed for mungbean and P-amended mungbean, respectively). Thus, N was mainly derived from FYM. However, FYM application either with P or without P on the shallow sandy soil produced lower rice yields than with the recommended N rate. The treatment ”grain legume+P/FYM-P” produced the highest rice yield; FYM was applied at the rate of 60 kg N ha^{-1}. The pre-rice grain legume applied with P fixed 10 kg N_2 ha^{-1}. Overall, the N received by rice in this treatment was 70 kg N ha^{-1}. Farmyard manure contributed 9 kg P ha^{-1}, which was beyond the recommended P for wet-season rice (4 kg P ha^{-1}). In this treatment, P was not applied directly to the rice, but to the preceding legume. Even though the legume used the applied P for its growth (Nuruzzaman et al. 2005a), the residual effect of P may have resulted from the previous grain legume period. Pheav et al. (2003) reported that P application has a residual effect on the next crop. In the present study, the rice crop may have benefited from this additional residual P. Despite the poor performance of the legume, organic-P mineralization could also have increased with the legume residue, resulting in the enhancement of soil-available P to the rice uptake (Randhawa et al. 2005). Nuruzzaman et al. (2005a&b) also reported that the certain legume crops contributed to a better uptake of P of the subsequent wheat crop. Considering the contribution of inputs (N and P) and better P availability, the “grain legume+P/FYM-P” treatment led to a higher rice yield than with the recommended N rate and the ”grain legume-P/FYM+P” treatment. In the “legume-P/FYM+P” treatment, the contribution of N to the rice was 61 kg N ha^{-1} (60 kg N ha^{-1} from FYM and an additional 1 kg N ha^{-1} from the pre-rice green manure without P application). Rice yield in the ”grain legume-P/FYM+P” treatment was more or less comparable to that of the recommended N treatment. However, this ”grain legume-P/FYM+P” treatment produced a significantly lower rice yield than “grain legume+P/FYM-P”. This may have been due to the advantages of higher N inputs and better green manure performance, which probably also led to better P availability in the ”grain legume+P/FYM-P” compared to the ”grain legume-P/FYM+P” treatment.

On the shallow sandy soil, application of FYM (60 kg N ha^{-1}) with P and without P to wet-season rice produced significantly lower panicle numbers per unit area, thus resulting in a lower rice yield than with the recommended N application treatment (urea 50). However, the rice yield obtained with FYM addition was significantly comparable to that with 50% of the recommended N (urea 25). The recommended NPK for shallow sandy soil (50:10:25 NPK kg ha^{-1}) is generally higher than for deep sandy soil. Application of FYM supplied 60 and 7 kg ha^{-1} of N and P, respectively. In the”FYM+P” treatment, an additional 10 kg ha^{-1} of mineral P was applied. The contribution of PK from both FYM treatments was more or less comparable to the recommended PK in the “urea 50” treatment. Due to the slow FYM decomposition in the short-term period (Levi-Minzi et al. 1990), the N and P available to the rice crop may not have been higher than the mineral N and P in the “urea 50” treatment. The treatment”FYM+P” tended to produce a higher rice yield than ”FYM-P”, but statistically rice yields were comparable. The difference in both treatments is additional mineral P. The FYM provided 7 kg P ha^{-1} to the rice crop, which was lower than the recommended dose P of 10 kg ha^{-1}. However, additional P could have been from the previous season fertilization as residual P. It was reported that, like elsewhere in the study region, P fertilizer was applied to the experimental fields in the previous season prior to the start of the experiment start, mainly through ammonium phosphate (DAP). Pheav et al. (2003) reported that P fertilizer had a residual effect on the next crop and recommended not to apply P to every single crop. The rice crop may have benefited from this residual P. This residual P may have been available in the organic P fraction, but not detected by Olsen extraction. The organic P fraction, which could be increased with organic matter supply (Zhang et al. 1994), can be easily available to the plants (Mo et al. 1991). Thus, addition of mineral P did not increase the grain yield.

Because of the small benefit of the legume residue in the ”legume-P/FYM+P” treatment in the deep sandy soil, this treatment can be cross-compared with FYM treatments on shallow sandy soil. The rice yield responded to FYM better on the deep sandy soil than on the shallow sandy soil.

5.4.2 Mungbean residual management and P application strategies

Irrespective of P application, the removal of the mungbean residue (forage legume) prior to the wet-season rice produced the lowest rice yield among the three residual management strategies (green manure, grain legume, forage legume) in the deep sandy soil. The low rice yield was identified by lowest panicle number per unit area. It is known that without the return of green manure residues, with P application or without, soil organic matter is lost from the system (Singh et al. 2007). The advantages of incorporating green manure or grain legume residues to benefit a subsequent crop of rainfed lowland rice has been reported by Suriyakup et al. (2007). The findings of the present study agree with those reported by Sharma and Prasad (1999) indicating that after the incorporation of mungbean residues, the rice yield was significantly higher compared to fallow before rice. Even though the legume was grown as pre-rice crop, it was not beneficial if the residue was removed. The advantageous effects of legume residue incorporation may be attributed to the increase in organic matter and total N in the soil (Mandal et al. 2003). The treatment “grain legume” residue incorporation led to the highest rice yield provided P was also applied to the legume crop; it was comparable to the yield obtained with the recommended N application. This was not the case for the “green manure” treatment (incorporation of residues at podding stage). No significant difference in rice yield was obtained from the incorporation of residues in both “green manure+P” and ”green manure-P”. Hirpa et al. (2013) reported incorporation may be at any growth stage with highest biomass and N accumulation. The results show the importance of P for legumes where residues were buried at the maturing stage. Suriyakup et al. (2007) reported that whether mungbean residues were incorporated during flowering stage or after grain harvest had a similar effect on the subsequent rice yield, but the total N return into the soil from residues at the maturing stage was even higher than that at the flowering stage. Legume applied with P (grain legume) fixed 21 kg N ha^{-1} and produced higher biomass than without P (grain legume-P). Residues of ”grain legume” may have contributed to reducing the N losses, thus conserving the soil N for plant nutrition (Linquist et al. 2007). Panda et al. (1994) reported that NO_3^- leaching was generally low with green manure amendment. NH_4^+-N from organic manure could have accumulated more than NO_3^- under anaerobic conditions, while rice plants prefer NH_4^+ to NO_3^- (Aulakh et al. 2000b).

In the shallow sandy soil, incorporation of legume residues did not show any significant difference whether urea was applied to wet-season rice or not. This shows that when the legume residues were buried, the legume crop contributed N through biological fixation, which provided sufficient N to the subsequent rice crop. In this case, the recommended urea is not needed. The N fixation in this soil was 78 kg N ha^{-1}. While the recommended N is generally 50 kg ha^{-1}, 78 kg N ha^{-1} fixed by the legume may have been sufficient for the crop-N demand. However, the grain yield obtained from “legume urea 50” tended to be lower than ”forage + urea 50” (residue was removed) as a result of decreasing panicles per unit area. This could be explained by the oversupply of N when the legume residues were buried and supplemented with the recommended NPK. The oversupply of N led to sterile grains, thus reducing the grains per panicle

(Dobermann and Fairhurst 2002). Peng et al. (2010) and Lin et al. (2007)reported that the excessive N input could cause rice crop lodging, thus decreasing the grain yield. In this study, lodging occurred when legume residues were incorporated with full NPK application to rice. Here the rice crop received N from both mineral fertilizer (50 kg N ha^{-1}) and legume N_2 fixation (78 kg ha^{-1}), in total accounting for 128 kg N ha^{-1}.

The results show a residual effect of mungbean at the maturing stage on the rice yield on the deep sandy soil provided P was applied. The response of rice yield to legume residue incorporation showed the ability of the legume to provide N through N_2 fixation. During one crop season, mineralization of most of the decomposable carbon fractions of the green manure could occur. The decomposition process is quite fast if sufficient soil moisture is available (Aulakh et al. 2001). Assuming that the C/N ratio of mungbean in this study was 15.9 as determined by Das et al. 1993, the mineralization of the incorporated green manure was even faster that reported by Aulakh et al. (2001). This is assuming that N from the legume could have been mineralized to NH_4^+, and this available N was rapidly released after the incorporation of the green manure (Nagarajah 1988). This could explain the response of rice yield to legume residue incorporation.

Overall, grain yield obtained from the shallow sandy soils was higher than that obtained from the deep sandy soils. The deep sandy soil has sandy material deeper than 1 m, and is thus prone to high percolation and drought. In the experiments, however, water was not limiting. Thus, leaching of N (and other nutrients) may have been the cause of the lower productivity than on the deep sandy soil (Bell and Seng 2005). This was also probably the reason for the better response of rice yield to organic materials (particularly FYM) in the deep compared to the shallow sandy soil.

