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NAME: Mr. Vongvilay Phengsouvana

THIS THESIS HAS BEEN ACCEPTED BY

____________________ **THESIS ADVISOR**

(Professor Tasnee Attanandana, D.Agr.)

____________________ **THESIS CO-ADVISOR**

(Professor Russell Yost, Ph.D.)

____________________ **DEPARTMENT HEAD**

(Assistant Professor Piboon Kanghae, M.Sc.)

APPROVED BY THE GRADUATE SCHOOL ON ____________________

____________________ **DEAN**

(Associate Professor Gungana Theeragool, D.Agr.)

THESIS

LIME APPLICATION IN TWO ACID UPLAND SOILS FOR SOYBEAN PRODUCTION IN CHAMPASAK PROVINCE, LAO PDR.

VONGVILAY PHENGSOUVANA

A Thesis Submitted in Partial Fulfilment of
the Requirements for the Degree of
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Vongvilay Phengsouvana 2010: Lime Application in Two Acid Upland Soils for Soybean Production in Champasak Province, Lao PDR. Master of Science (Soil Science), Major Field: Soil Science, Department of Soil Science. Thesis Advisor: Professor Tasnee Attanandana, D.Agr. 77 pages.

The major challenges to soybean production in Laos are high soil acidity and low nutrient contents in soils. In addition to the soil challenges, farmers still lack sufficient knowledge of nutrient management and fertilizer application. Together these factors have resulted in low yields of major food crops and preclude use of vast regions of acid, upland soils. Field experiments assessing and illustrating the need for lime application, as well as P, and K fertilizers are needed to help farmers learn to use lime and fertilizer effectively. This study consists of three experiments: One of which was a characterization of available lime materials. Three liming materials, including $Ca(OH)_2$, $CaCO_3$ and marl, were collected from representative suppliers and sources in Laos and Thailand. Key properties were measured including the percentage of calcium carbonate equivalent (CCE) and particle size distribution. Lime materials were sized to pass sieves of 10, 35 and 60 mesh which corresponds to particle diameters of 2.0, 0.5 and 0.25 mm, respectively. The particle size analysis of the three lime materials confirmed that calcium hydroxide ($Ca(OH)_2$) had a smaller particle size than calcium carbonate $CaCO_3$ and marl. The percentage of the liming materials that passed through the 60 (0.25) mm sieve were 93.8 and 88.8 % for $Ca(OH)_2$ and $CaCO_3$, respectively, indicating these two materials would be quite reactive and would neutralize soil acidity readily if they also were characterized by high CCE. Marl, on the other hand, appears to be too coarse to be highly effective. The high percent of CCE in these three liming materials indicated that all materials have the chemical composition necessary to increase soil pH. A second study was a comparison of four methods of lime requirement determination. Eight representative soybean soils were selected from representative locations of the Lao PDR for this study. Most soils are Ultisols soil. Approximately 2 kg of each soil was collected from the depth of 0 to 20 cm. Selected physical and chemical properties of the soils were analyzed. The incubation methods of Dunn and Kissel and buffer solution methods, of Adams-Evans, were compared for eight acid soils. The results showed that lime requirement by the Dunn incubation method, which increased soil pH to 5.5 of each soil, varied greatly with soil. The lowest and highest of lime requirements were Saravanh and Xiengkouang soils, respectively. There were many soils that required less than 1000 kg $CaCO_3$ ha^{-1} particularly when using the Kissel and extractable aluminum methods. The Bc, Xk and Ls soils would require maximum large amounts of lime according to the Adam-Evans methods. The highest amount of LR of Bc, Xk and Ls soils was estimated at 7,600, 6,100 and 4,900kg $CaCO_3$ ha^{-1} which illustrates the high levels of soil acidity in the soils of Laos. The lime prediction of these three soils using the other methods was much lower. A third experiment was conducted to determine the appropriate rate of lime application for soybean on acid soil in field conditions. Two field experiments were conducted in the wet seasons 2006-2007. The grain yields were highly significantly increased with increasing liming rates (2250 and 4590 kg $CaCO_3$ ha^{-1}) on the two contrasting soils. The amount of lime needed based on the field experiments on Bc and Hk soils was about 1125 and 1013 kg ha^{-1} in first and second year with the pH 5.2 and 5.7, respectively. The Kissel and extractable Al methods of estimating lime requirement were closely corresponded to the field lime requirement determination for the Bachieng soil. An economic dominance analysis of the soybean yields in Bachieng and Hoythakouane sites indicated very high returns to the addition of lime in both years. The net return of Bc soil was obtained extremely high in the treatment L1 (about $ 402 ha^{-1}) in 2006, while in 2007 the net return was about $ 519 ha^{-1}(L1). In the Hk soil, in 2006 the maximum net return was $503 ha^{-1} (L1) the maximum net benefit of soybean of 2007 was $ 544 ha^{-1} (L1). This illustrated that liming these soils resulted in remarkably high net benefit and would be extremely profitable.

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Vongvilay Phengsouvana

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TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF FIGURES

LIST OF ABBREVIATIONS

Al KCl	= Aluminum extracted by potassium chloride
Alo	= Aluminum extracted by acid ammonium oxalate
ANOVA	= Analysis of variance
Bc	= Bachieng
C. V	= Coefficient of variance
CCE	= Calcium carbonate equivalent
Ca-P	= Calcium phosphate
CRD	= Completely randomized design
DNA	= Deoxyribonucleic acid
DMRT	= Duncan's Multiple Range Test
DTPA	= Diethylenetriaminepentaacertic acid
Feo	= Iron extracted by acid ammonium oxalate
Fed	= Iron extracted by dithionite
HFS	= Hectare furrow slice
Hs	= Hoysai soil
Hk	= Hoythakoune soil
LRP	= linear Response plateau
LVN	= Lao-Vietnam
ns	= Not significant
Pe	= Pek soil
Ps	= Phasay soil
PDSS	= Phosphorus Decision Support System
SAS	= Statistical Analysis System
Xn	= xaithani soil
SR	= Saravanh
Vp	= Vapi soil

LIME APPLICATION IN TWO ACID UPLAND SOILS FOR SOYBEAN PRODUCTION IN CHAMPASAK PROVINCE, LAO PDR.

INTRODUCTION

More than 80 percent of population in the Lao PDR is involved in agriculture. The soils in the country are low in nutrient contents and acidic. Champasak province is one of seventeen provinces and located in the southern part of the Lao PDR. The province comprised of two ecosystems, lowland and upland. Most of the cultivated upland soils in Champasak province are generally acid (pH 4.5-5.0) and low in organic matter (Linquist and Sengxua, 2001). The acidic upland soils, which belong to the orders Oxisols and Ultisols are widespread in the Bachieng and Pathumphone districts, Champasak province. In strongly acid soil, excess soluble or exchangeable Mn and Al produce toxicity in many crops (Jackson *et al*., 1967). Uexkull and Bosshart (1989) characterized the low fertility of acid soils as a combination of Al, Mn, Fe toxicity and P, Ca, Mg, K deficiency. Andrade *et al*. (2002) found that soil acidity constrains plant growth due to many factors, including low pH, Al and Mn toxicity, Ca and Mg deficiency and low P availability. Borkert and Stredo (1994) reported that acid soil toxicity is not a single factor but a complex of factors that reduces the growth of plants.

Soybean [*Glycine max* (L) Merrill] is a potential crop for upland farmers in Bachieng and Pathumphone districts. Farmers in these areas have been cultivating several upland crops such as upland rice, maize, soybean and root crops. Many farmers attempt to cultivate legumes to increase their income; however low yields of soybean is largely due to farmers' lacking knowledge on soil nutrient management, and due to low soil pH. Unfortunately, upland farmers don't have any recommendations on how to manage acidic upland soils. Tropical subsoils are often very acidic and low in Ca content, which limits deep soybean root growth. Soybean, maize, peanut, and mungbean are sensitive to soil Al saturation compared to upland rice and cowpeas (Uexkull and Bosshart, 1989). To promote the cultivation of soybean and other legumes according to the government's policy and farmers' preferences, the soil pH needs to be increased with lime application. Lime application may be one option to increase soil pH, which would also improve crop yield for farmers in these areas. Lime can be applied to soybean and the residual effect of liming from the first application can be adequate for the next crop of soybeans (Anetor and Akinrinde, 2006). Pierce and Warncke (2000) found that the pH change was related to the amount of lime applied. Meng *et al*. (2004) found that liming at the highest rate resulted in a decline in subsoil acidity and increased grain yield. Son *et al*. (1994) studied acidic upland soils for crop production in Vietnam, and found that liming and fertilization reduced soil acidity and improved soil P and K availability. Lime is important for soybean because its effect to decrease in toxic concentrations of Al and Mn (Ranjit *et al*., 2007), and increase P, K and Ca uptake (Murata *et al*., 2002).

To increase soybean yields in diverse soils in Champasak province, therefore, research on lime rates application and N, P, K fertilizers is needed. Managing acidic soils to reduce the adverse effects of acidity for crop growth in Bachieng and Hoythakoune soils is a necessity. Thus, the study of reducing acid soil limitations to soybean production was carried out using the NuMaSS decision-aid for lime prediction.

The main objective of this study was to determine the appropriate amount of lime for soybean production on two acidic soils and to identify lime requirement methods that accurately predict lime requirements based on soil analysis. Decision aids based on the diagnosis, prediction, economic analysis, and recommendations are likely to assist in improving yields. This study was designed to test NuMaSS prediction of lime requirement for crops in the Bachieng and Hoythakoune soils.

