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THESIS

SITE-SPECIFIC NUTRIENT MANAGEMENT OF MAIZE IN SELECTED SOILS OF THAILAND AND LAO PEOPLE'S DEMOCRATIC REPUBLIC

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A Thesis Submitted in Partial Fulfillment of
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Maize (*Zea mays* L.) production in Thailand and in the Lao PDR is limited by many similar factors, such as the low nutrient contents in the soils, soil loss and runoff, and acidic soils (in the Lao PDR). These important problems must be solved in order to establish an appropriate technology for improving maize production. Site-specific nutrient management (SSNM) is an approach needed to increase fertilizer efficiency which emphasis on N fertilizer to increase maize yields in different soil types of the maize producing area of Thailand and Lao PDR.

This study consists of 6 experiments. 1) A laboratory study of the effect of wetting on nitrogen (N) mineralization potential in 6 soil series (Cd, Lb, Ln, Tk, Pc, and Wn) from Thailand, and 4 soils from Lao PDR (Bc, Km, Sd, St). Incubation study soils were treated at three different moisture levels, including air-dried soil, soil maintained at field capacity, and soil heated at a temperature of 40^{o}C for 24 hours. The soils were incubated at 30 ^{o}C for 0 to 70 days. N release of Cd, Tk, Lb and Ln soils tended to produce NO_3^--N rather than NH_4^+-N. The Pc, Wn, Bc, Km, Sd and St soils were high NH_4^+-N released at the initial stage of incubation, and NO_3^--N was increasingly released from 3 to 70 days. The NO_3^--N release was mainly affected by OC content, while NH_4^+-N release was affected by soil pH. Drying the soils resulted in higher NH_4^+-N and NO_3^--N released. High soils amino acid-N and amino sugar-N revealed high N mineralization. 2) The field study of the distribution of nitrate in the Lb and Pc soil series before and after maize planting. Field experiments were conducted in these soil series, which are the most representative soils of the maize producing region of Thailand. Subsoil NO_3^--N was measured before and after maize was grown. Subsoil NO_3^--N levels at the two sites increased with increasing N rate. Before maize was planted maximum levels of NO_3^--N were found at the 20-40 cm and 0-20 cm depths of Lb and Pc soils, respectively. Subsoil NO_3^--N declined at both sites after maize was more than 40 days old. 3) Measuring the amount of nitrate in the Lb and Pc soil series in maize fields under heavy rain. NO_3^--N status was assessed after heavy rains occurred were measured. Nitrate-N status was not significantly different between different depths; however, the maximum NO_3^--N levels in Lb and Pc soils were found at 40-60 cm and 20-40 cm depths, respectively. 4) A field study of maize root distribution at different stages of maize growth in the Lb and Pc soil series. Maize roots distributions were measured at 20, 40 and 60 days after emergence using pin board method. Maize roots were more voluminous in the 49-62 cm and 43-50 cm depths for the Lb and Pc soils; roots clearly grew into the soil zones where NO_3^--N was high. It is probable that N availability from subsoil NO_3^--N diminished the fertilizer N requirement of maize. 5) Determining the N status of maize leaves in the field using leaf color chart (LCC) in the Lb and Pc soil series. Field experiment was also conducted in Lb and Pc soil series. Maize leaf measurement was taken using LCC at 21, 30, 42, 50, 58 and 65 days after maize emerging. Leaf samples were collected for N determination. The leaf color level of maize in Lb and Pc soils was higher than the leaf color level (<3.5) and N symptom deficiency was not appeared on the maize grown on both soils. The use of leaf color chart for predicted N deficient symptom is does not work in the case of Lb and Pc soils because the soils are reached in subsoil nitrate status due to crop rotation with legume. 6) A field study on the nitrogen fertilizer response simulated from DSSAT software on some important maize soils in Thailand, and in the Lao PDR. Field experiments were conducted in the Lop Buri and Pak Chong soil series in Thailand and the other two were Saythong and Bachieng soils in the Lao PDR. Grain yields of maize grown on St and Bc soil series were increased with higher rate of N fertilizer of both years. The response of maize on different rates of nitrogen application in 2005 and 2006 were different. In 2005 maize grain yield of Lb and Pc soil did not respond to N fertilizer. Maize rotated with soybean and chicken manure application in the last season was the cause of no N response on maize. More available N was concentrated in Lb, Pc and Bc soils. With the low soil pH and high Al content in Bc soil led to low yield in both years.

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LIST OF ABBREVIATIONS

AA-N	= Amino acid-N
AD	= Air-dried soil
Al	= Aluminium
ANOVA	= Analysis of variance
AS-N	= Amino sugar-N
Bc soil	= Bachieng soil
Cd soil	= Chai Badan soil
CRD	= Completely Randomized Design
CV.	= Coefficient of variance
D_b	= Bulk density
DSSAT	= Decision Support System for Agro-technology Transfer
EDTA	= Ethylenediamine Tetraacetic Acid
EY	= Expected yield
FC	= Field capacity
Fe	= Iron
H40 soil	= Heat at temperature of 40 ^{o}C soil
HA-N	= Hydrolyzed ammonium- N
K	= Potassium
Km soil	= Khammouan soil
Lao PDR	= Lao People's Democratic Republic
Lb soil	= Lop Buri soil
LCC	= Leaf color chart
Ln soil	= Lam Narai soil
Min	= minimum value
N	= Nitrogen
NH_4^+-N	= Ammonium nitrogen
NO_3^--N	= Nitrate nitrogen
NR	= Nitrogen fertilizer rate
NuMaSS	= Nutrient Management Support System
ns	= Not significant

LIST OF ABBREVIATIONS (Continued)

OC	= Organic Carbon
OM	= Organic matter
P	= Phosphorus
Pc soil	= Pak Chong soil
PDSS	= Phosphorus Decision Support System
RCBD	= Randomized Complete Block Design
SAS	= Statistical Analysis System
Sd soil	= Sendin soil
SOM	= Soil organic matter
SSNM	= Site-Specific Nutrient Management
St soil	= Saythong soil
Tk soil	= Tahkli soil
Wn soil	= Warin soil
L	= Loam
LS	= Loamy sand
CL	= Clay loam
C	= clay
SL	= Sandy loam
SCL	= Silty clay loam
W_O	= Moisture content at field capacity

SITE-SPECIFIC NUTRIENT MANAGEMENT OF MAIZE IN SELECTED SOILS OF THAILAND AND LAO PEOPLE'S DEMOCRATIC REPUBLIC

INTRODUCTION

Maize (*Zea mays*, L.) is one of the most important cereal crops in Asia. Maize is increasingly used as animal feed and today maize starch is used for industrial purposes. Maize will continue to play a major role in food security in the future and the demand of maize grain for animal feed will increase greatly in the years to come. The Tropical Asian Maize Network was designed to strengthen the collaboration between national institutions in maize research and development. Founding members are Bangladesh, Cambodia, and People's Republic of China, India, Indonesia, Lao PDR, Malaysia, Philippines, Sri Lanka, Thailand and Vietnam (FAO, 2004). However, maize production in Thailand and in the Lao PDR is limited by many similar factors, such as the low nutrient contents in the soils, soil loss and runoff, and acidic soils (in the Lao PDR). Maize farmers are still lacking of knowledge on soil and nutrient management, which is one of the causes for low yield, soil degradation and economic hardship. These important problems must be solved in order to establish an appropriate technology for improving maize production.

Predicting N fertilizer requirements has been an important objective of several decision-aids and simulation models. Computer models such as NuMaSS and DSSAT have become useful management tools for assessing N fertilizer for crop production. Nitrogen often limits growth and productivity of maize in many soil series of Thailand and Lao PDR. Nitrogen fertilizer rates for maize cultivation in many soils series of Thailand are well known but are not yet adequately predicted. Maize yield with and without N was not significantly different in some soil series (Attanandana *et al*., 2004). The maize crops required much less fertilizer N than predicted by the models. In some maize growing soils of Thailand, there is the trend to have high subsoil nitrate contents because maize has been rotated with legumes and because some farmers over-apply N fertilizer which can increase the residual nitrate. Early attempts to apply nitrogen models for maize, such as DSSAT-N and the NuMaSS decision-aid were not successful when predictions far exceeded field-determined N requirements. One hypothesis for the over-prediction was that residual nitrate could be accumulating in the dry off-season and when maize was grown in the wet season, the maize root might be able to use the subsoil nitrate. However, there was insufficient information on the content of subsoil nitrate and the distribution of maize roots with depth to test the hypothesis. Subsoil nitrate was elevated after harvest where soil organic matter was high; this may have resulted from N mineralized between crop physiological maturity and soil sampling (Ferguson *et al*., 2002). Blumenthal *et al*. (1999) found that subsoil nitrate concentration in the root zone below 45 cm increased by 2 to 15 times compared to the amount at 0-20 cm depth which was lower than 1.7 mg kg^{-1}soil.

Accurate N fertilizer recommendations for maize production are important for maximizing productivity and profit while minimizing environmental impact of fertilizer use (Fageria *et al*., 1997). Nitrate is often the dominant source of nitrogen for maize since it generally occurs in higher concentrations than NH_4^+-N and it is free to move to the roots by mass flow. On-farm demonstrations have generally shown good estimation N needs but there are also situations where over or underestimates of N need occur. The over-estimation of N fertilizer application could result in even larger amounts of residual nitrate. The primary criterion used to evaluate potential NO_3^--N movement was soil residual NO_3^--N remaining in the root zone after harvest (Ferguson *et al*., 2002).

To increase maize yields in different soil types of the maize producing area of Thailand and Lao PDR, therefore, research on site-specific nutrient management was needed. Site-specific nutrient management (SSNM) is an approach to increase fertilizer efficiency with effective use of plant nutrients especially NPK fertilizer. Nitrogen fertilizer application for a yield increment of crop production is widely used, but the recommendation rate is very general. Farmers have attempted to increase N input to increase crop yield. With SSNM the application and management of nutrients are dynamically adjusted to crop needs of the specific location and season. The SSNM approach also aims to increase farmers' profit through: 1) increased yield of maize per unit of applied fertilizer; 2) reduced nutrient loss and 3) increased the profit. The features of site-specific nutrient management in Thailand (Attanandana *et al*., 2004) are: 1) Identify the soil series. 2) Test the soils for NPK at each location. 3) Apply nutrients according to decision-aids. 4) Evaluate the economics of the application. One part of this study was on site-specific nutrient management in which the nitrogen fertilizer requirements were simulated from DSSAT, phosphorus and potassium fertilizer are predicted by PDSS software according to basic soil data analysis adjusted to the specific locations and seasons.

Maize has moderate to deep roots depending on soil texture and soil moisture. Tardieu and Pellerin (1990) reported that early maize roots have a more horizontal orientation in the topsoil but are just as vertical as lateral roots in deeper soil layers. The main overall goal of this study was to determine the cause of the over-estimation of DSSAT-N for maize, and to test the rate of fertilizers prediction in the field, and to propose an improved procedure.

OBJECTIVES

1. Investigate the effect of wetting on nitrogen mineralization potential in ten maize soils from Thailand and Lao PDR that have undergone different drying methods.

2. Monitor the changes of nitrate at different soil layers during the vegetative growth stages of maize in Lop Buri (Lb) and Pak Chong (Pc) soil series.

3. Quantify the amount of nitrate in Lop Buri (Lb) and Pak Chong (Pc) soil series in maize fields under heavy rain.

4. Measure maize root depth at different stages of maize growth in the Lop Buri (Lb) and Pak Chong (Pc) soil series.

5. Test the optimum N use with a leaf color chart, a possible new approach for predicting N fertilizer requirements for maize in Lop Buri (Lb) and Pak Chong (Pc) soil series.

6. Test N, P, K fertilizer recommendations on some important maize soils (Lb, Pc series) in Thailand, and (Bc and St series) in the Lao PDR.

LITERATURE REVIEW

1. Site-Specific Nutrient Management (SSNM)

In tropical regions nutrient management in a specific location is important for most upland and lowland farms. Crop nutrients will be lost from soils in many ways but fertilizer application by inexperienced farmers has resulted in nutrient losses and low yields. The use of soil test kit is one alternative to enable SSNM for maize in Thailand. Based on test kit results, fertilizer was added according to the decision-aids predicted amount, which has been tested in the field. With soil testing, farmers apply balanced nutrients and higher yields and more profit were obtained (Attanandana and Yost, 2003). Site-specific nitrogen management has been suggested as one means of increasing the efficiency of N fertilizer use and reducing environmental impact (Ferguson *et al*., 2002). The University of Minnesota emphasizes that fertilizer applications which over-estimate or under-estimate the crops will reduce net returns. The recommendations of nitrogen and phosphorus fertilizers for maize and soybean were evaluated for profitability potential within a field and compared to actual crop response needs (Malzer *et al*., 2007).

The total area planted to maize in Southeast Asia is currently about 8.6 million hectares, with the largest areas in Indonesia (41%), the Philippines (29%), Thailand (13%), and Vietnam (12%). The growing demand in the region cannot be met despite the increase in domestic production and yield of maize in the last 15 years. Preliminary results of on-farm trials with maize in Indonesia, the Philippines, and Vietnam clearly indicate sufficiently large yield gaps and significant opportunities to increase yield and profitability, if crop and nutrient management are fine-tuned to site-specific conditions (Witt *et al*., 2006).

At present, general fertilizer recommendations to farmers are constrained by the nutrient content of particular fertilizer compounds available on local markets, which has resulted in unbalanced and inefficient fertilizer use. Soil testing is an important tool in site specific fertilizer recommendations but is little used by farmers due to the lack of supportive research (Attanandana and Yost, 2003). The cost of soil analysis and the limited capacity for soil testing at the provincial level and the inadequate delivery of recommendations to farmers has resulted in unacceptable fertilizer practice. Also, farmers have limited skill in the selection of suitable fertilizer. Koch *et al*. (2004) reported that less N fertilizer (6-46%) was used in the site-specific management zone and was more economically feasible than conventional uniform N application.

2. Nitrogen in crop production

The forecast of world demand for nitrogen fertilizer is for an increase at an annual rate of 1.2 percent until 2008. Total N demand will increase from 87.2 up to 92.4 million tonnes (Table 1). Nitrogen fertilizer demand is expected to grow in all regions with the exception of Western Europe, where a decline of 0.2 million tonnes by 2007/08 is predicted. Most of the growth in fertilizer N consumption will take place in Asia (73 percent), Latin America (12 percent) and Africa and North America (5 percent), with Oceania growing by 3 percent. Demand in Eastern Europe and Central Asia and in Central Europe should recover and increase by 1-2 percent during the period under consideration (FAO, 2003).

Table 1 World nitrogen supply and demand balance, 2003/04-2007/08.

Item	N (million tonnes)				
	2003/04	2004/05	2005/06	2006/07	2007/08
Total supply	93.0	93.8	96.0	97.9	99.8
Total demand	87.2	88.3	89.9	91.1	92.4
Surplus (deficit)	8.7	8.4	9.0	9.6	10.3

Source: FAO (2003)

All nutrient elements are required in optimum amounts to achieve high yields of maize. Compared with N, however, other nutrients can be adjusted more easily to optimum concentrations in the soil (Standford and Legg, 1981). Nitrogen is the most common and widely used fertilizer nutrient. It is probably the single most important factor limiting crop yields; and most plants require large quantities of nitrogen fertilizer. Organic matter mineralization and N fixation by living organisms are the major sources of available N in most soils (Jansson and Persson, 1982). The amount of nitrogen fertilizer applied is usually two to three fold higher compared to phosphorus and potassium. It is recognized that all nutrient elements are required in optimum amounts to achieve high yields. On the other hand, N fertilizers are highly soluble and may be readily leached, volatilized as NH_3, or denitrified when the NO_3^--N is under reduced conditions.

Nitrogen is essential for plant growth because it is the constituent of all protein and taken up by plants as ammonium or nitrate ions. There is an urgent need to improve the N factor in crop production, both by increasing the efficiency of N utilized by crop production and by reducing N losses. Recently fertilizer costs in 2008 have skyrocketed in response to higher prices of petroleum making it more important than ever to efficiently use N fertilizers.

3. Nitrogen mineralization

Nitrogen mineralization is the conversion of organic nitrogen to a mineral form as NH_4^+, NO_2^-, and NO_3^- (Tisdale *et al.*, 1985). Nitrogen mineralization occurs in three distinct steps. The first step is aminization, which involves the breakdown of proteins and release of amines and amino acids. The second step is ammonification. This second step involves the further breakdown of amines and amino acids and the release of ammonia, which equilibrates to ammonium. Nitrification is the third step of the process resulting in the oxidation of NH_4^+ to NO_3^- (Smit, 1982). Nitrification itself is a two-part process. The first step is primarily facilitated by a group of obligate autotrophic bacteria known as Nitrosomonas, and results in production of NO_2^-. The second step involves the oxidation of NO_2^- to NO_3^- and is primarily facilitated by a second group of obligate autotrophic bacteria known as Nitrobacter

(Tisdale *et al*., 1985). Deenik (2006) summarized research indicating that soil temperature and moisture content have a strong effect on nitrogen mineralization (ammonium and nitrate) reactions and that the maximum nitrogen mineralization occurs when the soil temperature reached 30 to 35 ^oC. Temperature and moisture levels favorable to ammonification are also favorable for nitrification. Nyborg and Hoyt (1978) incubated 40 acid (pH 4.5-5.6) mineral surface soils with and without lime and found that liming to about pH 6.7 almost doubled the amount of nitrogen mineralization.

4. Field nitrogen mineralization

Maximum nitrate production occurred at the start of the rains particularly in tropical soils subject to well defined wet and dry seasons (Birch, 1958). Nitrogen mineralization depends on the prior decomposition of organic material, the flush of decomposition following wetting of a dry soil (Birch, 1959). Nitrogen mineralized during short time periods under aerobic condition may be heavily influenced by the N derived from the decomposition of recently incorporated residues and microbial tissues relative to that from the mineralizable fractions of soil organic N (Stanford *et al*., 1974). The rates of nitrogen mineralized (NH_4^+-N and NO_3^--N) in calcareous soil are generally highest at high soil water content (80 to 90% of field capacity), and where temperatures were raised from 15 to 30 ^oC (Justice and Smith, 1962; Stanford *et al*., 1972). Nitrogen mineralization may vary three to five folds over the range of moisture contents that ordinarily occur in soils. However, Andersen and Jensen (2000) explained that the effect of temperature on the C mineralization and gross N transformation rates was clear, all rates increasing with increasing temperature.

Mineralization of organic nitrogen is possible only when the biological environment is favorable. A favorable environment includes the optimum amounts of mineral nutrients, as well as proper aeration, temperature, moisture and pH (Stanford and Smith, 1972). Mineralization of organic N is inhibited more by low pH in mineral soils than in peat and other high organic matter soils. The low soil pH slows the rate at which organic N is mineralized, probably because only a part of the microbial population is able to decompose the organic matter under more acid environment (Adams and Martin, 1984). Keeney and Bremner (1967) found that mineralization of different forms of N in soil under both aerobic and anaerobic incubations were highly correlated with N uptake by maize (R=0.93). Gasser and Kalembasa (1976) found a very high correlation(R=0.98) between N mineralized anaerobically (7 day, 40 ^{o}C) and N mineralized aerobically. Amounts of soil N mineralized in short-term incubations are dependent on the method used in preparing the soil before incubation (Bremner, 1965). Nitrogen mineralized during short time periods under aerobic conditions may be heavily influenced by N derived from decomposition of recently incorporated residues and microbial tissues relative to that from the mineralizable fractions of the soil organic N (Stanford *et al*., 1974). The amount of plant available N released from soil organic N depends on many factors affecting nitrogen mineralization, immobilization, and losses of NH_4^+ and NO_3^- from the soil (Havlin *et al*., 2005).

5. Nitrate in subsoil

The main sources of nitrogen in agriculture are commercial fertilizer, livestock wastes and legume plants, which can “fix” nitrogen from the air and convert it into organic form. Billen (1975) showed that nitrification of NH_4^+ accounted for the increase in NO_3^- level in the upper layer of the sediment. Ferguson (2002) reported that soil residual nitrate-nitrogen was higher where soil organic matter is high. The movement of nitrate below 3 cm depth is sometimes lost by denitrification. In addition, the flush of nitrate mineralized at the beginning of the rainy season is easily leached into deeper soil layers (Greenland, 1958). In other studies, a large amount of nitrate from early applied nitrogen fertilizer rapidly reached to a depth between 0.3 and 0.8 m, but was retained between 0.8 and 1.2 m depth during the rest of the cropping season (Lehmann *et al*., 2004). Gardner *et al*. (1965) reported that there are two main processes involved in the movement of nitrogen: (1) convection of substances dissolved in the soil solution due to the mass flow of the soil solution and (2) molecular or ionic diffusion due to concentration gradients. Lehmann *et al*. (2004) reported that in savanna Oxisols, a large amount of nitrate accumulated in the subsoil from 0 to 2 m depth and totaled 150-300 kg ha^{-1}, which nearly matched the total N uptake by the crops. The extent and direction of movement by convection depends upon the concentration of nitrogen in the soil solution, and upon the direction and rate of the movement of the soil solution (Bowen *et al*., 1993). The studies of Halvorson *et al*. (2005) revealed that soil NO_3^--N in the soil profile was concentrated in the 0 to 60 cm soil depth, with much lower levels of NO_3^--N at greater depths.

6. Nitrate status in the soil depths

Plants contain 1 to 6% N by weight and absorb most of their nitrogen in the NH_4^+ and NO_3^- forms. Nitrate is often the dominant source of nitrogen since it generally occurs in higher concentrations than NH_4^+ and it is free to move to the roots by mass flow. Nyamangara *et al*. (2003) found that in tropical soils higher NO_3^--N leaching in the mineral fertilizer treatments was attributed to the large amounts of readily available N early in the season, whereas most nitrogen derived from manure has to undergo mineralization before it becomes available for uptake and leaching. Tropical cropping systems have a high potential for NO_3^--N leaching loss (Date, 1973). Leaching is often the most important channel of nitrogen removal from field soils other than that accounted for in plant uptake (Allison, 1973). Losses occur mainly as NO_3^-, the movement of which is closely related to water movement. In intensively cropped soils where fertilizer has not been applied, the loss is greatly reduced, because the NO_3^- content of the soil is lower and less passes through the soil (Stevenson, 1982a). Ottman and Pope (2000) studied nitrogen fertilizer movement in the soil and found that nitrogen fertilizer rate and timing did not affect depth of N movement in the soil, but did affect the amount of fertilizer remaining in the soil after the season. This residual fertilizer could possibly be subject to leaching in future seasons. Greater N fertilizer rates increased the amount of residual N in the surface soil to a depth of >1 m.

The large accumulation of nitrate in the subsoil at the beginning of the experiment sometimes results from intensive leaching from the previous cropping season. A large amount of nitrate was adsorbed in the soil (150-300 kg NO_3^--N ha^{-1} at

2 m depth) which nearly matches total N uptake by the crops (130-400 kg ha^{-1}). Most of the applied N (80%) was found in subsoil at 0.15 to 2 m depth (Lehmann *et al*., 2004). Herron *et al*. (1968) summarized 3 years of experimentation on corn which had been cropped with alfalfa for several years, the optimal rate of N applied as NH_4NO_3 was approximately 84 kg ha^{-1} each year. Even with no N applied, appreciable amounts of NO_3^--N (115-140 kg ha^{-1}) were found at the 180 cm depth at the end of the season.

7. Symptoms of N deficiency and leaf color chart.

Throughout the history of crop cultivation, N deficiency has seriously limited crop production. Nitrogen is an essential constituent of amino acids, nucleic acids, nucleotides, and chlorophyll. It promotes increased plant height, leaf size, and seed protein content. Thus, N affects all parameters contributing to yield. Leaf N concentration is closely related to the rate of leaf photosynthesis and crop biomass production. When sufficient N is applied to the crop, the demand for other macronutrients such as P and K is increased. Nitrogen is required throughout the growth period, but the greatest requirement is between growth stages (30-55 days after emergence). Nitrogen is mobile within the plant and, because N is translocated from old senescent leaves to younger leaves, deficiency symptoms tend to occur initially in old leaves. Dobermann and Fairhurst (2000) reported that N deficiency is the most commonly detected nutrient deficiency symptom in crop leaves. Nitrogen deficiency may occur where the soil is particularly prone to N deficiency and even where a large amount of N fertilizer has been applied but at the wrong time or in the wrong way. The critical level for N concentration in maize hybrid in terms of % N in dry matter, varies from lower than 3, which is low, 3-5, which is medium to more than 5, which is high (Dierolf *et al*., 2001).

Originally, leaf color charts (LCC) have been used with rice (*Oryza sativa* L.) to determine nitrogen (N) status (Singh *et al*., 2002). The leaf color chart is easy to use and inexpensive diagnostic tool for monitoring the relative greenness of a rice leaf as an indicator of the plant N status (Alam *et al*., 2005). The standardized LCC is six inches long, made of high-quality plastic, consisting of six color shades from yellowish green to dark green (Figure 1).

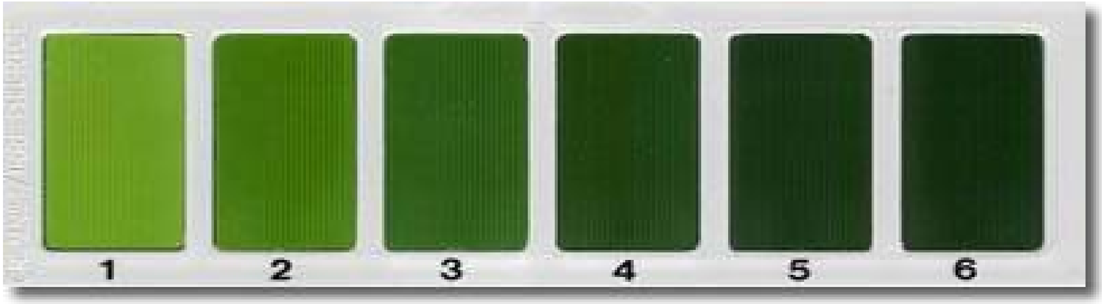

Figure 1 Leaf color chart shown with different color levels.

It is a tool to rapidly assess leaf N status and thereby guide the application of fertilizer N to maintain an optimal leaf N content. It can consequently be vital for achieving high rice yield with effective N management. The LCC is used at critical growth stages to decide whether the recommended standard N rate would need to be adjusted up or down based on leaf color. In a real-time approach, a prescribed amount of fertilizer N is applied whenever the color of rice leaves falls below the critical LCC value. The critical value might fall between two existing panels of the LCC, but guidelines can be adjusted so that the color panels of the LCC will not have to be changed. Local guidelines on LCC use have now been developed for the major irrigated rice domains in Asia (Witt *et al*., 2005).

8. Maize root system

The maize root system is comprised of several distinctive types of roots such as primary or tap root, associated lateral roots, adventitious seminal roots, and secondary lateral roots (Freldman, 1994). During an average period of growth, the root system of a single maize plant may exploit over 200 cubic feet of soil and may absorb 160-230 liters of water. Depending on soil texture, the lateral spread of a mature root system may be 1 to 1.3 m on all sides of the plant and typically penetrates to depths of 1.5 to 1.8 m, although depths of 2.5 m are not unusual (Weaver, 1926).

The maize root systems develop best in deep, well-drained soil that has an abundant supply of water throughout the growing season. Early maize roots have a more horizontal orientation in the topsoil but become vertical as later roots develop into deeper soil layers (Tardieu and Pellerin, 1990). Vertical root distribution in the soil profile was characterized by first increasing to a maximum at 25 cm depth and then decreasing at greater depth (Liedgens and Richner, 2001). The main root system continues to grow downward and to branch, and additional roots are produced in successive whorls from stem nodes above the crown.

Laboski *et al*. (1998) has investigated maize (*Zea mays* L.) root growth in fine sandy soil and found an average of 94% of the total root length occurred within the upper 0.6 m of soil with 85% in the upper 0.3 m of soil. Maizlish *et al*. (1980) reported that the average root diameter at 29 days after emergence was 1.5 mm for seminal root axes, 3.0 mm for the nodal first order laterals. Fort (1962) divided the corn root growth period into five stages on the basis of the progressive development of the plant: Stage 1 included the period from the time the plants were seedlings until they were knee-high (up to 37 days). The maximum root mass occurred in the 7.5 to 15 cm soil layer. Stage 2 included most of the vegetative growth and until the tassel was about to emerge (54 days). The root growth occurred largely in the upper soil column. At the end of stage 3, the plant attained the maximum height with the full development of the tassel (67 days), root growth occurred largely below 30 cm at this stage. Stage 4 included the period from ear development until early milk stage (80 days). Extension of brace roots was observed at this stage, which increased the root mass by nearly 50 percent. Stage 5 included the period from the 80^{th} day until maturity. An increase in soil bulk density decreased root length and increased the root diameter (Logsdon *et al*., 1987).