5.5 Implications

The experiments aimed at assessing the effect of different fertilizer management options, especially integration of pre-rice legume, on rice growth and grain yield. Because of uneven rainfall intensity during legume establishment in the two experimental years, the performance of the pre-rice legume (mung bean) varied with locations and years, resulting in modified and adjusted available-resource options.

Therefore, the implications from the experimental results are divided into two cases: under high rainfall intensity and low rainfall intensity.

5.5.1 High rainfall intensity during legume establishment (2013)

In 2013, higher rainfall intensity occurred during legume establishment. In the shallow sandy soil, the crop failed to establish due to waterlogging. It is known that legume crops are sensitive to waterlogging. However, on the deep sandy soil the crop performed well and even fixed a very small amount of atmospheric N_2 providing P was applied. High rainfall in the early season may not be favorable to legume crops, especially on shallow sandy soils. On deep sandy soils, the water from rainfall is not generally retained. In contrast, on the shallow sandy soils, the water is retained in the root zone, i.e. in the clay-loam subsoil (White et al. 1997), probably causing waterlogging. The poor performance of the legume crop on the deep sandy soil and its failure on the shallow sandy soil was minimized by the application of FYM to the rice crop. On the shallow sandy soil, application of FYM alone at 60 kg N ha^{-1} (4-7 Mg FYM ha^{-1}) produced a lower rice yield than with the recommended N rate. On the deep sandy soil, an acceptable legume performance and low N_2 fixation is possible provided that P is applied. Without P application, the legume is very sensitive to failure even on the well-drained deep sandy soil. However, a P-amended legume crop alone may not provide sufficient N from N_2 fixation to fulfill the rice crop demand. A combination with FYM (60 kg N ha^{-1}, i.e. 4-7 Mg FYM ha^{-1}) can provide a rice grain yield comparable to that with the recommended N rate. According to the cattle intensity classification in Asia, the annual N input from Cambodian cattle is approximately equivalent to 15 N kg (Gerber et al. 2005; Ly et al. 2012) . Thus, 4 cattle produced N input equivalent to 60 kg N in one crop cycle. Ly et al. (2012) reported a mean number of cattle per farmer in Tram Kak district of 3 to 4. This indicates that N accumulation from FYM was 60 kg N ha^{-1} per year if the farmers owned at least 4 cattle. This did not produce a higher rice yield than that with the recommended N rate on the deep sandy soils; however, the yield was comparable. On the shallow sandy soil, the yield was lower. Application of FYM beyond 60 kg N ha^{-1} is not likely to be possible.

5.5.2 Low rainfall intensity during legume establishment (2014)

Under low rainfall intensity during legume establishment, the legume developed better on the shallow than on the deep sandy soil. However, when growing legumes for incorporation of residues, P application to the legume crop and not directly to the rice may be a good option. The removal of legume residues for use as forage did not benefit the subsequent rice crop. The early incorporation of the legume crop did not increase the subsequent rice grain yield over incorporation after legume grain harvest. Thus, delaying the incorporation until grain harvest provided a beneficial bonus grain. Hirpa et al. (2013) observed that early incorporation of the legume crop did not contribute to the growth and yield of the subsequent maize crop, probably due to the N leaching losses before the nutrient was taken up by the subsequent crop. On the shallow sandy soil, the legumes performed the best. High biomass was achieved and N_2 fixation was as much as 78 kg N ha^{-1}. Here, FYM was applied prior to the legume crop.

Under these conditions, two conclusions can be drawn from the findings:

1) When farmers apply the recommended NPK to the wet-season rice, the legume residues can be removed for forage. Without this removal, the rice crop may face excessive N resulting in crop lodging.

2) The incorporation of legume residues can save N input through urea, thus the farmers need only to apply the recommended PK.

5.6 Conclusions

Fertilizer management options are generally driven by rainfall intensity during legume establishment and FYM availability, thus fertilizer strategies should be adjusted and managed accordingly. Integration of pre-rice legume crops as green manure is possible provided that waterlogging does not occur during the dry-wet transition period (legume establishment), especially during April and May, and that P is applied to the legumes. In this study, incorporating P-amended legume residues at the maturing stage after picking the grain produced rice yields in both soil types comparable to those with the recommended N application (mineral P and P-amended FYM on deep and sandy soils, respectively).

Besides residues, the legume provides economical grain yields. The N_2 fixation determined by the ``^{15}N natural abundance” method at five experimental locations varied from 0 to 78 kg N_2 ha^{-1} (Table 5.1 and 5.2). High N_2 fixation was mainly observed in the low rainfall intensity year (2014). Under high rainfall intensity (2013), the legume suffered from waterlogging. Therefore, erratic rainfall is still the most challenging factor for legume cultivation in the early wet season. Under severe waterlogging conditions, FYM is another potential N source. If the farmers own 4 cattle, the N inputs (60 kg N ha^{-1}) could produce rice yields comparable to those with the recommended N rate on deep sandy soils, but not on shallow sandy soils. Since N input from FYM beyond 60 kg N ha^{-1} may not be possible, FYM cannot compete with the recommended N rate on shallow sandy soils.

Compared to FYM, legume residues provided better agronomic benefits (both N input and grain yield). If some agronomic constraints are solved to maximize crop growth and yield, pre-rice legumes would improve the rice production system through their N_2 fixation ability and diversification purposes. Measures to minimize the risks for the legumes due to waterlogging could be, for example, construction of fallow raised beds and drainage. This needs further study.

The results of this study show that indigenous soil P or supplemented fertilizer P play an important role in the enhancement legume performance, mainly by stimulating biological N_2 fixation. This confirms the initial research hypothesis. The recommended P for rice could be applied to the pre-rice legume for better performance and N_2 fixation. In return, the incorporation of legume residues would benefit the subsequent rice crop, thus outweighing the effect of P directly applied to rice.

6 FARMERS´PERCEPTION OF LEGUMINOUS GREEN MANURE

6.1 Introduction

Infertile sandy soils are a major constraint to rainfed lowland rice production in smallholder systems of Cambodia. Particularly low N and P (and in some instances also sulphur) limit yields (Seng et al. 2001). In the lowland areas of the country, mostly a single crop of rainfed rice is grown during the wet season. Crop diversification by inclusion of non-rice crops is a recent development in several parts of Asia, but to date nearly absent in Cambodia. Different legumes, but also maize or vegetables can be included in the rice-based systems, either in the pre- or in the post-rice niches, provided that moisture is available and the growing period of the diversification crops fits the length of the cropping niche (Fukai and Ouk 2012). Particularly the inclusion of legumes in rice-based farming systems can play an important role in addressing soil fertility constraints, in addition to providing protein for human and animal nutrition and sources of additional income. Growing legumes for the sole purpose of soil improvement (green manure) may be less attractive to low-input farmers than using legumes with multiple purposes, such as grain for human consumption or forage for grazing animals (Ali 1999).

Despite several positive reports concerning legume effects on the yield of a subsequent crop or the improvement of resource base quality, the adoption of green manure technologies remains low and is even declining in many parts of Asia (Ladha and Garrity 1994). The decision to adopt any technology depends on its profitability, but also on associated risks and uncertainties. The factors involved in green manure adoption are the socioeconomic environment (i.e., market access) and the resource endowment of the farmers (i.e., land, labor, capital, and know-how) in combination with the efficiency of the technology options to address key constraints or enhance yields (Becker 2003). Soil water availability (both for the diversification crop, but also water competition for the main crop) is another factor influencing adoption in water-scarce environments. Green manure species are highly diverse and fit the growing environment in different ways. Key agronomic constraints are often the availability of high quality seeds, tillage requirements for crop establishment, and the availability of implements for biomass incorporation. In addition, it is likely that the adoption of green manure may also be influenced by farmers' experiences and awareness about uncertainties in the outcome of the investments. For example, unpredictable and erratic rainfall during the pre-rice niche can be a major disincentive for green manure adoption (Ladha and Garrity 1994).

In any case, the key to adoption of any innovation is related to farmers' expectations and perceptions. These differ between farms and will hence result in differentiated patterns of reasons and drivers for adoption and non-adoption(Feder and Umali 1993).

The present survey was conducted with the objectives: 1) to investigate the current practices of legume integration into rice-based farming systems and farmers' perception of green manure uses, and 2) to identify the constraints and opportunities for integrating legumes as green manure into rainfed lowland rice systems of Cambodia.