OBJECTIVES

1. Determine the effect of soil acidity on limiting yields of soybean in Laos

2. Determine appropriate rates of lime application on soybean

3. Investigate the effects of lime on phosphorus and potassium fertilization

4. Compare four lime requirement methods for possible use in acid soils of Laos.

LITERATURE REVIEW

1. Acid soils

Low pH is a characteristic feature in acid soils. Acid soils are strongly affected by the composition of the parent material from which they were formed. A low soil pH enhances solubility of toxic aluminum and manganese. Soils become acidic because of recurrent leaching, coupled with input of acids (substances capable of releasing H^{+}) (Singer and Munns, 2002). Acidic soils normally develop high levels of dissolved and exchangeable Al. Aluminum is a major element in the aluminosilicate and aluminum oxides of the clay fraction. As the soil becomes more acidic, these minerals become more soluble, releasing Al into solution. As its concentration rises, Al^{3+} displaces H^{+} and other exchangeable cations, occupying much of the exchange capacity. The solubility of Al and Mn in mineral soils increases rapidly when soil drops below a value of 5 so that low pH and high soluble Al and Mn concentration are interrelated. Although the availability of plant nutrients such as P and Ca can also be limiting at low soil pH, Al toxicity is probably the foremost growth-limiting factor in acid soils. Root growth, and consequently water and nutrient uptake, are inhibited when dissolved Al attains toxic levels in soil solution. The capacity factor of soil acidity is highly important because it represents that fraction of total soil acidity (solution and exchangeable) that must be neutralized to achieve a desired soil pH (McLean, 1982). Soil pH, as measure of active acidity in medium that behaves as a weak acid, gives little indication of the amount of lime to be applied (Tisdale and Nelson, 1975). Some methods of relating the change soil pH to the addition of known amounts of base are necessary and this is called a lime requirement determination.

2. Problems of acid soils

A problem acid soil has a pH of less than 5.6 and usually below pH 5.0, but also depends on the acid tolerance of the crop plant. Cregan (2008) reported that low soil pH is associated with a number of soil chemical and biological characteristics that manifest themselves as the components of the problem acid soil syndrome. These components may adversely affect plant growth. The following specific problems are associated with acid soils problem: aluminum toxicity; manganese toxicity; molybdenum deficiency; legume nodulation failures; increase in plant disease and, calcium and magnesium deficiency. Nutrients which are less available to plants as pH drops below 6.0 include P, K, Ca, Mg, S and Mo (Dorn, 1914).

Plants vary considerably in their tolerance to some of the components of the acid soil syndrome problem. Therefore, the expression of some acid soil problems is not merely one of soil chemical characteristics but rather the result of a complex interaction between the plant and the soil. Acidic soils normally develop high levels of dissolved and exchangeable Al (Singer and Munns, 2002). Acid soils are generally unproductive. Their low productivity may be due to soil acidity, aluminum toxicity, low content of major nutrients low base status and hydrogen aluminum, and iron (acidic cations) replace calcium, magnesium, potassium, and sodium (basic cations) on the soil cation exchange complex. Changes in fertility management and the use of acid-tolerant crops sometimes help (Michael and Donald, 2006). Acidic soils create production problems by limiting the availability of some essential plant nutrients and increasing toxic elements in soil solution, such as aluminum and manganese, the major cause of poor crop performance and failure in acidic soils (Uexkull and Bosshart, 1989). Below soil pH 5.5, aluminum may be concentrated enough to limit or stop root development. Soil acidity is, therefore, an important environmental factor which can influence plant growth, and can seriously limit crop production.

At pH values below 5.0, aluminum, iron and manganese are often soluble in sufficient quantities to be toxic to the growth of some plants (Brady, 1974). Uexkull and Bosshart (1989) described the major soil constraints to crop production of most acid upland soils may have one or more of the problem in the incomplete list below: low pH, high exchangeable Al concentration, high Al saturation percentage, high available concentration, low concentration of exchangeable Ca, Mg and K, low base saturation percentage, low available P and high P fixation capacity, low and pH-dependent CEC, low organic matter and absence of OM-clay mineral complexes, low microbial activity, sensitivity to erosion, low water-holding capacity, low permeability to air, water, and roots (high soil strength), slow water infiltration rate, and sensitivity to compaction by heavy machinery.

Acidity in the soil comes from different sources: humus or organic matter, aluminosilicate clays, hydrous oxides of iron and aluminum, soluble salts and carbon dioxide (Tisdale and Nelson, 1975). There are acid soil conditions in many regions of soybean production in the tropics and the detrimental effects of soil acidity include the reduction of rhizobia populations, limiting biological nitrogen fixation. Rhizobia are important to ensure the establishment of effective N_2 fixing symbioses in acidic soils (Andrade *et al*., 2002). Manganese toxicity is a problem in many acid Oxisols of Hawaii with low soil pH (<5.6), low available Ca and where large amounts of organic amendments have been added (Hue *et al*., 2001). Neutralization of soil acidity resulted in optimal balance of biological processes related to soil organic matter transformation and provided for its conservation (Dierolf *et al*., 2001).

3. Management of acid soils

Management of acid soils is needed for increasing crop yields. There are many ways to correct acid soils. The first step in the management of acid soils is to identify the extent and severity of the problem. Poor yields of acid sensitive crops may indicate an acid soil condition, but soil tests are the only sure method of identifying an acidity problem. With careful sampling of fields, soil tests can determine the extent and severity of soil acidity, the rate of lime required, and provide an estimate of crop response to lime. An estimate of crop response along with the cost of lime provides a basis for assessing the economics of liming. Each field that is to be limed should be carefully sampled. Divide a field into areas on the basis of soil type or differences in crop growth and sample each of these areas separately. In some cases, growing crops that are more tolerant to acidity is an alternative to liming. But as soils gradually become more acid, the choice of crops becomes limited. The long-term goal should be to lime soils to a pH value best suited to the crops being grown. After a desired soil pH has been achieved, the amount of lime required to maintain soils in a suitable pH range will depend on fertilizer rates, soil type and cropping practices (Farhoodi and Coventry, 2008)

4. The importance of lime

The role of lime in determining the availability of phosphate in soil has been the subject of controversy for many years. While increased availability of phosphorus is observed on some soils, on others availability is not increased and some reduction in availability takes place. Pavan *et al*. (1984) found that $CaCO_3$ applications can reduce exchangeable aluminum and manganese while increasing exchangeable capacity. When soils are acid, there may be many benefits from liming. Liming to a pH of 6.0 to 6.5 or higher provides an ideal environment for bacteria in soils. The effects of liming are therefore a combination of (a) physical, (b) chemical, and (c) biological. Physical properties: Improved soil structure is somewhat encouraged in an acid soil by the addition of lime, although the influence is largely indirect. The effect of lime usually improves water drainage and air circulation. Improve crop response to fertilizer by improving the uptake of primary nutrients.

The following chemical changes occur if soil with a pH of 5.0 is limed to a more suitable pH value of 6.5:

4.1 The concentration of hydrogen ions will decrease.
4.2 The solubility of iron, aluminum, and manganese will decline.
4.3 The availability of phosphates and molybdates will increase.
4.4 The exchangeable calcium and magnesium will increase.
4.5 The percentage base saturation will increase (Brady, 1974).

Of the specific chemical effects of lime, reduction in acidity is one commonly recognized and usually the most important. However, the indirect effect of increasing nutrient availability and reducing the toxicity of certain elements are probably the most important. The liming of acid soil enhances the availability and plant uptake of elements such as Mo, P, Ca, and Mg. At the same time, liming reduces concentrations of Fe, Al, and Mn, which under strongly acid condition the latter two elements are likely to be present in toxic quantities (Brady, 1974)

Biological properties such as the microbial activity are limited in strongly acid soil. Most microorganisms function most effectively in soils that are weakly acid or neutral. When lime is applied to acid soil, it can improve the microbial activity in the soil enhancing microbial mediated processes such as mineralization, the decomposition of organic matter in the soil and increasing nutrient availability in soil (Brady, 1974)

Kamprath (1970) reported that neutralization of the toxic aluminum was one of the most important benefits of liming and could be used as a basis for estimating lime requirement. Subsequently, Cochrane *et al*. (1980) showed how the different tolerance of tropical crops could also be incorporated into making lime recommendations while reducing the amounts of KCl-exchangeable aluminum. Rehm *et al*. (2002) reported that the availability of phosphorus is also affected by soil pH; liming to a pH of 6.0 to 6.5 also increases the supply of soil phosphorus which is available to plants.

Kissel *et al*. (2007) developed an alternative pH and titration method of determining lime requirement was to implement a single-addition titration with calcium hydroxide to determine the lime requirement of soils. Negative effects of liming can include reduced phosphate availability, suppressed availability of Mg and K, and induced deficiencies of micronutrients such as boron and iron (Cregan *et al*., 1980).

Liming is the addition of alkaline material to soil. Favored liming materials are crushed limestone, containing calcite, and dolomite limestone, containing calcium and magnesium and carbonate. Liming as the term applies to agriculture is the addition to the soil of any calcium and magnesium containing compound that is capable of reducing acidity (Tisdale and Nelson, 1975). Agricultural lime is a primary material for improving soil condition and it is important to produce high yields with best quality (Plaster, 1985). There are characteristics of particular lime material for it to be considered a satisfactory material for raising soil pH_w (water1:1) it should have a mild alkalizing (pH increasing) effect, 2) it should result in a desirable proportion of cations adsorbed on the cations exchange soil. The added cations should be mostly Ca^{++}, although some Mg^{++} is required. Little or Na^{+} should be included, 3) it should have a favorable effect on soil structure. The most favorable base for good soil structure is Ca^{++}, and 4) it should not be expensive. Almost all liming material used is ground limestone rock. However, excessive amounts of lime may result in yield reduction and induced deficiencies of micronutrients. Tisdale and Nelson (1975) reported that the neutralizing value relative to calcium carbonate of some common liming materials containing no contaminants included calcium hydroxide ($Ca(OH)_2$), calcium carbonate ($CaCO_3$) and marl were 136, 100 and 70-90 %, respectively.