9. Nitrogen fertilizer recommendations

Nitrogen is the most limiting essential nutrient for maize production in the humid and subhumid tropics (Fageria *et al*., 1997). It is the main driving force to produce large yields because nitrogen is a vitally important and is required in large amounts. The management of nitrogen is required to adjust the quantity of nitrogen applied in relation to the variation in the supply from soil. Stanford (1973) presented convincing evidence that reasonable estimates of internal N requirements can be derived in supplying N fertilizer needs for maximum crop production. In one case crop residue decomposition and SOM mineralization provided a large quantity of available N to the first corn crop following watermelon, which was not reflected in the residual soil NO_3^--N at planting; thus, N fertilizer needs were overestimated (Halverson *et al*., 2005). Viets (1965), however, concluded that the total N requirement of a crop cannot be accurately predicted. The University of Nebraska, however, has developed an algorithm for estimating N fertilizer recommendations in corn for achieving a certain yield goal as a function of soil organic matter, residual soil nitrate content in spring, and N credits from previous crop, manure and irrigation (Hergert *et al*., 1997). Dobermann and Fairhurst (2002) developed the formula N estimation as follow:

$$NR\ (kg\ ha^{-1}) = 35 + (1.2 \times EY) - (8 \times NO_3\text{-}N) - (0.14 \times EY \times SOM)$$

Where: NR = recommended N fertilizer rate (kg ha^{-1})

EY = expected yield (kg ha^{-1})

NO_3^-N = mean soil root zone residual nitrate-N (mg kg^{-1}).

SOM = soil organic matter (%).

The N algorithm has been validated to generally estimate N needs in numerous on-farm demonstration studies in Nebraska during the past 15 years, but there are also situations where it over or under-estimates N need (Ferguson *et al*., 2002). Recent research has developed the Decision Support Systems for Agro-technology Transfer (DSSAT), and Nutrient Management Support System (NuMaSS) softwares for nitrogen fertilizer prediction; and use the Phosphorus Decision Support System (PDSS) for phosphorus and potassium predictions. The nitrogen prediction was always too high (Yost *et al*., 1992). Attanandana and Yost (2003) observed that maize yield with and without N was not significantly different in some soils.

10. DSSAT and NuMaSS

Predicting N fertilizer requirement has been a part of several decision-aids and simulation models. Computer models such as NuMaSS and DSSAT have become useful management tools for assessing N fertilizer for crop production. DSSAT is one of the most widely used modeling systems. It is the Decision Support System for Agrotechnology Transfer models which was initially developed under auspices of the International Benchmark Sites Network for Agrotechnology Tranfter (Hoogenboom and white, 2003). DSSAT is also used to evaluate nitrogen fertilization strategies on nitrogen uptake and nitrogen leaching from soil. The model has been used in global climate change research to evaluate the potential effects of climate change and changes in precipitation and water use efficiency due to increasing carbon dioxide. NuMaSS is also widely used to predict N and lime requirement. The nitrogen module of NuMaSS is primarily designed to determine appropriate nitrogen fertilizer rates after accounting for any organic applications (Osmond *et al*., 2002). Predicted P and K fertilizers using Phosphorus Decision Support System (PDSS) was designed to assist in the diagnosis and correction of P deficiencies in soils and crops, with emphasis on tropical conditions (Yost *et al*., 1992).

MATERIALS AND METHODS

This study consisted of six experiments:

Experiment 1: A laboratory study of the effect of wetting on nitrogen (N) mineralization potential in some maize soils of Thailand and Lao PDR that have undergone drying.

Experiment 2: A field study of the distribution of nitrate in the Lb and Pc soil series before and after maize planting.

Experiment 3: Measuring the amount of nitrate in the Lop Buri (Lb) and Pak Chong (Pc) soil series in maize fields after heavy rain.

Experiment 4: A field study of maize root distribution at different stages of maize growth in the Lop Buri (Lb) and Pak Chong (Pc) soil series.

Experiment 5: Determining the N status of maize leaves in the field using a leaf color chart (LCC) in the Lop Buri (Lb) and Pak Chong (Pc) soil series.

Experiment 6: A field study on the nitrogen fertilizer response simulated from DSSAT software on some important maize soils in Thailand, and in the Lao PDR.

Materials for the field experiments

1. Fertilizer (Urea, Triple superphosphate, Potassium chloride)
2. Maize (*Zea mays*, L.) hybrid seed
3. Soil auger
4. Ice cooler
5. Rain gauge
6. Leaf color chart
7. Balance

8. Ply wood pin board
9. Long nails
10. Grain moisture meter
11. Net blue polyethylene bag
12. Hammer and hoe

Materials and equipment for soil and plant analysis

1. Spectrophotometer
2. Block digester
3. Electric hot plate
4. pH meter
5. Analytical balances
6. Plant and grain sample grinder
7. Electric hot plate
8. Reagents for N, P and K analysis in soil and plant samples
9. Fume hood.

Six experiments were conducted, one experiment was carried out in the laboratory and five experiments were conducted in the field.

1. Experiment 1: A laboratory study of the effect of wetting on nitrogen (N) mineralization potential in some maize soils of Thailand and Lao PDR that have undergone drying.

1.1 Nitrogen mineralization

1.1.1 Soil sampling and analysis

The study on determination of nitrogen mineralization potential at the beginning of the wet season was conducted in the laboratory. In the early May 2006, approximately 3 kg of soil was collected from the depth of 0 to 20 cm in 10 different sites on farmers' farms. The samples were collected from the representative sites with varying physical, chemical and mineralogical properties. The soils included 6 soil series: Chai Badan (Cd), Lop Buri (Lb), Lam Narai (Ln), Takhli (Tk), Pak Chong (Pc), and Warin (Wn) from Thailand, and 4 soils from Lao PDR: Bachieng (Bc), Khammouan (Km), Sendin (Sd), and Saythong (St).

All ten soils were air-dried and crushed to pass a 2 mm sieve and thoroughly mixed. Soil pH was determined by glass electrode (soil: water ratio of 1:1), organic matter was determined by the Combustion method (Nelson and Sommers, 1996), total N was determined by the Kjeldahl method. Selected physical and chemical properties of the soils were determined prior to the incubation experiments.

1.1.2 Soil incubation study

The soils for the incubation study were air-dried and crushed to pass a 2 mm sieve. The percentage soil moisture content at field capacity was measured using a pressure plate apparatus. Each sample of the ten soils was divided into three parts, and prepared at three different soil moisture levels, including air-dried soil (AD) as treatment 1 (T1), soil maintained at field capacity (FC) as treatment 2 (T2), and soil heated at a temperature of 40 ^oC for 24 hours (H40) as treatment 3 (T3). The soils with three different moisture treatments were placed in plastic bottles and they were adjusted to field capacity moisture and incubated at 30 ^oC for different periods of time (0, 3, 7, 14, 21, 28, 35, 42, 56 and 70 days). Bottles were not closed to enable aeration. Field capacity moisture conditions were maintained during the incubation period by weighing the soils and adding water to the containers. After each specified incubation period, samples were taken for inorganic N (NO_3^--N and NH_4^+-N) analysis.

1.1.3 Analytical methods of soil nitrate and ammonium

After each specified incubation period, the amounts of soil NH_4^+-N and NO_3^--N were extracted with 50-mL Mehlich 1 extracting solution at a 1:5 soil: solution ratio (Jones, 1985). The soils were shaken for 5 minutes. The filtered extracts were analyzed for NO_3^--N and NH_4^+-N using a colorimetric method (Jackson, 1958). For NO_3^--N analysis a ten mL aliquot was dispensed into a 25-mL volumetric flask and treated with 1-mL of EDTA, 1-mL of citric acid solution, and 0.5 g of a powder mix (napthlylamine + Zn-powder + sulfanilic acid + manganese sulfate). The solution was brought to volume with deionized water. After 30 minutes, percent transmittance was read using a spectrophotometer at a wavelength of 520 mμ. The analysis of NH_4^+-N was carried out as follows: A 5-mL aliquot was dispensed into a 25-mL volumetric flask and treated with 5-mL of a solution (sodium salicylate + sodium hydroxide + sodium nitroprusside) add 3-mL of 2% hypochlorite and then brought to the volume with deionized water. After 30 minutes, percent transmittance of NH_4^+-N was recorded using a spectrophotometer at a wavelength of 650 mμ.

1.1.4 Statistical analysis of nitrate and ammonium release

Statistical computations were performed by procedures of SAS Version 8.1 (SAS, 1985). The nitrogen mineralization rate (NH_4^+-N and NO_3^--N release) data were examined using analysis of variance (ANOVA) and repeated measures analysis (SAS PROC MIXED) procedures. Statistical analyses were carried out for all soil data, and were used to evaluate differences among treatments and among incubation periods (soil nitrogen mineralization data for each soil series were analyzed separately to assess the wetting and drying effects and changes over time of incubation). Significant among treatment means was assessed using least significant difference tests ($P < 0.05$). The release of nitrate and ammonium was measured at 0, 3, 7, 14, 21, 28, 35, 42, 56 and 70 days of incubation, the "repeated" variable was days as described by Littell *et al*. (1998), and the compound symmetry variance structure was assumed for the PROC MIXED analysis.

1.2 Organic nitrogen fractions in soil hydrolyzates

Organic nitrogen fraction compounds were determined in hydrolysates of the ten soils. The procedure used to determine the form of organic-N in soil hydrolysates followed the description of Mulvaney *et al*. (2001a), and is described in the following steps:

1.2.1 Soil hydrolysates preparation

To prepare soil hydrolysates, triplicate samples of soil containing approximately 10 mg of N were heated under reflux for 12 hours after treatment with 20-mL of 6 *M* HCl and two drops of octylalcohol. The hydrolysis mixture was filtered through Whatman no. 50 filter paper under vacuum, after which replicate hydrolysates were combined and transferred to a refrigerator for storage (5 ^{o}C). Prior to use, the hydrolysates was neutralized by the addition of NaOH (Bremner, 1965; Stevenson, 1982a) to obtain a pH of 6.5 to 6.8.

1.2.2 Hydrolyzable ammonium-N

A ten mL aliquot of soil hydrolysate was placed in a Mason jar and treated with 0.05 g of MgO using a calibrated spoon. The jar was swirled to mix the contents, and then sealed by attaching a lid equipped with a modified Petri dish containing 5-mL of H_3BO_3 indicator solution. Diffusion was performed for 2 hours on a hot plate (48-50 ^{o}C), followed by titrimetric determination of the NH_4^+-N captured in the boric acid solution.

1.2.3 Amino sugar-N (AS-N)

Two mL of 10 *M* NaOH was added to 10-mL of soil hydrolysate in a Mason jar. After swirling the jar to mix the contents, a lid equipped with a modified petri dish containing 5-mL of H_3BO_3 solution was attached within 30 seconds, and the jar was heated on a hot plate (48-50 ^oC) for 5 hours. The amount of NH_4^+-N captured in the boric acid was determined as described previously.

1.2.4 Amino acid-N (AA-N)

After completing diffusion of amino sugar-N, 2.5-mL of 5 *M* H_2SO_4 was added to the jar, followed by 1-mL of ninhydrin solution. The jar was swirled to mix the contents, and after being covered (but not sealed) with the same Mason jar lid to minimize the loss of water, the jar was placed in the central area of a hot plate, and heated for 90 min at 95 to 100 ^oC. A few minutes were allowed for the jar to cool, after which the contents were treated with 1-mL of 10 *M* NaOH and mixed by swirling. Within 30 seconds, the jar was sealed by attaching a lid with 5-mL of H_3BO_3 solution in a modified petri dish, and then heated at 48 to 50 ^oC for 2 hours on a hot plate. The H_3BO_3 solution was titrated as described previously to assay the captured ammonium-N.

2. Experiment 2: A field study of the distribution of nitrate in Lop Buri (Lb) and Pak Chong (Pc) soil series before and after maize planting.

2.1 Site description

The study areas were located in the central part of Thailand in the Phra Puttabat district, Saraburi province (14°32′N 101°0′E) about 115 km North of Bangkok. Two sites, representing two soil series, namely; Lop Buri (Lb) and Pak Chong (Pc) were selected for these studies because they are representative of the soils in the maize belt of Thailand. The distance between the two sites was about 8 kilometers. The two soils were classified as an isohyperthermic, Typic Haplustoll (the Lb soil), and a Rhodic Kandiustox (the Pc soil) and initial soil samples were taken for chemical and textural analysis. The differences between the two soils in the study sites, including both physical and chemical properties, were analyzed. During the experimental period soil bulk density, total porosity and field water holding capacity of the soils were measured at the soil depths of 10, 30, 50, 70 and 90 cm.

The mean daily temperature and annual rainfall of this region during 30 years (1968-1998) was around 27-28 ^{o}C and 1200 mm, respectively.

2.2 Crop management

Maize (hybrid ‘CP989’) was planted on 5 June, 2005 at the Lb site. At the Pc site, maize (hybrid ‘NK48’) planting was delayed until 1 July; due to the late rain. Both maize varieties are widely used in this region. The growth period of the two maize varieties varies from 105 to 115 days after emergence. Weeds were controlled after the maize had emerged at 15 days and at 30 days by hand weeding. Maize was harvested on 25 Sept (115 days after emergence), and 15 Oct, 2005 (110 days after emergence) for Lb and Pc sites, respectively.

2.3 Experimental design and treatments

Nitrate distribution, nitrate status and maize root development

Experiments were established at each of the two sites. Soil nitrate distribution was measured at zero, two and four weeks before maize was planted, and at 2, 4, 6, and 8 weeks after emergence, comprising the majority of the vegetative stage of the crop. Nitrate status was measured at 0, 3, 5, and 7 days after a specific heavy rain occurred at each site. Root depth was measured at selected stages of plant development. The experiments were arranged in a completely randomized design (CRD). The individual plot size was 6 x 8 m; plant spacing was 75 x 20 cm. Each plot consisted of 8 rows, with 200 plants per 30 m^2 or planted at a density of 66,666 plants ha^{-1}. Two different N rates were used with two replications at 0 and 188 kg N ha^{-1} (Table 2). The amounts of phosphorus and potassium fertilizer were recommended by the PDSS (Phosphorus Decision Support System) software. Phosphorus was applied at 44 kg P_2O_5 ha^{-1} for both soils while potassium fertilizer was applied at 50 and 75 kg K_2O ha^{-1} for Lb and Pc soils, respectively, to ensure adequate levels at the two sites.

Table 2 Nitrogen, phosphorus and potassium fertilizer rates for the nitrate distribution study.

Soil series	Lop Buri soil	Pak Chong soil
Treatment	- - - - - - N, P_2O_5 and K_2O fertilizer rates (kg ha^{-1})	- - - - - -
N0-P-K	0- 44- 50	0- 44- 75
N4-P-K	188- 44- 50	188- 44- 75
DSSAT predicted N	50	82

2.4 Sampling for soil profile nitrate distribution

At each of the two sites, soil nitrate distribution was measured at 0, 2, and 4 weeks before maize was planted and at 2, 4, 6, and 8 weeks after emergence. Soil sample collection at the two sites differed by the time, from 6 May to 30 July for Lb soil series, and from 25 May to 25 August for Pc soil series, which approximated similar stages of plant development. Three soil profiles, randomly selected per plot, were sampled by auger to collect soil from the following depths (0 to 20, 20 to 40, 40 to 60, 60 to 80 and 80 to 100 cm). About 100 g of moist soil from each layer was taken. Soil samples were stored in plastic bags and placed in an ice cooler, brought to the laboratory for NO_3^--N analysis. A portion of the wet soil sample was put in an oven at 105 ^{o}C for moisture content determination. We calculated the concentration of NO_3^--N (kg ha^{-1}) in every depth considering the soil bulk density.

Sampling for nitrate status, therefore, occurred in three stages: preplant nitrate status, nitrate status after planting and during plant growth, and nitrate status immediately after a heavy rain. The sampling times in relation to planting and harvesting are given in Figures 3 and 4.

2.5 Soil bulk density determination and analysis methods

Soil field bulk density of Lb and Pc soils was taken using soil cores taken from the different depths (10, 30, 50, 70 and 90 cm) during similar maize growing stages. The nitrate analysis was done using the same methods as described earlier. We calculated the concentration of nitrate (kg ha^{-1}) in every soil depth and measured the soil bulk density (D_b), total porosity and moisture content.

2.6 Statistical analysis of grain yield, total N, P, K uptake and soil available N

Statistical computations were performed by procedures within the SAS (Version 8.1). The data were examined using analysis of variance (ANOVA) procedures. Separate analyses were carried out for maize grain yield, total nitrogen uptake by grain and stover, and soil available nitrogen of different treatments to evaluate differences among treatments. Significant among treatment means was assessed using least significant difference tests ($P < 0.05$). The SigmaPlot (Systat, Inc., 2008) program was used to develop figures from the experimental data.

2.7 Statistical analysis of nitrate distribution with maize root development

The data analyses were performed by Proc Mixed (SAS, 1985) due to the correlated nature of measurements taken at the same soil depth over time. For the analysis of nitrate distribution at 0, 2, 4, 6, and 8 weeks after planting, the "repeated" variable was weeks as described by Littell *et al*. (1998), and the compound symmetry variance structure was selected because the data were insufficient to individually estimate variances for each time as required for the "unstructured" estimation of variances. The data were analyzed for each depth increment to evaluate differences among treatments and among interactions between treatment and weeks for nitrate status and among interaction of treatment and day for nitrate status after heavy rain. Treatments were analyzed as fixed effects, whereas replications were considered random, and week of sampling were treated as repeating variables. Similarly, depths were treated as repeated because of the expected correlation among depths. The summation of the NO_3^--N profile of nitrate distribution and nitrate status for each soil series was analyzed separately to assess the effects of N application. Significant among treatment means was assessed using least square means. Because there were only two treatments and least squares means were used to compare effects over time, we present the means and discuss only significant effects. Effects are described as being significant if they differed at a probability level of 0.05 or less.

3. Experiment 3: Measuring the amount of nitrate in the Lop Buri (Lb) and Pak Chong (Pc) soil series in maize fields under heavy rain.

For the nitrate status study, the experiments were carried out at the same place and same time with the study of nitrate distribution (experiment 2). The site description, crop management, experimental design and treatments were the same as in experiment 2 but differed in the time and date of soil sample collection.

3.1 Soil sample collection

Nitrate status in relation to a rainfall event

3.1.1 Sampling for nitrate status after a large rain

Nitrate status in relation to a rainfall event was estimated in both Lb and Pc soil series at the vegetative stage of maize growth after a heavy rain occurred (>45 mm day^{-1}). At the Lb site, a heavy rain occurred on July 4 with the amount of 128 mm day^{-1} when the maize was 31 days old. For the Pc site, a heavy rain occurred on August 19 with the amount of 65 mm day^{-1} when the maize was 48 days old. Soil samples from both sites were collected for three randomly selected points in each plot using a soil auger (bucket type) at 0, 3, 5, and 7 days after rain. Mean daily rainfall in 2005 for the months of May to September, which was related to nitrate measuring after heavy rain occurred are also presented in Figure 2.

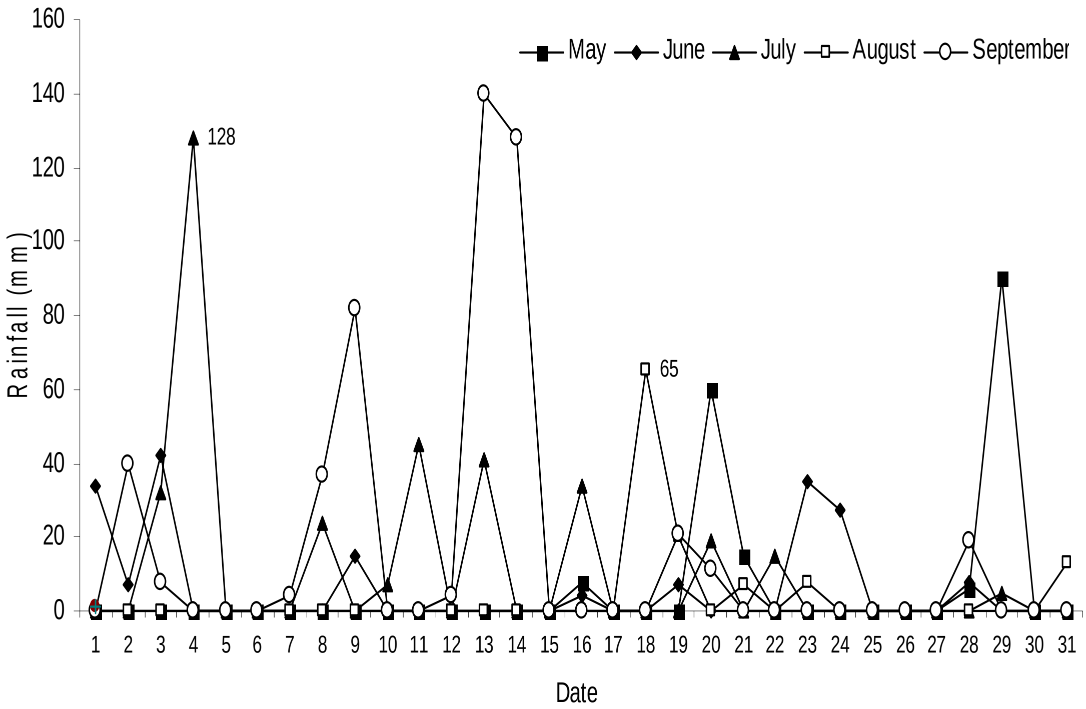

Figure 2 Daily rainfall distributions, which were recorded during the field experiment from May to September, 2005. Source: Sweet Seed Corn Center. Phra Phuttabat district, Saraburi province.

The sampling times in relation to planting and harvesting differed slightly for the Lb and Pc soils. The timing of sampling is illustrated in Figures 3 and 4. About 100 g of moist soil was taken at 0 to 20, 20 to 40, 40 to 60, 60 to 80 and 80 to 100 cm depths. All soil samples were immediately placed in plastic bags, put into a container with ice, and brought to the laboratory for NO_3^--N analysis. A “heavy” rainfall event criteria was any rainfall greater than 45 mm as measured at each site using a rain gauge at the field experiment.

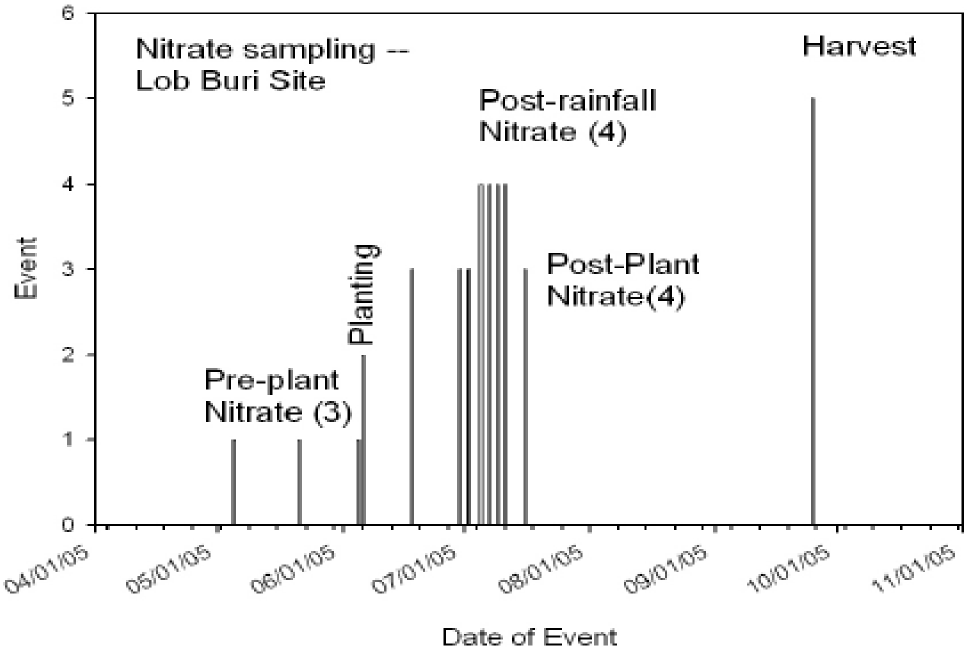

Figure 3 Date of soil nitrate distribution sampling before and after planting, nitrate post-rainfall, and nitrate sample collection of Lb soil.

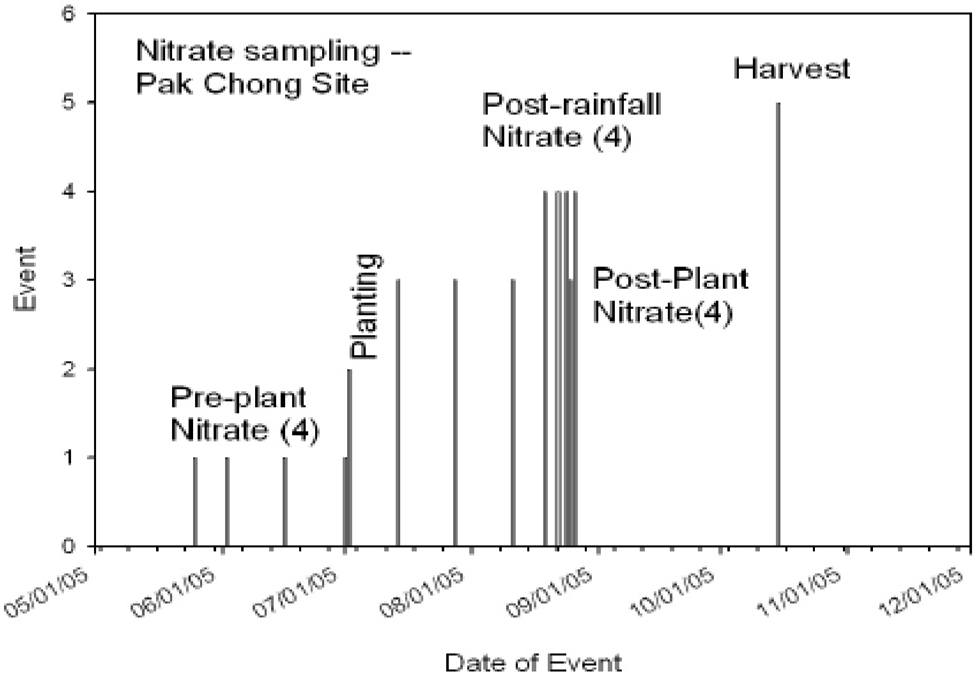

Figure 4 Date of soil nitrate distribution sampling before and after planting, nitrate post-rainfall, and nitrate sample collection of Pc soil.

3.1.2 Statistical analysis of nitrate status in relation to rainfall level

Nitrate status in soil profiles in relation to major rainfall was also analyzed by SAS Proc Mixed, as previously mentioned for experiment 2, except that days after a major rainfall were analyzed as a “repeated” variable. Compound symmetry was chosen to represent the correlation among measures of nitrate in the samples again because of the small number of degrees of freedom available for the analysis.

4. Experiment 4: A study maize root depth at different stages of growth in the Lop Buri (Lb) and Pak Chong (Pc) soil series.

In supporting the subsoil nitrate distribution and nitrate status studies, the study of maize root depth and length were conducted in the field at the same sites as experiment 2 and 3. The study sites were located in two maize fields (Lop Buri and Pak Chong soil series) in the wet season 2005, at Praphuttabat district, Saraburi province.

4.1 Root profile preparation and measurement

Maize root measurement using the pin-board method was rather tedious and heavy work requiring profile excavation and removal of a soil monolith. Therefore, maize root studies were done only at the high rates of N fertilizer applied treatment (188 kg N ha^{-1}); at three different periods of maize age (20, 40 and 60 days). The square monolith pin-board method was the technique used for root study (Bohm, 1979). The board was made from 5 cm thick plywood with three different sizes, 40 x 50; 60 x 80 and 80 x 100 cm. The soil profile was dug as a trench to the maximum rooting depth. The size of the soil monoliths thus varied according to the size of the root profile. Before removal of the monolith from the soil, a wood board was placed against one side of soil monolith wall; long nails (15 cm) were then pushed through the board into the soil monolith with a spacing of 8.5 cm. The soil monolith was carefully removed and positioned for careful washing.

4.2 Root measurement

Root depth and root length were measured at 10 points on the board. Root length was measured considering two dimensions: depth and lateral distance.