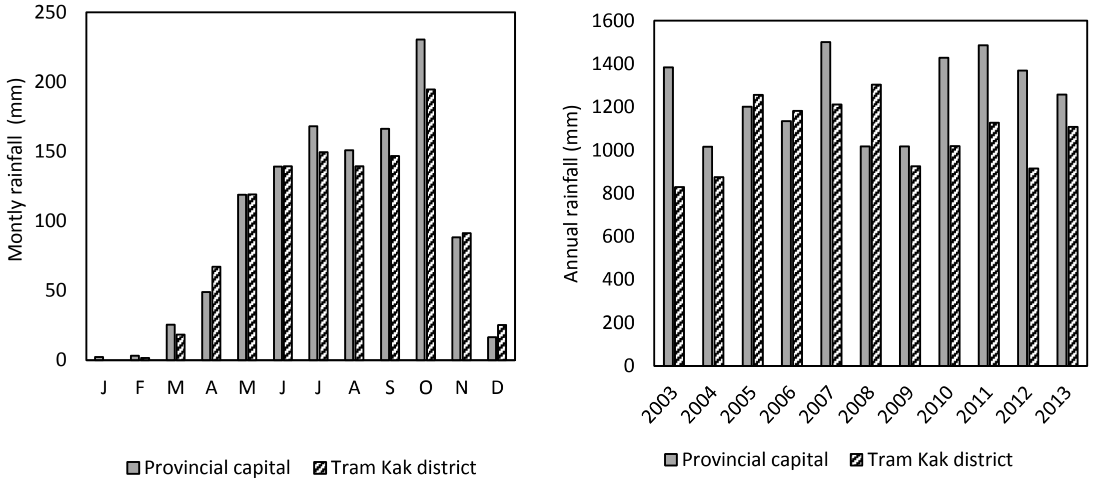
6.2 Materials and methods

6.2.1 Survey sites

The study was conducted in the main rice-growing Takeo province in southern Cambodia. Takeo province is one of five provinces with lowland plains and constituted in 2002 the major rainfed rice production zone of Cambodia (MAFF, 2013). The districts Tram Kak (90 km from the capital city of Phnom Penh) and Prey Kabas (65 km from Phnom Penh) were selected for this study. They are both characterized by a prevalence of sandy soils, which are the most common soil types for rice production in Cambodia. The two districts share similar biophysical, socio-economic and environmental conditions as detailed hereafter.

According to the Köppen-Geiger classification (Peel et al., 2007), the climate of the study sites belongs to the Tropical Rainforest type (Af) and is characterized by one distinct wet season between May and October and a dry season between November and April. Annual rainfall ranges from 1,250 to 1,750 mm (White et al. 1997) with highest precipitation occurring in October. The temperature varies from 21°C in November-January to 35°C in April-May. The climatic conditions during the field study years (2013) are presented in Figure 6.1.

Most lowland areas of the study districts are under paddy rice cultivation systems. While one single crop of wet season rice is the most common, two crops per year are also possible in some parts of the districts. Most fields are left to bare fallow during the dry season. In some cases, short-cycle crops are grown during the short dry-to-wet season transition period in the pre-rice niche before the onset of the main rainy season, or in the post-rice niche using the residual soil moisture after rice harvest. Such diversification crops comprise mainly vegetables, mungbean, and maize. In both study districts, the most common diversification option in the rice cultivation systems is mungbean *(Vigna radiate* L.*)*, both during the early wet season (pre-rice niche) as well as in the early dry season (post-rice niche), provided that soil moisture suffices for cultivation or that supplementary irrigation can be provided.



(a) (b)

Figure 6.1 a) Monthly (average 2003-2013) and b) annual rainfall (sum of monthly data). Source: Ministry of Water Resources and Meteorology of Cambodia.

Table 6.1 Selected biophysical and socio-economic attributes of the study districts in Cambodia

Parameter	Districts	
	Tram Kak	**Prey Kabas**
Total land area	54,694 ha	26,910 ha
Cultivated area	35,677 ha	20,737 ha
Area under wet season rainfed rice (%)	32,322 ha (86)	10,419 ha (88)
Population	171,532	103,294
Total number of families	34,629	20,916
Number of families engaged in agriculture (%)	33,445 (97)	19,206 (92)
Families engaged in rice farming (%)	33,415 (96)	19, 179 (92)

Source: National Committee for Sub-National Democratic Development (NCDD): Prey Kabas and Tram Kak districts data book of Takeo province, Cambodia 2009. Data for 2008.

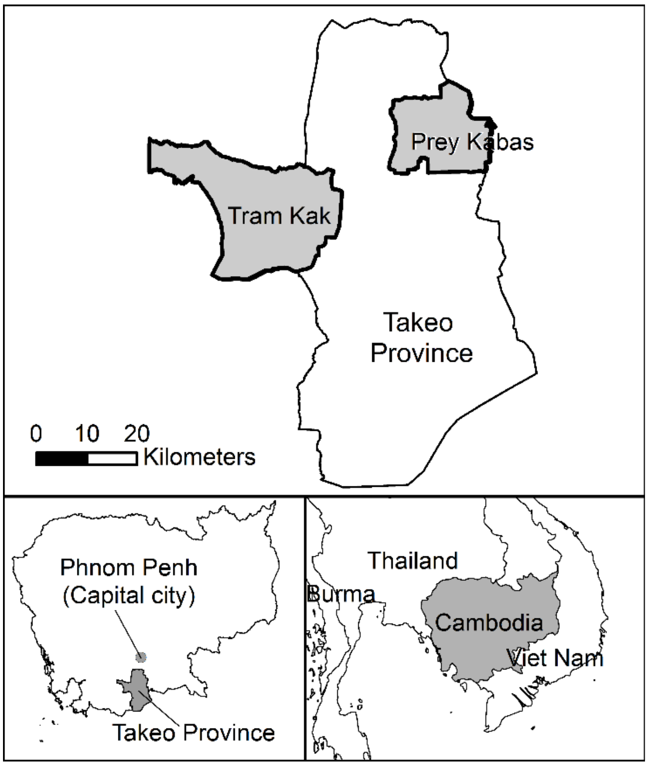


Figure 6.2 Geographic location of the study districts Tram Kak and Prey Kabas

6.2.2 Questionnaire design

A farm survey was conducted to understand the adoption capacity, constraints and factors influencing farmers’ adoption of green manure technologies by taking into account the feasibility, profitability, interest and perception of farmers. The survey was undertaken in the years 2013-2014. It aimed at assessing niches or windows of opportunity for the inclusion of green manure technologies into existing rainfed lowland rice systems. The survey was undertaken through individual interviews with farmers using open-ended questionnaires. Questionnaires addressed issues such as household attributes, general resource endowment, agronomic practices, acceptance and perception of green manure technologies and the specific availability of land, capital, and labor in relation to legume adoption. During the interviews, field observations were used to supplement and validate the data and the information collected in the interviews.

The survey was conducted by a researcher and two well-trained assistants. While the study was undertaken between December 2013 and the beginning of the wet season in 2014, the questions referred to the year 2013. Prior to the survey, a pre-test of the survey questionnaire was undertaken with eight farmers to improve it and to facilitate the feasibility of answers.

6.2.3 Interview sampling and procedure

In consultation with district authorities, the target administrative units (communes) were identified. Systematic sampling was used to select the households per commune. Prior to the interviews, the local authority in each commune was contacted for formalities. The interviews started with a random household near the commune hall as a starting point, and the subsequent households selected for interview were after every 10th household.

Table 6.2 Number of sample households selected for the green manure adoption survey from each commune in Tram Kak and Prey Kabas districts in Cambodia

District	Commune	Number of interviewed households
Tram Kak	Tram Kak	11
	Srae Ronoung	10
	Kus	10
	Leay Bour	12
	Samraong	8
	Ta Phem	8
	Otdom Souriya	11
	Popel	8
	Trapeang Thum Khang Cheung	8
	Trapeang Thom Khang Tboung	9
	Cheang Tong	10
	Ou Saray	8
Sub-total		**113**
Prey Kabas	Champa	23
	Char	15
	Prey Lvea	15
	Taing Yab	20
	Kdanh	21
	Prey Phdau	19
	Snao	12
Sub-total		**125**
Total		**238**

The sample size was calculated based on the formula of Magnani (1999) as follows:

$$n = D\,[(Z_\alpha + Z_\beta)_2 * (P_1(1-P_1)+P_2(1-P_2))/(P_2-P_1)_2] \qquad (6.1)$$

n = number of households to be interviewed

D = design effect, which is set to be the default value of 2

P_1 = estimated level of proportion at the time of the survey. It was estimated that 20% (0.2) of the farmers grow green manure at the time of the survey.

P_2 = expected level of proportion at some future date. It was predicted that there will be a decrease by 10% (0.1) in the number of farmers who grow green manure.