5. Lime requirements

The lime requirement is the amount of base needed to produce a certain pH increase in soil pH. A major problem of managing acid soil is to estimate the quantity of lime required to raise the soil pH to a certain pH level (Bohn *et al.*, 1985). Some areas of a field may require higher rates than others and some areas may not require any in the usually spatially variable fields. A lime requirement test should be requested in order to determine the amount of lime required. A variety of techniques have been developed to measure the lime requirement of soils, including Dunn, Kissel Adams-Evans and extracble Al methods. The lime affects the labile P fractions (Curtin and Syers, 2001). All lime requirement methods, however, are based on similar underlying principles. First is the obvious fact that the measured lime requirement must accurately reflect the amount of liming material needed to raise the pH of the soil to the target pH when the lime applied under field conditions. To arrive at a satisfactory solution to the problem of how much lime to apply one must consider the proposed crop as well as the actual pH of untreated soil. The lime requirement is a measure of the base required to neutralize a fraction of the total acidity to attain a desired soil pH for favorable crop growth (McLean, 1982).

A limiting factor in many acid soils is aluminum toxicity and this has led to the development of methods to assess lime requirement based on exchangeable aluminum. Commonly the exchangeable aluminum value is multiplied by factor to determine a lime rate sufficient to neutralize most of the exchangeable aluminum (Cregan *et al*., 1980). Because crops differ in their sensitivity to soil acidity, recommendation for liming may differ with crops.

6. Soil pH and lime application

Lime applications are designed to neutralized soil acidity. Occasionally, as much as six months may be needed before pH changes significantly (Mamo *et al*., 2003). Neutralization was quicker if particle size is smaller (less than 60 mesh) and the lime was well mixed with the soil. Typically, it requires two to three years to observe the full effect of lime application on soil pH. Benefits from lime application, however, often occur within 4 weeks with adequate soil incorporation and moisture. Improving soil condition is important to produce high yields with best quality.

Lime can improve acid soil physical properties. If a lime recommendation exceeds 4 tons ha^{-1}, the lime should be thoroughly mixed in the plow layer by applying one-half the recommended rate before plowing and the other half after plowing followed by harrowing (Murdock, 2007). The rate of neutralization of soil acidity is related to fineness, uniformity of distribution in the soil, and the rate of diffusion of Ca from the lime particles to the soil of neutralization (Henry and Boyd, 1997).

Lime is dissolved slowly by moisture in the soil to produce Ca^{2+} and HCO_3 according to the following reaction.

$$CaCO_3 + H_2O + CO_2 \Rightarrow Ca(HCO_3)_2,\ Ca(HCO_3)_2 \Rightarrow Ca^{++} + 2HCO_3^-$$

Newly produced Ca^{2+} can be exchanged with Al^{3+} and H^+ on the surface of acid soils

$3Ca^{2+} + 2Soil\text{-}Al \Rightarrow 3Soil\text{-}Ca + 2Al^{3+}$

HCO_3^- will neutralize H^+ and H_2CO_3 is formed.

$HCO_3 + H^+ \Rightarrow H_2CO_3$, $Al^{3+} + 3OH^- \Rightarrow Al(OH)_3$, $H^+ + OH^- \Rightarrow H_2O$

The principle is that the anion must belong to the weak acid category, which means that the anions readily combine with protons, which are the source of acidity. The beneficial effect of liming is increases the soil pH to neutralize toxic elements such as Al and Mn and to supply calcium and magnesium as a nutrient and to increase crop yields (Veloso *et al*., 1992). Turan *et al*. (2002) studied on effect of different doses on soil properties and indicated that the application of lime materials improved plant growth and the N, P, K, Ca and Mg contents of plant increased by increasing rates of lime. Meng *et al*. (2004) found that soil pH was sharply increased by liming in the first year and thereafter gradually declined. All lime rates maintained a higher pH than that of the check treatment in the plough layer (0 to 20 cm) for 15 years. Liming increased pH of the soil which promoted a better soil physical condition and consequently helped in achieving higher system productivity (Kuntal *et al*., 2008).

7. Lime recommendation for field crops

Soil pH is usually referred to as the intensity factor of soil acidity and reflects the amount of acidity present in the soil solution and serves as an index of the acid base status of the soil. Therefore, accurate and rapid methods to determine the amount of liming material to affect a soil pH change are needed (Adams and Evans, 1962). Cornell University (2008) reported that lime recommendations depends on 1) Current and desired pH, 2) Exchangeable acidity, 3) Base saturation of the soil at the current and at the desired pH and 4) Tillage depth. Lime is usually a mixture of calcite and dolomite that has been crushed so that it is sufficiently fine to react readily with the soil. The rock from which the product is obtained may contain silica and other impurities that have no effect on soil acidity (Borkert and Stredo, 1994). Lime recommendations are usually made to reach a target pH in the top 15 cm of soil.

Large doses of lime, which are not uniform mixed, have a small or variable effect on the content of calcium, potassium and magnesium in the soil (Loide, 2004). If the soil is tilled deeper than 15 cm, then proportionately more lime is required to reach the same target soil pH. When tillage depths are reduced lime application rates should be reduced proportionately. More frequent liming will be needed.

MATERIALS AND METHODS

This study consists of three experiments:

Experiment 1: Characterization of lime materials

Experiment 2: Comparison of four methods of lime requirement determination

Experiment 3: Test the appropriate rate of lime application for soybean on acid soil in field conditions in Southern Laos

1. Experiment 1: Characterization of liming materials

Three liming materials include hydrated lime ($Ca(OH)_2$), calcium carbonate ($CaCO_3$) and marl were selected and collected from representative sources in Laos and Thailand. In Laos, hydrated lime was collected from Khammouane province. From Thailand two agriculture limes (lime ($CaCO_3$) and marl) were selected from the Department of Land Development. The two critical properties of lime were measured including the percentage of CCE (calcium carbonate equivalent) and the particle size distribution.

1.1 Particle size analysis

One hundred grams of each lime ($CaCO_3$), hydrated lime ($Ca(OH)_2$) and marl) was sieved to pass particle size of 10, 35 and 60 mesh which corresponds to range from 2.0, 0.5 and 0.25 mm, respectively. The size distribution was presented as weight percentage of the materials passing the large sized sieve and remaining on the smaller.

1.2 CCE analysis

A 0.500g sample of lime was put into a 125-mL Erlenmeyer flask to which 25-mL of standard 1.00 *M* HCl was added. The solution was boiled on the hot plate for 5 minutes, cooled and titrated with 1.0 *M* NaOH using 0.25 *M* phenolphthalein as an indicator. The molarity of NaOH was determined with standard acid, the percentage of calcium carbonate equivalent was determined with the following formula calculation.

$$\% \text{ CCE} = [(\text{mL HCl} \times M)-(\text{mL NaOH} \times M) \times 50 \times 100] / [1000 \times \text{lime wt (g)}]$$

Where:

CCE = Calcium carbonate equivalent

Lime Wt = weight of liming material (g)

M = Molarity

2. Experiment 2: Comparison of five methods of lime requirement determination

2.1 Soil sampling

Eight representative soybean soils were selected from different locations of the Lao PDR for this study. The soils included Vapi (Vp), Bachieng (Bc), Hoythakoune (Hk), Phonthong (Pt), Nasaithong (Ns), Xaitany (Xn), Xiengkhouang (Xk) and Latsen (Ls) soils. Vapi soil was collected from Vapi district, Saravanh province. The three soils (Bc, Hk and Pt) were collected in Champassak province, Bachieng, Phatumphon and Phonthong districts, respectively. For Ns and Xn soils were collected from the central part of Laos in Nasaithong and Xaitany districts, near Vientiane. For the other two soil samples were selected in Pek and Phasay districts, Xiengkhouang province, respectively. Most soils are classified as Ultisols according to Soil Taxonomy. Approximately 2 kg of each soil was collected from the depth of 0 to 20 cm.

2.2 Basic soil analyses

All eight soil samples were air-dried and crushed to pass a 2 mm sieve and thoroughly mixed. Some physical and chemical properties of the soils were analyzed. Soil pH was determined by glass electrode (soil water ratio 1:1), organic carbon was determined by method of Walkley Black titration (Walkley and Black, 1934). Extractable aluminum was analyzed by three methods, 1) Extractable Al and Fe were measured by acid ammonium oxalate, citrate-bicarbonate-dithionite methods (Loeppert and Inskeep, 1996). Extractable Fe, was determined by diethylenetriaminepentaacertic acid, (DTPA) pH 7.3 (Tan, 2005). Extractable Al by KCl method (Barnhisel and Bertsch, 1982). Phosphorus was extracted by Bray-2 (Bray and Kurtz, 1945). Effective cation exchange capacity (ECEC) was measured by ammonium acetate (pH7) method (Rhoades, 1982; Chapman, 1965). Extractable K was analyzed by NH_4OAc pH 7. Total N was analyzed by the Kjeldahl method (Bremner, 1996).

2.3 Soil incubation study

Methods of lime requirement determination

2.3.1 Dunn method

Ten grams of each air-dried soil were placed in a 100-mL beaker and 0, 5, 10, 20, 30 and 40-mL of 0.05 *M* $Ca(OH)_2$ solution was added to the soils. There were 3 replications with 18 beakers for each soil sample. Deionized water was added to adjust the final volume to be 50-mL, and 3 drops of chloroform was added to inhibit microbial activity. The soil sample was incubated at room temperature for 4 days and soil pH was determined. The incubated samples were shaken 2 times a day. The resulting pH and amount of added lime was plotted to make the titration graph.