5. Experiment 5: Determining the N content of maize leaves in the field using leaf color chart.

The study sites were also located on two maize fields (Lop Buri and Pak Chong soil series) in the wet season 2005, at Praphuttabat district, Saraburi province which was the same area of the experiment 2, 3 and 4. The site description, crop management, experimental design and treatments were the same as in experiment 2. However, the rate of nitrogen fertilizer was 52 kg N ha^{-1} for Lb soil and 82 kg N ha^{-1} for Pc soil. The basal N fertilizer application was half of the total dose (26 and 41 kg N ha^{-1} for Lb and Pc soil series, respectively). The rest of the N fertilizer was added as topdressing when the maize leaves showed critical level of less than 3 units (LCC) or when the N deficiency symptoms appeared.

5.1 Maize leaves measurement

At 21 days after maize emergence, the leaf color was taken using LCC as the first reading, while the second, third and fourth readings were taken at eight to ten days after first reading (21, 30, 42, 50, 58 and 65 days for Lb and Pc soils). The leaf selection was randomly done at the first fully expanded leaves and 10 plants were used for color comparison by placing its middle part on top of the color strips of the chart, leave color reading was done at the same time of the day (8-10 am). The comparison of the leaf with LCC was done every week until the tasseling stage at which time, the topdressing of fertilizer was done according to the recommended amount. Ten fully expanded leaf samples were collected for N determination on the same day as the color-chart reading was recorded. Regression analysis was performed on the data to quantify the relationship among color-chart reading values, leaf N content and yield.

5.2 Leaf N analysis

All leaf samples were dried at 70 °C until a constant weight was obtained (48-72 hours). The midrib was removed and the remaining tissue was cut and ground to less than 1 mm size. The samples were analyzed for N contents.

5.3 Soil sample analysis

Soil samples were also collected for nitrate analysis from 21 days after maize planting to tasselling stage at 0 to 20, 20 to 40 and 40 to 60 cm depths. All moist soil samples were immediately placed in plastic bags and chilled in an ice cooler and brought to the laboratory. On the same day, 10 grams of each soil sample were extracted with 50-mL of Mehlich 1 extracting solution, and soil nitrate was determined using a colorimetric method (Jackson, 1958).

6. Experiment 6: A field study of the nitrogen fertilizer response including predictions from DSSAT software on some important maize soils in Thailand and Lao PDR in 2005-2006.

The studies of site-specific nutrient management using DSSAT for N fertilizer prediction and PDSS for the phosphorus and potassium prediction were conducted in selected maize soils at the farmer's field in Thailand and in the Lao PDR.

6.1 Location and soil in the study sites

Field experiments were conducted to test the maize response to N fertilizer in the wet season 2005 and 2006 at four sites. Two sites in Thailand were located at maize farmers' fields in Praphuttabat district, Saraburi province, the same location as experiment 2. However, the other two experiments were located in the Lao PDR. One of them was situated at Sendine village, Nasaytong district, 30 km North of Vientiane city, and the other one was located at the Agricultural Station, Bachieng district, about 24 km from the center of Champasak province in Southern part of Laos. The soils were Saythong (St) and Bachieng (Bc) soils which were Ultisols and Oxisols, respectively. The St soil was gray in color, with a clay content of 290 g kg^{-1}, soil pH of 5.2 and 18 g kg^{-1} of organic matter content. The Bc soil was reddish, with a clay content of 490 g kg^{-1}, soil pH of 4.7 and 43 g kg^{-1} of organic matter. Extractable phosphorus content of these soils were 4, 7, 12 and 3 mg kg^{-1}, while the extractable potassium content were 130, 65, 77 and 103 mg kg^{-1}, for Lb Pc, St and Bc soils, respectively (Tables 6 and 7). The mean temperature and annual rainfall of the two regions (Vientiane and Champasak) during past 15 years (1985-1999) were around 26-27 ^{o}C, 1400 mm, and 28 ^{o}C, 2000 mm, respectively.

6.2 Experimental design and land preparation

In 2005 and 2006, the experiments were conducted at the same locations using randomized complete block designs (RCBD), with 5 treatments and 4 replications. The individual plot size was 6 x 5m (30 m^2) with plant spacing of 75 by 20 cm. Each plot consisted of 8 rows and the plant population was 200 plants per plot, giving approximately 66,666 plants ha^{-1}.

Land preparation at the four locations was done in a similar manner. Firstly, all fields were deeply ploughed in early May to kill hibernating insects, pests and pernicious weeds. A second tilling was made one day before maize planting whereby the soil surface was smoothed and furrows were drawn to a depth of 15 cm. The distance between rows was 75 cm.

6.3 Crop management

Hybrid maize variety NK48 was used for Pc, St and Bc soils, while the hybrid CP898 was chosen for experiments on the Lb soil. Maize planting dates differed at each location according to the local weather conditions. In 2005, maize was planted on June 5, 11 and 14 for Lb, Bc and St soils, respectively, and on July 1, for the Pc soil. In 2006, maize variety CP989 was planted on May, 24 for Lb soil and on June 2, 5 and 7 for Pc, Bc and St soils, respectively.

6.4 Fertilizer treatments in 2005 and 2006

Nitrogen fertilizer for maize in both years was applied at 5 different levels according to the N recommendation derived from simulation results of the models, which included an assessment of nutrient content in each soil. The different N rates were used to develop response curves that permitted testing the amounts of N predicted by the DSSAT-CERES-Maize software (Version 4.0). In 2005, the N requirement was predicted at 50, 82, 75, and 50 kg N ha^{-1} for Lb, Pc, St and Bc soils (Table 3).

In 2006, it was predicted at 80, 87, 82, 75 kg N ha^{-1} for those four soils, respectively (Table 4). In the case of phosphorus and potassium fertilizer, they were applied as recommended by PDSS (Phosphorus Decision Support System) software, which was designed to meet the phosphorus and potassium requirements of the maize crops (Yost *et al*., 1992). Nitrogen fertilizer was applied as urea; the application was done two times: once application was half of N rate as basal (at the planting time) and once as topdressing when the maize was 30 days after maize emergence. In 2006, a lime application was proposed to increase soil pH of the Bc soil. The lime ($Ca(OH)_2$) was applied at 0.5 t ha^{-1}according to recommendation by NuMaSS (Nutrient Management Support System). Lime was incorporated into the soil at two weeks before maize planting.

Table 3 Nitrogen, phosphorus and potassium fertilizer rates of the four experiments in Thailand and the Lao PDR, conducted in 2005.

Soil series	Lb soil	Pc soil	St soil	Bc soil
Treatment	- - - - - - - - - N, P_2O_5 and K_2O fertilizer rates (kg ha^{-1}) - - - - - - - -			
N0- P-K	0-44-50	0-44-75	0-32-44	0-44-50
N1- P-K	32-44-50	44-44-75	38-32-44	25-44-50
N2- P-K	50-44-50	82-44-75	75-32-44	50-44-50
N3- P-K	100-44-50	125-44-75	113-32-44	75-44-50
N4- P-K	188-44-50	188-44-75	188-32-44	150-44-50
Predicted N	50	82	75	50

Note Lb - Lop Buri (Thailand), Pc - Pak Chong (Thailand), St - Saythong (Laos), Bc - Bachieng (Laos)

Table 4 Nitrogen, phosphorus and potassium fertilizer rates of the four experiments in Thailand and the Lao PDR, conducted in 2006.

Soil series	Lb soil	Pc soil	St soil	Bc soil
Treatment	- - - - - - - - - N, P_2O_5 and K_2O fertilizer rates (kg ha^{-1}) - - - - - - - -			
N0- P-K	0-19-25	0-19-25	0-19-69	0-44-81+500 kg $Ca(OH)_2$
N1- P-K	25-19-25	25-19-25	25-19-69	25-44-81+500 kg $Ca(OH)_2$
N2- P-K	50-19-25	50-19-25	50-19-69	50-44-81+500 kg $Ca(OH)_2$
N3- P-K	100-19-25	100-19-25	100-19-69	75-44-81+500 kg $Ca(OH)_2$
N4- P-K	150-19-25	150-19-25	150-19-69	150-44-81+500 kg $Ca(OH)_2$
Predicted N	80	87	85	75+500 kg $Ca(OH)_2$

Note Lb - Lop Buri (Thailand), Pc - Pak Chong (Thailand), St - Saythong (Laos), Bc - Bachieng (Laos)

6.5 Harvest, plant and soil data collection

In both years of 2005 and 2006, maize grain and stover were harvested at different dates. In the Lb soil, the harvesting was done on September 9, 2005 and September 16, 2006. For the Pc soil, it was on October 17, 2005 and September 16, 2006, respectively. In the case of the Bc and St soils, the maize was harvested on 27 and 29 Sept, 2005 and on 23 and 25 Sept, 2006, respectively. Plants were recorded including plant heights at 30 days and 60 days by sampling 10 plants per plot. The flowering date at 50 and 100 % of each treatment were recorded. Plant and ear numbers were recorded after maize harvest. Maize was harvested from the 6 middle rows in the 4.2 x 4.5 m (18.9 m^2) per plot. The grain weight was adjusted to 15% moisture. Maize grain and stover samples were randomly selected from each plot for nutrient analysis.

6.6 Soil analyses

Eighty soil samples from four sites were secured and analyzed for selected soil chemical properties. Soil samples were taken after maize harvest and air-dried and crushed to pass a 2 mm sieve. Chemical properties to be analyzed included the following: Organic carbon determined by the combustion method (Nelson and Sommers, 1996), soil pH was measured electrometrically by a pH meter at a soil to water ratio of 1:1. Available N was extracted with 50-mL Mehlich 1 extracting solution at a 1:5 soil: solution ratio (Jones, 1985). Extractable phosphorus (P) was extracted with Bray II (Bray and Kurtz, 1945), and determined by spectrophotometer at a wavelength of 882 mμ. Exchangeable potassium (K) was extracted by 1 *M* ammonium acetate (NH_4OAc) pH 7 (Jones, 2001) and determined by an Atomic absorption spectrophotometer. Nitrate and ammonium (NH_4^+-N and NO_3^--N) were analyzed as previously described. The extracts were analyzed for NO_3^--N and NH_4^+-N using a colorimetric method (Jackson, 1958).

6.7 Plant sample analyses

Plant and grain samples were taken in both years. Grain and stover samples were weighed and air dried until the weight was constant. The grain and plant samples were crushed and analyzed for total nitrogen, phosphorus and potassium content after digestion using mixture (H_2SO_4-Na_2SO_4-Se) at the ratio of 1000-mL: 100 g: 1 g respectively by Kjeldahl digestion (Bremner, 1996).

6.8 Statistical analyses

The statistical computations were performed by procedures within the SAS Version 8.1 (SAS 1985). The data were examined using analysis of variance (ANOVA) procedures.

Maize grain, stover yield and nutrient contents in the soil and crops of different treatments were statistically analyzed by SAS. The SigmaPlot software was used to fit a linear plateau curve for the nitrogen response study.

RESULTS AND DISCUSSION

1. Experiment 1: The effect of wetting on nitrogen (N) mineralization in some maize soils of Thailand and Lao PDR that have undergone drying.

1.1 The characteristics of ten selected soils

The six Thai soils used in this study were Chai Badan (Cd), Lop Buri (Lb), Lam Narai (Ln), Takhli (Tk), Pak Chong (Pc), Warin (Wn), and the four soils from the Lao PDR were Bachieng (Bc), Khammouan (Km), Sendin (Sd), Saythong (St). The ten soils belong to the Entisol, Mollisol, Oxisol, Ultisol, and Vertisol orders of Soil Taxonomy (Soil Survey Staff, 1999). The soils were classified according to the USDA Soil Taxonomy (Table 5).

Table 5 Soil Taxonomy classification of the ten representative maize soils.

Soil Series	Soil Taxonomy classification
Cd	Fine, smectitic, isohyperthermic, Leptic Haplusterts
Tk	Loamy-skeletal, carbonatic, isohyperthermic, Entic Haplustolls
Lb	Very-fine, smectitic, isohyperthermic, Typic Haplusterts
Ln	Fine, smectitic, isohyperthermic, Vertic Haplustolls
Pc	Very-fine, kaolinitic, isohyperthermic, Rhodic Kandiustox
Wn	Fine-loamy, siliceous, isohyperthermic, Typic Kandiustults
Bc	Very-fine, kaolinitic, isohyperthermic, Rhodic Kandiustox
Km	Very-fine-loamy, siliceouse, isohyperthermic, Typic Kandiustults
Sd	Very-fine-loamy, isohyperthermic, Oxyaquic Paleustalf
St	Very-fine-loamy, isohyperthermic, Oxyaquic Paleustalf

Source: Soil Survey Staff (1999).

Major physical and chemical properties of the ten selected soils are presented in Tables 6 and 7. The soils were arranged into two groups: (i) soils with clay and clay loam texture, high OM content and pH higher than 6, which included the Cd, Tk, Lb and Ln soil series. Clay content of these soils ranged from 309 to 610 g kg^{-1}, and OC content ranged from 9.6 to 22.5 g kg^{-1}; (ii) soils with clay, clay loam, loamy sand, sandy loam and loam textures, clay content of these soils ranged from 149 to 489 g kg^{-1}, they were low and high OM content but with a soil pH less than 6, which included Pc, Wn, Bc, Km, Sd and St soils.

Table 6 Selected physical and chemical characteristics of the first group soils (Cd, Tk, Lb, Ln and Pc) used in the study.

Properties	Cd	Tk	Lb	Ln	Pc
Textural class	Clay	Clay loam	Clay	Clay	Clay loam
Clay (g kg^{-1})£	589	309	600	610	349
pH $_{water}$ (1:1)	6.3	7.8	7.1	7.5	5.7
OC (g kg^{-1})$^{+}$	15	19.5	16.4	22.5	9.6
Total N (g kg^{-1})*	1.7	1.6	2.0	1.7	1.9
OM (g kg^{-1})$^{+}$	24	20	28	26	25
C:N ratio	8.8	24.7	8.2	13.2	7.4
Avail. P(Bray 2) (mg kg^{-1})#	28	1	4	11	7
Extractable K (mg kg^{-1})**	105	295	130	60	65
Extractable Al ($cmol_c$ kg^{-1})€	11.1	8.1	7.2	7.3	11.4
Extractable Al (g kg^{-1}) ††	10.9	5.5	7.9	7.7	3.1
Extractable Al (g kg^{-1})$^{\pm}$	46.1	5.6	38.2	12.9	23.9
Extractable Fe (g kg^{-1})††	1.1	0.04	0.62	0.02	0.13
Extractable Fe (g kg^{-1})$^{\pm}$	12.9	1.1	9.5	2.9	7.7

Note £ Hydrometer method (Gee and Bauder, 1986)

$^{+}$ Combustion (Nelson and Sommers, 1996)

* Kjeldahl method (Bremner, 1996)

\# Bay II (Bray and Kurtz, 1945)

** NH_4OAc pH 7 (Jones, 2001)

€ 1 *M* KCl (Bertsch and Bloom, 1996)

†† Oxalate pH 3 in darkness (Loeppert and Inskeep, 1996)

$^{\pm}$ Citrate-bicarbonate-dithionite (Loeppert and Inskeep, 1996)

Table 7 Selected physical and chemical characteristics of the second group soils (Wn, Bc, Km, Sd and St) used in the study.

Properties	Wn	Bc§	Km§	Sd§	St§
Textural class	Loamy sand	Clay	Sandy loam	Silty clay loam	Loam
Clay (g kg^{-1})£	170	489	149	429	290
pH $_{water}$ (1:1)	4.4	4.7	6.1	5.2	5.4
OC (g kg^{-1})+	6.1	25.3	8.3	20.1	12.8
Total N (g kg^{-1})*	0.8	2.4	1.2	2.2	1.5
OM (g kg^{-1})+	9	43	11	39	22
C:N ratio	7.6	10.5	6.8	9.2	8.5
Avail. P (Bray 2) (mg kg^{-1})#	5	3	18	10	12
Extractable K (mg kg^{-1}) **	21	103	83	80.5	77
Extractable Al (mg kg^{-1})€	49.6	36.4	7.5	6.2	6.6
Extractable Al (g kg^{-1}) ††	7.4	19.9	3.0	8.0	6.1
Extractable Al (g kg^{-1})±	35.8	195.2	14.3	56.9	38.8
Extractable Fe (g kg^{-1})††	0.05	0.65	0.05	0.79	0.02
Extractable Fe (g kg^{-1})±	2.5	17.2	1.3	11.5	3.9

Note The same methods were used as in Table 6

§ Some soils from Laos are named by location (Bc, Bachieng; Km, Khammouan; Sd, Sendin and St, Saythong)

1.2 Soil nitrogen mineralization potential

Mineralization seemed, in general, to follow two patterns, one in which no ammonium was released early and another where large of ammonium were released initially. The nitrogen mineralization potential of ten soils was significantly affected by the two different drying regimes. Mineralization varied greatly as presented in Figures 5-14. The step of N mineralization explanation was according to soil group as mentioned in an above: (i) soils with a pH higher than 6 including the Cd, Tk, Lb and Ln soil series; and (ii) with a soil pH less than 6, which included Pc, Wn, Bc, Km, Sd, and St soils.

Nitrogen mineralization in clayey, high OM, high pH soils (Cd, Tk, Lb & Ln)

Nitrate-N release

The results of this incubation revealed that four soil series (Cd, Tk, Lb and Ln) exhibited similar patterns of nitrogen mineralization, under different treatments. Nitrogen mineralization tended to produce NO_3^--N rather than NH_4^+-N in all three incubation treatments of this group of soils. The soils which were high in total N, total organic carbon content, and high soil pH tended to have high NO_3^--N liberation. The release of NO_3^--N was high after all periods of incubation. The amount of NO_3^--N release from the three different treatments was higher in T3 (heated to 40 ^oC (H40) than T1 (air-dried (AD) and T2 (field-capacity (FC), respectively (Figure 5, 6, 7 and 8). High NO_3^--N release was observed throughout the incubation period in the Cd and Tk soils. The amount of NO_3^--N released from the Cd soil ranged from 16.2 to 23.9, 16.9 to 21.7 and 17.5 to 28.1 mg kg^{-1} for air-dried, field-capacity, and heated to 40 ^oC soils, respectively. For the Tk soil, NO_3^--N release ranged from 18.3 to 23.6, 14.6 to 29.7 and 18.3 to 25.6 mg kg^{-1} for air-dried, field-capacity, and heated to 40 ^oC soils, respectively. The nitrate-N release from the Cd and Tk soils in air-dried, field-capacity, and heated to 40 ^oC soils was 6 to 7 times larger than the amount of NH_4^+-N released (17 to 28 mg NO_3^--N $kg^{-1}$and 2.8 to 4 mg NH_4^+-N kg^{-1}) (Figures 5, 6). The maximum NO_3^--N release from the Cd and Tk soils was 24.9, 21.6, 28.1 and 23.6, 21.7 24.7 mg kg^{-1} for air-dried, field-capacity, and heated to 40 ^oC soils, respectively. The time of maximum NO_3^--N release from both Cd and Tk soils was during the 28 to 42 days period (Figures 5, 6).

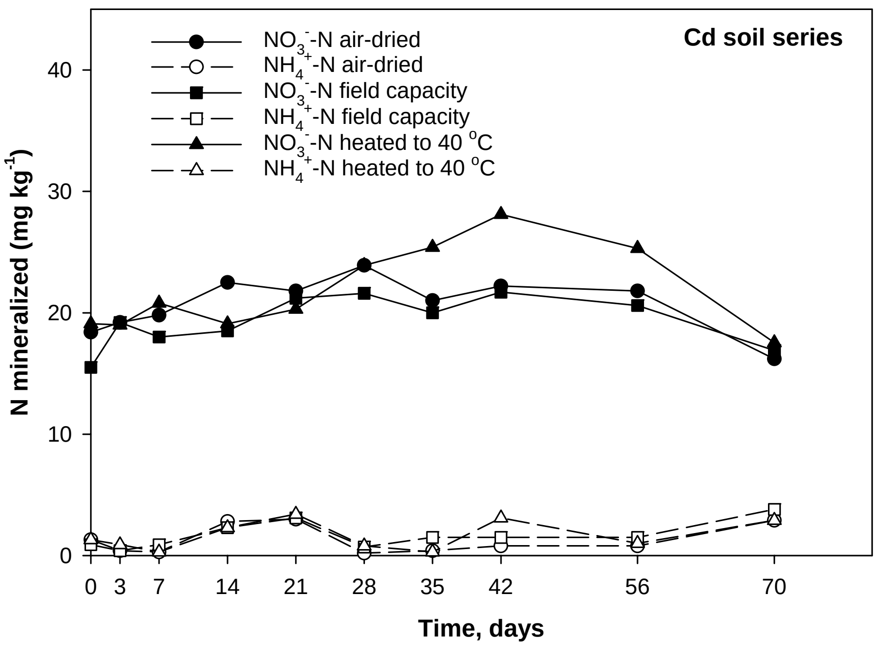

Figure 5 Nitrogen mineralization (NH_4^+-N and NO_3^--N) in the Cd soil as affected by selected pre-treatments under aerobic incubation.

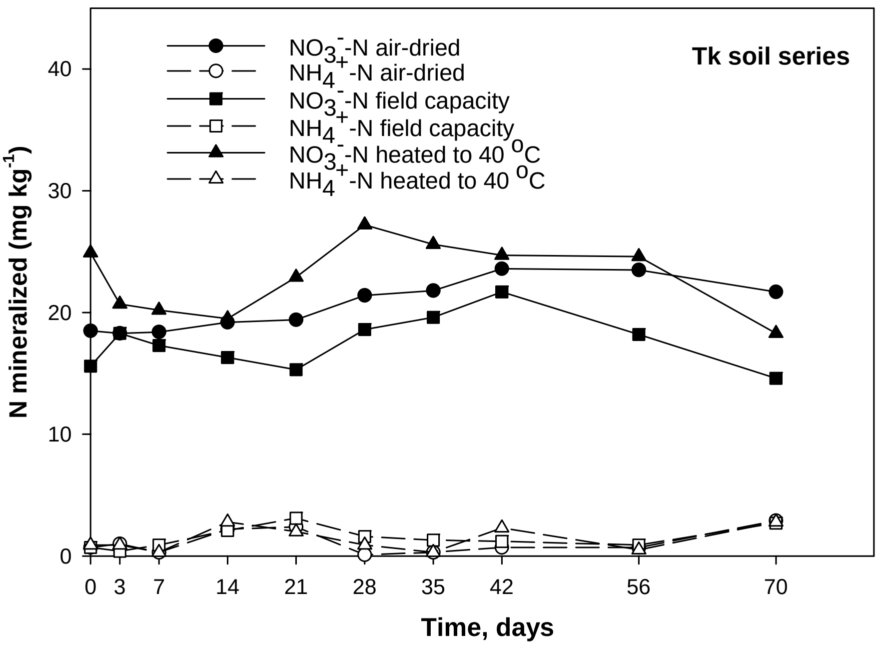

Figure 6 Nitrogen mineralization (NH_4^+-N and NO_3^--N) in the Tk soil as affected by selected pre-treatments under aerobic incubation.

The nitrogen mineralization in the Lb and Ln soils series was highest during the initial and last periods of incubation. Nitrate-N release from all incubation treatments of the Lb soil increased continuously with time (Figure 7). The highest release of nitrate of Lb soil was obtained with air-dried soil followed by the soil heated to 40 ^{o}C and soil maintained at field capacity (18.7, 18 and 16.9 mg NO_3^--N kg^{-1}, respectively). The amount of NO_3^--N released was different with different drying conditions. In contrast, NO_3^--N release from the Ln soil rapidly increased after the initial stage (day zero) of the incubation period with 20.8, 27.1, and 27.4 mg kg^{-1}, for field-capacity, air-dried, and heated to 40 ^{o}C soils, respectively, (Figure 8). The high NO_3^--N release from the Ln soil was probably due to the fact that this soil contained a relatively high level of amino acid-N. The investigation of organic N fractions using diffusion method developed by Mulvaney *et al*. (2001a) revealed that amino acid-N was 373 mg kg^{-1} in Ln soil series, which was the highest among all soils (Figure 15).

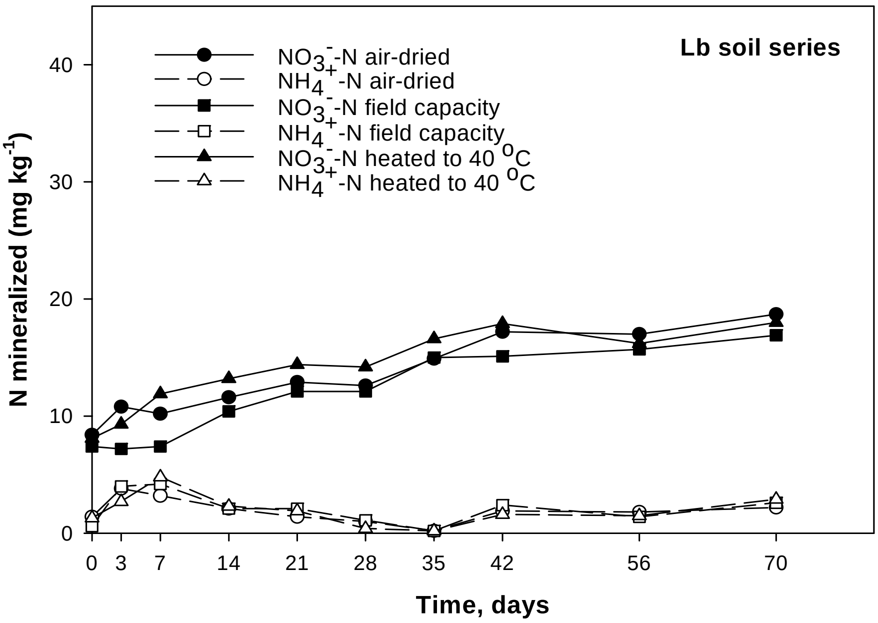

Figure 7 Nitrogen mineralization (NH_4^+-N and NO_3^--N) in the Lb soil as affected by selected pre-treatments under aerobic incubation.

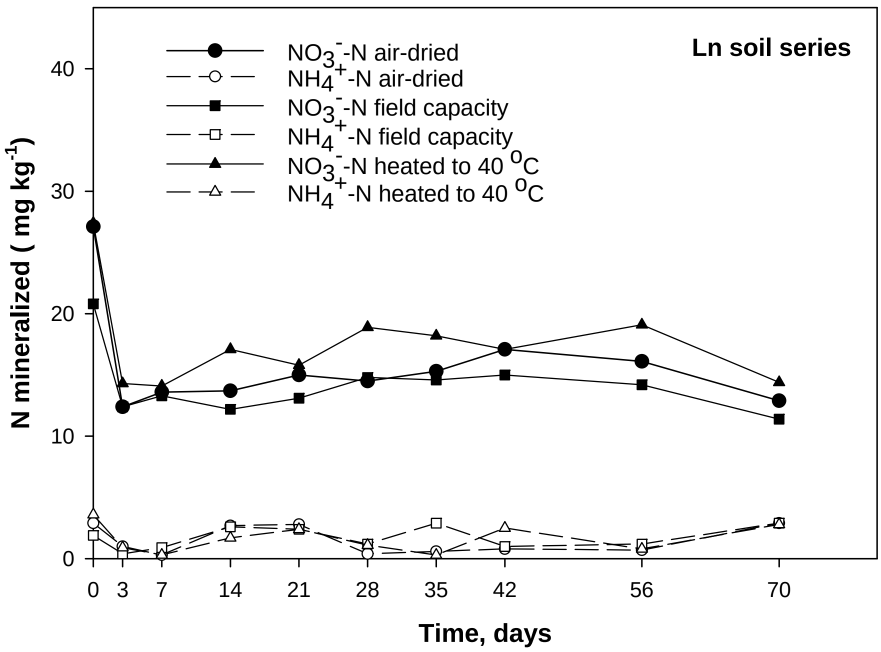

Figure 8 Nitrogen mineralization (NH_4^+-N and NO_3^--N) in the Ln soil as affected by selected pre-treatments under aerobic incubation.