$Z\alpha = 1.645$ and $Z\beta = 1.282$

The levels of significance (α) at 95 and 80% (β) were selected, resulting in values of Zα and Zβ at 1.645 and 1.282, respectively. This resulted in a total number of at least n = 222 households to be sampled. To account for missing data, a total of 238 households from both study districts was selected (Table 6.2).

6.2.4 Statistical analysis

Data were analyzed using the Statistical Package for the Social Sciences (SPSS, version 22). Simple frequencies and descriptive statistics were generated. The chi-square test detected relationships between selected variables and legume adoption attributes.

6.3 Results and Discussion

6.3.1 General household characteristics

In general, the household attributes and the distribution of characteristics were similar in both districts, except for the average land size (Table 6.3). In both districts, more respondents were female than male, the majority of household heads was 40 to 60 years old, and the average household size was >7 family members. The education level of the household heads was distributed equally among illiterate, primary, secondary, and upper secondary. Most households in Prey Kabas (86%) but only about 50% in Tram Kak possess 1-3 rice field plots. The farm size distribution revealed a majority of small-scale farmers, where 50% of the respondents owned < 1 ha of land at both sites.

As in many other parts of Cambodia, all respondents cultivate rice in the wet season. However, in addition to the wet-season rice, around 25% of the farmers in Prey Kabas was also engaged in either early wet-season or early dry-season cultivation, but only around 15% of the farmers in Tram Kak. Apart from agricultural activities, the majority of the households (80%) had off-farm income. However, the main income was generated from agriculture (92% of respondents), mainly from rice cultivation.

Table 6.3 General characteristics of households in the study districts, Cambodia

Variable	**Description**	**Tram Kak**	**Prey Kabas**
		%(no.)	
Respondent gender	Female	64 (72)	57 (71)
	Male	36 (40)	43 (54)
Age of household head	<39	25 (27)	19 (23)
	40-60	60 (66)	49 (61)
	>60	15 (17)	32 (41)
Household size	<= 7	27 (30)	26 (32)
	>7	73 (80)	74 (93)
Education level	Illiterate	28 (31)	10 (12)
	Primary	31 (34)	41 (51)
	Secondary and upper	41 (45)	49 (61)
Number of fields	1-3	53 (59)	86 (107)
	4-6	34 (38)	14 (18)
	>7	13 (15)	0
Average field area	<0.5 ha	34 (38)	51 (63)
	0.5-1 ha	50 (55)	27 (34)
	> 1ha	16 (18)	22 (27)
Soil texture[1]	Sandy	46 (52)	23 (36)
	Loamy sand	54 (60)	57 (88)
Rice ecosystem	Only wet season	71 (81)	51 (63)
	Early-wet and wet season	14 (16)	27 (33)
	Wet season and dry season	13 (15)	23 (28)
Off-farm job	Yes	82 (90)	86 (106)

[1] Respondent answers, based on the top soils

6.3.2 Frequency of non-legume green manure and legume crops

Out of 238 households, 16% occasionally use non-legume green manures, mainly the Asteracaea *Chromalaena odorata* (locally known as *Antreang Khet*), which is collected from wild stands surrounding the housing areas. One third of the respondents (31%) cultivate legume crops. The proportion of legume growers was similar in both study districts. Among legume growers, around 50% of the respondents grew legume every year during the past 10 years, while other 50% grew legumes only during some of those years (Table 4). By far the most popular legume is mungbean (92%), followed by groundnut (8%).

Table 6.4 Frequency of use and cultivation of non-legume green manure and legume crops

Variable	**Application**[1]	**Number of responses (%)**	**Crop species (%)**
Non-legume green manure	Used (occasionally)	39 (16)	*Chromalaena odorata*
	None	199 (84)	
	Total	*238*	
Legume	Cultivated every year	36 (15)	Mungbean: 67 (92)
	Cultivated but not every year	38 (16)	Peanut: 6 (8)
	Never	164 (69)	-
	Total	*238*	

[1] *over the last 10 years*

6.3.3 Characteristics of legume growers

Most farmers used only a portion of their rice fields to cultivate legumes. Thus, among legume growers, only about 33% of the rice field areas was under legume cultivation (Table 5). The average land size for legume cultivation was 0.27 ha with 50% used to intercrop the legumes with vegetables rather than sole cultivation.

Table 6.5 Characteristics and agronomic practices of legume growers (n = 74)

Variable	Answer	Description
Proportion to total farm size	-	32 %
Land ownership	Owned land	99%
Loan in the production	Yes	0.5%
Mungbean area	ha	0.27 (±0.46)
Labor (domestic)	-	2.81 (±0.14)
Intercropped	Yes	43%
Fertilizer used	Cattle manure	62%
	Chemical fertilizer	24%
	No-use	14%
Average legume yield	kg ha^{-1}	169
Trend of grain yield	Increase	67%
Cultivation method	Direct seeding	27%
	Broadcasting	73%

As part of the legume establishment method, 73% of the respondents used broadcasting, while 27% row-planted the legume. While row planting provides higher grain yield, it is more labor intensive than broadcasting the seeds (IRRI, 1985 and 1987). The current broadcasting practice by the majority of the respondents may explain the relatively poor performance and legume crop establishment as suggested before (Fukai and Ouk 2012).

The majority of the farmers (86%) apply fertilizers to the legume, mainly in the form of farmyard manure (62%), followed by mineral fertilizer (24%). However, the application rates are generally low, as fertilizers are prioritized to the main crop of rice. The legume yields in the farmers' fields were highly variable in 2013, ranging from 80 to 310 kg ha^{-1} with an average of 169 kg ha^{-1}.

Legume seeds are affordable and widely available on local markets (Figure 6.3). While farmers recognized that seeds obtained from research institutes have a better performance (i.e. the mungbean genotypes CARDI Chey and CMB3), most will obtain seeds from local markets, from neighbors, or reuse their own seeds from the previous year's harvest. Almost 80% of the growers own farm implements (hoes, rakes and weeders), and >50% have access to supplementary irrigation. However, a large share of the farmers (>50%) claims to face serious problems with the incorporation of crop residues, mainly because of the non-suitability of the available draft cattle.

The majority of legume growers harvest the grain and incorporate the crop residue as green manure. Consequently, the purposes for legume cultivation are three-fold: 1) sole green manure - practiced by only 4%, 2) grain legume with residues incorporated as green manure - practiced by 77%, and 3) forage legume with grains harvested and residues fed to cattle - practiced by 19% of interviewed growers (Figure 4a). This implies that farmers prefer cash crops (grain legume) rather than sole green manures. The considerable proportion of legume growers using legume residues as animal feed suggests that future legume-based technologies in rice-based farming systems will compete with forage uses, and are likely to even further reduce the acceptance of green manure practices.

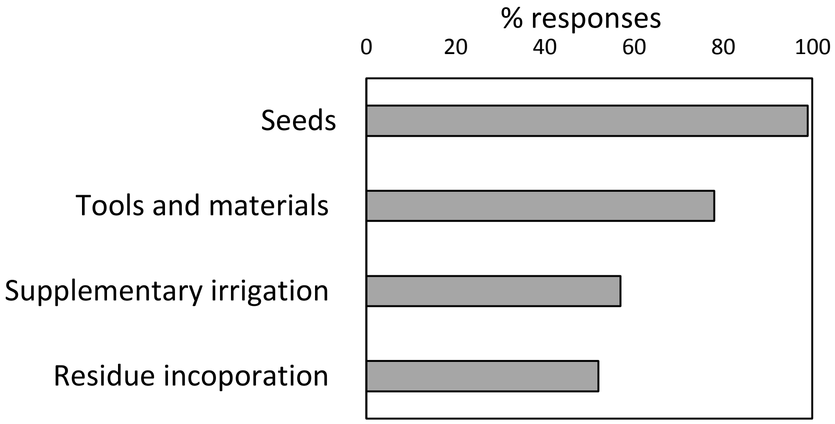
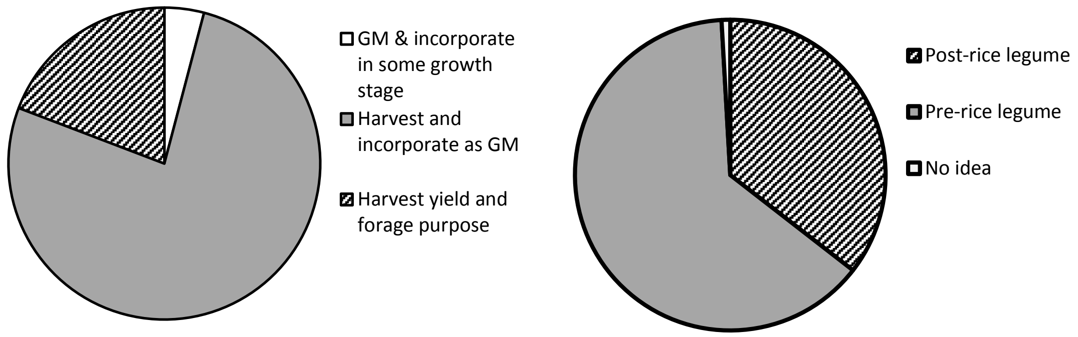