2.3.2 Adams-Evans's method

Adams-Evans Buffer Solution, pH 8.0±0.1

Dissolve 20 g of *p*-nitrophenol, 15 g of boric acid (H_3BO_3), 74 g of potassium chloride and 10.5 g potassium hydroxide in 750-mL beaker and dilute to l0-fold with deionized water. Adjust pH to 8.0 with potassium hydroxide.

Soil pH measurement

Weigh 10 g of air-dried soil, pulverized to pass a 10 mesh sieve (<2.0 mm) into a 50-mL beaker. Add water and soil to soak for one hour. Read soil suspension pH on a standardized pH meter. Add 10.0-mL of Adams-Evans Buffer and stir to each soil suspension for one minute, and every five minutes for twenty minutes. Immediately following the final stirring at twenty minutes after addition of Adams-Evans buffer solution, insert the electrodes and observe the pH reading of the suspension while stirring gently. Record the pH reading to the nearest ± 0.1 unit as pH and compare with the graph in the reference section on the Adams-Evans buffer (Adams and Evans, 1962). The following equation was used for calculation of the lime requirements**.**

LR = (VmL*0.2 *M* HCl)*(mol$_c$ $CaCO_3$* soil weight kg ha^{-1})*(pH unit)/ (1000 kg*mL buffer solution)

2.3.3 Kissel's method

Lime requirement was determined in agricultural lime of the eight soils of the Lao PDR. The procedure used to determine the lime requirement in soil followed the description of Kissel *et al*. (2007) and is described in the following steps:

Determination of the Lime Buffer Capacity (LBC) in Routine Laboratory Practice.

Twenty g of each air-dried soil, pulverized to pass 10 mesh sieve (<2.0 mm), into a 50-mL beaker, 20-mL of 0.01 *M* calcium chloride ($CaCl_2$) was added, the mixture was equilibrated for at least 15 min, and pH (referred to pH_1) was measured using a glass electrode. This was followed by the addition of $Ca(OH)_2$ while stirring [currently 1.8-mL saturated $Ca(OH)_2$], the mixture was equilibrated for an additional 30 min, and a second measurement of pH (referred to as pH_2) was taken. The following equation is used for calculation of the lime buffer capacity (LBC):

$$LBC = mL \times N \times EWCaCO_3 / (\text{Soil weight} \times (pH_2 - pH_1)) \quad [1]$$

Where:

mL is the volume of $Ca(OH)_2$ added

N is the normality of the saturated $Ca(OH)_2$ (0.046 N)

EW is the equivalent weight of $CaCO_3$ (50 mg kg^{-1})

Soil weight was 20 g for each sample is adjusted according to soil province region based on an average bulk density (assumers BD=1.5 g cm^{-3})

pH_1 and pH_2 are the measured values of soil pH before and after the addition of $Ca(OH)_2$.

LBC to be directly expressed as mg $CaCO_3$ kg^{-1} pH^{-1}, the soil weight for Equation (1) is entered as kg (20 g = 0.020 kg).

Calculation of the Lime Requirement

To calculate the Ag lime recommendation in kg of agriculture lime per hectare, the following equation is used:

$$\text{Lime kg ha}^{-1} = LBC \times (\text{target } pH_W - pH_{CaCl2}) \times 2 \times 1.5 \times (\text{soil depth}/15) \quad [2]$$

3. Experiment 3: Test the appropriate rate of lime application for soybean on acid soil in field conditions.

3.1 Experimental soils and soil properties

Two field experiments were carried out in the wet season of 2006 and 2007, in Champasak province, with elevation of 204 m. One soil was located at the Horticulture Research Station in Bachieng district, about 24 km from Pakse city. The second soil was located at the Hoythakoune Seed Multiplication Station in Pathumphone district, about 70 km of Pakse city. The distance between the two soils is about 90 km. Two representative upland soils (Bachieng and Hoythakoune) were selected for study because these soils are extensively used by farmers for upland crops. The majority of the land is fallow; however, a minor agricultural land use system in these areas is upland rice, coffee, soybean, peanut and other crops.

3.2 Crop management, liming and fertilizer rates

Soybean (*Glycine max*. L., "Chiang Mai 60") was selected for the Bachieng and Hoythakoune experiments. The soybean seeding rate was 18 kg ha^{-1}. Before planting, soybean seeds were mixed with rhizobium at the ratio of 4000 g: 200g of seed: rhizobium. In the wet season of 2006, soybeans were planted in the Bachieng experiment on July 10, and July 1 for Hoythakoune experiment. In 2007, soybean was planted on June 28, and July 10 for Bc and Hk soils, respectively. The growth period of soybean is about 90 days after emergence. Weeds were controlled by hand weeding at 15 and 35 days after emergence. In 2006, soybean was harvested on October 10 and November 2 for Bachieng and Hoythakoune soils, respectively. In 2007, soybean was harvested on September 29, and November 9 for Bachieng and Hoythakoune soils, respectively.

Lime applications consisted of five different rates according to the prediction from the NuMaSS model for each soil. Lime application in 2006 was used to develop a response curve with different liming rates of 0, 360, 730, 1600, and 2160 kg $CaCO_3$ ha^{-1} for Bachieng soil and 0, 330, 670, 1000, and 1300 kg $CaCO_3$ ha^{-1} for Hoythakoune soil (Table 1). In 2007, lime was re-applied for a total application of 0, 620, 2170, 2990, and 4320 kg ha^{-1} for Bc soil and 0, 170, 330, 1250, and 1700 kg $CaCO_3$ ha^{-1} for Hoythakoune soil. The lime rate was increased because the soil pH after first crop did not increase as expected and remained less than 6. Soil phosphorus and potassium were applied at 19 kg P_2O_5 and 74 kg K_2O ha^{-1} for Bachieng and 13 kg P_2O_5 and 60 kg K_2O ha^{-1} for Hoythakoune soils, respectively (Table 2).

Table 1 Lime and fertilizer rates for soybean experiment of Bc and Hk soils in 2006

Bachieng soil		Hoythakoune soil	
Lime rate	N-P_2O_5-K_2O	Lime rate	N-P_2O_5-K_2O
- - - - - - - - - ($kg\ ha^{-1}$) - - - - - - - - -		- - - - - - - - - ($kg\ ha^{-1}$) - - - - - - - - -	
L0 (control)	0-19-74	L0 (control)	0-13-60
L1 (360)	0-19-74	L1 (330)	0-13-60
L2 (730)	0-19-74	L2 (670)	0-13-60
L3 (1600)	0-19-74	L3 (1000)	0-13-60
L4 (2160)	0-19-74	L4 (1300)	0-13-60

Table 2 Lime and fertilizer rates for soybean experiment of Bc and Hk soils in 2007

Bachieng soil		Hoythakoune soil	
Lime rate	N-P_2O_5-K_2O	Lime rate	N-P_2O_5-K_2O
- - - - - - - - - ($kg\ ha^{-1}$) - - - - - - - - -		- - - - - - - - - ($kg\ ha^{-1}$) - - - - - - - - -	
L0 (control)	0-19-74	L0 (control)	0-13-60
L1 (620)	0-19-74	L1 (170)	0-13-60
L2 (2170)	0-19-74	L2 (330)	0-13-60
L3 (2990)	0-19-74	L3 (1250)	0-13-60
L4 (4320)	0-19-74	L4 (1700)	0-13-60

3.3 Experimental design

The experiment was conducted using a randomized complete block design (RCBD), with 5 treatment and replication. The individual plot size was 5 x 8 m with the harvested area was 4.5 x 4 m. The plant spacing was 50 x 20 cm. Each plot consisted of 10 rows and the plant population was 400.plant per plot or 100,000 plant ha^{-1}. The re application of lime use was handled in each plot according to different lime rate.

3.4 Soil samples; plant data collection and analysis

At both sites, soil samples were taken from each plot at 0 to 20-cm depth before planting and after each harvest. All soil samples were air-dried and processed in the soil testing laboratory. Twenty soil samples for each plot were randomly taken and mixed together as a composite sample, and ground to pass through a 0.5 mm screen prior to analysis. Soil physical and chemical properties analyzed included the following: Soil texture was determined by the pipette method (Day, 1965; Gee and Bauder, 1986). Organic carbon was determined by the $K_2C_{r2}O_7$ + H_2SO_4 digestion method (Walkley and Black, 1934). Soil pH was determined by electrode method at a 1:1 soil to water ratio. Cation exchange capacity (CEC) by ammonium acetate pH 7 method (Rhoades, 1982). Exchangeable aluminum was determined by the 1 *M* KCl-extractable methods and extractable Al and Fe were measured by acid ammonium oxalate, citrate-bicarbonate-dithionite methods (Loeppert and Inskeep, 1996). Exchangeable Ca, Mg and K by NH_4OAc pH 7 (Jones, 2001). Total N was determined by the Kjeldahl method. Available P was extracted by Bray II (Bray and Kurtz, 1945).

Soybean was collected from the sampled plots with a randomized collection procedure and prepared for plant nutrient analysis. Soybean was harvested from the 8 middle rows or 18 m^2 per plot. At the same time all plants in the harvest area were cut at the soil surface and the fresh weight was recorded. Twenty soybean plants were collected from each plot for analysis. Grain yield was adjusted to 15 %

moisture content. The grain yield, fresh weight and dry weight were recorded for analysis.

3.5 Statistical and economics analysis

Statistical computations were performed by SAS (version 8.1). The SigmaPlot program was used to fit a linear plateau curve to quantify the response of lime on soybean grain yield. In addition the economic benefit of lime applications for the Bachieng and Hoythakoune experiments was determined using the “economic dominance analysis” methods of CIMMYT (Harrington, 1998). Economic dominance analysis determines the net benefit of one experimental treatment in comparison to others by comparing both the net benefits and the costs required for the treatment.

RESULTS AND DISCUSSION

1. Experiment 1 Characterization of liming materials

The characterization of liming materials analysis was comprised of two determinations: 1) particle size and 2) percentage of calcium carbonate equivalent.