Nitrogen mineralization during short time periods under aerobic conditions is likely to be heavily influenced by the mineralizable fractions of the soil organic N (Stanford *et al*., 1974). The conditions were favorable for mineralization (increase in NO_3^--N) throughout the incubation periods. The highest rate of NO_3^--N release of four soils varied from 16.9-21.7, 18.7-24.9, and 18.9-28.1 mg kg^{-1}(Table 8), for field-capacity, air-dried, and heated to 40 ^oC soils, respectively. The effects of increasing N release (NH_4^+-N + NO_3^--N) was due to the soils were high in organic carbon and total N content. This result was similar to that of Haque and Walmsley (1972) who found that nitrogen mineralized was significantly correlated with total nitrogen. Sahrawat (1982) found that in soils having a pH more than 6.0, nitrification occurred at a rapid rate and released NO_3^--N ranging from 98 to 123 mg kg^{-1}. The liberated NO_3^--N of Lb and Ln soils was much higher in the heated at 40 ^oC treatments than in soil maintained at field capacity. The reason for this disparity may be due to the effect of heating which stimulates microbial activities. Keeney and Bremner (1967) found that the value of 40 ^oC is a maximum temperature for nitrification. The release of nitrate in the first group of soils was not significantly different among treatments. Stepwise multiple regressions indicated that maximum NO_3^--N release of these soils depended on organic carbon while NH_4^+-N release depended on soil pH (Tables 9 and 10). High soil pH and high soil organic carbon content probably are the causes for the high nitrate release from the four soils during incubation. In the case of the Ln soil, the relatively high rate of nitrate release found in the initial period of incubation probably was due to its higher clay content, higher soil pH, and higher organic carbon than other soils (Y=2.24743+1.09 organic C with the adjusted R^2 of 0.85). In addition, the Ln soil is high in amino acid-N and amino sugar-N.

Ammonium-N release

The NH_4^+-N release from four soil series (Cd, Tk, Lb and Ln) was similar in pattern throughout the incubation periods. Very little NH_4^+-N (<4 mg kg^{-1}) could be detected even after 70 days of aerobic incubation (Figures 5, 6, 7 and 8). The low ammonium N release might be due to aerobic conditions, which enhances the nitrification after ammonification process (Jansson and Persson, 1982). It may be that incubation under high pH, aerobic soil conditions may enhance nitrification of soil N. The small amount of ammonium detected might be due to the ammonium was converted into nitrate under aerobic condition. This was similar to Olson and Kurtz (1982) who reported that ammonium release under soil aeration condition was limited due to the conversion to nitrate.

Nitrogen mineralization in low pH soils (Pc, Wn, Bc, Km, Sd, and St).

Ammonium-N release

The soils of group two (Pc, Wn, Bc, Km, Sd, and St) were sharply different in physical and chemical properties from the first group as mentioned above, being highly weathered, leached, and some with coarse texture. The pattern of nitrogen mineralization of the six soils was similar to each other, high NH_4^+-N released at the initial stage of incubation. The results indicated that NH_4^+-N release rates were higher than in the first group of soils (Cd, Tk, Lb and Ln). The maximum NH_4^+-N production occurred during the initial stage of incubation period (zero, and three days). After 3 to 70 days the rate of NH_4^+-N release was substantially reduced for all treatments in most soils (Figures 9, 10, 11, 12, 13 and 14). This behavior has been observed by other researchers in aerobic incubation studies (Sanchez *et al*., 1997; Madrid *et al*., 2001; Burgos *et al*., 2006). The maximum NH_4^+-N release was higher with the soils (Pc, Wn, Bc, Km, Sd, and St) heated to 40 ^oC and air-dried, which varied from 12.8 to 39.8 and 14.9 to 29.1 mg kg^{-1}, respectively, than under field capacity, which was less than 7 mg kg^{-1} (Figures 9, 11, 12, 13 and 14), except Wn soil. This indicated that after the soil was dried; wetting resulted in the highest NH_4^+-N release during the initial period of incubation. According to Gupta and Reuzer (1967) and Chew *et al*. (1976), the high rate of mineralization of organic matter during initial incubation periods was due to the consumption of most easily decomposable organic compounds by soil organisms. From 3 to 70 days, the released NH_4^+-N slowly declined and there was no difference in the amount between treatments. The NH_4^+-N release pattern during 7 to 70 days was very similar to that of the first soil group (Cd, Tk. Lb and Ln soils).

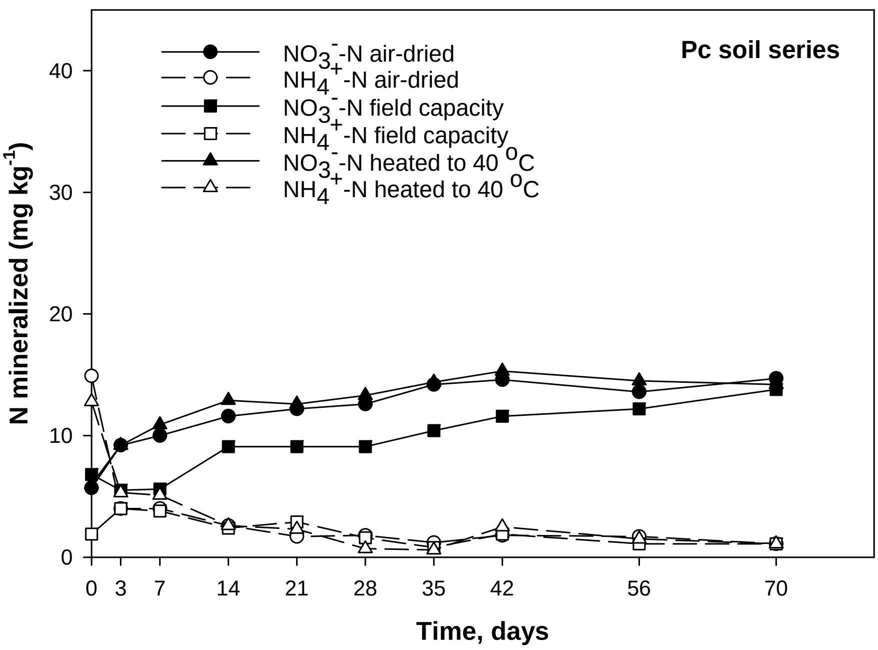

Figure 9 Nitrogen mineralization (NH_4^+-N and NO_3^--N) in the Pc soil as affected by selected pre-treatments under aerobic incubation.

The decline in the rate of NH_4^+-N production from 7 to 70 days may be attributed to the nitrification of the released NH_4^+-N. The amounts of NO_3^--N slightly increased after 3 days of incubation. These results were similar to those of He *et al*. (2000) who found that the decrease in NH_4^+-N levels in compost was generally accompanied by a corresponding increase in NO_3^--N because NH_4^+-N released from compost materials was nitrified to NO_3^--N.

Nitrate-N release

A small amount of NO_3^--N was released from the Wn and Km soils (<10 mg NO_3^--N kg^{-1}) compared to other soils. This might be due to low clay content and very low OM content of these two soils (Figures 10 and 12). The release of NH_4^+-N and NO_3^--N differed among the treatments for Bc and Sd soils. A high nitrogen mineralization occurred in the air-dried and heated to 40 ^oC treatments of the Bc and Sd soils. This might be also due to the effect of drying and mineralization on the high amino sugar-N and amino acid-N content in these soils. High nitrogen mineralization was probably due to the high soil organic matter content and that the soils were developed from old volcanic ash. This is similar to the report by Deenik (2006) who observed that volcanic ash soils rich in organic matter tend to have high nitrogen mineralization rates. The results illustrated that NH_4^+-N was rapidly released at the initial incubation period for all treatments, however, there were higher amounts of N mineralized (NH_4^+-N and NO_3^--N) from soils that were air-dried and heated to 40 ^oC soils than from soils maintained at field capacity. The amount of nitrogen mineralized (NO_3^--N, NH_4^+-N) in most soils was not different between treatments except for the Bc and Sd soils. This case was similar to the report from MSU (2005) which indicated that samples taken in late May or in June after the soil has warmed-up usually contain the greatest amount of nitrate because much of the ammonium and some of the organic N has converted to nitrate. In the case of NH_4^+-N release from Pc, Wn, Bc, Km, Sd and St soils. The air-dried soil and that heated to 40 ^oC soil released large amounts NH_4^+-N during the initial stages of the incubation (day zero to three).

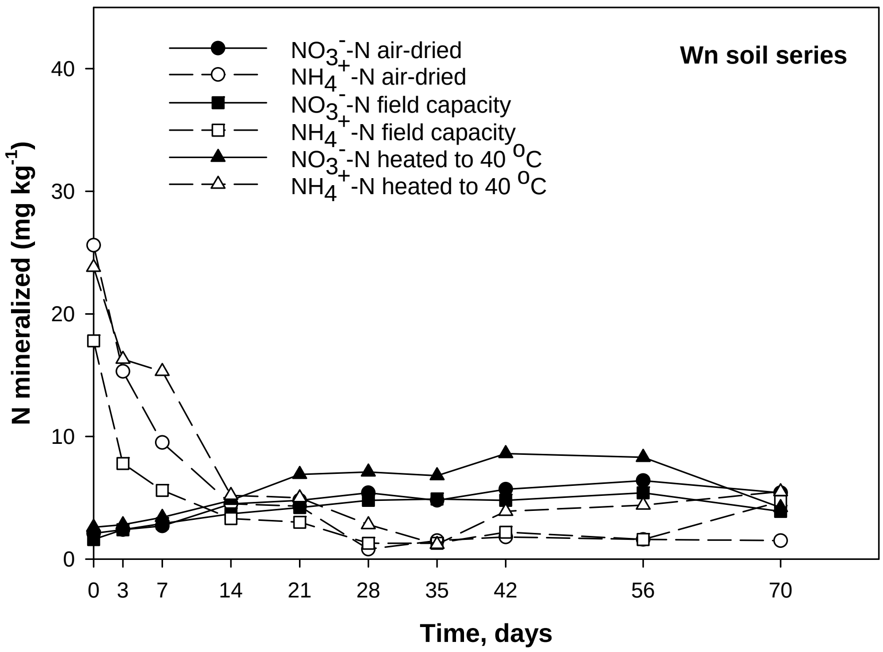

Figure 10 Nitrogen mineralization (NH_4^+-N and NO_3^--N) in the Wn soil as affected by selected pre-treatments under aerobic incubation.

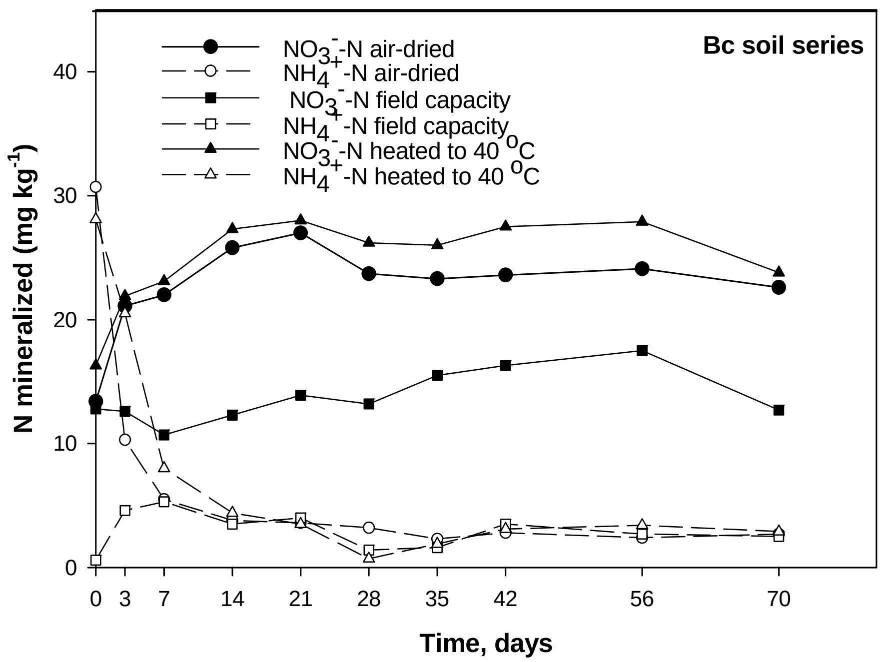

Figure 11 Nitrogen mineralization (NH_4^+-N and NO_3^--N) in the Bc soil as affected by selected pre-treatments under aerobic incubation.

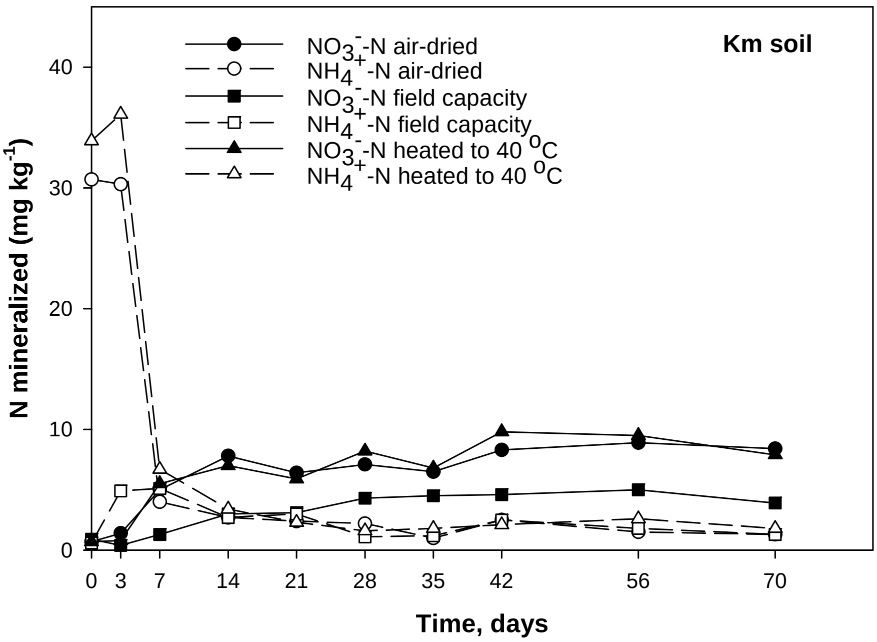

Figure 12 Nitrogen mineralization (NH_4^+-N and NO_3^--N) in the Km soil as affected by selected pre-treatments under aerobic incubation.

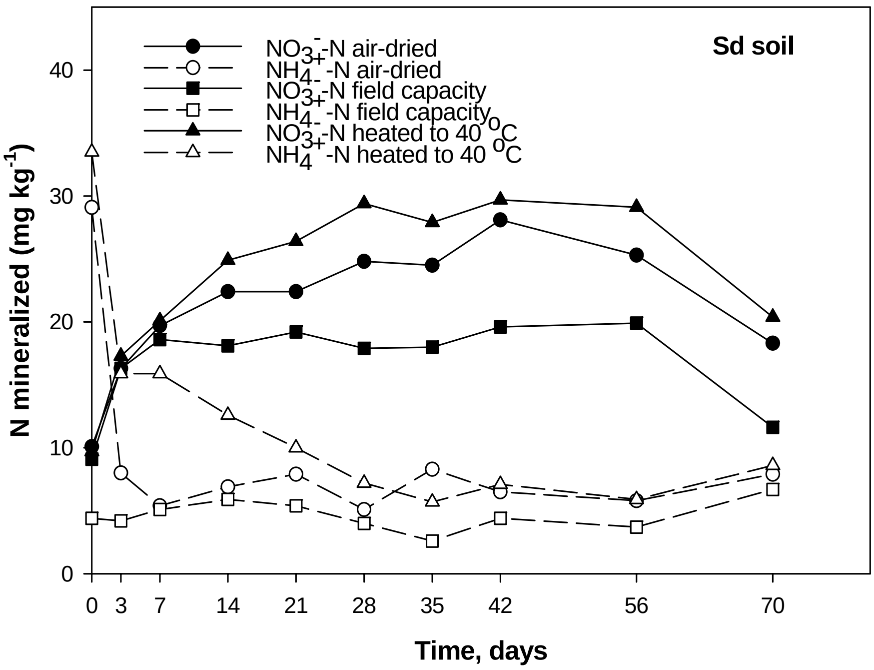

Figure 13 Nitrogen mineralization (NH_4^+-N and NO_3^--N) in the Sd soil as affected by selected pre-treatments under aerobic incubation.

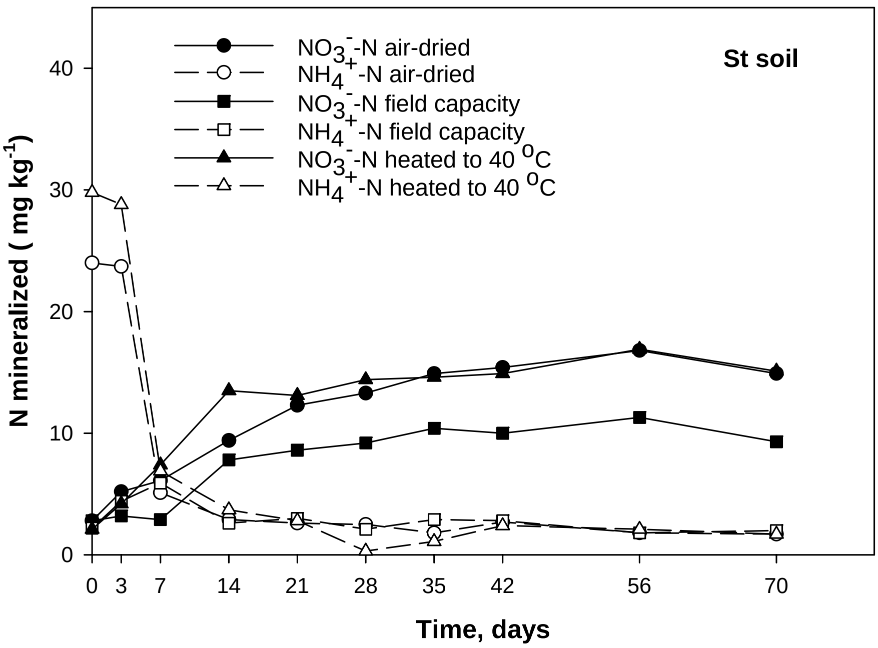

Figure 14 Nitrogen mineralization (NH_4^+-N and NO_3^--N) in the St soil as affected by selected pre-treatments under aerobic incubation.

The maximum release of NO_3^--N in most soils of all treatments was found at 28, 42, 56 and 70 days, respectively, except for the Ln soil, where the highest amount was found at zero days of incubation (Table 8). It can be noted that mineralization of N (NO_3^--N) seemed to be slower in soils with a soil pH lower than 6 during the initial stages of incubation. This probably reflect the frequent observation that low soil pH can limit mineralization. The mineralization of organic N is inhibited by low pH in mineral soils (Adams and Martin, 1984). Nyborg and Hoyt (1978) incubated 40 acid (pH 4.5-5.6) mineral surface soils with and without lime and found that liming to about pH 6.7 almost doubled the amount of nitrogen mineralization. The nitrate results were similar to those of Page-Dumroese *et al*. (2007) who reported that nitrate release was highest at pH values greater than 5.0 and decreased as pH decreased indicating that nitrification is inhibited at lower pH.

Table 8 Time required for maximum ammonium and nitrate (NH_4^+-N and NO_3^--N) release at different treatment by ten soil series of Thailand and Lao PDR.

Soils series	Maximum NH_4^+-N release						Maximum NO_3^--N release					
	Air-dried		Field capacity		Heated to 40 °C		Air-dried		Field capacity		Heated to 40 °C	
	mg/kg	Ds#	mg/kg	Ds	mg/kg	Ds	mg/kg	Ds	mg/kg	Ds	mg/kg	Ds
Cd	2.9	70	3.8	70	2.7	70	24.9	28	21.6	28	28.1	42
Lb	3.8	3	4.0	3	4.8	4	18.7	70	16.9	70	18.9	70
Ln	2.9	0	2.9	35	3.6	0	27.1	0	20.8	0	27.4	0
Tk	2.9	70	2.7	70	2.8	70	23.6	42	21.7	42	24.7	42
Pc	14.9	0	4.0	3	12.8	0	14.7	70	13.8	70	14.2	70
Wn	25.6	0	17.8	0	23.8	0	6.4	56	5.4	56	8.6	42
Bc	30.7	0	5.3	70	28.1	0	27.0	21	17.5	56	28.0	21
Km	30.6	0	5.1	7	33.9	0	8.9	56	5.0	56	9.7	56
Sd	29.1	0	6.6	70	33.5	0	25.3	56	19.9	56	29.7	42
St	24.0	0	5.9	7	29.8	0	16.8	56	11.3	56	16.9	56

Note # Days of incubation

The statistical analysis of the ten incubated soils indicated a significantly different amount of N was mineralized (ammonium + nitrate) among treatments and over time. The release of NH_4^+-N and NO_3^--N was not significantly affected by the interaction between soil series and different treatments except the duration of incubation. Stepwise multiple regression analyses of the mineralizable nitrogen with the various combinations of soil properties (clay, OM, total N, OC, pH, AM-N, AS-N and AA-N) indicated that soil pH was the main factor affecting maximum NH_4^+-N release with the adjusted R^2 = 0.82, 0.34 and 0.62 for air-dried soil, soil maintained at field capacity and soil heated to 40 °C, respectively. This result was similar to that of Persson *et al*. (1989) who found that nitrogen mineralization seemed to increase when acidity was reduced and liming increased the availability of C and N to the microorganisms. However, the NO_3^--N release was related to soil OC as indicated by the adjusted R^2 = 0.85, 0.60 and 0.78, respectively (Table 9). There was a highly significant correlation of soil pH and organic carbon with ammonium-N and nitrate-N release, respectively. Regarding the cumulative N release (NO_3^--N + NH_4^+-N) during the incubation period (0-70 days), it was found that total N was the main factor that affected N release for air-dried and heated to 40 ^oC soils while soil organic carbon affected N release from field capacity soil as indicated by an adjusted R^2 = 0.73, 0.45, and 0.57 (Table 10). There were highly significant correlations of N released from air-dried and heated to 40 ^oC soils with the total N and clay content. Nitrate release occurs through the activity of heterotrophic microorganisms that require organic C for energy (Havlin *et al*., 2005).

Table 9 The effects of soil pH and OC content on maximum NH_4^+-N and NO_3^--N release of different treatments resulting from stepwise multiple regression.

Maximum N release	Treatment	Equation	Adj R^2
NH_4^+-N	AD[£]	Y = 71.916-9.385 pH	0.82***
	FC[¥]	Y = 19.614-2.333 pH	0.34[ns]
	H40[€]	Y = 76.758-9.877 pH	0.62**
NO_3^--N	AD[£]	Y = 2.247+1.098 organic C	0.85***
	FC[¥]	Y = 2.963+0.799 organic C	0.60**
	H40[€]	Y = 3.076+1.127 organic C	0.78***

Note [£] Air-dried soil

[¥] Soil moisture content at field capacity

[€] Heated to 40 ^oC soil

** Significant at the 0.01 probability level

*** Significant at the 0.001 probability level

ns =Not significant

Table 10 The effect of total N and OC on cumulative N release (NH_4^+-N + NO_3^--N) after 70 days of incubation under different treatments using stepwise multiple regression.

Cumulative N	Treatment	Equation	Adj R^2
NH_4^+-N + NO_3^--N	AD£	Y = 1.035+118.537 total N	0.73**
	FC¥	Y = 41.982+6.329 organic C	0.45*
	H40€	Y = 15.317+122.242 total N	0.57**

Note £ Air-dried soil

¥ Soil moisture content at field capacity.

€ Heated to 40 °C soil

*Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

1.3 Organic nitrogen fractions in soil hydrolyzates.

Hydrolyzable ammonium-N.

The analyses of organic N fractions were conducted to investigate the distribution of hydrolysable N fractions in the ten selected soils and their relationship with nitrogen mineralization potential. The total hydrolyzable ammonium-N (HA-N) of all soils ranged from 39-186 mg kg^{-1}soil (Figure 15). The data indicate that the highest total hydrolyzable NH_4^+-N was found in Lb, Tk, Pc, Sd and St soils (177, 150, 177, 186 and 168 mg kg^{-1} soil, respectively). In contrast, there was a very small amount of HA-N found in the Wn soil (sandy soil).

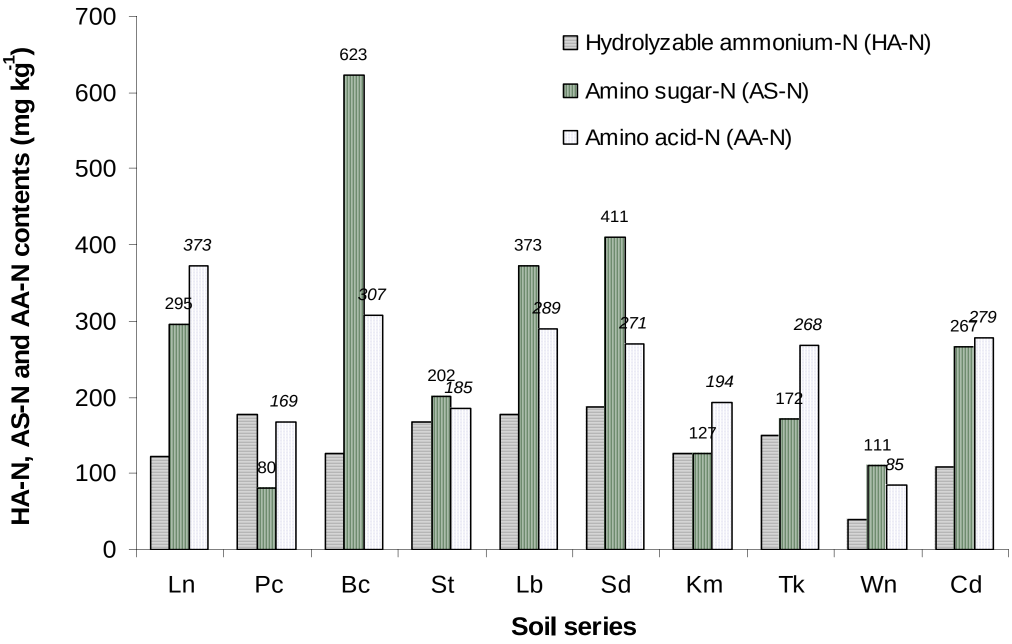

Figure 15 Organic nitrogen fraction analysis in the ten selected soils.

Amino sugar-N.

The amount of amino sugar-N (AS-N) of the ten soils ranged from 80-623 mg kg^{-1}soil. AS-N was high in Bc, Sd, Lb, Ln and Cd soils, respectively (Figure 15). In the same case AS-N content of Bc, Sd and Lb soil was higher than the HA-N and AA-N.. The greater content of AS-N in these soils (Bc, Sd, Lb, Ln and Cd) may have been the source of nitrogen mineralization. Stevenson (1982b) reported that amino sugars play the dual roles in soils by serving as a source of N for plant growth and promoting good soil structure. According to the stepwise regression analysis the high content of AS-N was significantly related to high nitrogen mineralization during the initial stage of the incubation from soils that were air-dried and heated to 40 ^{o}C. A relationship between amino sugar-N and nitrogen release was found with adjusted R^2 = 0.36* and 0.41* for the air-dried and heated to 40 ^{o}C soils, respectively (Table 11). Amino sugar-N analysis may be useful to estimate nitrogen mineralization. The maximum AS-N content was 623 and 411 mg kg^{-1} for Bc and Sd soils, respectively, these soils also had the high nitrogen mineralization (NO_3^--N and NH_4^+-N).

Table 11 The effect of amino sugar-N on N mineralization (NH_4^+-N+NO_3^--N) in the initial period of incubation under different treatments using stepwise multiple regression.

Initial N release	Treatment	Equation	Adj R^2
NH_4^+-N+NO_3^--N	AD[£]	Y = 18.268 + 0.032 AS-N^	0.36*
	FC[¥]	no significant relationship	-
	H40[€]	Y = 19.128 + 0.033 AS-N^	0.41*

Note [£] Air-dried soil

[¥] Soil moisture content at field capacity

[€] Heated to 40 °C

^ Amino sugar-N

*Significant at the 0.05 probability level

Amino acid-N.

Total amino acid-N (AA-N) in the soils varied from 85-373 mg kg^{-1}soil. The data indicated that there were very small amounts of AA-N content in the Pc, Wn and Km soils (Figure 15). The highest amount of amino acid-N was found in the Ln soil series (373 mg kg^{-1}), followed by Bc, Tk, Lb, Cd, and Sd soils (307, 269, 289, 279, and 271 mg kg^{-1} soil), respectively. Greater amounts of total amino acids were found in the soils with high in clay and OC contents, which was similar to the results of Senwo and Tabatabai's (1998) who found that the highest concentration of amino acids was found in the soils which contained highest amounts of organic matter and clay. Incubation experiments indicate that the turnover of amino acids is rapid, which suggests high rates of gross nitrogen mineralization in arctic tundra soils (Kielland, 1995).

2. Experiment 2: The distribution of nitrate in Lop Buri (Lb) and Pak Chong (Pc) soil series before and after maize planting.