Figure 6.3 Availability of growing legumes (N = 74, multiple answers)



(a) (b)

Figure 6.4 (a) Purposes for growing legumes; (b) rice-legume cropping patterns (N = 74). *GM= green manure*

6.3.4 Growing schedule

The farmers‘ perceptions of the integration of legumes into the cropping calendar of rice-based farming system show that 64% consider legumes in the pre-rice niche while only 35% prefer the use of the post-rice cropping niche (Figure 6.4b). Post-rice legumes, however, are largely limited to situations where supplementary irrigation water is available (Chea et al. 2011). Some farmers argued that the crop always faces drought at the later stage when residual moisture after rice harvesting is rapidly diminishing. Farmers reported that the pre-rice legumes are prone to fail due to waterlogging rather than to drought.

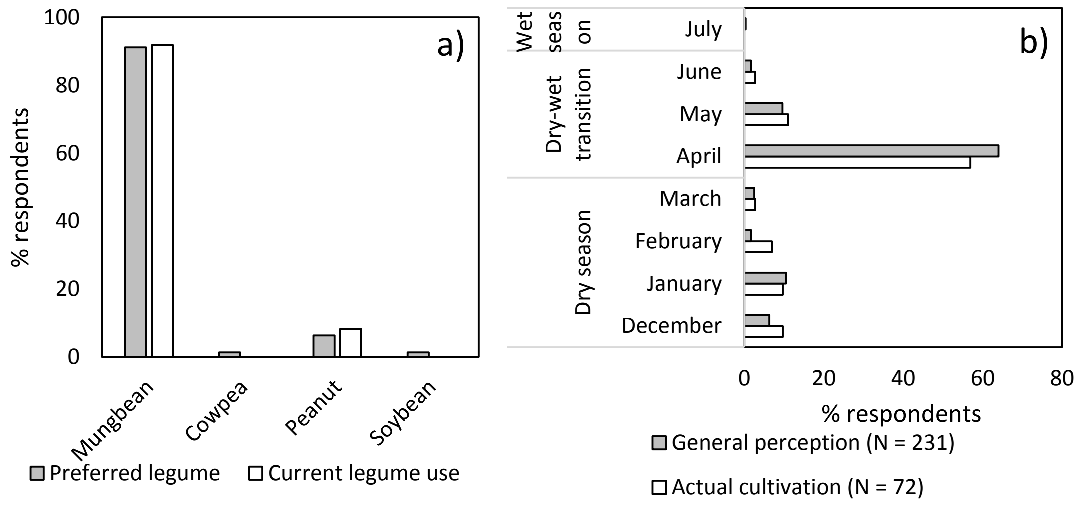


Figure 6.5 a) Preferred and currently grown legumes; b) legume growing schedule

Among the legume species, 91% of the respondents perceived mungbean as the preferred crop, and 95% actually grow mungbean. Groundnut, cowpea and soybean are preferred by only 1% of the legume growers (Figure 6.5a). The preference of mungbean by the majority of farmers is related to its short growth duration and relatively high market price. Groundnut is less favored due to its longer growth duration and high labor demand (Whitmore et al. 2000), while soybean is highly sensitive to insect damage (Seng et al. 2008). When asking about appropriate schedules for growing legumes, the majority of the respondents replied that April was the ideal month for seeding, and thus, most respondents seeded their legumes in this month (Figure 6.5b). The common practice is to broadcast the legume seeds when the first rain falls. If there is little or no rain during April or May, a delayed legume crop would overlap to the time of rice transplanting. In this case, the farmers may not proceed with legume seeding but wait for the wet-season rice. In most areas of rainfed lowland rice in Cambodia, rice is sown in May to June, which allows rice transplanting in July to August (harvest between November and December). Consequently, the available pre-rice niche between the first rain and the transplanting of lowland rice is 8-10 weeks. Any delay in the rainfall will shorten this niche and increasingly limit the possibility of legume inclusion in the rainfed rice-based systems.

6.3.5 Constraints to legume cultivation

As stated above, legumes are rarely cultivated every year. In years without legumes (here only pre-rice legumes), cultivation was mainly constrained by erratic rainfall, followed by competition for land and the lack of labor (Figure 6.6). Various reasons were mentioned for growing legumes only on small portions of the total rice field area. The primary reason was land shortage, as farmers tended to allocate fields first for high-value crops (mainly vegetables) before using land for green manure. Generally, legume cultivation was restricted to field plots close to the homestead.

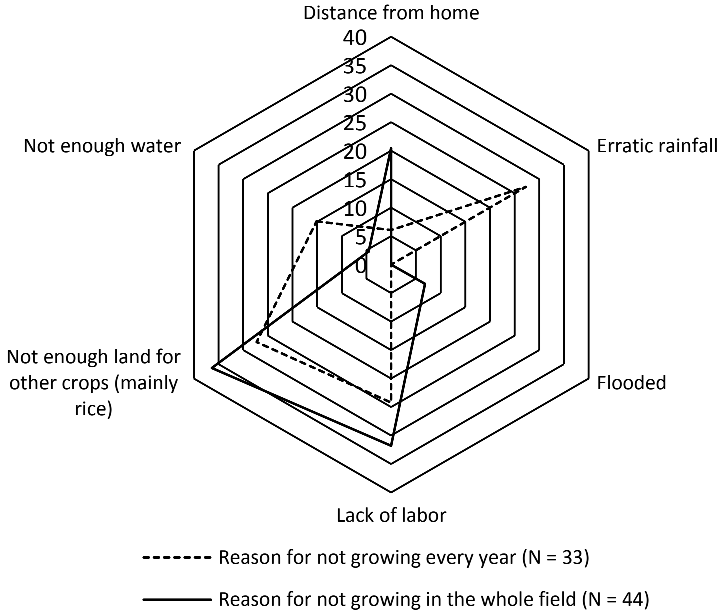


Figure 6.6 Reasons for not growing legumes every year (n=33) or using only parts of the field area (n =44). Number on radar chart is percentage.

The profitability of legume crops is competitive with other small-scale vegetable crops, while lack of labor is becoming a challenge. High labor requirement during first establishment and incorporation was perceived to be a major constraint. On the one hand, legumes need intensive tillage for better early growth conditions. If the family members were available for labor, their interest to invest labor deviated towards other enterprises or off-farm jobs. Moreover, most of the rice land sacrificed for legumes was adjacent to their housing because it could be protected from free-grazing-cattle.

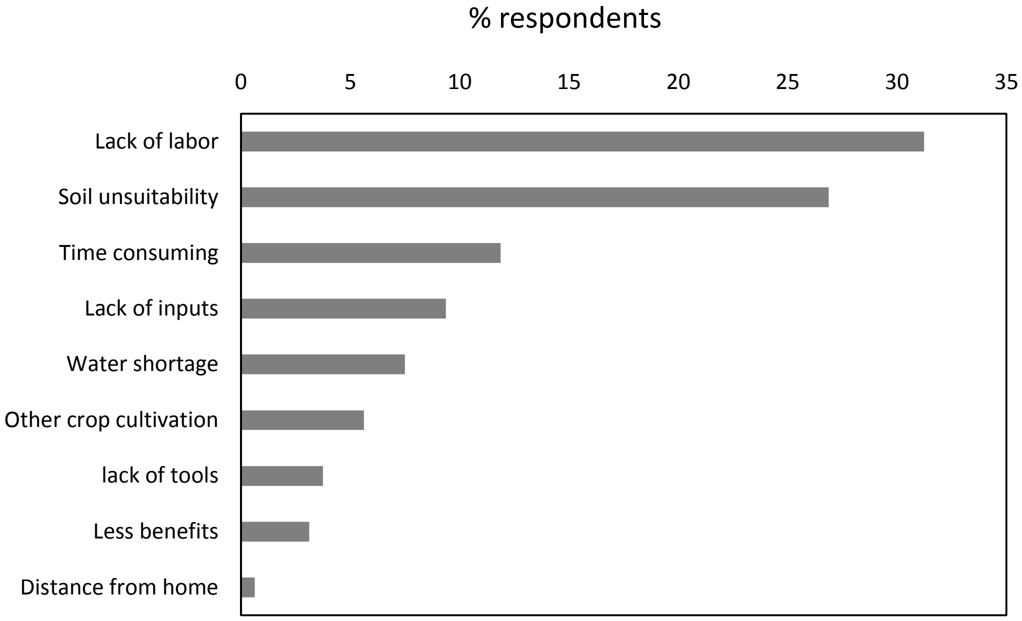


Figure 6.7 Reasons for not growing legume crops of non-legume growers (n = 164)