1.1 Particle size analysis

Particle size was measured by sieves (Table 3) and is one of the main factors that influence the rate of reaction of lime when applied to soil. Mesh size is a measure of number of opening per inch of a sieve. The relative sizes of lime particles of different meshes are shown in (table 3). The particle size of three selected limestone materials indicate that calcium hydroxide ($Ca(OH)_2$) had a smaller particle size than calcium carbonate ($CaCO_3$) and marl, respectively.

A certain percentage of the particles in a liming material must be sufficiently fine (pass a 60-mesh sieve) in order to react rapidly with soil acidity and supply the calcium and magnesium, with the remainder (that which passes a 10-mesh sieve) reacting in a period of two to three years. Barber (1967) reported that the 8 to 20 mesh material has a small effect for time periods of six months or more. A high-quality agricultural limestone has a range of particle size that allows it to have both immediate and long-tern (as much as three-year) capacity to react soil acidity. Lime quality is improved when a greater percentage of the particles pass through finer mesh sieves, such as a 60 or 100 mesh. Particle sizes of <0.25 mm were regarded as 100% effective (Tisdale and Nelson, 1975). The two major factors influencing the effectiveness of a limestone product are its purity and its particle size distribution (Tisdale and Nelson, 1975). The effectiveness of lime on neutralizing soil pH is based on the chemical purity. The higher the percentage of fine particles, the faster lime neutralizes soil acids (Mamo *et al*., 2003).

Data in the Table 3 indicated that percentages of liming material that passed through the selected sieves sizes. The percentage of liming material that passed through a 60 (<0.25) mm sieve were 93.8 and 88.8 % for calcium hydroxide and calcium carbonate, respectively, unlike the percentage passing of marl which was lower (33.96%). Scott *et al*. (1992) found that limestone particles <0.25 mm are fully effective in amending acidic soils. In the case of marl only a small amount passed sieves 10 and 35 (Table 3). The comparison of three liming materials indicated that calcium hydroxide particles were smaller than either calcium carbonate or marl.

The large particle size of marl is expected to lead to slow reaction when applied to acid soils. This result was similar to that of Peters *et al*. (1996) who reported that marl is typically a deposit of calcium carbonate derived from mollusk shells and mixed with silt and clay.

Table 3 Particle size of the liming materials in Laos and Thailand.

Sieve number (in mm)	Calcium hydroxide ($Ca(OH)_2$)[L]	Calcium carbonate ($CaCO_3$)[T]	Marl [T]
	- - - - - - - - - (Material in size ranges %) - - - - - - - - -		
>10 (>2.0 mm)	0.73	0.20	0.28
10-35 (2.0 - 0.5 mm)	0.73	0.80	30.02
35-60 (0.5 - 0.25 mm)	4.69	10.20	35.74
<60 (<0.25 mm)	93.85	88.80	33.96

Note [L] Lime material from Laos

[T] Lime materials from Thailand

1.2 Calcium carbonate equivalent (CCE) analysis.

The percentage of calcium carbonate equivalent (CCE) of the liming materials expresses their chemical reactivity and purity, which determine lime effectiveness when incorporated into the soil. The results of this analysis revealed that the probable effectiveness of three liming materials were different. The percent of calcium carbonate equivalent (CCE) ranged from 95 to 107 % (Table 4). As expected the CCE of calcium hydroxide ($Ca(OH)_2$) was higher than 100 %, reflecting its lower molecular weight. In the case of calcium carbonate and marl both contained a lower percent of CCE. These results similar to Tisdale and Nelson (1975) who reported that the CCE expected percent of "calcium carbonate" and "marl" was 100 and 70-90, respectively. The marl CCE measurement was 95 percentage which was less than that of both $Ca(OH)_2$ and $CaCO_3$. This lower CCE may have been the result of the inclusion of clay with the calcium carbonate.

Several researchers reported that lime quality depends on three factors: Chemical purity and neutralizing value; particle size of fineness of pulverizes and moisture content. Generally, marl is a mixture of materials composed of calcium carbonate, and impurities that are mainly sand, silt, and clay. However, the comparison of percent of CCE expected and CCE measured of calcium hydroxide material was quite different (a value of 136 was expected but only 107% was measured) suggesting the purchased product contained materials beside calcium hydroxide.

Based on the CCE alone the two materials calcium hydroxide ($Ca(OH)_2$) and calcium carbonate ($CaCO_3$) would be suggested. The high percent of CCE content in these two liming materials indicated that these materials have a high ability to increase soil pH. Calcium hydroxide is usually finely powdered as a result of the burning process, but calcium carbonate effectiveness also depends on the fineness of the grinding. The majority of the material should be smaller than 60 mesh (less than 0.25 mm).

Table 4 Percent calcium carbonate equivalent (CCE) of liming materials in the Lao PDR and Thailand.

Local material	Formula	£CCE Expected (%)	CCE Measured (%)
Calcium hydroxide	$Ca(OH)_2$	136	107
Calcium carbonate	$CaCO_3$	100	98.7
Marl	-	70-90	95

Note £ Tisdale and Nelson (1975)

2. Experiment 2 Comparison of four methods of determining lime requirement

2.1 Determine the lime requirement by four different methods.

The lime requirement is amount of lime needed to neutralize the soil acidity and permit the plant or crop to reach the maximum yield possible. The requirement was estimated by four different methods for soybean production. Lime requirements were estimated on the eight acid upland soils by laboratory incubation, including the use of buffer solutions that are amenable to routine laboratory use.

2.1.1 Soil properties studied

Eight important soils for upland agriculture in Laos were selected to estimate lime requirement. Soil chemical and physical analyses are shown in Table 5. All soils were acidic with pH ranging from 4.3 to 5.3. The clay content of these soils was higher in the Sv and Bc of 573 and 407 g kg^{-1}, except Ns soil which was very low in clay with 200 g kg^{-1}. The extractable Ca in Pt was obviously higher than that of the other soils (Table 5). The amounts of dithionite Fe and Al in the Bc soil were the highest among all soils. The organic carbon in the Xk and Ls soil was the highest. The high organic carbon content of the Xk soil may be a result of the high elevation and cool temperatures in Xiengkouang province as well as the low pH and organic carbon of the soil.

Table 5 Characteristics of the eight soil samples before conducting experiments.

Soil properties	Soil							
	Sv	Bc	Hk	Pt	Ns	Xn	Xk	Ls
Texture	CL	CL	SL	SL	L	CL	SL	SL
Clay ($g\ kg^{-1}$)[1]	573	407	202	234	199	289	270	215
Soil pH [2]	5.30	4.30	4.70	5.00	4.80	4.80	4.40	4.60
OC($g\ kg^{-1}$) [3]	7.4	24	4.7	4.6	0.9	15.9	30.0	27.8
ECEC ($cmol_c kg^{-1}$) [4]	2.52	1.46	1.8	2.14	1.14	3.11	2.19	1.62
Total N ($g\ kg^{-1}$) [5]	0.50	0.80	0.40	0.30	0.40	0.80	1.00	1.80
P ($mg\ kg^{-1}$) [6]	5.70	4.20	4.00	3.30	2.70	2.20	5.10	3.60
K ($cmol_c kg^{-1}$) [7]	0.8	0.16	0.24	0.05	0.03	0.23	0.12	0.10
Ca ($cmol_c kg^{-1}$) [7]	0.73	0.66	0.55	1.25	0.30	0.78	0.56	0.09
Mg ($cmol_c kg^{-1}$)[7]	1.02	0.26	0.30	0.21	0.07	0.68	0.09	0.05
Na ($cmol_c kg^{-1}$) [7]	0.47	0.31	0.31	0.08	0.28	0.35	0.33	0.49
Fe_o ($g\ kg^{-1}$) [8]	2.60	2.90	1.50	1.50	1.50	2.20	1.60	0.90
Fe_d ($g\ kg^{-1}$) [9]	13.10	55.20	9.00	0.40	3.30	9.60	16.05	2.60
Al_o ($g\ kg^{-1}$) [8]	1.60	3.60	1.20	2.30	2.50	2.70	1.50	5.60
Al_d ($g\ kg^{-1}$) [9]	27.90	31.50	25.20	34.20	34.20	27.40	28.20	27.80
KCl Al ($cmol_c kg^{-1}$)	0.22	0.47	0.4	0.21	0.14	1.07	1.09	0.89

Note Sv - Saravanh, Bc - Bachieng, Hk - Hoythakoune, Pt - Phonthong, Ns - Nasaithong, Xn - Xaithani, Xk - Xiengkoung, Ls - Latsen.

[1] Pipette method (Day, 1965)

[2] Glass electrodes, 1:1 soil: water

[3] Walkley Black titration (Walkley and Black, 1934)

[4] NH_4OAc, pH 7 replacement method (Rhoades, 1982)

[5] Macro Kjeldahl methods (Bremner, 1996)

[6] Bray-2 methods (Bray and Kurtz, 1945)

[7] Conc. HNO_3-H_2SO_4-$HClO_4$, ratio 5:1:2 (Yoshida et al, 1972)

[8] Oxalate pH 7.3 (Loeppert and Inskeep, 1996)

[9] Citrate-bicarbonate-dithionite (Loeppert and Inskeep, 1996)

2.1.2 The characteristics of the eight selected soils

Eight soils used in this study were Saravanh (Sv), Bachieng (Bc), Hoythakoune (Hk), Phonthong (Pt), Nasaithong (Ns), Xaitany (Xn), Xiengkhouang (Xk) and Latsen (Ls) soils. Most acid upland soils were classified as Alfisols and Ultisols of Soil Taxonomy (Soil Survey Staff, 1999). The soils were classified according to the USDA Soil Taxonomy (Table 6).