During the experimental period, soil bulk density, total porosity and moisture content of the soils were measured at the soil depths of 10, 30, 50, 70 and 90 cm (Table 12). The data illustrated that the bulk density of two soils was different. The surface of the Pc soil (0 to 20 cm) was more dense than the Lb soil. In this case higher density may have been in the Pc soil because farmers used large tractors to prepare the land for a long time. In contrast, the deeper layers of the Lb soil (70 and 90 cm) were more dense than similar layers of the Pc soil. The high soil bulk density of Lb soil at the deeper depth may be that the soil at that depth contained many rock fragments. The soils also differed in the moisture content (Table 12).

Table 12 Soil bulk density, porosity and moisture content at field capacity of Lb and Pc soil series in the wet season 2005.

Soil depth (cm)	Soil D_b (g cm^{-3})		Total soil porosity (%)		Soil W_O (%)	
Soil series	Lb	Pc	Lb	Pc	Lb	Pc
10	1.38	1.52	47.82	42.61	22.16	18.52
30	1.36	1.37	48.58	48.22	24.08	22.42
50	1.47	1.41	44.47	46.71	22.09	23.42
70	1.68	1.39	36.45	47.51	20.77	25.57
90	1.59	1.40	40.06	46.99	21.51	26.49

Note D_b = Soil bulk density

W_O = Moisture content at field capacity

2.1 Nitrate pre-season distribution and maize root development

Lop Buri soil series

Pre-season nitrate content and distribution:

Subsoil NO_3^--N was measured three times before maize planting. The distribution of subsoil nitrate at the 0 to 20 cm depth varied from 36.4 to 80.3 kg ha^{-1} (Figure 16). At four, two weeks and one day before maize was planted, the NO_3^--N distribution ranged from 23 to 80 kg ha^{-1} at the 20 to 40 cm depths, respectively. Total amounts of nitrate in the 0 to 100 cm depths were 101.9; 119.4, and 163.3 kg ha^{-1} at four weeks, two weeks, and one day before planting, respectively. The high nitrate concentration in the subsoil was probably due to the mineralization of soil organic matter and perhaps the previous soybean crop. The farmers also reportedly applied 2000 kg ha^{-1} poultry manure in the previous wet and dry seasons. We expect that this amount of manure might provide as much as 20 kg N ha^{-1}, which would be a relatively minor portion of the overall crop requirements. The preseason nitrate distribution at the 40 to 60 cm depths of different periods varied from 8.2 to 21.6 kg ha^{-1}. The amount of nitrate at the 0 to 20 cm depths two weeks before maize planting was markedly higher (80 kg NO_3^--N ha^{-1}) than the other period (Figure 16). This might be the result of soil moisture remaining steady at about 30 % at the 0 to 20 cm depth, whereas at the other period the soil moisture content was less than 30 %. One day before maize planting (5 June) the amount of 52.1, 70.4 and 21.6 kg of NO_3^--N ha^{-1} was measured at the 0 to 20, 20 to 40 and 40 to 60 cm depths, respectively. This indicated that in the early season nitrate begun to move into deeper layers, probably because soil moisture increased as the rain began. However, a large amount of nitrate remained in the 20 to 40 cm layers.

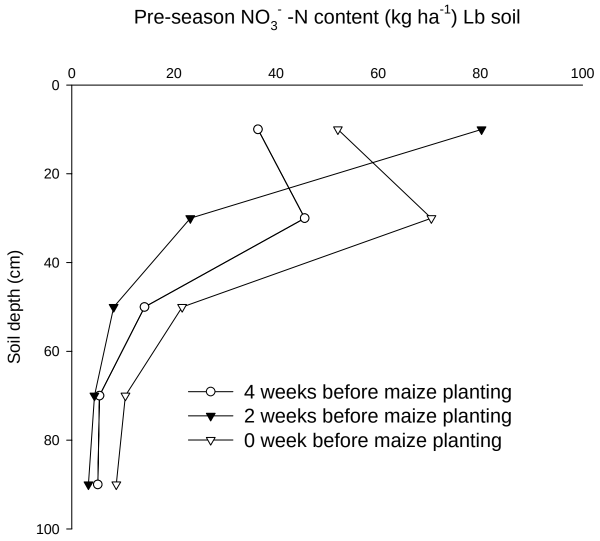

Figure 16 NO_3^--N distribution in the bare field of Lb soil series, preplant sampling

Nitrate distribution and maize root development.

Nitrate-N distribution in the Lb soil during the two to eight weeks period after maize planting, but without N fertilizer application is given in Figure 17. At two weeks, the amount of nitrate was 38 and 58 kg ha^{-1} at the 0 to 20 and 20 to 40 cm depths, respectively. These data indicated a lower amount of nitrate was retained at these depths compared with 1 day before maize was planted. At four, six, and eight weeks after planting, the amount of nitrate was usually reduced in the 0 to 20 and 20 to 40 cm depths. However, nitrate greatly increased in concentration at the 40 to 60 cm depth (18-20 kg NO_3^--N ha^{-1}), probably because of the heavy rain (128 mm day^{-1}) when the maize was 31 days old. The nitrate concentration was 16 kg ha^{-1} at the 60 to 80 cm depth at 8 weeks after maize planting. It was noted that the nitrate concentration at 8 weeks after maize planting was sharply reduced from 38 to 5 and from 58 to 3 kg ha^{-1} at the 0 to 20 and 20 to 40 cm depths (Figure 17). Statistical analysis indicated a significant reduction in profile nitrate with time (P = 0.04). Plants apparently absorbed more nitrate during this period, and some nitrate moved through the soil and concentrated at the 40 to 60 cm depth.

With the 188 kg N ha^{-1} treatment, nitrate was concentrated in the topsoil (0 to 20 cm) at two weeks after planting, and reached a maximum of 99.6 kg ha^{-1}.

SAS analysis indicated, as expected, a significant increase in nitrate where N fertilizer had been applied. There were 69 and 32 kg of NO_3^--N ha^{-1} in the 20 to 40 and 40 to 60 cm layers (Figure 18). We observed that at 4 weeks, the amount of nitrate in the 0- to 20 and 20 to 40 cm depths was reduced to 32 and 59 kg ha^{-1}. The amount of nitrate was close to previous levels (before maize was planted). This suggests a reduction of nitrate in two top layers because of maize uptake. At 6 weeks' sampling, which was 10 days after topdressing, there was not much difference in the amount of nitrate-N among depths of 0 to 20, 20 to 40 and 40 to 60 cm (34, 37, and 42 kg NO_3^--N ha^{-1}, respectively), but the amount was markedly lower at the deeper layers. However, at 8 weeks' sampling, the nitrate that accumulated was 44 and 32 kg ha^{-1} at the 40 to 60 and 60 to 80 cm depths, respectively. These results showed that NO_3^--N ha^{-1} observed at the 0 to 20, 20 to 40 cm depths of Lb soil series was less after 8 weeks. More nitrate accumulated in the root zone (40 to 60 cm depths) of the treatments with and without fertilizer N, suggesting that either downward movement or mineralization occurred.

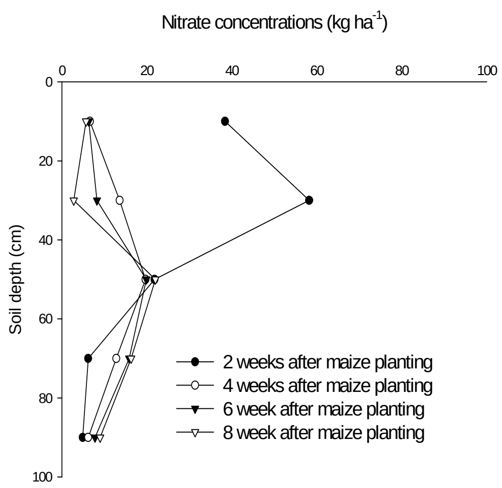

Figure 17 NO_3^--N distribution in the control treatment of Lb soil series postplant sampling.

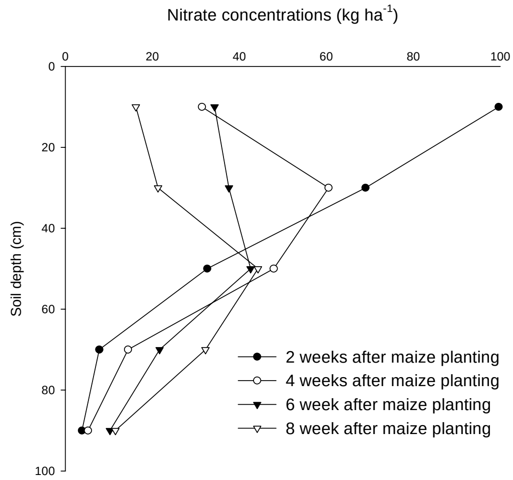

Figure 18 NO_3^--N distribution in the 188 kg N ha^{-1} treatment of Lb soil series postplant sampling.

The high amount of nitrate that accumulated in the root zone (20-43 kg NO_3^--N ha^{-1}) might be the cause of no N response of maize in previous studies. Profile nitrate-N, averaged over time was 120 kg ha^{-1} which was significantly higher for the Lb soil than that of the Pc soil.

Pak Chong soil series

Pre-season nitrate content and distribution:

The investigation of subsoil nitrate distribution began in the Pc soil series before maize planting (May to June). The sampling indicated that at the 0 to 100 cm depth nitrate did not differ at 4 and 2 weeks before maize planting (30.5 and 33.5 kg NO_3^--N ha^{-1}), respectively. At 1 day before maize was planted, however, the maximum concentration of NO_3^--N was 57.9 kg ha^{-1} at 0 to 100 cm depth (Figure 19). There were no differences in the amount of nitrate at the depths of 20 to 40, 40 to 60, 60 to 80 and 80 to 100 cm. In this case, it might be because of insufficient moisture during the period (during the end of May to June) which limited the decomposition of organic matter and nitrate release in the soil.

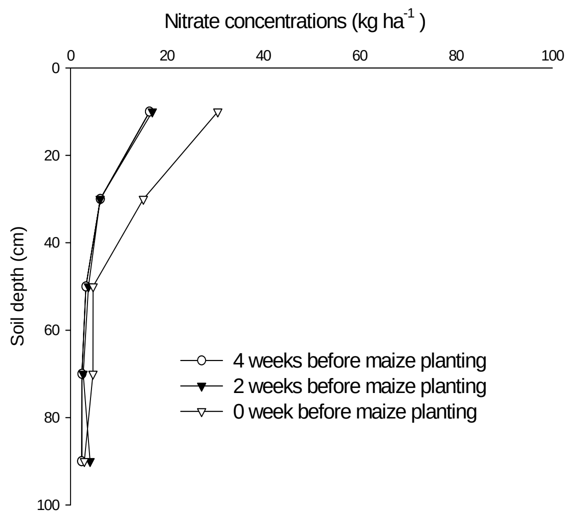

Figure 19 NO_3^--N distribution in the bare field of Pc soil series preplant sampling

Nitrate distribution and maize root development.

At 2 weeks after maize planting (15 July), the soil nitrate level of control treatment of Pc soil was 26.2 and 17.8 kg ha^{-1} at the depth of 0 to 20 and 20 to 40 cm, respectively (Figure 20). At eight weeks after maize planting nitrate concentration was reduced to 13.7 and 11.7 kg ha^{-1} at the 0 to 20, 20 to 40 cm depths, respectively. The reduction in nitrate was probably because of plant absorption. Statistical analysis indicated a significant difference between the Lb and Pc soils, and between the 0 and 188 kg N ha^{-1} rates at the depth of 0 to 100 cm.

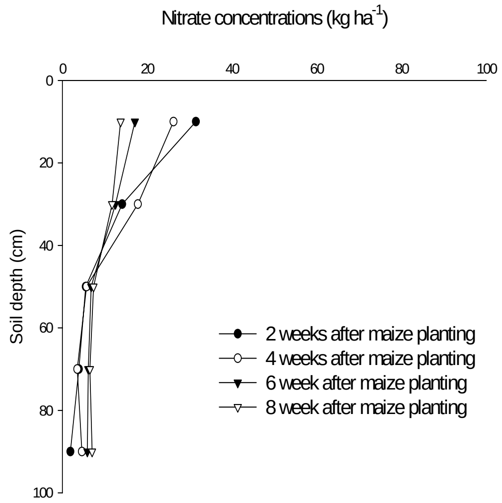

Figure 20 NO_3^--N distribution in the control treatment of Pc soil series postplant sampling.

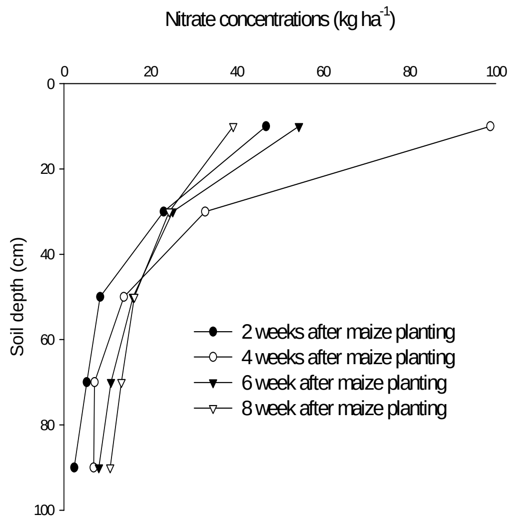

Figure 21 NO_3^--N distribution in the 188- kg N ha^{-1} treatment of Pc soil series postplant sampling.

For the 188 kg N ha^{-1} applied treatment at 2, 4, 6 and 8 weeks after maize emergence, most of nitrate was located in the 0 to 20 and 20 to 40 cm depths (Figure 21). However, there was an increase in nitrate concentration in each soil layer when compared to the fertilizer treatment without N. The unusually high concentrations of nitrate at four weeks after maize planting (98 kg NO_3^--N ha^{-1}) might be because the nitrate measurement took place only three days after top dress N fertilizer was applied. Nitrate concentration declined by six and eight weeks (40-56 days) after emergence. A small amount of nitrate may have moved downward and increased nitrate concentrations with increasing depth. The subsoil nitrate (0 to 60 cm) of the treatment without N remained very low compared to the N fertilizer treatment, and there was difference in nitrate concentration between the two treatments.

3. Experiment 3: Measuring the amount of nitrate in the Lop Buri (Lb) and Pak Chong (Pc) soil series in maize fields after heavy rain.

Nitrate status in relation to a rainfall event

Lop Buri soil series (Lb)

Subsoil nitrate status of Lb soil series was observed after a heavy rain occurred, in the amount of 128 mm day^{-1} (Figure 2), when maize was 31 days old. The nitrate concentration at different soil depths of the without N treatment was not different at 0, 3, 5 and 7 days after rain. The amount of nitrate in most soil layers had not changed (Figure 22). Nitrate concentrations were 5.3, 7.2, 45.1, 31.6 and 12 kg ha^{-1} at 0 to 20, 20 to 40, 40 to 60, 60 to 80 and 80 to 100 cm depths for day zero, respectively, and totaled 101 kg N ha^{-1}. However, after 7 days of rain 12.6, 17.9, 53.9, 30.9 and 11 kg NO_3^--N ha^{-1} were found at the specified depths for a total of 126 kg ha^{-1}in the whole profile. Nitrate amounts at 0 to 20 and 20 to 40 cm depths appeared to increase by day 3, 5, and 7, probably because of mineralization related to the rainfall. SAS analysis, however, indicated no significant increase. We observed that during 0 to 7 days, nitrate levels were greater at 40 to 60 cm, where the nitrate levels were about 53.9 and 30.9 kg ha^{-1}. Nitrate levels at the 60 to 80 and 80 to 100 cm depths did not increase, probably because there was not enough rainfall to leach the nitrate downward to that depth. Nitrate status at the 20 and 40 cm depths of days 3, 5 and 7 increased to about 16, 14.8 and 17.9 kg ha^{-1}, respectively, compared with day zero (7.2 kg NO_3^--N ha^{-1}) after rain. During the short duration (7 days) the nitrate level in the 40 to 60 and 60 to 80 cm layers measured slightly higher (53.9 and 30.9 kg NO_3^--N ha^{-1}), possibly because of water movement to deeper layers due to rain. However, at this tasselling stage maize also absorbed more nutrients for growth. Although plants might have absorbed large amounts of nutrient at this stage, the concentration of nitrate remained high in the 40 to 60 cm depths. The high nitrate accumulation in subsoil might be because of high organic matter and total N contents in the soil (Table 6). Mentle *et al.* (2002) found that chicken manure application to maize field increased soil organic matter content and had a positive, long term effect. Results from nitrogen mineralization studies in the laboratory of the Lb surface soil indicated that high levels of nitrate were continuously released from 0 to 70 days.

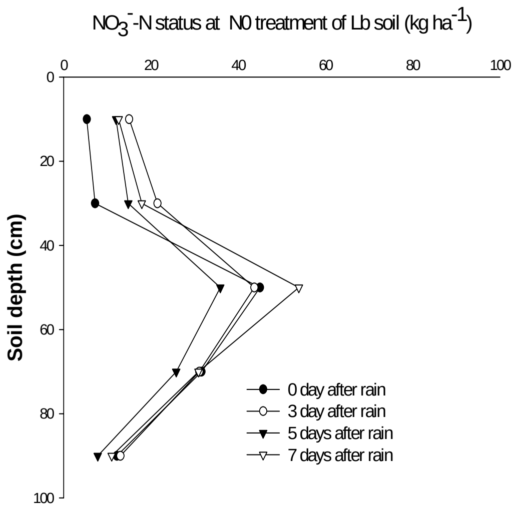

Figure 22 NO_3^--N status in the control treatment of Lb soil series postplant sampling.

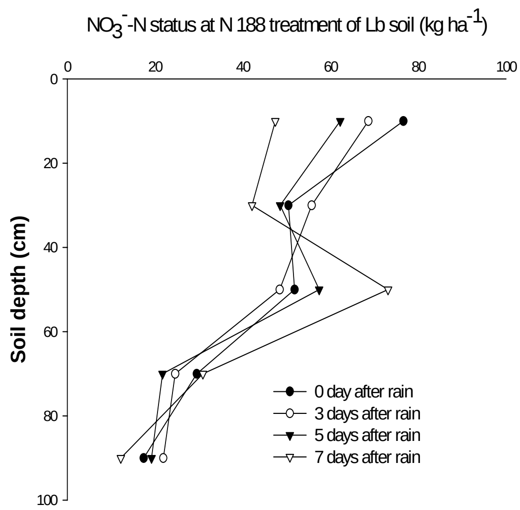

Figure 23 NO_3^--N status in the 188 kg N ha^{-1} treatment of Lb soil series postplant sampling.

For the high-N fertilizer treatment (188 kg N ha^{-1}) at 0, 3, and 5 days after rain, the nitrate concentrations of Lb soil were 76.6, 68.6, and 62.2 kg ha^{-1}, respectively, at the 0 to 20 cm depth (Figure 23). These high levels were probably because the soil samples were collected only 3 days after fertilizer topdressing. Statistical analysis indicated a significantly higher amount of profile nitrate where 188 kg N ha^{-1} had been applied. However, the amount of nitrate at the depth of 0 to 20 cm was reduced at days 5 and 7 after rain and with a high concentration at the 40 to 60 cm depth at 7 days (73 kg NO_3^--N ha^{-1}). This result was similar to that of Lehmann *et al.* (2004), who found that large amounts of percolating N from applied N rapidly moved to a depth between 30 and 80 cm. In the Lb soil, nitrate did not appear to move to depths greater than 80 cm, possibly because low total porosity of the deeper layers. The second reason is that the soil had more clay at depths of 40 to 60 and 60 to 80 cm and, consequently, a higher water holding capacity.

Pak Chong soil series (Pc)

The status of nitrate was measured in the Pc soil after a rainfall event of 65 mm day^{-1} when the maize was 48 days old. Statistical analysis indicated significantly less N in the Pc soil after the rainfall event than in the Lb soil. The results, however, indicated not much difference in the amount of nitrate at 0, 3, 5, and 7 days at each soil depth for the without N fertilizer treatment. From 0 to 7 days after rain, the concentration of nitrate was no more than 8 kg ha^{-1} at each depth (Figure 24). This indicated that the Pc soil contained very little nitrate unless fertilized.

With the high N fertilizer treatment, 63.3 kg of NO_3^--N ha^{-1} was concentrated in the surface soil (0 to 20 cm) (Figure 25). However, from 0 to 7 days after rain, nitrate concentrations ranged from 41.8 to 63.3 kg ha^{-1} and from 27.4 to 53.2 kg ha^{-1} at the 0 to 20 and 20 to 40 cm depths, respectively. These results also were similar with those of Iqbal (2005), who found that nitrate accumulation in a clay loam soil (44% clay content) was highest in the 30 cm layer. In the top layers, nitrate was slightly reduced and concentrated at depths of 40 to 60 cm. However, at 7 days after rain, soil nitrate was more concentrated (53.7, 27.4, and 16.8 kg NO_3^--N ha^{-1}) at the shallow rather than deeper layers (0 to 20, 20 to 40, and 40 to 60 cm) (Figure 25). At this site, a heavy rainfall of 65 mm day^{-1} might not be sufficient water to bring reaching NO_3^--N the deep layers of the soil. The second possible limiting factor was soil compaction, which was relatively high (bulk density = 1.52 g cm^{-3}), and low soil porosity (42%) at 0 to 20 cm compared with Lb soil with bulk density of 1.38 g cm^3 and 47.8 % of soil porosity (Table 12). The compaction might be because of the use of heavy machinery and can also result from the tillage at the same depth for many, many years. Jabro *et al*. (2006) reported that 80% of soil compaction from wheel traffic occurred on the first pass especially when the soil was wet.

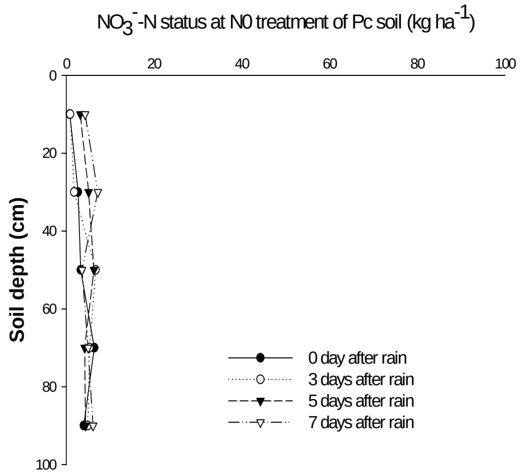

Figure 24 NO_3^--N status in the control treatment of Pc soil series postplant sampling.

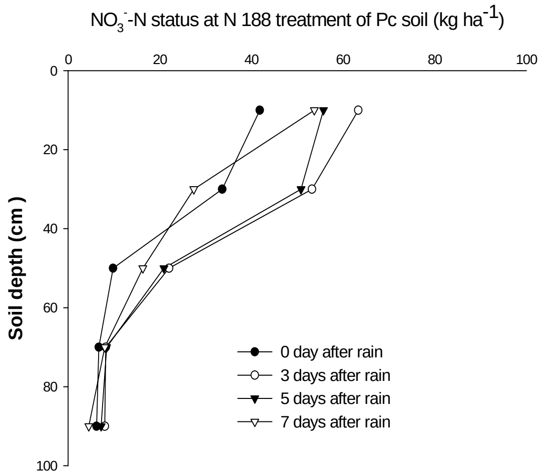

Figure 25 NO_3^--N status in the 188 kg N ha^{-1} treatment of Pc soil series postplant sampling.

4. Experiment 4: Maize root depth at different stages of maize growth in the Lop Buri (Lb) and Pak Chong (Pc) soil series.

As indicated earlier, maize rooting was measured at the same time as nitrate status, four times during the first 8 weeks of crop growth. With the use of a square monolith pin board method, we assessed root depth and root length in field conditions (Figure 26). The extensive penetration of roots is clearly seen in Figure 27. The root distribution in Lb soil at different soil depths showed that by the second stage of maize growth (40 days after planting) roots were concentrated at the depth of 49cm (Figure 28). Crops with a deep root system, such as maize, can efficiently absorb nitrogen accumulated in the subsoil (Saito, 1991). The distributions of root length and root depth were different in the two soils, most roots increased at 40 days after planting. At the age of 60 days there was the maximum of root hairs and maximum root depth was at 62 cm. This result was similar to that of Fort (1962), who found that maize attained the maximum height with the full development of the tassel (at 67 days). Profuse branching of brace roots was observed at this stage and root growth below 30 cm occurred.

The characteristics of roots at different depths of Pc soil and different stages of maize growth are shown in Figure 29. The rooting depth at 40 and 60 days was not much different; roots penetrated to the depth of 43 and 50 cm on both dates. The farmer had been using a large tractor for land preparation; consequently there was a possibility of increased bulk density and reduced porosity resulting from soil compaction. Opera-Nadi and Lal (1987) reported that the use of heavy machinery resulted in an increase in soil bulk density and a decrease in macro porosity and permeability. Topsoil bulk density was a limiting factor for shoot and root growth according to one report (Chassot and Richner, 2002). We observed that the maximum distribution of roots at 40 days of Lb and Pc soils was correlated with the maximum nitrate concentration accumulated at the same depth.

Figure 26 Square monoliths preparation for root examination before removal from soil profile.

Figure 27 Maize root position after taken while maize was 40 days old.

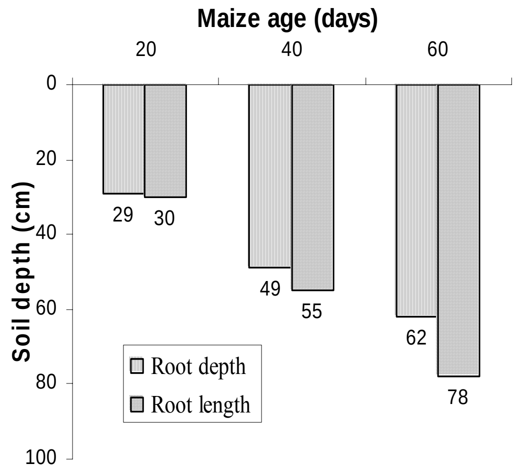

Figure 28 Maize roots distributions at different growing stage in Lb soil series.

Figure 29 Maize root distributions at different growing stages in Pc soil series.

Maize grain yield

The grain yields of maize from the experiment on both the Lop Buri and Pak Chong soils were generally good (Table 13). The yields and N removal by maize from the two sites was very similar. In Lb soil series, the grain yield of 188 kg N ha^{-1} treatment was actually lower (5,491 kg ha^{-1}) than the control treatment (6,868 kg ha^{-1}). In this particular case, the farmer rotated the soybean (with the fresh pod yield of 7.8 t

ha^{-1}) with maize. The residues of soybean and maize together with poultry manure were incorporated in the last wet and dry seasons, which may have resulted in more subsoil nitrate concentration. This result is similar to those reported by Lory *et al*. (1995) who found that cereal crops and non-legume plants, as expected, required less N when grown after legumes. In the case of the Pc soil series, the grain yield was slightly increased (22%) with N fertilizer compared to the control treatment (5,185 kg ha^{-1}). In 2004, at the Pc site, farmers rotated mung bean (*Vigna radiata* L.) for seed with maize (with the grain yield of 935 kg ha^{-1}). The residues were also incorporated in the last wet and dry season. The maximum grain yield of the two soils was lower than the predicted yield by DSSAT. There was no significant difference in grain yield between N fertilizer and control treatments.

Soil, plant and grain analysis after maize harvest

The soil's available nitrogen, total nitrogen uptake in grain and stover after maize harvest is presented in Table 13. The results indicated that available N was high, both with and without N fertilizer in Lb and Pc soils. The soybean residue and chicken manure that was incorporated into the Lb and Pc soils during the previous season probably contributed to high available N. The high available nitrogen of Lb and Pc soils is consistent with the lack of response of maize on the N fertilizer treatment. The N uptake of grain in N0 and 188 kg N was extremely high, which varied from 81.1 to 98.2 and 62.7 to 88.6 kg N ha^{-1}, for Lb and Pc soils, respectively. The N uptake of stover yield showed a similar pattern to grain yield. High N uptake was observed in all treatments of Lb soil. There was no significant difference in N uptake of the two soils due to different N fertilizer application (Table 13).

Table 13 Grain yield of maize, total N uptake by stover and grain and available N on Lb and Pc soil series of N0 and 188 kg N ha^{-1} treatments.

Treatment	Maize grain yield		Stover	Grain	Stover	Grain	Available N	
	- - (kg ha^{-1}) - -		- - Total N uptake (kg N ha^{-1}) - -				- - (kg ha^{-1}) - -	
Soil series	Lb	Pc	Lb	Lb	Pc	Pc	Lb	Pc
Control	6,868 a[1/]	5,185 a	45.1 a	98.2 a	32.4 b	62.7 b	78.1 a	95.2 a
188 kg N	5,491 a	6,328 a	53.6 a	81.1 a	42.9 a	88.6 a	85.8 a	110.7a

Note [1/] In a column, means followed by a common letter are not significantly different at 5% by Duncan's Multiple Range Test ($p \leq 0.05$).