Regarding the perceptions of the non-legume growers, lack of labor (31% of the respondents) and soil unsuitability (27%) were the main constraints for not cultivating legumes. This was followed by other reasons like time consuming, lack of inputs, water shortage, off-season crop competences, lack of tools, less benefits and distance from home (Figure 6.7). When legumes were not cultivated, 75% of the respondents allocated labor to other jobs/activities (Figure 6.8, a), mainly weaving (especially in Prey Kabas district). This was followed by cultivation of other crops and industrial work (mainly textile). The crops grown were mainly early-wet season rice and vegetables on a small scale. The vegetables included cucumbers, water melon, spinach, etc., grown mainly in the dry season with supplementary irrigation or near the early wet season. The new short-duration rice variety (IR66) was introduced for the early wet-season period (May-August) and is cultivated by a considerable number of farmers with supplementary irrigation. The non-legume growers were generally not experienced with legumes, but consider these as not suitable in lowland soils. The farmers´ perception is bound to the traditional rice-growing practice.

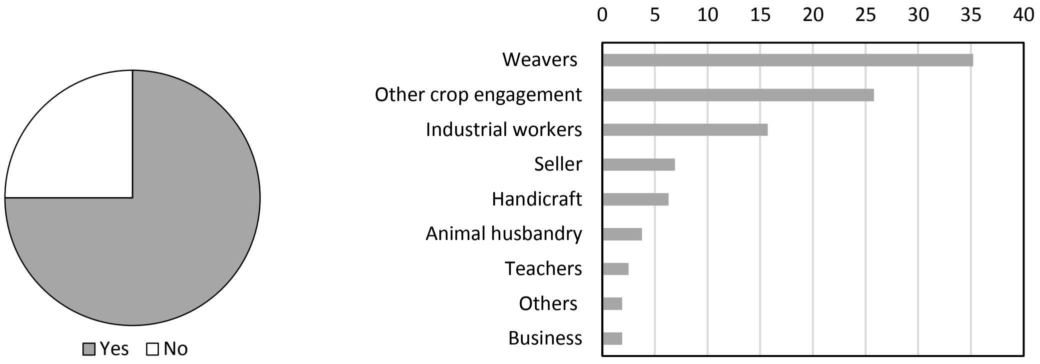


Figure 6.8 a) Proportion of off-farm jobs of non-legume growers; b) types of off-farm jobs of non-legume growers (n = 164)

In case labor was available, the interest to invest free time in off-farm jobs was higher than to use the labor for green manuring. Pests were generally not considered to be a problem.

It can be summarized that the most important constraint to growing legumes in the study area is lack of labor. The labor forces engaged in the agricultural sector declined from 56% in 2011 to 49% in 2013, mainly due to the migration for jobs in cities or outside the country (MAFF 2015). Around 11% and 6% of the people migrated for off-farm jobs (company/factory/uncertain jobs) in Tram Kak and Prey Kabas, respectively in 2010 (NCDD 2010).

6.3.6 Perception of suitability and advantages of legumes

Among the possible factors favoring the use of legume green manures, farmers mentioned the availability of suitable varieties, soil conditions, general climatic conditions, and cropping calendar. The majority of respondents perceive that current varieties, soil conditions and climatic conditions are generally suitable for integration of legumes into existing rice-based systems (Figure 6.9 a). Farmers generally recognized the benefits of using certified seeds.

The perceived advantages of green manure were related primarily to benefits derived from legume residues (Figure 6.10 a). The main advantages stated were reduced soil compaction and improved soil fertility (79% of the respondents), followed by the increase in rice grain yield (62%). Other advantages were mentioned less frequently, and concerned savings in mineral fertilizer N (31%), income generation (23%) and soil structure improvement (5%). A large proportion of the farmers showed an interest in growing legumes and the use of legumes as green manure in the future (Figure 6.10 b).

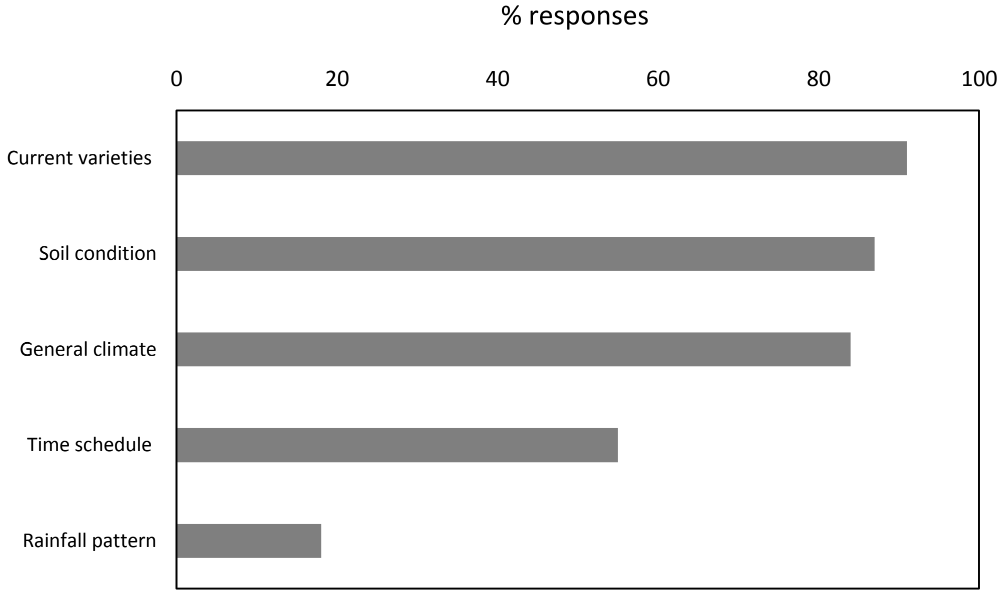


Figure 6.9 Farmers' perception of the suitability of legumes as green manure (multiple answers)

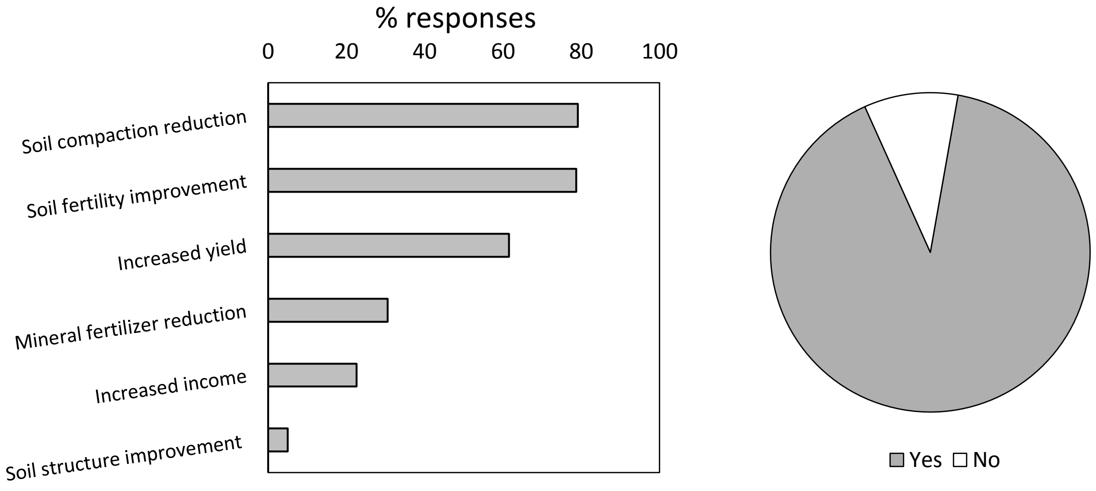


Figure 6.10 a) Perceived advantages of green manure use (multiple answers): b) interest in growing legumes and their use as green manure in the future (n = 238)

Table 6.6 Relationship of household characteristics with legume green manure (GM) user