Table 6 Soil Taxonomy classification of the eight representative soils

Soil	Soil Taxonomy classification
Saravanh (Sv)	Coarse-loamy, isohyperthermic, Kandic Plinthaquult
Bachieng (Bc)	Very-fine kaolinitic, isohyperthermic, Rhodic Kandiustox.
Hoythakoune(Hk)	Fine-sandy-loam, isohyperthermic Typic Kandiudult
Phone thong (Pt)	Fine-sandy-loam, isohyperthermic Typic Paleaquult
Nasaithong (Ns)	Very-fine-loamy, isohyperthermic, Oxyaquic Paleustalf
Xaithani (Xn)	Very-fine-loamy, isohyperthermic, Oxyaquic Paleustalf
Xiengkhouang (Xk)	Fine-sandy-loam, isohyperthermic, Typic Paleaquult
Latsen (Ls)	Fine-sandy-loam, isohyperthermic, Typic Paleaquult

Source: Soil survey Staff (1999)

Major physical and chemical properties of the eight selected soils are presented in Table 5. The soils were arranged in two groups based on clay fraction, organic carbon content and soil pH: (i) Soils with clay loam, sandy loam texture, high organic carbon content and pH less than 5, which included the Bc, Xn, Xk and Ls soils. The organic carbon content of these soils was 24.0, 15.9, 30.0 and 27.8 g kg^{-1}. (ii) Soils with clay loam, loam and sandy loam texture, organic carbon content of less than 0.9 g kg^{-1} and soil pH ranged from 4.8-5.3, included Sv, Hk, Pt and Ns soils.

2.1.3 Dunn incubation

The titration curves of the eight selected soils resulting from the addition of different volumes of lime solutions of 0.05 *M* of $Ca(OH)_2$ and adjusted R^2 are shown in Table 7 The data illustrate that the amount of added calcium hydroxide needed to reach the target pH of 5.5 was highly correlated with initial soil pH. The highest adjusted R^2 occurred with the Pt, Ns and Ls soils, respectively (0.99).

Table 7 A summary of prediction equations and the adjusted R^2 of eight soils titrated with volumes of lime solutions of 0.05 *M* $Ca(OH)_2$, Y is the pH after 4 days of incubation, x is amount of $Ca(OH)_2$ added.

Soils	Equation	Adj. R^2
Saravanh (Sv)	Y = 5.0 + 0.128 * x	0.93
Bachieng (Bc)	Y = 5.0 + 0.183 * x	0.98
Hoythakoune(Hk)	Y = 5.2 + 0.153 * x	0.98
Phonthong (Pt)	Y = 5.25 + 0.175 * x	0.99
Nasaithong (Ns)	Y = 4.7 + 0.170 * x	0.99
Xaithani (Xn)	Y = 4.1 + 0.156 * x	0.98
Xiengkhouang (Xk)	Y = 4.3 + 0.160 * x	0.98
Latsen (Ls)	Y = 4.5 + 0.156 * x	0.99

2.1.4 Lime requirement incubation by the Dunn method

The incubation of soils with $Ca(OH)_2$ was considered the standard method for lime requirement determination in this study. Other methods suitable for routine laboratory use were compared with this incubation method.

Lime requirements of the eight soils differed greatly (Table 8). To reach a soil pH of 5.5, the lime requirement of eight soils ranged from 750 to 4290 kg lime ha^{-1} (Table 8). The higher amount of lime requirement was correlated with lower soil pH which was found in Xk and Bc soils. The lowest lime requirement was in the Sv soil, this soil's pH was high and the Ca and Mg contents were higher than that of the other soils (Table 5). Neither the amount of clay nor the soil bulk density had a significant effect on lime requirement. The highest lime requirement occurred in two acid soils (Xk and Xn soils). These soils were higher in Al content, 1.07 and 0.89, $cmol_c kg^{-1}$ (Table 5) (Using 1 *M* KCl in Table 5) than other soils. In general, soils with high clay and CEC content and low pH were highly correlated with lime requirement. Likewise, Tisdale and Nelson (1975) reported that lime requirement of soils was higher with high buffer capacity as resulting from high contents of clay and organic matter

Table 8 Lime requirements (LR) of eight soils using the Dunn Method.

Soil	pH		Clay	BD	Target pH (5.5)
	$H_2O_{(1:1)}$	$CaCl_2$	(g kg^{-1})	(Mg m^{-3})	LR (kg ha^{-1})
Saravanh (Sv)	5.3	4.0	573	1.16	750
Bachieng (Bc)	4.3	3.7	407	1.10	2100
Hoythakoune (Hk)	4.7	3.9	202	1.24	1400
Phonthong (Pt)	5.0	4.0	234	1.50	1050
Nasaythong (Ns)	4.8	3.6	199	1.20	3150
Xaithani (Xn)	4.8	3.9	289	1.08	3600
Xiangkhouang (Xk)	4.4	3.5	270	1.16	4290
Latsen (Ls)	4.6	3.9	215	0.95	2750

2.1.5 Lime requirement as estimated by the Adams-Evans method

Table 9 Lime requirements (LR) of eight soils using Adams-Evans Buffer pH 8.0.

Soil	pH		Clay	BD	Target pH (5.5)
	$H_2O_{(1:1)}$	$CaCl_2$	(g kg^{-1})	(Mg m^{-3})	LR (kg ha^{-1})
Saravanh (Sv)	5.3	4.0	573	1.16	890
Bachieng (Bc)	4.3	3.7	407	1.10	7600
Hoythakoune (Hk)	4.7	3.9	202	1.24	1400
Phonthong (Pt)	5.0	4.0	234	1.50	360
Nasaythong (Ns)	4.8	3.6	199	1.20	470
Xaithani (Xn)	4.8	3.9	289	1.08	1080
Xiangkhouang (Xk)	4.4	3.5	270	1.16	6120
Latsen (Ls)	4.6	3.9	215	0.95	4920

The Adams-Evans method of estimating lime requirement was reach target pH_w of 5.5(Table 9). Three of the eight soils, Bc, Xk, and Ls, required amounts of lime much higher than the other soils (7600, 6120 and 4920 kg of $CaCO_3$ ha^{-1}, respectively. In contrast, according to this method, the Pt and Ns soils required only 360 and 470 kg of $CaCO_3$ ha^{-1}. The Adams-Evans method is suitable for accurately determining lime requirement in soils with low cation exchange capacity and soils with small amounts of clays content (Plank, 2009). Although the Pt and Ns soils were quite acid (pHs of 4.8, 5.0), they required only a small amount of lime probably because they were low in clay and Al content (clay contents of 234 and 199 g kg^{-1} and KCl-Al of 0.21 and 0.14 $cmol_c$ kg^{-1}) respectively. In general, lime requirement as estimated by the Adams-Evans method was much higher than that estimated by the Dunn method except for Sv, Pt and Ns soils (Table 9). For these soils with the soil pH, clay, and organic carbon content were the main soil factors affecting the lime requirement. Similar results were obtained by Ketterings *et al.* (2006) who reported that the lime requirement depends on soil texture and organic matter content which affects the soil's capacity to buffer changes in pH.

2.1.6 Lime requirement as estimated by the Kissel method

The lime requirements as estimated by the Kissel method are given in Table 11. The two soils with the highest lime requirement using this method were the Bc and Xn soils. The differences in pH_W and pH_{CaCl2} for Bachieng and Xiengkhouang soils were 0.6 and 0.9, respectively. The Bc soil may have had a higher lime requirement because of the high clay and cation echange capacity. Rossel and McBratney (2001) reported that soil organic matter and clay content increased predictions of lime requirement probably because they are positively correlated with the soil's buffering capacity.

Table 10 Lime requirements (LR) of eight soils using Kissel method.

Soil	pH		Clay	BD	Target pH (5.5)
	$H_2O_{(1:1)}$	$CaCl_2$	(g kg $^{-1}$)	(Mg m^{-3})	LR (kg ha^{-1})
Saravanh (Sv)	5.3	4.0	573	1.16	959
Bachieng (Bc)	4.3	3.7	407	1.10	3200
Hoythakoune (Hk)	4.7	3.9	202	1.24	580
Phonthong (Pt)	5.0	4.0	234	1.50	450
Nasaythong (Ns)	4.8	3.6	199	1.20	800
Xaithani (Xn)	4.8	3.9	289	1.08	2700
Xiangkhouang (Xk)	4.4	3.5	270	1.16	1200
Latsen (Ls)	4.6	3.9	215	0.95	1300

Table 11 Lime requirements (LR) of eight soils using the extractable Al method.

Soil	pH		KCl-Al	Clay	BD	Target pH (5.5)
	$H_2O_{(1:1)}$	$CaCl_2$	($cmol_c\ kg^{-1}$)	($g\ kg^{-1}$)	($Mg\ m^{-3}$)	LR ($kgha^{-1}$)
Saravanh (Sv)	5.3	4.0	0.22	573	1.16	444
Bachieng (Bc)	4.3	3.7	0.47	407	1.10	900
Hoythakoune (Hk)	4.7	3.9	0.4	202	1.24	800
Phonthong (Pt)	5.0	4.0	0.46	234	1.50	900
Nasaythong (Ns)	4.8	3.6	0.14	199	1.20	286
Xaithani (Xn)	4.8	3.9	0.85	289	1.08	1600
Xiengkouang (Xk)	4.4	3.5	1.09	270	1.16	2100
Latsen (Ls)	4.6	3.9	0.89	215	0.95	1700

2.1.7 Lime requirement as indicated by extractable Al methods

The exchangeable aluminum value from extraction of soil with an unbuffered KCl solution was used to estimate the lime requirement (Kamprath, 1970). This method indicated that smaller amounts of lime when compared to Dunn, Adams-Evans and Kissel methods. The lime requirement estimated by this method was highest for Ls, Xk and Xn soils (1,700, 2,100, and 1,600 kg ha^{-1}), respectively. The lime requirement of the Xk soil was much higher than that of the other soils according to this method.