Suggestions for improving the decision-aids

Based on these observations and results from previous studies (Nitrate distribution and maize root development, nitrate status in relation to a rainfall event), it seems clear that the amount of subsoil nitrate needs to be included in the decision-aids for adequate prediction of maize N requirements. The DSSAT-N model already includes options to record and consider subsoil nitrate, however in simplifying the model for use in a decision-aid environment this data requirement was removed. It appears that considering of subsoil nitrate needs to be re-entered for the DSSAT-derived decision-aids.

Previous research in the drier portions of the maize belt (usually ustic soil moisture regimes) indicates the importance of including assessments of subsoil nitrate (Ferguson *et al*., 2002). Subsoil nitrate seems to be important in other soils, especially in the ustic soil moisture regime, and also in the tropics (Grove *et al*., 1980; Lehman *et al*., 2004).

5. Experiment 5: Determining the N status of maize leaf using leaf color chart.

According to the hypothesis of this study, the leaf color chart was hypothesized to be a possible new approach for predicting crop nitrogen requirements. The previous researchers and farmers have successfully used the leaf color chart (LCC) tool in paddy rice. Alam *et al*. (2005) found that use of the LCC for N management increased average grain yield by 0.1 to 0.7 mg ha^{-1} or 107 to 750 kg ha^{-1} across villages and seasons. The leaf color chart developed by IRRI for efficient N management in rice has been suggested to be suitable for maize (Witt *et al*., 2007). Studies were carried out to measure maize critical color grades and critical values during maize growing stages of two soils (Lb and Pc soils series). The leaf color measurement was done during 21 to 65 days after maize was emerged. Leaf measurement and observation from young maize through tasseling stage (21 to 65 day after maize emerging) revealed no appearance of nitrogen deficiency symptoms in either Lb or Pc soil series. Most of leaf color level was higher than the proposed critical value which was 3.5 units and increased slightly over time (Figures 30, 31, 32 and 33). Maize leaf color became darker and more green with age indicating sufficiency by the LCC, even in plants that was deficient in N according to the foliar N content and on treatments that received suboptimal amounts of fertilizer N. Witt *et al*. (2007) reported that maize leaf color dark green with LCC was higher than 4.5.

The leaf color level of maize in Lb soil from the beginning to tasseling stage (21-60 days) ranged from 3.5 to 4.7 and 3.7 to 5.0 unit for without and with N fertilizer treatment and 26 kg N ha^{-1} (Figures 30 and 31), while Pc soil was ranged from 3.5 to 4.0 and 3.5 to 4.2 unit for the without N fertilizer and with 42 kg N $ha^{-1}$of applied fertilizer, respectively, (Figures 32 and 33). The leaf color level was always higher than the critical level (>3.5) and symptoms of N deficiency did not appear on the maize grown on either soil. This might be due to sufficient soil nitrogen content for maize uptake. During 21 to 60 days, the N status of maize leaf did not vary much between the control and the applied N fertilizer treatments. However, high total N content in maize leaf of Lb soil was found when maize was 30 to 45 days after emergence (0.72 to 0.61 % and 0.75 to 0.60 % for control and N treated (26 kg N ha^{-1}), respectively, while in Pc soil, it was 0.64 to 0.60 and 0.65 to 0.65 to 0.60 % of N for control and N fertilizer treatments (41 kg N ha^{-1}) at the same age. The high N content in leaf was probably due to high levels of nitrate that accumulated in subsoil, which lead to high N uptake by maize. The high degree of mineralization of soil N may have resulted from the adequate to high levels of moisture during this period. Total N content in the maize leaf gradually declined after maize was 30 days old. The leaf color did not change with the decline of N status in maize leaf during vegetative stage as can be seen because of no N deficiency symptoms. In contrast, maize leaf color level gradually increased for both the control and with N fertilizer treatments of the Lb and Pc soils.

Soil nitrate analysis indicated that the concentration of nitrate was not significantly different between without N and with N fertilizer treatments of both soils. We observed that during 21 to 30 days after planting more nitrate concentrated in the depth of 20 to 40 cm and 40 to 60 cm for Lb soil, and at the depth of 0 to 40 cm for Pc soil (Figures 34, 35, 36 and 37). The constant release of nitrate in the subsoil may have led to N sufficiency for maize uptake.

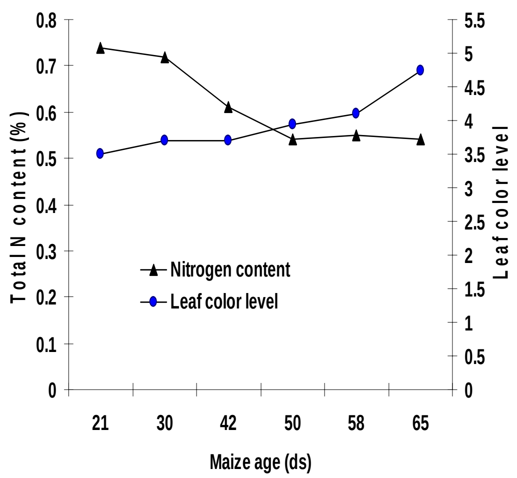

Figure 30 Total N content and corresponding LCC reading of maize in the N0 of Lb soil.

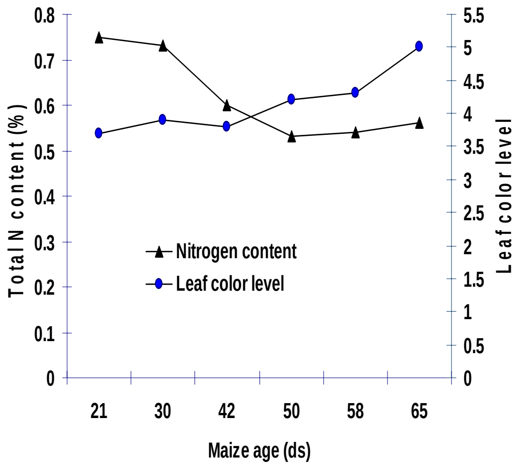

Figure 31 Total N content and corresponding LCC reading of maize in the 26 kg N $ha^{-1}$of Lb soil.

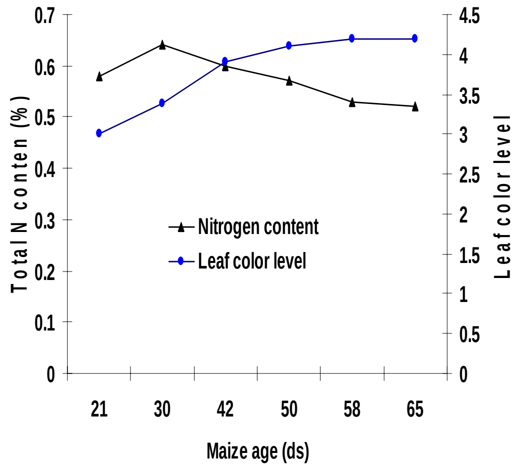

Figure 32 Total N content and corresponding LCC reading of maize in the N0 of Pc soil.

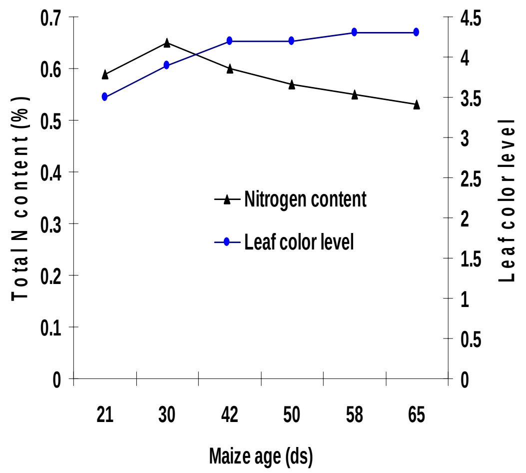

Figure 33 Total N content and corresponding LCC reading of maize in the 41 kg N ha^{-1} Pc soil.

The relationship of total N in the leaf and the amount of soil nitrate in the depth of 0 to 60 cm was observed (Figures 34, 35, 36 and 37). In Lb soil total N in leaf of without N and with N fertilizer treatments was high during 21 to 30 days postplant sampling while nitrate content in soil was 16.6 and 20.1 mg NO_3^--N kg^{-1} for the control treatment (Figure 34) and 17.1 and 23.6mg NO_3^--N kg^{-1} for the 26 kg N ha^{-1} treatment (Figure 35). Thereafter, total nitrogen content in leaf of without and with n fertilizer treatments slightly declined as well as the amount of nitrate in the soil.

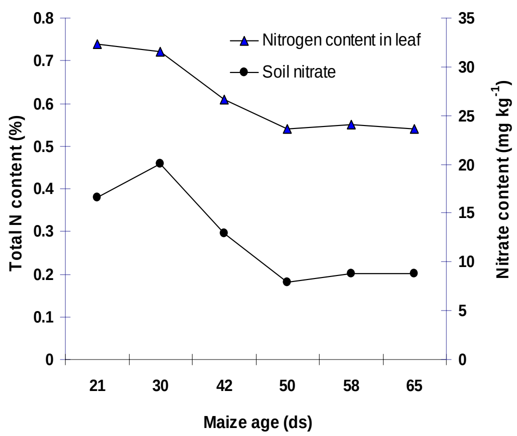

Figure 34 Total N content in the leaf and soil nitrate content in the depth of 0-to 60 cm in the N0 of Lb soil.

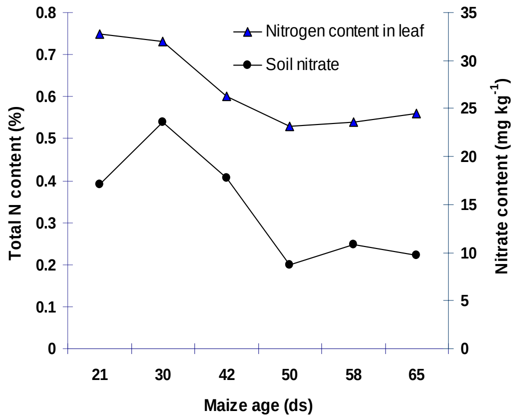

Figure 35 Total N content in the leaf and soil nitrate content in the depth of 0-to 60 cm in the 26 kg N $ha^{-1}$of Lb soil.

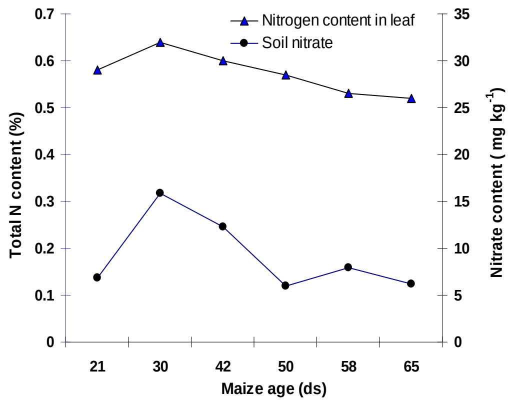

Figure 36 Total N content in the leaf and soil nitrate content in the depth of 0-to 60 cm in the N0 of Pc soil.

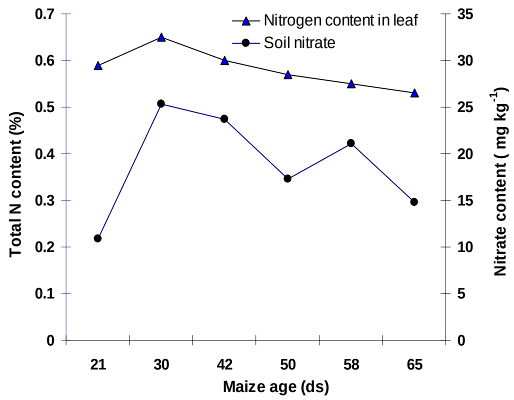

Figure 37 Total N content in the leaf and soil nitrate content in the depth of 0-to 60 cm in the 41 kg N $ha^{-1}$of Pc soil.

Data indicated that soil nitrate in the control and with N fertilizer treatments of Pc soil was higher at 30 days after maize planting (15.9 and 25.8 mg N kg^{-1}, respectively). The amount of nitrate of N fertilizer treatment was doubly increased compare to control treatment. Nitrate content of both treatments was declined at 30 days after maize planting, and the declination of soil nitrate was parallel with total N in leaf (Figures 36 and 37). The concentration of nitrate in the control and N fertilizer treatments of both soils was different in amount but N was sufficient for maize growth. This study revealed the relationship of total N in the leaf and soil nitrate at particular soil depth but LCC could not detect the variation of soil nitrate nor total N in the maize leaves.

6. Experiment 6: Study on the nitrogen fertilizer response simulated from (DSSAT) software on some important maize soils in Thailand and in the Lao PDR.

6.1 Maize grain yield response to N fertilizer in the wet season 2005.

The grain yields of maize from the four soils (two in Thailand and two in the Lao PDR) were significantly increased with increasing rates of N fertilizer compared with the control treatment (N0), except on the Lb and Pc soils (Table 14).

In Lb soil series, there was no significant difference in maize yield between N fertilizer treated and control plots. In the case of Pc soil series, the grain yield was not significantly increased with increasing N fertilizer. However, the maximum grain yield of the four soils was lower than the predicted yield by DSSAT (7,000 kg ha^{-1}). In this particular case, in both Lb and Pc sites, the farmers rotated the soybean with maize in the last wet and dry seasons (2004-2005), and poultry manure was applied to the Lb soil. Deng and Tabatabai (2000) concluded that nitrogen mineralization under aerobic conditions at 30.7 ^{o}C for 24 weeks of soybean rotated with meadow increased the amount of cumulative N mineralized from 137 to 1500 mg kg^{-1} soil. During the experiment, it was clearly seen through the vegetative stage that maize plants did not show N deficiency symptoms in the control treatments of both soils. Lory *et al*. (1995) also found that cereal crops and other non legume plants require less nitrogen when grown after legume. The response of maize to N fertilizer of Lb and Pc soils was overestimated (Figures 38 and 39).

Maize grain yield of St soil was, however, greatly increased with high N rates by 52, 128, 178, and 194 %, respectively. The yields of the two highest N fertilizer treatments (113, 188 kg N ha^{-1}) of St soil were obviously higher than the yields of maize in the other soils which received similar high N treatments; there were highly significant differences in grain yield (Table 15). This indicated that the response of N fertilizer for maize in the St soil was very high, probably because St soil was low in organic matter content, and low N mineralization. Sipaseuth *et al*. (2006) found that soil nitrate in St soil slowly increased from 0.7 to 13.8 mg kg^{-1} during 0 to 42 days of incubation.

Table 14 Grain and stover yield of maize on Lb and Pc soils under different N fertilizer management in the wet season 2005.

Lop Buri (Lb)			Pak Chong (Pc)		
Applied N fertilizer	Grain	Stover	Applied N fertilizer	Grain	Stover
---------- ($kg\ ha^{-1}$) -----------			---------- ($kg\ ha^{-1}$) -----------		
0	6,868	6,935	0	5,185	5,544
32	6,434	7,245	44	5,542	5,675
50	6,916	8,236	82	5,841	6,299
100	6,440	7,681	125	6,565	6,350
188	5,491	7,277	188	6,328	6,852
Prob.	ns	ns	Prob.	ns	ns

Note †Linear (slope b) of equation Yield = a + b*min (Node, x)
Node is the join point and x is the amount of added N
ns=Not significant

The grain yield of Bc soil was slightly increased with increasing N fertilizer, about 33, 44, 56, and 81 % increase, respectively, compared to control treatment (2,931 kg ha^{-1}) (Table 15). There were no significant differences between different N rates and without N fertilizer treatment. Soil OM of Bc soil was relatively high compared to other soils. This soil was lower in pH and higher in 1 *M* KCl extractable aluminum content (36.4 mg kg^{-1}) compared to the other soils (Table 7).

Table 15 Grain and stover yield of maize on St and Bc soils as affected by increasing levels of fertilizer N in the wet season 2005.

Saythong (St)			Bachieng (Bc)		
Applied N fertilizer	Grain	Stover	Applied N fertilizer	Grain	Stover
- - - - - - - - - - ($kg\ ha^{-1}$) - - - - - - - - - -			- - - - - - - - - - ($kg\ ha^{-1}$) - - - - - - - - - -		
0	2,539	4,398	0	2,931	3,980
38	3,855	5,550	25	3,903	4,110
75	5,806	6,893	50	4,246	4,179
113	7,306	7,433	75	4,568	4,365
188	7,470	8,152	150	5,314	4,872
Linear†	43.20	33.25	Linear†	-	-
Max N	116.52	103.18	Max N	-	-
Prob.	0.0029	0.0403	Prob.	ns	ns
Adj R^2	0.99**	0.94*	Adj R^2	-	-

Note † Linear (slope b) of equation Yield = a + b*min (Node, x)

Node is the join point and x is the amount of added N.

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level

ns=Not significant

The maize responded to as much as 116.5 kg N ha^{-1} which was 40 kg N higher than DSSAT prediction for the St soil (Figure 40). This illustrated that the response of maize to N fertilizer of the St soil was underestimated. The grain yield was increased with increasing N fertilizer, with the increases of 33, 44, 56, and 81 %, respectively. In the case of Bc soil, the response was obtained to 45.7 kg N ha^{-1}, which was very close to the DSSAT prediction of 50 kg ha^{-1} (Figure 41). The maize grain yields were still lower than the other soils; this was probably due to the Bc soil properties and growing conditions. The soil was low in pH, high in Al content and there was a lot of rain during the maize growth.

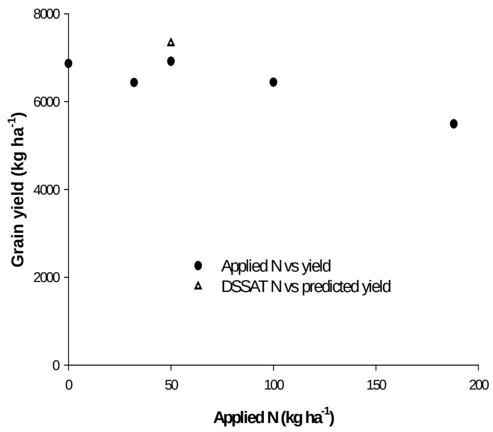

Figure 38 Maize yield response to N fertilizer in the Lb soil in the wet season 2005.

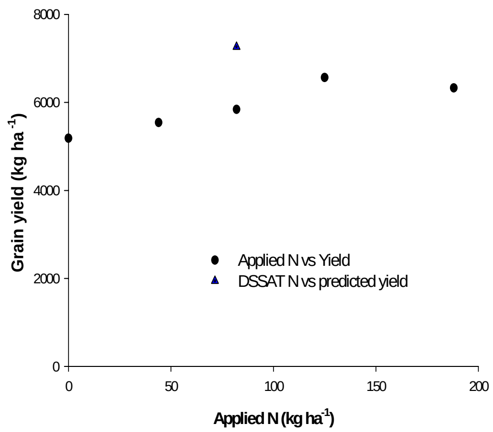

Figure 39 Maize yield response to N fertilizer in the Pc soil in the wet season 2005.

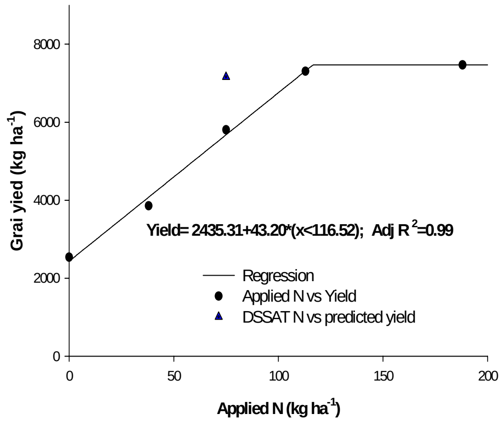

Figure 40 Maize yield d response to N fertilizer in the St soil in the wet season 2005.

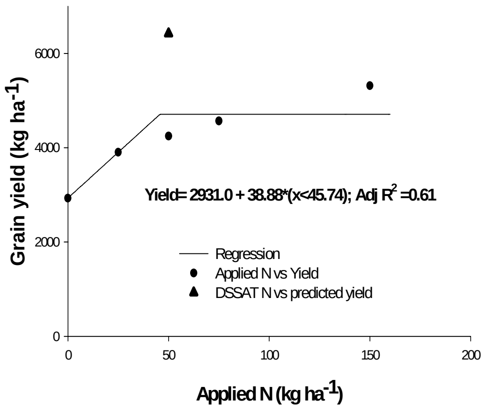

Figure 41 Maize yield response to N fertilizer in the Bc soil in the wet season 2005.

6.2 Maize stover yield at different rates of N fertilizer in the wet season 2005.

The maize stover yield increased with increasing rates of N fertilizer except on the Lb soil. Stover yield of Lb soil was higher in the N3 treatment, which also produced high grain yield (Table 14). Higher nitrogen fertilization resulted in higher maize stover of 133 and 188 kg N ha^{-1} treatments (N3 and N4) on the St soil, which was more than double the yield of the control treatment (Table 15). The increase in stover yield on all soils was not significantly different between control and rates of N fertilizer except for the St soil. The stover yield on the Bc soil was also lower than the other soils (Table 15); this was probably due to low soil pH and high Al concentration as mentioned previously.

6.3 Total N, P and K uptake by grain and stover in the wet season 2005.

The N uptake of grain and stover yield in 2005 illustrated that with increasing rates of N fertilizer more N was taken up by grain than stover. The N uptake of grain in Lb, and Pc soils was higher than in the St and Bc soils, which varied from 83-99, 62-88 compared to 34-91 and 32-56 kg ha^{-1} for St and Bc soils. High N uptake of all treatments of Lb soil was probably due to high subsoil nitrate content. However, there was no significant difference in the amount of N uptake in grain with different grain yield except St soil (Table 16). The higher N uptake in Lb, Pc and St soils was related to the higher grain and stover yields. The lower N uptake by grain in the Bc soil was due to low yield.

Table 16 Total N uptake in grain and stover of maize on St and Bc soils under different N fertilizer management in the wet season 2005.

Saythong (St)			Bachieng (Bc)		
Applied N fertilizer	Total N in grain	Total N in stover	Applied N fertilizer	Total N in grain	Total N in stover
---------- ($kg\ ha^{-1}$) ----------			---------- ($kg\ ha^{-1}$)----------		
0	33.6	24.2	0	33.2	19.6
38	50.3	29.7	25	44.9	18.6
75	75.3	37.4	50	49.6	22.9
113	84.7	42.2	75	51.8	21.1
188	94.9	40.6	150	56.6	23.3
Linear†	0.55	0.17	-	-	-
Max N	104	100	-	-	-
Prob.	0.0355	0.0125	Prob.	ns	ns
Adj R^2	0.94*	0.98*	-	-	-

Note † Linear (slope b) of equation N uptake = a + b*min (Node, x)
Node is the join point and x is the amount of added N.
* Significant at the 0.05 probability level
ns = Not significant

Total P uptake by maize grain and stover of all soils revealed that total P uptake was not significantly increased between the control and increasing rates of N fertilizer treatments except the grain yield of St and Bc soils (Table 17). The P uptake was higher in grain compared to the amount taken up in stover. Total P uptake by maize grain of the four levels of added N ranged from 17.7-20.1; 12.7-18.8; 6.5-23.6 and 6.5-10.6 kg ha^{-1} for Lb, Pc, St and Bc soils, respectively. The P uptake in maize stover was 4.4-5.2; 2.9-4.7; 2.6-3.5 and 1.7-2.6 kg ha^{-1} for Lb, Pc, St and Bc soils, respectively. There were no significant differences in the amount of P uptake by grain and stover between treatments of most soils except in the case of the St soil. The total P uptake in grain on maize grown on the St soil was highly significantly different among the different N treatments. However, higher P uptake occurred in the Lb, Pc and St soils at the higher rate of N fertilizer (100, 188 and 188 kg N ha^{-1}, respectively) except for the Bc soil. The high P uptake of maize grown on the Lb soil occurred at a lower N rate than in the Pc and St soils. It seems, in general, that higher total P uptake of both grain and stover occurred at the higher rates of nitrogen fertilizer treatments (N2, N3 and N4) of all soils except the N4 treatment of Lb soil. It was indicated that P uptake was not correlated with the high rates of N fertilizer but it was more related to grain and stover yields. The P uptake by maize was higher with the N0 treatment of Lb soil probably because of a sufficient amount of N, which led to nutrient balance and high yield.

Table 17 Total P uptake in grain and stover yield of maize on St and Bc soils under different N fertilizer management in the wet season 2005.

Saythong (St)			Bachieng (Bc)		
Applied N fertilizer	Total P in grain	Total P in stover	Applied N fertilizer	Total P in grain	Total P in stover
- - - - - - - - - - (kg ha^{-1}) - - - - - - - - - -			- - - - - - - - - - (kg ha^{-1}) - - - - - - - - - -		
0	6.5	2.3	0	6.5	1.7
38	10.8	2.6	25	8.6	1.8
75	15.1	3.1	50	10.3	2.6
113	18.3	3.5	75	9.9	2.1
188	23.6	2.6	150	10.6	2.0
Linear†	0.10	-	Linear†	0.08	-
Max N	160	-	Max N	45	-
Prob.	0.0025	ns	Prob.	0.0500	ns
Adj R^2	0.99**	-	Adj R^2	0.95*	-

Note † Linear (slope b) of equation P uptake = a + b*min (Node, x)

Node is the join point and x is the amount of added N.

* Significant at the 0.05 probability level

** Significant at the 0.01 probability level

ns = Not significant

The K uptake by stover was higher than the amount in grain in all treatments. There were no significant differences in total K uptake under different N treatments of most sites except for the grain yield of Pc and St soils (Tables 18, 19). The level of K uptake by maize grain varied from 26.3-32.1; 17.3-31.6; 14.9-39 and 16.2-21.9 kg ha^{-1}, respectively, for Lb, Pc, St and Bc soils. The amount of K removed by stover ranged from 38.7-44.9; 35.7-59.1; 38.1-75.2 and 25.1-31 kg ha^{-1} for Lb, Pc, St and Bc sites, respectively. The lower K uptake of some treatments was commensurate with low maize grain yield.

Table 18 Total K uptake in grain and stover yield of maize on Lb and Pc soils under different N fertilizer management in the wet season 2005.

Lop Buri (Lb)			Pak Chong (Pc)		
Applied N fertilizer	Total K in grain	Total K in stover	Applied N fertilizer	Total K in grain	Total K in stover
- - - - - - - - - - (kg ha^{-1}) - - - - - - - - - -			- - - - - - - - - - (kg ha^{-1}) - - - - - - - - - -		
0	30.6	38.7	0	17.3	35.7
32	30.5	39.3	44	23.6	34.1
50	32.1	43.2	82	24.9	45.8
100	31.3	44.9	125	31.6	46.4
188	26.3	44.8	188	31.5	59.1
Linear†	-	-	Linear†	0.10	-
Max N	-	-	Max N	129	-
Prob.	ns	ns	Prob.	0.021	ns
Adj R^2	-	-	Adj R^2	0.94*	-

Note † Linear (slope b) of equation P uptake = a + b*min (Node, x)

Node is the join point and x is the amount of added N.

* Significant at the 0.05 probability level

ns = Not significant

The results indicated that higher K uptake was found with the high application rate of N fertilizer treatments (N2, N3 and N4) for most soils. Comparison of K uptake among four sites, it was clearly seen that lower K uptake in grain or stover was found in the Bc soil (Table 19), which is one of the most highly weathered and acid soils.

Table 19 Total K uptake in grain and stover yield of maize on St and Bc soils under different N fertilizer management in the wet season 2005.

Saythong (St)			Bachieng (Bc)		
Applied N fertilizer	Total K in grain	Total K in stover	Applied N fertilizer	Total K in grain	Total K in stover
- - - - - - - - - - ($kg\ ha^{-1}$) - - - - - - - - - - -			- - - - - - - - - - ($kg\ ha^{-1}$) - - - - - - - - - -		
0	14.9	38.1	0	16.2	25.1
38	21.4	50.1	25	16.8	26.2
75	34.3	49.4	50	18.9	22.5
113	33.9	59.2	75	21.9	31.0
188	39.0	75.2	150	16.9	28.4
Linear†	0.25	-	Linear†	-	-
Max N	88	-	Max N	-	-
Prob.	0.050	ns	Prob.	ns	ns
Adj R^2	0.90*	-	Adj R^2	-	-

Note † Linear (slope b) of equation k uptake = a + b*min (Node, x)
Node is the join point and x is the amount of added N.
* Significant at the 0.05 probability level.
ns = Not significant

6.4 Soil analyses after maize harvest in the wet season 2005

The soil available nitrogen (NH_4^+-N + NO_3^--N) after maize harvest indicated that available N was very high in Lb and Pc soils while it was lower in Bc and St Soils, respectively. There were no significant differences in available nitrogen (NH_4^+-N + NO_3^--N) between different N fertilizer rates. Most soils contained more nitrate than ammonium N. The amount of remaining N in all soils was more related to soils than to the rates of N fertilizers. The amount of available N of Lb, Pc, Bc soils was double that remaining in the St soil. High organic matter (OM) content in Bc soil, and soybean residues from last season incorporated in Lb and Pc soils or other forms of N apparently resulted in higher available N in these soils.