Variable	Description	(%)		Sig. level
		GM-User	Non-GM User	
Family size	1-5	29.7	70.3	0.444 n.s
	>5	34.8	65.2	
Household gender	Male	36.6	63.4	0.132 n.s
	Female	27.3	72.7	
Age group	0-39	22	78	0.088 n.s
	40-60	30.2	69.8	
	>60	41.4	58.6	
Education	Illiterate	41.9	58.1	0.252 n.s
	Primary	26.6	58.4	
	Secondary and Upper Secondary	29.5	70.5	
No. of rice fields	1-4	28	72	0.038*
	>5	44.2	55.8	
Rice farm size	<0.5	24.8	75.2	0.011*
	0.5-1	28.1	71.9	
	>1	48.9	51.1	
Off-farm job	Yes	30.1	69.9	0.543
	No	35.1	64.9	

** ** *** means significance levels at 0.10, 0.05 and 0.01, respectively (chi-squared)*

6.3.7 Effect of household characteristics on legume cultivation

The chi-square analysis (Table 6.6) shows that there was a significant association between the number of rice fields per household ($0.01<P< 0.05$) and the rice farm size ($0.01<P< 0.05$), irrespective of whether legumes were grown. Family size, gender, age or educational status of the household head, and the availability of off-farm income sources had no significant association with legume cultivation. This suggests that the decision whether to grow legume or not is associated with farm size and land-use intensity. With land limitations, farmers tended to grow vegetables rather than green manures to improve the household nutritional status or generate additional income. Otherwise the land was kept fallow or labor was allocated in off-farm jobs. In case of access to irrigation, farmers tended to prioritize early wet-season rice rather than other crops. Around 40% of the farmers cultivated an early crop of wet-season rice prior to the main wet-season rice. Chea et al. (2011) also found that more than 50% of the farmers accessing irrigation in Takeo province used rice double cropping. In such conditions, no land will be available for the cultivation of legumes.

6.4 Conclusions

Crop diversification with legumes reportedly benefits rainfed lowland rice systems. In the case of Cambodia, mungbean was introduced as a diversification crop in the pre-rice niche. While occasional crop failure occurred due to excessive rainfall and soil flooding, in most cases the mungbean increased the yield of the subsequent rice crop, and was able to contribute 40-80 kg N ha^{-1} to wet-season rice. Despite such favorable reports, the use of leguminous green manures has major limitations. Only 30% of households grow legumes and 50% of these cultivate legumes only occasionally and only on parts of their rice land. Key reasons for low legume use are related to the unpredictability of the rainfall and to labor shortages for legume establishment and biomass incorporation. Mainly farmers without off-farm income sources include legumes in their-rice-based systems. Consequently, farmers have a clear preference for legumes with multiple use options over sole green manure species.

The findings suggest that despite numerous perceived constraints to legume adoption, there are available cropping windows in the pre-rice niche, when leguminous green manures are beneficial and adoptable. Most perceived constraints can be addressed by a mechanization of the agricultural sector. Thus, farm implements are required to permit legume cultivation on furrows or raised beds to minimize risks associated with flooding and to facilitate the incorporation of the biomass of legume residues.

7 GENERAL DISCUSSION, CONCLUSIONS AND FUTURE OUTLOOKS

In some rainfed lowland environments in Cambodia, high sand fractions and soil infertility predominate (White et al. 1997), negatively affecting rice productivity (Seng et al. 2004b). These soils are generally low in N (Seng et al. 2001) and available P (White et al. 1997). As N is the most limiting nutrient, it must be either supplied by the soil or added in the form of mineral or organic N fertilizers (Kundu and Ladha 1999). However, the use efficiency of applied mineral nutrients (N) in rainfed rice is reportedly low, and the outcome of nutrient application strategies is highly variable. Therefore, it is crucial to explore alternative resources for mineral-N replacement for rainfed production systems. The main goal of this study is to investigate the potential of organic manures in rainfed lowland rice-based production systems on sandy soils of Cambodia.

7.1 General discussion

7.1.1 Performance of leguminous crops

The field experiments conducted in 2013 and 2014 assessed the performance of leguminous green manure in comparison to farmyard manure and the recommended mineral fertilizer rate. Growth and yield of mungbean strongly varied between soil type and year. Growth and biological N_2 fixation were more in 2014 than in 2013 due to lower rainfall intensity during crop establishment. This highlights on the one hand the central role of soil aeration status on the establishment of upland legumes (Fukai and Ouk 2012), on the other hand it also points out the risk of crop failure associated with highly variable climates. As the first rainfall with onset of the monsoon is generally not very intense, it permits soil tillage and the establishment of an upland legume such as mungbean. However in heavy rainfall years (i.e. La Niňa) as experienced by South East Asia in 2013, soil flooding and hence mungbean failure may occur during the dry-to-wet season transition period. Such negative effects are likely to be exacerbated in low-lying flood-prone areas such as the coastal lowlands of Cambodia, and the frequency of such events is likely to increase with growing unpredictability of the monsoon rains as forecast with climate change (IPCC, 2014). Thus, in 2013, the legume could not be established in the shallow sandy soil due to intense rains and to early and severe flooding of the sites. Despite the sandy texture of the soils, drainage of the excess water was too slow in the shallow soils. On the other hand, the deep sandy soil permitted rapid drainage, allowing a partial recovery of the mungbean stands. In years with normal or low early rains (i.e. in 2014), the soil remained aerobic for much of the legume growing period, resulting in a high performance of mungbean crops, even in the shallow sandy soils. Hence, the pre-rice crop options that are based on flood-sensitive upland crops such as mungbean will need to be reevaluated in the face of different climate change scenarios. One alternative avenue may be to use flood tolerant species (Becker 2003) or to restrict pre-rice mungbean to deep well-draining soil environments. Another option is to shift from the pre-rice to the post-rice niche for growing legumes on residual moisture or receding water tables in view of minimizing flood-related production risks. Thus, Rahmianna et al. (2000) showed that even late rainfall after rice harvest did not result in soil anaerobiosis for post-rice legumes.

Another observation relates to the need for supplying P to enhance legume growth and N_2 fixation. In the deep sandy soil, the addition of only 10 kg P ha^{-1} was sufficient to nearly double the fixation rates of mungbean. However, these effects were much less on shallow soils, and the expected carry-over effects on the subsequent rainfed rice crops were very limited. The hypothesis that P application will benefit both the legume by stimulation N_2 fixation and the rice by recycling legume-absorbed P as well as fixed legume N was not confirmed. Significant carry-over effects were observed in only few cases. However, effects on soil C and N contents were significant and indicate possible longer-term benefits of the modified P management on soil fertility and future productivity. While the Nfda% was stimulated by P application in the deep sandy soils, the Nfda% and total N_2 fixed was an average 25 % lower than reported from other studies in the area. The Nfda% in this study was comparable to that reported by Toomsan et al. (2000). Toomsan et al. (2000) reported low N_2 fixation in mungbean of 25%, accounted for only 10 kg N_2 fixed ha^{-1} on a sandy soil in northeast Thailand. Compared to previous studies on other legume crops, this was quite low. It is noted that the recommended NPK for legume (particularly mungbean) is 40:26:25 NPK kg ha^{-1} (Cheth 2011). However, this rate is rarely applied by the farmers due to uncertainty of profitability and crop performance depending on environmental factors (rainfall). The low N_2 fixation in the deep sandy soils may be due to the fact that the low amount of P applied (10 kg P ha^{-1}) was not sufficient for optimum Nfda%. Qiao et al. (2007) reported that P deficiency delayed the nodule function and decreased nodule development, which in turn negatively affected N_2 fixation. Effects of higher rates of P on N_2 fixation need further study. Apart from P, N_2 fixation may also be restricted by K deficiency. A meta-analysis study conducted by Divito and Sadras (2014) revealed that K deficiency also affected the biological N_2 fixation (BNF) of legumes. Thus, the low K in both soil groups may have effected BNF. However, this needs further investigation.