The estimates of lime requirement according to extractable Al were based on the equation LR (ton/ha $CaCO_3$) = 1.5-2.0 x exch. Al (Kamprath, 1970). Among the methods, the extractable Al method produced results most similar to those of the lime requirement compared to Dunn method, and therefore the method may be regarded as a suitable routine method for estimating lime requirement. The extractable Al method is recommended for determining the lime requirements of soils with a clay-loam or loam texture, a pH from 4.3 to 5.3 (Kamprath, 1970). Kamprath (1970) reported that liming rates calculated based on exchangeable Al raise the soil pH to 5.5 to 6.0 in most mineral soils.

2.1.8 Comparison of lime requirement methods

Lime requirements of soils were different depending on the physical and chemical properties of the soils. The results showed that lime required by the Dunn incubation method to increase a target pH to 5.5 of each soil ranged from 750 to 4290 of $CaCO_3$ kg ha^{-1} (Figure 1). The lowest and highest lime requirements were of the Sv and Xk soils, respectively. Lime requirement of Xk soil was higher than that of the other soils, probably because an extractable aluminum content of the soil was higher than the other soils. Foth and Ellis (1996) reported that each $cmol_c$ of soil Al required 1.65 ton of $CaCO_3$ ha^{-1}. However, there were many soils that required less than 1000 kg $CaCO_3$ ha^{-1}, particularly according to the Kissel and extractable aluminum methods. For example, the amount of lime requirement using the Kissel and extractable aluminum method was about 450 and 580 kg ha^{-1} of $CaCO_3$ for Hk, Pt and Ns soils, respectively. These soils probably had lower lime requirements because they contained less clay and organic carbon. The Bc, Xk and Ls soils required higher amount of lime for Adam-Evans method (Figure 1). The highest amount of lime requirement of Bc, Xk and Ls soils was 7600, 6120 and 4920 kg $CaCO_3$ ha^{-1} according to Adams-Evans methods. The lime prediction of these three soils according to the other methods was much lower; nevertheless the lime requirement of these three soils remained higher than that of other soils. This suggests that the Bc, Xk and Ls soils simply have high lime requirements, probably because these soils have more clay, Al and lower initial soil pH content and high organic carbon content (Table 5). The Adams-Evans and Kissel methods predicted low lime requirement for most soils; however, these methods still predicted high amounts of lime for Bc, Xk and Ls soils. These results may be related to those of Kettering *et al*. (2006) who reported that the lime requirement depends on soil texture and organic matter content which affects the soil's capacity to buffer changes in pH. Soils with a large buffer capacity will need more lime to neutralize acidity. The Bc and Xk soil lime requirements were extremely high with the Adam-Evans methods (7600 and 6120 kg $CaCO_3$ ha^{-1}, respectively). The highest estimated lime requirement occurred on soils with the lowest soil pH and the highest clay content (pH 4.3 and 4.4 and clay contents of 407 and 270 g kg^{-1}, respectively).

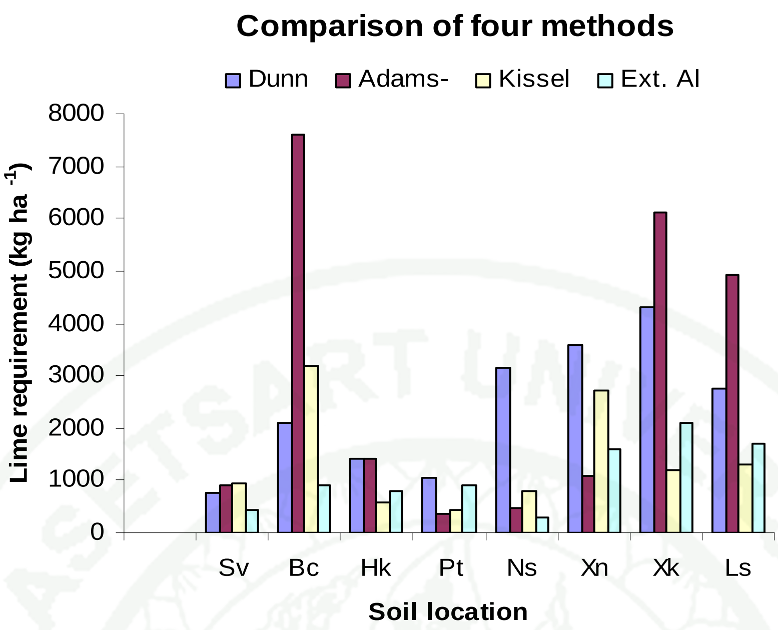

Figure 1 Comparison of lime requirements of eight Lao soils using four methods Dunn, Adams-Evan, Kissel and extractable Al methods**.**

2.1.9 A field comparison of lime requirement

While laboratory methods of estimating lime requirement are important and useful, they must be compared and tested with actual field experiments. In this section the various laboratory methods compare with the actual lime requirement determined from field experiments. It was not possible to conduct two year experiments on all eight soils selected for the laboratory analysis. Results of two field experiments and the change in soil pH compared with $CaCO_3$ applied are presented in Figures 2 and 3. The highest soil pH of Bc and Hk was 5.8 and 6.1, respectively - achieved with the high lime rate application. Lime requirement determined from field experiments differed from the lime requirement estimated by the four methods compared with field experiment (Figure 4). The higher lime requirement based on field observations may be a result of surface application of liming material. Lack of a thorough and deep (15 cm) incorporation may have slowed the neutralization of soil acidity, thereby limiting the change in pH of these soils compared with thorough incorporation of lime in the laboratory tests. Most often this difference is explained by the incomplete reaction of the lime due to insufficient time or mixing of the liming material with the soil under field conditions.

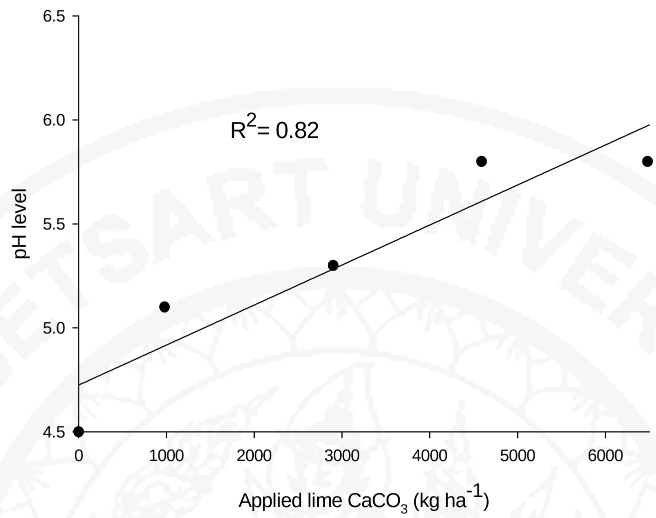

Figure 2 The increase in pH resulting from $CaCO_3$ applications, field results, Bc soil.

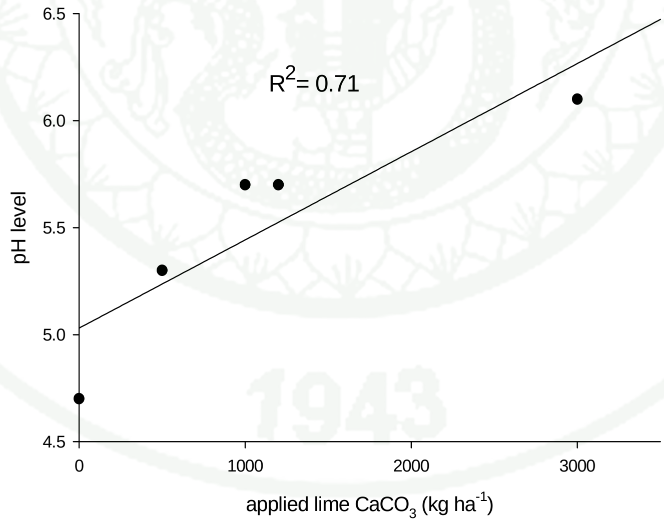

Figure 3 The increase in pH resulting from $CaCO_3$ applications, field results, Hk soil.

The lime requirement as estimated from the field experiment of Bc and Hk soils was about 1125 with a corresponding pH of 5.1 and 1013 kg ha^{-1} with a corresponding pH of 5.7. The lime requirement of these soils according to the extractable Al method was roughly nearly amounts of lime 980 and 1000 kg ha^{-1}. However, the lime requirement of the Hk soil by extractable Al method at 1000 kg was obviously higher than the field estimate of 1013 kg ha^{-1} (Figure 14). One of four methods, the Adams-Evans very much over-predicted the lime requirement as determined in the field and by the Dunn method. A closer look at the Adams-Evans method is suitable for accurately determining lime requirement in soils with low cation exchange capacity and soils with small amounts of clays content. As expected with the higher clay content the Bc soil lime requirement was higher than that of the Hk soils by other method.

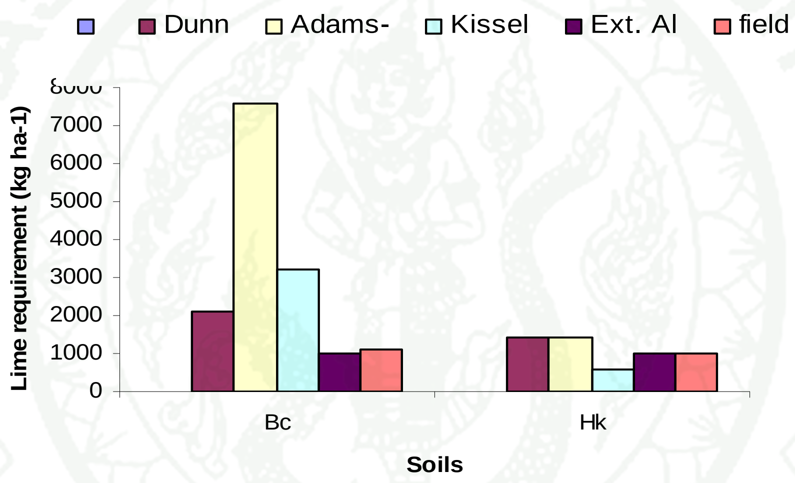

Figure 4 Comparison of lime requirements of two soils of Laos using four methods compare with field experiment.