Table 20 Available N content on Lb, Pc, St and Bc soils after maize harvest in the wet season 2005.

Lop Buri (Lb)		Pak Chong (Pc)		Saythong (St)		Bachieng (Bc)	
Applied nitrogen fertilizer (kg ha^{-1})	Avail. N ($mgkg^{-1}$)	Applied nitrogen fertilizer (kg ha^{-1})	Avail. N ($mgkg^{-1}$)	Applied nitrogen fertilizer (kg ha^{-1})	Avail. N ($mgkg^{-1}$)	Applied nitrogen fertilizer (kg ha^{-1})	Avail. N ($mgkg^{-1}$)
0	78.1	0	95.2	0	33.5	0	74.3
32	96.0	44	100.3	38	31.2	25	72.2
50	80.7	82	93.1	75	34.1	50	70.8
100	82.7	125	92.8	113	34.6	75	77.4
188	85.8	188	110.7	188	36.0	150	80.8
Prob.	ns	Prob.	ns	Prob.	ns	Prob.	ns

Note † Linear (slope b) of equation NH_4^--N and NO_3^--N = a + b*min (Node, x)
Node is the join point and x is the amount of added N.
ns = Not significant

The higher available nitrogen in Lb and Pc soils resulted in no response of maize on N fertilizer treatments (Table 20). The levels of available N content in St soil were low as expected from the substantial response of maize to the N fertilizer treatments. The relatively lower available nitrogen in St and Bc soils explains the high response to fertilizer nitrogen on maize observed in these two soils (Table 20).

Available P after maize harvest of Lb, Pc, St and Bc soils ranged between 4.4-8.8; 16.9-21.1; 16.7-22.1 and 2.9-3.8 mg kg^{-1}, respectively (Tables 21 and 22). Soil available P in Lb, Pc and St soils was higher at all treatments compared to the amount in the soils before maize planting. This is expected because P fertilizer was applied at the same rate for each site. There were no significant differences in extractable P between different rates of N fertilizer application. The results indicated that the amount of soil P remaining did not differ between treatments except N2, N3 and N4 of Lb soil, because of high grain yield of N0 and N1 probably led to higher total P uptake, which can cause less residual P in the soil. The data indicated that P fertilizer application in the three soils (44 kg P_2O_5 ha^{-1} for Lb, Pc and Bc soils and 32 kg P_2O_5 ha^{-1} for St soil) was sufficient for maize and increased the residual soil P after maize harvest except in the Bc soil. Soil P levels at Bc site was the same as before maize planting, this soil have inherently low P levels due to low soil pH and high soil adsorption of P. Maize did not grow well in this soil, P deficiency symptoms occurred when maize was two to three weeks old. Thus, it is especially important to re-examine the soil P status and crop response and likely apply more P fertilizer to achieve high yields in the Bc soil.

Table 21 Soil pH, Available P and extractable K on Lb and Pc soils under different N fertilizer management after maize harvests in the wet season 2005.

Lop Buri (Lb)			Pak Chong (Pc)		
Applied N fertilizer (kg ha^{-1})	P	K	Applied N fertilizer (kg ha^{-1})	P	K
	- (mg kg $^{-1}$soil) -			- (mg kg $^{-1}$ soil) -	
pH $_w$ (1:1)	7.1		pH $_w$ (1:1)	5.7	
0	4.4	127.3	0	17.5	145.0
32	5.1	121.3	44	17.6	124.0
50	8.8	123.7	82	16.9	121.5
100	7.6.	117.4	125	16.3	117.1
188	7.1	112.0	188	21.7	141.3
Prob.	ns	ns	Prob.	ns	ns

Note † Linear (slope b) of equation Available P, Extractable K= a + b*min (Node, x)
Node is the join point and x is the amount of added N.
ns = Not significant.

Extractable K at harvest was relatively high in the Lb and Pc soils, with values ranging from 112-127.3 and 117.1-145.0 mg kg^{-1} but low soil K was measured in the St and Bc soils which varied from 52.9-65.2 and 57.1-70.3 mg kg^{-1}, respectively (Tables 21 and 22). Potassium content in all soils was not significantly different with different N treatments. The relatively high value of K content in Lb and Pc soils was probably related to clay mineral type in the soils. Other research indicated that Lb soil was high in smectite while Pc was high in kaolinite (Nilawonk *et al*., 2008). The release of mica interlayer K in the high K smectite soil may have supplied sufficient K to plants even under intensive cropping (Badraoui *et al*., 1992). Black (1968) stated that soils containing predominantly kaolinitic clay have less exchangeable K to release. However, the release of nonexchangeable K is generally too slow to meet crop demand. In addition, Lb and Pc soils were rotated with maize and legume for a long time and crop residues were incorporated into the soil and K fertilizer was applied each year, which may have led to high soil K content. The data showed that the amount soil K content in control treatment (N0) of all sites was slightly higher than K content at all N treatments (N1, N2, N3 and N4). The high remained levels of soil K found in the control treatment of all soils might be due to without N fertilizer treatment resulted low grain and stover yield. This caused the low uptake K from the soil.

Table 22 Soil pH, Available P and extractable K on St and Bc soils under different N fertilizer management after maize harvests in the wet season 2005.

Saythong (St)			Bachieng (Bc)		
Applied N fertilizer	P	K	Applied N fertilizer	P	K
(kg ha^{-1})	-(mg kg $^{-1}$ soil)-		(kg ha^{-1})	-(mg kg $^{-1}$ soil)-	
pH $_w$ (1:1)	5.4		pH $_w$ (1:1)	4.7	
0	22.1	65.2	0	3.8	70.3
38	21.4	53.3	25	3.3	62.1
75	18.0	56.6	50	2.9	59.2
113	15.7	52.9	75	3.7	56.8
188	16.7	55.8	150	3.7	57.1
Prob.	ns	ns	Prob.	ns	ns

Note † Linear (slope b) of equation Available P, Extractable K= a+b*min (Node, x)
Node is the join point and x is the amount of added N.
ns = Not significant

6.5 Maize grain yield response to N fertilizer in the wet season 2006.

The grain yields of maize at the four sites were increased with increasing rates of N fertilizer. The maize yield increased with increasing N on the Lb and Pc soils, which contrasted with the results in 2005. The maximum grain yield at the four sites was still lower than the DSSAT prediction (8,000 kg ha^{-1}) except for the St Soil. There was a significant difference in grain yield between N fertilizer and control treatments (Table 23). Maize responded to N fertilizer at the rate of 75 and 81 kg N ha^{-1} for Lb and Pc sites, respectively, (Figures 42 and 43), which was lower than the DSSAT prediction (80 and 87 kg N ha^{-1}, for Lb and Pc soils, respectively). Grain yields on the St and Bc soils were greatly increased with higher N rates as well. Maize yield of St soil increased 29, 71, 104 and 113 %, respectively, with increasing rates of N fertilizer respectively, compared to control treatments of 4,211 kg ha^{-1} (Table 23).

Table 23 Grain and stover yield of maize on Lb and Pc soils under different N fertilizer management in the wet season 2006.

Lop Buri (Lb)			Pak Chong (Pc)		
Applied N fertilizer	Grain	Stover	Applied N fertilizer	Grain	Stover
- - - - - - - - - - (kg ha^{-1}) - - - - - - - - - -			- - - - - - - - - - (kg ha^{-1}) - - - - - - - - - -		
0	4,374	5,662	0	3,093	4,817
25	4,920	5,780	25	4,505	6,897
50	5,493	5,723	50	5,079	7,747
100	6,062	6,657	100	6,409	7,829
150	6,047	6,878	150	6,475	7,834
Linear†	23.38	-	Linear†	39.72	83.19
Max N	75.29	-	Max N	80.79	35.89
Prob.	0.0002	ns	Prob.	0.0289	0.0011
Adj R^2	0.99***	-	Adj R^2	0.97*	0.99*

Note † Linear (slope b) of equation Yield = a + b*min (Node, x)

Node is the join point and x is the amount of added N.

* Significant at the 0.05 probability level

*** Significant at the 0.001 probability level.

ns = Not significant

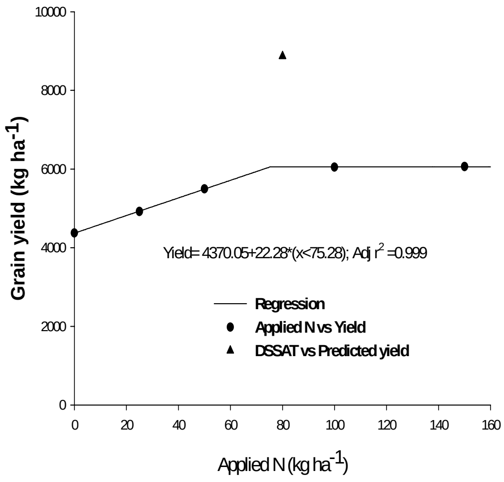

Figure 42 Maize yield response to N fertilizer of Lb soil in the wet season 2006.

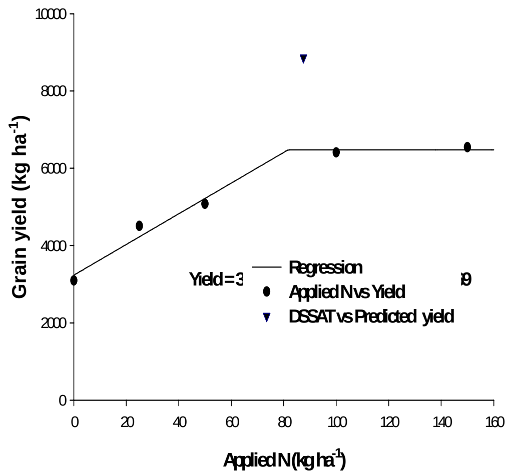

Figure 43 Maize yield response to N fertilizer in Pc soil in the wet season 2006.

The grain yield of all treatments for St soil was higher than in 2005. The yields of the two highest rates of N treatments (N3 and N4) of St soil were obviously higher (8,622 and 8,977 kg ha^{-1}) than the yields of maize in the other soils (Table 24). The grain and stover yields of maize of the St and Bc soils were significantly increased with N applications at the rates of 100 and 150, and 75 and 150 kg N ha^{-1}, respectively, except the grain yield of Bc soil. The response of maize on N fertilizer in St soil was very high for both years, and in 2006 maize responded to 78 kg N ha^{-1}

(Figure 44), this result was very close to the DSSAT prediction of 85 kg N ha^{-1}. The grain yield of Bc soil in 2006 was increased with increasing N fertilizer (17, 87, 122, 125%, respectively) compared to control treatment (1,940 kg ha^{-1}) (Table 23). The maximum response was obtained at 64 kg N ha^{-1}, which was close to the DSSAT predicted requirement of 75 kg N ha^{-1} (Figure 45). The grain yield of maize in the Bc soil for all treatments was lower than the yield in 2005. The lower maize yield of Bc soil in 2006 probably occurred due to three main reasons (1) during maize growth rainfall was heavy with heavy cloud cover for an extended periods of time, probably reducing solar radiation and potential maize yield. In addition the high rainfall may have led to nutrient loss by leaching thus leading to reduced growth of maize. It was observed that the maize plants were stunted, (2). The maize plant population was less than desired and (3) with the low soil pH, Al toxicity probably reduced yields (36.3 mg Al kg^{-1}, using 1 *M* KCl) content compared to 0 for the other soils (Table 7).

Table 24 Grain and stover yield of maize on St and Bc soils under different N fertilizer management in the wet season 2006.

Saythong (St)			Bachieng (Bc)		
Applied N fertilizer	Grain	Stover	Applied N fertilizer	Grain	Stover
- - - - - - - - - - ($kg\ ha^{-1}$) - - - - - - - - - -			- - - - - - - - - - ($kg\ ha^{-1}$) - - - - - - - - - -		
0	4,211	5,449	0	1,940	2,776
25	5,449	6,411	25	3,416	4,066
50	7,191	7,369	50	3,635	4,491
100	8,622	8.511	75	4,320	5,257
150	8,977	8,544	150	4,366	5,409
Linear†	59.60	38.40	Linear†	-	34.3
Max N	78.39	80.15	Max N	-	70.34
Prob.	0.0117	0.0001	Prob.	ns	0.0433
Adj R^2	0.98*	0.99***	Adj R^2	-	0.93*

Note † Linear (slope b) of equation Yield = a + b*min (Node, x)

Node is the join point and x is the amount of added N

* Significant at the 0.05 probability level

*** Significant at the <0.00l probability level

ns = Not significant

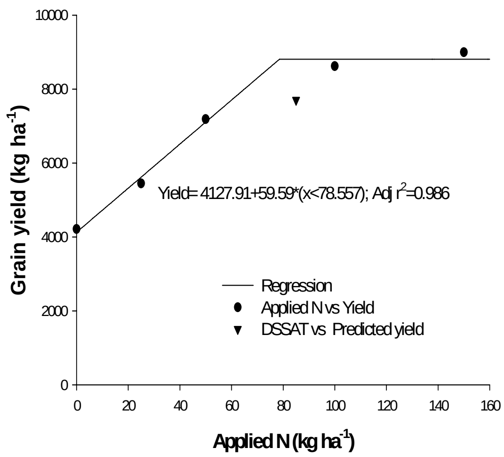

Figure 44 Maize yield response to N fertilizer of St soil in the wet season 2006.

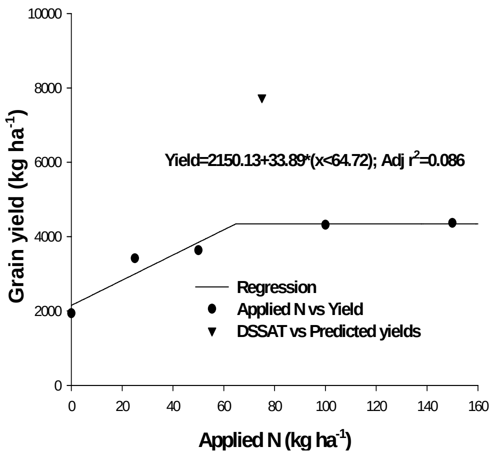

Figure 45 Maize yield response to N fertilizer of Bc soil in the wet season 2006.

6.6 Maize stover yields at different rates of N fertilizer in the wet season 2006

The maize stover yield of all soils in 2006 also increased with increasing N fertilizer rates; there was a significant difference in stover weight between higher rates of N fertilizer compared to control treatment except Pc, Bc soil (Table 23 and 24). Stover yield in Lb and St soils strongly increased with additional N. In the case of Pc and Bc soils, however, yields where N2, N3 and N4 treatments (50, 100 and 150 kg N ha^{-1}, respectively) were applied, were not significantly increased. Yields of maize stover on the Pc soil were the highest (6.9 to 7.8 t ha^{-1}) of all treatments. For the stover yield of Bc soil where nitrogen fertilizer was applied was lower than 5.5 t ha^{-1}. We observed that maize plants were unhealthy, weak and plants matured too early (about 80 days after emergence). The low pH and high Al contents in Bc soil probably inhibited maize growth. With Al toxic subsoil, maize roots could not penetrate into the subsoil (Bushamuka and Zobel, 1998). The observation on maize growth and development during the course of experiment revealed that the plants were stunted and the roots were poorly proliferated which was attributed to Al toxicity. Dobermann and Fairhurst (2000) described that an excess Al^{3+} concentration in the soil solution was caused by low soil pH (<5), and the most important effect of Al toxicity is the inhibition of root growth. Aluminum toxicity reduced plant growth, mainly reducing root system was reported (Foy, 1984). The Al related root damage may be a consequence of an effect such as the limitation of cell wall synthesis due to a depletion in uridine diphosphate glucose, the glucose carrier for the production of cell wall polysaccharides (Pfeffer *et al.*, 1986).

6.7. Nitrogen, phosphorus and potassium uptake in grain and stover in 2006.

The N uptake in grain increased with higher rates of N fertilizer application in most soils. There was a significant difference in total N uptake by grain and stover yield among higher rates of N fertilizer (100, 150 kg N ha^{-1}) and control treatments of most soils except in grain yield of the Bc soil.

Table 25 Grain and stover N uptake by maize on Lb and Pc soils under different N fertilizer management in the wet season 2006.

Lop Buri (Lb)			Pak Chong (Pc)		
Applied N fertilizer	N uptake in grain	N uptake in stover	Applied N fertilizer	N uptake in grain	N uptake in stover
	- - - - - - - - - - (kg ha^{-1}) - - - - - - - - - -			- - - - - - - - - - (kg ha^{-1}) - - - - - - - - - -	
0	54.7	16.8	0	32.0	14.8
25	62.1	23.1	25	57.1	19.7
50	79.7	23.4	50	71.2	27.4
100	95.4	29.9	100	90.3	30.6
150	99.4	41.3	150	95.9	34.1
Linear†	0.49	0.15	Linear†	0.78	0.25
Max N	89	188	Max N	76	71
Prob.	0.0382	0.0209	Prob.	0.0225	0.0438
Adj R^2	0.96*	0.91*	Adj R^2	0.97*	0.94*

Note † Linear (slope b) of equation N uptake = a + b*min (Node, x)
Node is the join point and x is the amount of added N.
* Significant at the 0.05 probability level

High N uptake in grain yield was found in 100 and 150 kg N ha^{-1} treatment of Lb, Pc and St soils with 95.4-99.4, 90.3-95.9 and 103.4 and 113.4 kg N ha^{-1}, respectively, (Tables 25, 26). The grain and stover yields of Bc soil was low and led to low N uptake. The total N uptake by grain and stover was increased with the increasing rates of N fertilizer application. N uptake by stover was significantly different between N treatments. Total N uptake of Bc soil ranged from 18.3 to 43.8 and 9.4 to 26.4 kg ha^{-1} for grain and stover, respectively (Table 26).

Table 26 Grain and stover N uptake by maize on St and Bc soils under different N fertilizer management in the wet season 2006.

Saythong (St)			Bachieng (Bc)		
Applied N fertilizer	N uptake in grain	N uptake in stover	Applied N fertilizer	N uptake in grain	N uptake in stover
- - - - - - - - - - ($kg\ ha^{-1}$) - - - - - - - - - -			- - - - - - - - - - ($kg\ ha^{-1}$) - - - - - - - - - -		
0	37.1	14.5	0	18.3	9.4
25	54.4	16.5	25	34.8	14.8
50	76.3	24.1	50	36.0	15.4
100	103.4	30.1	100	43.8	18.9
150	113.5	35.9	150	43.8	26.4
Linear†	0.78	0.16	Linear†	-	0.10
Max N	92	132	Max N	-	159
Prob.	0.0337	0.0211	Prob.	ns	0.0251
Adj R^2	0.97*	0.96*	Adj R^2	-	0.90*

Note † Linear (slope b) of equation N uptake = a + b*min (Node, x)
Node is the join point and x is the amount of added N
* Significant at the 0.05 probability level.
ns = Not significant

Total P uptake by maize grain and stover from Lb, Pc, St & Bc soils in the wet season 2006 was different from the previous season (2005). Total P content in maize grain ranged from 14.9 -28.7, 15.7-24.5, 10.6-25.9 and 4.8-8.9 kg ha^{-1} for Lb, Pc, St and Bc sites, respectively. The results revealed that most of P uptake by grain and stover on all soils was not significantly different between the control and the application of N fertilizer (50 to 150 kg N ha^{-1}). Obviously, the P uptake by grain of Bc soil of all treatments was low (<10 kg P ha^{-1}) and was due to low grain yield. Low grain yields on the Bc soil are probably due to the highly acidic nature of the soil. The native P content of this soil is usually low and the soil tends to fix P rapidly. This may cause a low efficiency of P fertilizer use for the first and second crop. The application of 0.5 t of lime ($Ca(OH)_2$) ha^{-1} to the Bc soil enabled an increase in soil pH from 4.7 to 5.1. It is likely that much more lime will be needed on this soil. The soil pH of 5.1 did not enhance P uptake, which is led to low grain and stover yield. This case is similar to that described by Ruaysoongnern and Keenrati-Kasikorn (1998), which indicated that in acid soils, P is usually precipitated as aluminium (Al) and iron (Fe) phosphates or adsorbed to clay surfaces.

The total P uptake by stover in each treatment of the Lb and Pc soils was lower than in 2005. The total P uptake ranged from 1.5-3.2, 1.4-2.5, 1.7-3.9 and 1.1-2 kg ha^{-1}, for Lb, Pc, St and Bc soils, respectively, There were no significant differences in amount of P uptake with different N treatments. The low P uptake by stover of Lb, Pc and St soils might be due to the reduction in P fertilization rate (19 kg P_2O_5 ha^{-1}) in 2006 while in 2005, 44 kg P_2O_5 ha^{-1} was applied. Higher P uptake in stover was found in N3 and N4 treatments of St and Bc soils compared to control treatment.

The K uptake by maize grain and stover in all soils in 2006 was higher than in 2005. In Lb and Pc soils, K uptake by stover was twice as high as in grain in all treatments. However, there were no significant differences in total K uptake of both grain and stover under different N treatments except K uptake by grain of the Pc soils (Table 27). Total K in the Lb and Pc soils varied from 36.3-45.9, 79.8-94.8 and 23.5-58.1, 62.1-114.5 kg ha^{-1} for grain and stover, respectively. On the St and Bc soils, K uptake by grain and stover varied from 29.0-63.3, 72.6-108.2 and 23.5-28.7, 62.1-114.5 kg ha^{-1}, respectively (Table 28). The amount of K removed by stover ranged from 79.8-94.1; 62.1-114.5; 72.6-108.4 and 34.5-70.1 kg ha^{-1} for Lb, Pc, St and Bc sites, respectively. The higher K uptake probably occurred because K was added and crop residues were incorporated into the soils. The data clearly showed that K uptake was increased with increasing rates of N fertilizer for most soils. For the Bc soil, lower total K uptake by grain and stover was observed although K fertilizer was applied.

Table 27 Potassium uptake by maize grain and stover on Lb and Pc soils under different N fertilizer management in the wet season 2006.

Lop Buri (Lb)			Pak Chong (Pc)		
Applied N fertilizer	P uptake in grain	P uptake in stover	Applied N fertilizer	P uptake in grain	P uptake in stover
- - - - - - - - - - ($kg\ ha^{-1}$) - - - - - - - - - -			- - - - - - - - - - ($kg\ ha^{-1}$) - - - - - - - - - -		
0	36.3	79.8	0	23.5	62.1
25	37.8	82.1	25	41.1	75.3
50	37.5	82.1	50	49.4	94.8
100	39.6	97.1	100	68.1	99.5
150	45.9	94.8	150	64.8	114.5
Linear[†]	-	-	Linear[†]	0.54	-
Max N	-	-	Max N	74.99	-
Prob.	ns	ns	Prob.	0.0127	ns
Adj R^2	-	-	Adj R^2	0.96*	-

Note [†] Linear (slope b) of equation K uptake = a + b*min (Node, x)

Node is the join point and x is the amount of added N

* Significant at the 0.05 probability level.

ns = Not significant

Table 28 Potassium uptake by maize grain and stover on St and Bc soils under different N fertilizer management in the wet season 2006.

Saythong (St)			Bachieng (Bc)		
Applied N fertilizer	K uptake in grain	K uptake in stover	Applied N fertilizer	K uptake in grain	K uptake in stover
- - - - - - - - - - ($kg\ ha^{-1}$) - - - - - - - - - -			- - - - - - - - - - ($kg\ ha^{-1}$) - - - - - - - - - -		
0	29.0	72.6	0	13.2	34.5
25	34.8	80.5	25	22.9	50.1
50	48.0	90.8	50	21.9	55.4
100	55.5	108.4	100	25.1	70.1
150	60.3	108.2	150	28.7	78.5
Linear†	0.37	0.47	Linear†	-	0.44
Max N	87.32	80.24	Max N	-	95.42
Prob.	0.0107	0.0174	Prob.	ns	0.0152
Adj R^2	0.97*	0.95*	Adj R^2	-	0.96*

Note † Linear (slope b) of equation K uptake = a + b*min (Node, x)
Node is the join point and x is the amount of added N.
* Significant at the 0.05 probability level.
ns = Not significant

6.8 Soil analysis after maize harvest in 2006

The available soil nitrogen in Lb and Pc soils was higher than the amount in St and Bc soils in 2006. The amounts were higher just as were grain yields. The results indicated, however, that available N in 2006 was lower in Lb and Pc soils compared to the year 2005, which resulted in response of N fertilizer application. The low soil available nitrogen may explain the greater nitrogen response in these soils. The relatively lower available nitrogen in St and Bc soils in 2005 and 2006 supported the higher response of nitrogen on maize in these two soils. There were no significant differences of available nitrogen with different rates of nitrogen fertilizer in the soils after maize was harvested (Table 29).

Table 29 Available N content on Lb, Pc, St and Bc soils after maize harvest in the wet season 2006.

Lop Buri (Lb) soil		Pak Chong (Pc) soil		Saythong (St) soil		Bachieng (Bc) soil	
Applied nitrogen fertilizer (kg ha^{-1})	Avail. N ($mgkg^{-1}$)	Applied nitrogen fertilizer (kg ha^{-1})	Avail. N ($mgkg^{-1}$)	Applied nitrogen fertilizer (kg ha^{-1})	Avail. N ($mgkg^{-1}$)	Applied nitrogen fertilizer (kg ha^{-1})	Avail. N ($mgkg^{-1}$)
0	50.6	0	43.7	0	20.0	0	33.7
25	47.4	25	42.7	25	20.9	25	31.9
50	50.3	50	44.7	50	19.7	50	33.1
100	49.7	100	42.0	100	18.7	100	35.3
150	52.4	150	48.2	150	19.7	150	33.8
Prob.	ns	Prob.	ns	Prob.	ns	Prob.	ns

Note † Linear (slope b) of equation NH_4^--N and NO_3^--N = a + b*min (Node, x)
Node is the join point and x is the amount of added N.
ns = Not significant

After two years (2005 and 2006) of P fertilizer application, it was found that soil available P remaining after maize harvest was not much different from that measured before conducting the experiments. Soil P content after maize harvest in 2006 ranged from 4.7-5.8, 16.9-18.6, 10.9-16.8 and 6.1-6.7 mg kg^{-1}, for Lb, Pc, St and Bc soils, respectively (Tables 30 and 31). The average of soil P at the second year (2006) of most soil was not much different from first year (2005). The reduction of P fertilizer from 44 kg P_2O_5 ha^{-1} in the first year to 19 kg P_2O_5 ha^{-1} in second years did not appear to affect maize yield and available soil P content. This indicated that P fertilizer prediction by PDSS software was likely accurate. The available soil P content of all soils was not significantly different between treatments. Obviously, the remaining available soil P in Bc site after harvesting (2005 and 2006) was low compared to Lb, Pc and St soils due to the low native P content in this soil (Tables 21, 22, 30 and 31).

Table 30 Soil pH, Available P and extractable K on Lb and Pc soils under different N fertilizer management after maize harvests in the wet season 2006.

Lop Buri (Lb)			Pak Chong (Pc)		
Applied N fertilizer	P	K	Applied N fertilizer	P	K
(kg ha^{-1})	- (mg kg^{-1} soil) -		(kg ha^{-1})	- (mg kg^{-1} soil) -	
pH_w (1:1)	7.1		pH_w (1:1)	5.6	
0	5.2	99.0	0	16.9	84.7
25	5.8	97.3	25	18.3	87.6
50	5.0	99.2	50	17.4	87.4
100	4.7	104.2	100	17.9	75.8
150	5.5	103.8	150	18.6	76.6
Prob.	ns	ns	Prob.	ns	ns

Note † Linear (slope b) of equation Available P, Extractable K= a + b*min (Node, x)
Node is the join point and x is the amount of added N.
ns = Not significant

The soil pH of most soils after two years of maize planting is given in Tables 30 and 31. Throughout the experiments, pH levels of Lb, Pc and St soils were constant at 7.1, 5.7, and 5.4, respectively. For the Bc soil pH was 4.7 (air-dried soil) before and after maize planting in 2005. In 2006, soil pH of Bc soil was only slightly increased (from soil pH 4.7 to 5.1) due to lime ($Ca(OH)_2$) application at the rate of 0.5 t ha^{-1} for all treatments, it was later shown to be insufficient lime application.