The effects of farmyard manure were generally present and highlight the need to apply more recalcitrant carbon sources that contribute potentially more to soil fertility building than fast-decomposing legume residues. Additionally, FYM adds other nutrient elements and may enhance water-holding capacity. However, in the face of declining numbers of farm animals in South Cambodia and competitive uses of quality manure for vegetables and other high-value crops, FYM may become increasingly limited and will no longer be available to improve soil quality in the unfavourable rainfed environments on sandy soils. An alternative strategy may consist in producing grain or green manure legumes with lower quality (more phenolic compounds or higher lignin:N ratios) as suggested before (Becker et al. 1995; Becker and Ladha 1996)

Additional mineral N application may help to enhance the growth and economic yield of both mungbean and rainfed rice in sandy soils. Sadeghipour et al. (2010) and Ayub et al. (1999) also reported that the optimum mungbean growth and yield was between 30 and 40 kg of N application ha^{-1}. Cheema and Ahmad (2000) reported that even though legumes are self-sufficient for N requirements, additional N may stimulate growth and yield. On the other hand, combined N is known to reduce N_2 fixation. Otieno et al. (2009) reported that N decreased the nodule numbers in most of the legume species. The inhibitory effects on legume root nodulation by N application are well documented by Becker et al. (1991); Becker et al. (1986); Khalilzadeh et al. (2012); Leidi and Rodríguez-Navarro (2000); Amba et al. (2013); Dean and Clark (1980); Jefing et al. (1992). If the legume crops could nodulate and sufficiently fix N_2, N amendment through urea application can be neglected and previous fertilizer recommendations can be adjusted (Hin et al. 2005). Whether mineral N is required for legume establishment is a question that strongly depends on site and soil attributes as well as on the specific purpose of the legume. The production of high quality grain may thus necessitate some combined N in addition to P. The commonly available Di-ammonium phosphate, containing both N and P, appears to be suitable in such situations. The feasibility, affordability and the necessity of such complementary fertilizer uses are however highly site and system-specific and the targeting of such solutions requires a careful definition of social-ecological niche environments. Further investigations are needed here.

7.1.2 Potential of organic sources for rainfed lowland rice productivity

Overall, organic manures (FYM and green manure) were equivalent to approximately 50% of the recommended mineral N amounts for both soil types. The results indicate that organic sources cannot fully replace the mineral N amounts recommended for sandy soils. However the performance variability with organic amendments tended to be less than with urea and residual effects are likely to occur when considering the observed pool changes of C and N. In addition, the efficiency of applied mineral N is so low and erratic in rainfed environments on sandy soils, that the reliance on sole mineral sources is both economically and environmentally questionable.

The present study was limited to only one crop cycle. The long-term application of organic manures as mineral N replacement may show enhance effects and provide long-term benefits as suggested before (Mandal et al. 2003; Liu et al. 2013).

The residual incorporation of P-amended mungbean at the maturing stage after grain harvesting produced comparable rice yields to those with the recommended N application rates for both soils. Incorporation of mungbean biomass prior to the maturing stage did not result in higher rice yield increase. This finding could be of interest to the farmers because of a bonus economical legume yield. However, the recommended P fertilizer amounts for rice in deep sandy soils are only 4 kg P ha^{-1}, and the alternative P application to pre-rice legume in this study was 10 kg P ha^{-1} (not direct to rice). Therefore, the investment of an additional 6 kg ha^{-1} of mineral P is required for pre-rice legume. Application of FYM (60 kg N ha^{-1}) as mineral N replacement produced comparable rice yields to those with the recommended N rate in the deep sandy soils but not in the shallow sandy soils.

According to the farmers' perceptions documented in the survey, farmers tend to prefer FYM over any other fertilizer source., Farmyard manure from cattle is also widely applied to lowland rainfed paddy, and it is the preferred source among small-scale farmers. Thus, it is one of the main factors explaining the rice yield increase (Ly et al. 2012). In this study, FYM was applied at an equivalent rate of 60 kg N ha^{-1}. Based on the cattle intensity classification, Gerber et al. (2005) and Ly et al. (2012) estimated the annual N input from FYM to be 15 kg ha^{-1}. Since most of the small-scale farmers in the study area own less than 1 ha of paddy, it is possible that the 60 kg of N can be derived from cattle manure as the cattle owned varied from 2 to 5 heads per household (Ly et al. 2012; Pen et al. 2009; Serey et al. 2014). Availability of FYM beyond 60 kg N ha^{-1} is not likely to be possible. Furthermore, recent reports by MAFF (2015) showed that the number of small-scale cattle raising operations is declining in Cambodia, which is most likely due to the increasing trend in mechanization. Therefore, the use of FYM as mineral N replacement is potential limited.

The relatively low adoption of legume based technologies in the study was mainly associated with the unpredictability of rainfall and consequently of the limited suitability of only one legume species or one single mungbean genotype for the observed range of environmental and climatic situations. There is a need to compare more genotypes and species and to target appropriate legumes to given situations to minimize the risk of climate-induced legume failure.

The second key constraint to legume adoption is the unavailability of labor for green manure or residue incorporation. Whitmore et al. (2000) reported that full operation for mungbean establishment required 79 days labor ha^{-1}. Considering the average farm size observed in this study, 21 days labor is required per household, especially during the early stage of establishment where intensive tillage for biomass incorporation requires intensive labor (Becker et al. 1995). MAFF (2015) reported that the labor force engaged in the agricultural sector declined from 55.8% in 2011 to 48.7% in 2013, mainly due to migration for jobs to the cities or outside the country. In the study area, around 11% and 6% of the people (mainly potential labor force) migrate for off-farm jobs (company/factory/unknown jobs) in Tram Kak and Prey Kabas, respectively, in 2010 (NCDD 2010), reducing the potential labor force. Solutions may pertain to developing and providing simple implements for biomass incorporation, testing possibilities of biomass mulching (surface application without incorporation), or a more specific targeting of legume technologies to households with sufficient labor availability or possibilities for mechanization.

Finally, the competition of a green manure legume with other (more economic crops) for land during the off-season appears to constrain the adoption of legume-based technologies. Rather than relying on one specific crop, diverse crops are planted on rainfed lowland paddy by some farmers. Therefore, the direct economic benefits from leguminous green manure to rice yield increase and an economical legume yield must outweigh those of other off-season crops. Here again, legume selection, particularly focusing on multi-purpose species, may help to overcome this perceived constraint.

It can be summarized that the adoption of leguminous green manure must be technically and economically feasible from the farmers´ point of view and that solutions differ between soil types, sites and farms. Targeting specific technology packages to clearly defined social-ecological niches will be the key challenge for research and extension in the coming years.

7.2 General conclusions

The study explores the potential of organic manures for rainfed lowland rice production on sandy soils of Cambodia. Two organic sources, i.e. green manure and FYM, are the main focus. The research objective addresses the hypothesis that organic manures, particularly green manure with a short-cycled grain legume (mungbean) during the pre-rice niche, are a suitable technology to address the prevailing soil fertility constraints and to enhance rice productivity on the different sandy soils of Cambodia.

Overall, organic manures have shown potential benefits for rainfed lowland rice production systems provided that agronomic and social-economic constraints are not limiting factors. In the case of green manure, P has to be applied for enhancement of N_2 fixation. Green manure biomass should be incorporated at the maturing stage. Concomitantly, soil moisture regimes need to be favorable for legume establishment. In addition, legume establishment and biomass incorporation should be less labor demanding in order to ensure high adoption of green manures. The sole reliance on FYM as mineral N replacement is in question and appears to be only feasible in the future if cattle numbers do not decline further.

Conclusions that can be drawn from the results of the study are as follows:

- The application of organic sources (green manure and FYM) was equivalent to around 50% of the national recommended N rate for both studied soil groups, and showed residual N and C effects after only one crop cycle. Therefore, organic manure application is likely to play a crucial role in sustaining and enhancing the fertility of the poor sandy soils in Cambodian rainfed rice environments
- Leguminous green manure establishment and N_2 fixation were constrained by intense rainfall and low native soil P. The supply of P enhanced legume growth, yield and N_2 fixation and P application should thus be shifted from rice to legumes that are grown in rotation.
- Key reasons for low legume use and adoption by farmers are related to the unpredictability of the rainfall and to labor shortages for legume establishment and biomass incorporation.
- While short-cycled mungbean is the preferred legume among lowland rainfed rice farmers, there is a need to use a larger legume diversity, particularly of multi-purpose species and to target legumes to specific niche environments.

7.3 Outlook for future research

The findings in the study are based on one-crop-cycle experiments. Therefore, long-term investigation of organic sources should be implemented, especially targeting the potential buildup of a soil N reservoir by green manure treatment. As the lack of labor and off-season crop competition are the main challenges for leguminous green manure establishment, further research should focus on shifting from traditional tillage to minimized or zero tillage practices. The economic return of leguminous green manure must outweigh that from other crops. Despite the increase in N_2 fixation of mungbean due to P application, the level of fixation is still low. Mungbean was not inoculated in this study. Therefore, the effect of mungbean inoculation should be studied further. Furthermore, the effect of higher P amendment should be tested. As N may improve legume growth and yield but may suppress N_2 fixation, a further study should include the interaction of P and N applications with the aim to assess optimum N_2 fixation. The organic sources showed rice yields comparable to those obtained with mineral-N fertilizer, thus these could replace mineral fertilizer N. The economic returns of leguminous green manure against mineral fertilizer N need to be investigated taking into account the production costs. Further research should focus on ways to alleviate socio-economic constraints, so that legumes can be integrated in rice cropping systems on Cambodian soils.

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