Table 31 Soil pH, Available P and extractable K on St and Bc soils under different N fertilizer management after maize harvests in the wet season 2006.

Saythong (St)			Bachieng (Bc)		
Applied N fertilizer	P	K	Applied N fertilizer	P	K
(kg ha^{-1})	- (mg kg^{-1} soil) -		(kg ha^{-1})	- (mg kg^{-1} soil) -	
pH_w (1:1)	5.4		pH_w (1:1)	5.1	
0	10.9	45.8	0	6.1	54.7
25	14.6	43.7	25	5.9	50.8
50	15.2	46.9	50	4.6	47.8
100	13.2	55.6	100	6.2	51.9
150	16.8	46.4	150	6.7	47.8
Prob.	ns	ns	Prob.	ns	ns

Note † Linear (slope b) of equation Available P, Extractable K= a+b * min (Node, x) Node is the join point and x is the amount of added N.
ns = Not significant

Extractable soil K content after the 2006 harvest was lower for most soils compared to the results of year 2005. Total K uptake by grain and stover of most soils was not influenced significantly by the increasing rates of N fertilizer. The soil K ranged from 99-103.8, 77.6-86.4, and 43.7-55.6 and 47.8-54.6 mg $kg^{-1}$for Lb, Pc, St and Bc soils, respectively (Tables 30 and 31). The low soil K content in Lb and Pc soils in 2006 perhaps was due to reduction of K fertilizer application from 50 to 25 and 75 to 25 K_2O kg ha^{-1}, and the lower amount of K removed with maize grain yield. For the St and Bc soils, it was observed that soil K content was also lower than in 2005 even though in 2006 K fertilizer application increased from 44 to 69 and 50 to 81 kg K_2O ha^{-1} for St and Bc soils, respectively. The low soil K content in the St soil probably was due to high K uptake by maize stover, which was 1.5 fold of the K uptake by stover in 2005. Extractable soil K could be constant if maize stover is incorporated into the soil. In the case of K content in Bc soil, it tended to decline over time compared to the content in the year 2005. In 2006, the K fertilizer application in the Bc soil was increased from first year (69 to 81 kg K_2O ha^{-1}). Even 81 kg ha^{-1} of K_2O was applied, we found that maize plants were still thin and some plants died early (plants broke and lodged some 90 days before harvest). This indicated that K was insufficient for maize growth and for increasing crop yield. Havlin *et al*. (2005) described the K-deficiency symptoms as a weakening of plant, which causes lodging in small grains and stalk breakage in corn. However, the leaching loss of K was not investigated in Bc soil but we suspected that low K content might be due to K loss by leaching because heavy rains occur in this area.

CONCLUSION AND RECOMMENDATION

Nitrogen mineralization amount and allocation as ammonium or nitrate depended on soil pH and soil organic carbon. Nitrogen mineralization from high pH soils (Cd, Tk, Lb and Ln) resulted in large amounts of NO_3^--N throughout the incubation period as well as in Sd and Bc soils, which were more acid. The effect of heating the soil at 40 ^oC tended to further increase nitrate-N release. The most NO_3^--N and NH_4^+-N was released when the pre-incubation treatments were heating at 40 ^oC and at air-drying, respectively. Soils with a pH higher than 6 and high in clay content favored mineralization as NO_3^--N. The release of NH_4^+-N by mineralization was less throughout the incubation period in clay soils (Cd, Tk, Lb and Ln). Soils with pH less than 6 and a coarse texture, including Pc, Wn, Bc, Km, Sd and St mineralized high amounts of NH_4^+-N during the early period (zero to three days) and then high NO_3^--N from 14 to 70 days of incubation, probably as a result of conversion of NH_4^+-N to NO_3^--N. Maximum NO_3^--N release of different soils occurred from 14 to 70 days of incubation. However, for the time of maximum NH_4^+-N release was during the initial stage of incubation (zero to 3 days).

Organic carbon and soil pH were the main factors that affected NH_4^+-N and NO_3^--N release. High levels of amino acid-N and amino sugar-N were associated with increased N mineralization in soils under drying conditions (air-dry and heated to 40 ^oC). The results of this study suggested that soil pH, soil organic carbon level and amino sugar-N were useful predictors of potential mineralizable nitrogen in these soils. Continuous release of NO_3^--N throughout the incubation period by most soils indicated a high N mineralization potential, and probably was one of the reasons for the over-prediction of the N fertilizer requirements by DSSAT and NuMaSS decision-aids. These decision-aids make fertilizer N predictions based on preplant N levels and, thus, only approximate N release during the maize crop. To improve the prediction of DSSAT and NuMaSS, improved estimates of N mineralization are needed. Measurements of N hydrolysates such as amino sugar N seem promising.

Subsoil nitrate levels appeared to be an important indicator of available soil nutrient N level. Thus N fertilizer predictions that do not include this source of N could easily over-predict N fertilizer requirements. The presence of subsoil nitrate and maize roots in the same zone are evidence to support the proposed explanation for the over-prediction of N fertilization by the decision-aids and models. The results indicated that subsoil nitrate accumulation in these soil series can be substantial and large enough to reduce N fertilizer application. High subsoil nitrate concentrations in the root zone could sustain crop growth and cause the lack of crop response to N fertilizer. Soil tests in the period of two weeks before and after maize planting revealed that subsoil nitrate levels could be relevant to maize growth. Consequently, it seems that the models and decision-aids need to include estimates of subsoil nitrogen in order to more accurately estimate fertilizer N needs on maize soils of Thailand.

A large amount of nitrate was found during two to three weeks after maize emergence at the 0 to 20 and 20 to 40 cm depths of no N treatment in the Lop Buri (Lb) soil, and the amount of nitrate greatly declined over time. Nitrate-N accumulated at the 20 to 40 and 40 to 60 cm depths was likely absorbed by the crop. Nitrate-N was present in small amounts in the Pak Chong (Pc) soil without N fertilizer treatment. Initial subsoil nitrate content in the Pc soil series was lower than in the Lb soil series but enough to support maize growth. Nitrate contents were significantly different between the no N fertilizer and the N treated plots. For the high applied N treatment of Pc soil, nitrate exceeded 102 kg ha^{-1} at the depth of 20 to 100 cm during 4 to 8 weeks after planting. Nitrate in both Lb and Pc soil series accumulated at soil depths where maize root density was high. The relatively high levels of subsoil nitrate suggested that high levels of N fertilizer would not be needed for the next season.

Maize roots in the Lb soil reached the depth of 49 to 62 cm, while roots in the Pc soil were found only as deep as 43 to 50 cm. Roots, after 40 to 60 days of growth, occurred in the depths where nitrate-N content was highest. High nitrate concentrations in the same layer as maximum maize root density suggested that the nitrate could have been taken up by the maize. The amount of subsoil nitrate-N was significant in relation to the N fertilizer prediction. The subsoil nitrate appears to be one of the reasons for a low response of maize to N fertilizer. Initial nitrate-N measurements to at least 40 cm would likely be useful to increase decision-aid accuracy in predicting N requirements.

Maize leaf color changed depending on maize growing stage. Consequently, the use of leaf color chart measurements was not related to nitrate status in the surface soils, nor to the N content of the maize leaves. For these reasons the leaf color chart technique was not promising to identify the soil nitrogen status. Maize leaf color changed due to maturity as well as due to soil N content.

In the wet season of 2005, maximum grain yields on four soils were lower than DSSAT's estimation. In Lb and Pc soils, the maize did not respond to N fertilizer, probably due to soybean and chicken manure application in the previous season. Large amounts of available N occurred in Lb, Pc and Bc soils probably as a result of N mineralization. Maize grain yield of St soil was, however, greatly increased with high N rates (113, 188 kg N ha^{-1}) and was higher than the yields of maize in the other soils. The low organic matter content and low N mineralization of St soil probably led to the substantial maize response to N fertilizer. The grain yield of Bc soil was only slightly increased with increasing N fertilizer. Soil OM of Bc soil was relatively high but this soil was lower in pH and higher in extractable Al content that probably caused the low yields.

In the wet season of 2006 the maize yields of the four sites (St, Bc, Lb, and Pc) in both Laos and Thailand were compared. The maximum grain yield at the four sites was still lower than the DSSAT prediction (8,000 kg ha^{-1}) except for the St Soil. Results with Lb and Pc soils contrasted with the results in 2005. Maize responded to N fertilizer at the rate of 75 and 81 kg N ha^{-1} for Lb and Pc soils. Grain yields on the St Soil were greatly increased (8,622 and 8,977 kg ha^{-1}) with higher N rate (100 and 150 kg N ha^{-1}) than the yields of maize in the other soils. The response of maize on N fertilizer in St soil was very high for both years. The grain yield of maize in the Bc soil for all treatments was lower than the yield in 2005. The lower maize yield of Bc soil probably occurred due to during maize growth rainfall was heavy with heavy cloud cover for an extended periods of time and high rainfall may have led to nutrient loss by leaching. The Bc soil was low in pH and high in KCl- extractable Al, indicating toxic levels of Al, which probably resulted in lower yields of maize grown on this soil in both years. Hydrated lime application of 0.5 t ha^{-1} for Bc soil in 2006 increased soil pH from 4.7 to 5.1, which was probably still limiting because of Al toxicity.

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APPENDIX

Appendix Table 1 Total N uptake in grain and stover yield of maize on Lb and Pc soils under different N fertilizer management in the wet season 2005.

Lop Buri (Lb)			Pak Chong (Pc)		
Applied N fertilizer	Total N in grain	Total N in stover	Applied N fertilizer	Total N in grain	Total N in stover
---------- (kg ha^{-1})----------			---------- (kg ha^{-1})----------		
0	98.1	45.1	0	62.7	32.7
32	94.8	59.2	44	69.6	33.6
50	99.9	58.8	82	72.5	36.5
100	90.6	66.6	125	81.8	40.1
188	83.7	53.7	188	88.6	49.9
Prob.	ns	ns	Prob.	ns	ns

Note † Linear (slope b) of equation N uptake = a + b*min (Node, x)
Node is the join point and x is the amount of added N.
ns = Not significant

Appendix Table 2 Total P uptake in grain and stover yield of maize on Lb and Pc soils under different N fertilizer management in the wet season 2005.

Lop Buri (Lb)			Pak Chong (Pc)		
Applied N fertilizer	Total P in grain	Total P in stover	Applied N fertilizer	Total P in grain	Total P in stover
---------- (kg ha^{-1})----------			---------- (kg ha^{-1})----------		
0	19.7	4.4	0	12.7	2.9
32	19.4	4.8	44	13.7	3.2
50	20.1	4.9	82	12.8	3.1
100	20.9	5.2	125	15.8	3.5
188	17.7	4.3	188	18.5	4.7
Prob.	ns	ns	Prob.	ns	ns

Note † Linear (slope b) of equation P uptake = a + b*min (Node, x)
Node is the join point and x is the amount of added N.
ns = Not significant

Appendix Table 3 Available N (NH_4^+-N, NO_3^--N) content on Lb and Pc soils after maize harvest in the wet season 2005.

	Lop Buri (Lb)			Pak Chong (Pc)			
Applied N fertilizer ($kg\ ha^{-1}$)	NH_4^+-N	NO_3^--N	Avail. N	Applied N fertilizer ($kg\ ha^{-1}$)	NH_4^+-N	NO_3^--N	Avail. N
	- - - - ($mg\ kg^{-1}$ soil) - - - -				- - - - ($mg\ kg^{-1}$ soil) - - - -		
0	69.8	8.3	78.1	0	94.1	1.1	95.2
32	86.1	9.9	96.0	44	98.9	1.4	100.3
50	71.2	9.5	80.7	82	90.7	1.4	93.1
100	71.8	10.9	82.7	125	91.4	1.4	92.8
188	76.1	9.7	85.8	188	109.4	1.3	110.7
Prob.	ns	ns	ns	Prob.	ns	ns	ns

Note † Linear (slope b) of equation NH_4^--N and NO_3^--N = a + b*min (Node, x)
Node is the join point and x is the amount of added N.
ns = Not significant

Appendix Table 4 Available N (NH_4^+-N and NO_3^--N) content on St and Bc soils after maize harvest in the wet season 2005.

	Saythong (St)			Bachieng (Bc)			
Applied N fertilizer ($kg\ ha^{-1}$)	NH_4^+-N	NO_3^--N	Avail. N	Applied N fertilizer ($kg\ ha^{-1}$)	NH_4^+-N	NO_3^--N	Avail. N
	- - - - ($mg\ kg^{-1}$ soil) - - - -				- - - - ($mg\ kg^{-1}$ soil) - - - -		
0	32.9	0.6	33.5	0	70.5	3.8	74.3
38	30.8	0.4	31.2	25	70.9	1.3	72.2
75	33.7	0.4	34.1	50	69.1	1.7	70.8
113	33.0	0.9	34.6	75	74.9	2.5	77.4
188	35.8	0.2	36.0	150	78.2	2.6	80.8
Prob.	ns	ns	ns	Prob.	ns	ns	ns

Note † Linear (slope b) of equation NH_4^+-N and NO_3^--N = a + b*min (Node, x)
Node is the join point and x is the amount of added N.
ns = Not significant

Appendix Table 5 Soil pH, Available P and extractable K on Lb and Pc soils under different N fertilizer management after maize harvests in the wet season 2005.

Lop Buri (Lb)			Pak Chong (Pc)		
Applied N fertilizer	P	K	Applied N fertilizer	P	K
(kg ha^{-1})	- - (mg kg $^{-1}$soil) -		- - (kg ha^{-1}) - -	- (mg kg $^{-1}$ soil) -	
pH $_w$ (1:1)	7.1		pH $_w$ (1:1)	5.7	
0	4.4	127.3	0	17.5	145.0
32	5.1	121.3	44	17.6	124.0
50	8.8	123.7	82	16.9	121.5
100	7.6.	117.4	125	16.3	117.1
188	7.1	112.0	188	21.7	141.3
Prob.	ns	ns	Prob.	ns	ns

Note † Linear (slope b) of equation Available P, Extractable K= a + b*min (Node, x)
Node is the join point and x is the amount of added N.
ns = Not significant.

Appendix Table 6 Soil pH, Available P and extractable K on St and Bc soils under different N fertilizer management after maize harvests in the wet season 2005.

Saythong (St)			Bachieng (Bc)		
Applied N fertilizer	P	K	Applied N fertilizer	P	K
- - - (kg ha^{-1}) - - -	-(mg kg $^{-1}$ soil)-		- - - (kg ha^{-1}) - - -	-(mg kg $^{-1}$ soil)-	
pH $_w$ (1:1)	5.4		pH $_w$ (1:1)	4.7	
0	22.1	65.2	0	3.8	70.3
38	21.4	53.3	25	3.3	62.1
75	18.0	56.6	50	2.9	59.2
113	15.7	52.9	75	3.7	56.8
188	16.7	55.8	150	3.7	57.1
Prob.	ns	ns	Prob.	ns	ns

Note † Linear (slope b) of equation Available P, Extractable K= a+b*min (Node, x)
Node is the join point and x is the amount of added N.
ns = Not significant

Appendix Table 7 Phosphorus uptake in grain and stover yield of maize on Lb & Pc soils under different N fertilizer management in the wet season 2006.

Lop Buri (Lb)			Pak Chong (Pc)		
Applied N fertilizer	Grain	Stover	Applied N fertilizer	Grain	Stover
- - (kg ha^{-1}) - -	- - (kg ha^{-1})-.-		- - (kg ha^{-1}) - -	- -(kg ha^{-1}) - -	
0	14.9	3.2	0	15.7	2.5
25	20.8	2.1	25	19.1	1.4
50	22.4	1.5	50	22.5	1.5
100	28.7	2.5	100	24.5	1.7
150	23.8	3.2	150	22.1	1.7
Prob.	ns	ns	Prob.	ns	ns

Note † Linear (slope b) of equation P uptake = a + b*min (Node, x)
Node is the join point and x is the amount of added N.
ns = Not significant

Appendix Table 8 Phosphorus uptake in grain and stover yield of maize on St and Bc soils under different N fertilizer management in the wet season 2006.

Saythong (St)			Bachieng (Bc)		
Applied N fertilizer	Grain	Stover	Applied N fertilizer	Grain	Stover
- - (kg ha^{-1}) - -	- - (kg ha^{-1}) - -		- - (kg ha^{-1}) - -	- - (kg ha^{-1}) - -	
0	10.6	1.9	0	4.8	1.1
25	12.2	1.7	25	7.4	1.2
50	22.8	2.5	50	7.3	1.6
100	25.3	3.9	100	9.6	1.4
150	25.9	2.8	150	8.9	2.0
Prob.	ns	ns	Prob.	ns	ns

Note † Linear (slope b) of equation P uptake = a + b*min (Node, x)
Node is the join point and x is the amount of added N.
ns = Not significant.

Appendix Table 9 Available N (NH_4^+-N, NO_3^--N) content on the Lb and Pc soils after maize harvest in the wet season 2006.

Lop Buri (Lb)				Pak Chong (Pc)			
Applied N fertilizer ($kg\ ha^{-1}$)	NH_4^+-N	NO_3^--N	Avail. N	Applied N fertilizer ($kg\ ha^{-1}$)	NH_4^+-N	NO_3^--N	Avail. N
	- - - - ($mg\ kg^{-1}$ soil) - - - -				- - - - ($mg\ kg^{-1}$ soil) - - - -		
0	47.6	3.0	50.6	0	42.5	1.2	43.7
25	44.2	3.2	47.4	25	41.1	1.6	42.7
50	47.0	3.2	50.3	50	42.8	1.9	44.7
100	46.2	3.5	49.7	100	40.1	1.9	42.0
150	47.5	4.9	52.4	150	44.6	1.6	48.2
Prob.	ns	ns	ns	Prob.	ns	ns	ns

Note † Linear (slope b) of equation NH_4^--N and NO_3^--N = a + b*min (Node, x)

Node is the join point and x is the amount of added N.

ns = Not significant

Appendix Table 10 Available N (NH_4^+-N, NO_3^--N) content on St and Bc soils after maize harvest in the wet season 2006.

Saythong (St)				Bachieng (Bc)			
Applied N fertilizer ($kg\ ha^{-1}$)	NH_4^+-N	NO_3^--N	Avail. N	Applied N fertilizer ($kg\ ha^{-1}$)	NH_4^+-N	NO_3^--N	Avail. N
	- - - - ($mg\ Kg^{-1}$ soil) - - - -				- - - - ($mg\ Kg^{-1}$ soil) - - - -		
0	18.4	1.6	20.0	0	29.6	4.1	33.7
25	19.5	1.4	20.9	25	28.7	3.2	31.9
50	16.7	2.0	19.7	50	29.6	3.5	33.1
100	17.7	1.0	18.7	100	31.8	3.5	35.3
150	17.9	1.8	19.7	150	30.4	3.4	33.8
Prob.	ns	ns	ns	Prob.	ns	ns	ns

Note † Linear (slope b) of equation NH_4^--N and NO_3^--N = a+b*min (Node, x)

Node is the join point and x is the amount of added N.

ns = Not significant

Appendix Table 11 Soil pH, Available P and extractable K on Lb and Pc soils under different N fertilizer management after maize harvests in the wet season 2006.

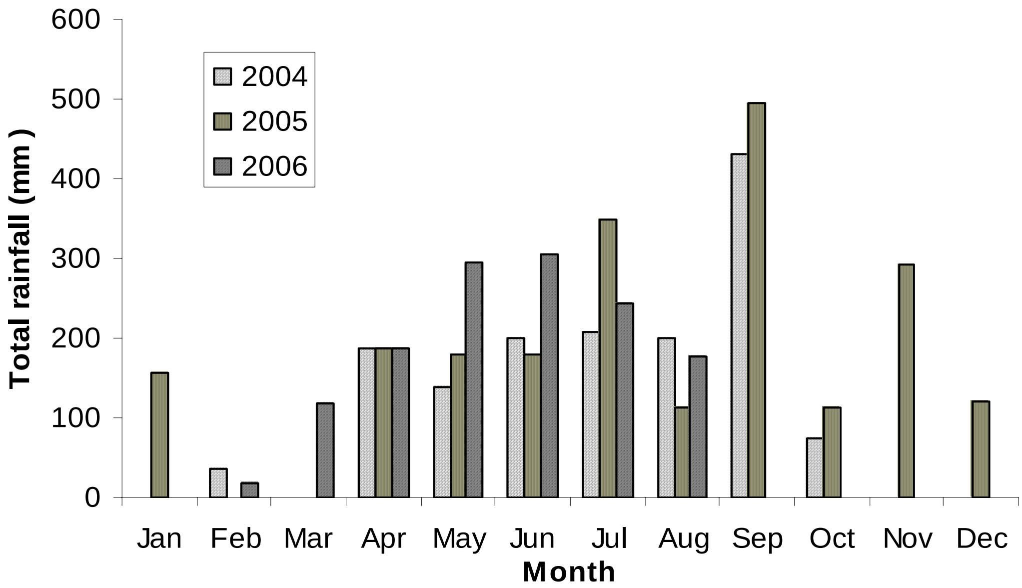
Lop Buri (Lb)			Pak Chong (Pc)		
Applied N fertilizer	P	K	Applied N fertilizer	P	K
- (kg ha^{-1}) -	- (mg kg $^{-1}$ soil) -		- (kg ha^{-1}) -	- (mg kg $^{-1}$ soil) -	
pH $_w$ (1:1)	7.1		pH $_w$ (1:1)	5.6	
0	5.2	99.0	0	16.9	84.7
25	5.8	97.3	25	18.3	87.6
50	5.0	99.2	50	17.4	87.4
100	4.7	104.2	100	17.9	75.8
150	5.5	103.8	150	18.6	76.6
Prob.	ns	ns	Prob.	ns	ns

Note † Linear (slope b) of equation Available P, Extractable K= a + b*min (Node, x)
Node is the join point and x is the amount of added N.
ns = Not significant

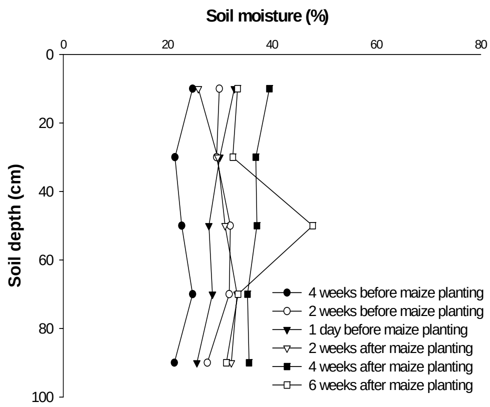
Appendix Table 12 Soil pH, Available P and extractable K on St and Bc soils under different N fertilizer management after maize harvests in the wet season 2005.

Saythong (St)			Bachieng (Bc)		
Applied N fertilizer	P	K	Applied N fertilizer	P	K
- (kg ha^{-1}) -	- (mg kg $^{-1}$ soil)-		- (kg ha^{-1}) -	- (mg kg $^{-1}$ soil) -	
pH $_w$ (1:1)	5.4		pH $_w$ (1:1)	5.1	
0	10.9	45.8	0	6.1	54.7
25	14.6	43.7	25	5.9	50.8
50	15.2	46.9	50	4.6	47.8
100	13.2	55.6	100	6.2	51.9
150	16.8	46.4	150	6.7	47.8
Prob.	ns	ns	Prob.	ns	ns

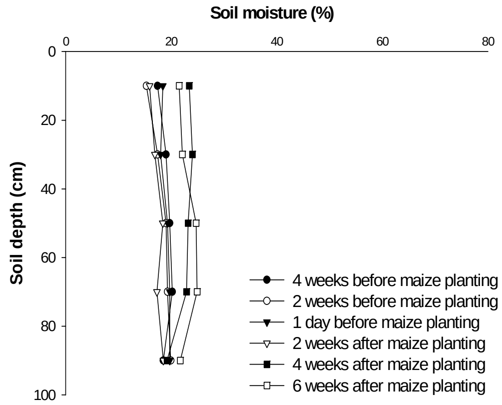
Note † Linear (slope b) of equation Available P, Extractable K= a+b * min (Node, x)
Node is the join point and x is the amount of added N.
ns = Not significant



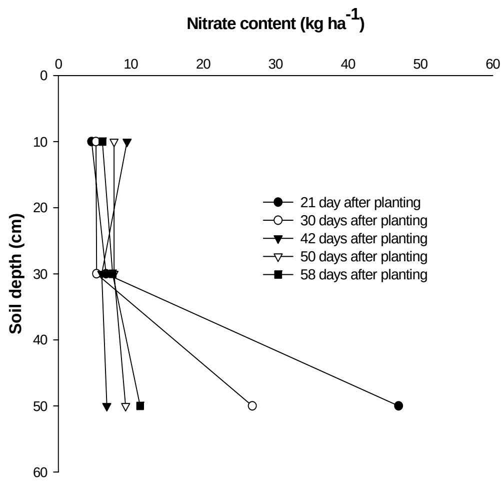
Appendix Figure 1 Total rainfall in 2004 to 2006, which were recorded during field experiments conducting in Source: Sweet Seed Corn Center. Phraphuttabat district, Sararuri province.



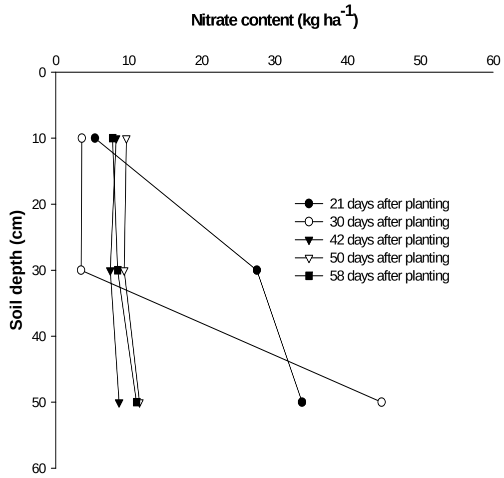
Appendix Figure 2 Soil field moisture content in Lb soil before and after maize planting (5 May to 3 July, 2005).



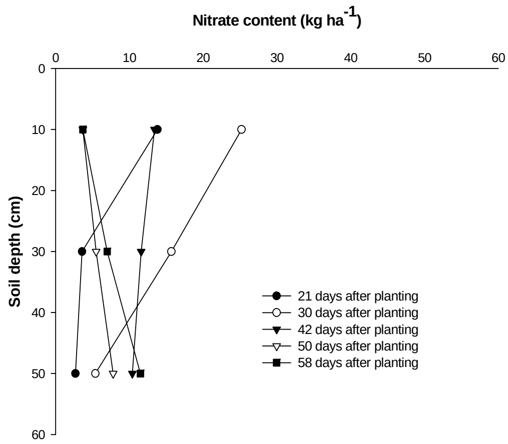
Appendix Figure 3 Soil field moisture content in Lb soil before and after maize planting (1 June to 3 August, 2005).



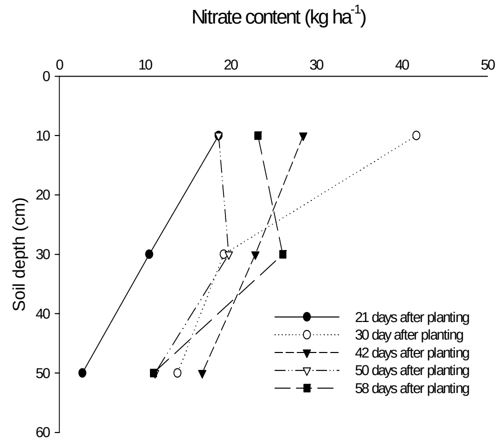
Appendix Figure 4 Nitrate content at control treatment of Lb soil series during vegetative stage.



Appendix Figure 5 Nitrate content at with N fertilizer treatment of Lb soil series during vegetative stage



Appendix Figure 6 Nitrate content at control treatment of Pc soil series during vegetative stage



Appendix Figure 7 Nitrate content at with N fertilizer treatment of Pc soil series during vegetative stage

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CONFERENCES	: 1) Nivong Sipaseuth, Pheng Xengxua, Haefele Stephan, and Linquist Bruce. 2004. Nutrient Management of Rainfed Lowland Rice in Laos: Achievement and Opportunities. Mekong Rice Conference, 15-17 October, 2004. Ho Chi Minh City, Vietnam. 2) Nivong Sipaseuth, Tasnee Attanandana, and Russell S. Yost. 2006. Nitrogen fertilizer response which is simulated from DSSAT software on some important maize soils in Thailand and Laos. NAFRI-SM-CRSP Regional Workshop, Pakse, Laos, 17-19 July, 2006.