3. Experiment 3 Determine the appropriate rate of lime for soybean grown in acid soils under field conditions

3.1 Soils of the study sites

The Bachieng soil (Bc) was classified as an Ultisol, while the soil at the Hoythakoune (Hk) was also classified as an Ultisol, but as a Typic Kandiudult. The high concentrations of Mn and Al may inhibit root growth of sensitive crops (Uexkull *et al*., 1982). The Ultisols with their slowly permeable argillic horizons may pose physical barriers to root growth as well. The two soils differed in clay content with higher clay content in the Bc soil (407 g kg^{-1} soil) while the Hk soil contained only 202 g kg^{-1} (Table 12). The lower clay content of the Hk soil increase susceptibility to soil erosion. This soil is vulnerable to erosion due to a number of factors: the high rainfall (2000 mm $year^{-1}$), poor crop management, and low organic carbon content (4.7 g kg^{-1}, Table 5). The annual rainfall at Champasak province during the past 10 years (1990-2000) averaged about 2000 mm, and the mean temperature was 28 ^{o}C.

3.2 Field experiments in the wet season 2006

3.2.1 Soybean yield in Bachieng and Hoythakoune soils, in 2006

The grain and haulm yields were highly significantly increased by increasing liming rates. Grain yields were 2180 and 2210 kg ha^{-1}, for Bc and Hk soils, respectively (Table 12). Soybean in the Bc soil responded to lime at 1710 $CaCO_3$ kg ha^{-1} with the yield of about 2200 kg ha^{-1} (Figure 5). As expected from the low soil pH, liming rates had a positive effect on soybean yield

In the Hk soil, grain and haulm yields of soybean increased at higher liming rates (Table 12). The grain yield where 1000 kg lime ha^{-1} was applied was 2019 kg ha^{-1} which was significantly higher than the control treatment of 960 kg ha^{-1}. Lime applications on sandy soils may be as high as 2 to 4 tons ha^{-1} (Adams and Robert, 1967, 1967; Jackson *et al.*, 1967; Weeks and Lath well, 1967). Figures prepared by the SigmaPlot software and the linear response plateau equation fitted to the data indicated that soybean responded to 550 kg $CaCO_3$ ha^{-1} (Figure 6) while the predicted lime requirement was at 670 kg $CaCO_3$ ha^{-1} according to the NuMaSS software, which uses the extractable Al method of estimating lime requirement (Osmond *et al*., 1999).

Table 12 Grain and haulm yield of soybean grown on Bachieng and Hoythakoune soils as affected by lime rates in the wet season 2006.

Bachieng soil			Hoythakoune soil		
Lime rate	Grain	Haulm	Lime rate	Grain	Haulm
(kg ha^{-1})	- - - - - - (kg ha^{-1}) - - - - - -		(kg ha^{-1})	- - - - - - (kg ha^{-1}) - - - - - -	
L0 (0)	1462 b	1508 c	L0 (0)	962 d	1607 c
L1 (360)	1688 b	2168 b	L1 (330)	1562 c	2165 b
L2 (730)	1699 b	2192 b	L2 (670)	1769 b	2422 b
L3 (1600)	2182 a	2196 b	L3 (1000)	2019 ab	2480 b
L4 (2160)	2206 a	2726 a	L4 (1300)	2102 a	2689 a
F- test	**	**	F- test	**	*
CV (%)	15.7	12.2	CV (%)	6.8	13.1

Note Means within a column followed by the same letter were not significantly at $\alpha = 0.05$ by Duncan's Multiple Range Test (DMRT)

* Significant at the 0.05 level

** Significant at the 0.01 level

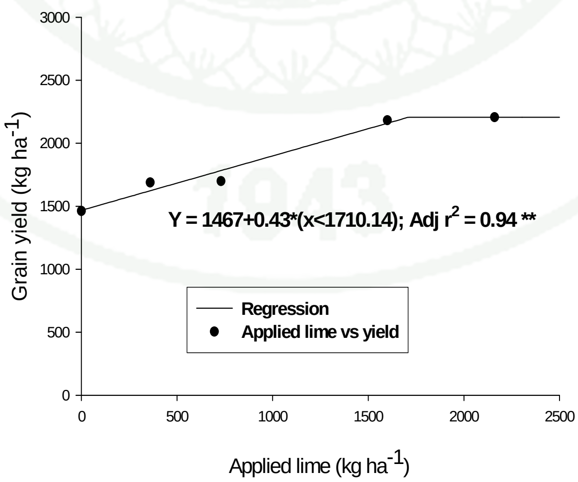

Figure 5 Soybean yield response to lime application in Bachieng soil.

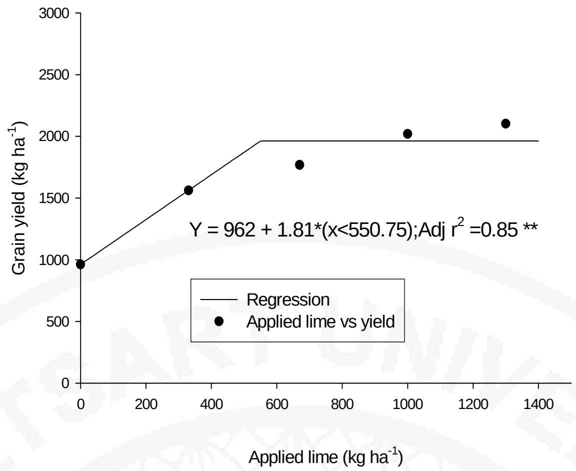

Figure 6 Soybean yield response to lime application in Hoythakoune soil.

3.2.2 Effect of lime application on grain and haulm nutrients in the wet season 2006

Bachieng soil

In Bc soil, higher Ca and Mg uptake by soybean plants occurred in plots receiving the high liming rate treatments (Table 13). Calcium in grain was 12.1 and in haulm 27.4 kg ha^{-1}, Mg in grain was 8.3 and in haulm was 22.6 kg ha^{-1}, respectively. Randall *et al*. (2006); Franzen and Gerwing (1997) found that Ca and Mg uptake in grain were lower than that of haulm of soybean. The quantity of P and K uptake by grain and haulm were higher in the higher liming rate of 2160 kg $CaCO_3$ ha^{-1}. There were highly significant differences between treatments. Where grain yields were high, the uptake of K was three fold higher than haulm uptake (Table 13). This was similar to the results of Thompson and Troeh (2005), who reported that K content in grain and haulm was 55 and 22 kg ha^{-1}, respectively. Potassium uptake was much greater when lime had been applied. This was probably because of grain and haulm yield was increased (Table 13).

Table 13 Effect of lime on total P, K, Ca and Mg uptake in grain yield of Bachieng soil in the wet season 2006.

Lime rate	Nutrient uptake in grain in Bc soil			
	P	K	Ca	Mg
(kg ha^{-1})	(kg ha^{-1})			
L0 (0)	5.6 c	34 c	3.2 b	1.9 b
L1 (360)	5.8 c	38 bc	3.2 b	2.3 b
L2 (730)	6.6 bc	46 ab	4.2 ab	2.3 b
L3 (1600)	7.8 ab	52 a	4.7 ab	3.5 a
L4 (2160)	10 a	52 a	5.5 a	3.6 a
F- test	***	**	*	**
CV (%)	11.1	13.3	13.4	14.8

Note Means within a column followed by the same letter were not significantly at $\alpha = 0.05$ by Duncan's Multiple Range Test (DMRT)

* Significant at the 0.05 level , ** Significant at the 0.01 level ,

*** Significant at the 0.001 level

Table 14 Effect of lime on total P, K, Ca and Mg uptake on haulm yield of soybean, Bachieng soil in the wet season 2006

Lime rate	Nutrient uptake in haulm in Bc soil			
	P	K	Ca	Mg
(kg ha^{-1})	(kg ha^{-1})			
L0 (0)	0.9 d	10 c	6.1 b	4.3 c
L1 (360)	1.3 c	15 b	8.3 a	6.0 b
L2 (730)	1.5 bc	15 b	8.1 a	6.0 b
L3 (1600)	1.6 ab	16 b	9.0 a	6.2 b
L4 (2160)	1.9 a	18 a	9.0 a	8.2 a
F- test	***	***	**	***
CV (%)	12.4	7.4	13.1	12.8

Table 14 (Continued)

Note Means within a column followed by the same letter were not significantly at $\alpha = 0.05$ by Duncan's Multiple Range Test (DMRT)
* Significant at the 0.01 level, ** Significant at the 0.001 level

Hoythakouane soil

Total P, K, Ca and Mg uptake in soybean grain of Hk soil was similar to that of soybean grown on the Bc soil. The quantity of P, K, Ca, and Mg uptake by grain and haulm were higher in the higher liming rates (1300 kg $CaCO_3$ ha^{-1}). This was probably because of grain and haulm yield were increased. Higher Ca and Mg uptake by plants in high liming rate treatments was observed (Tables 15, 16).

Table 15 Effect of lime on total P, K, Ca and Mg uptake in grain yield of soybean of Hoythakoune soil in the wet season 2006.

Lime rate	Nutrient uptake in grain in Hk soil			
	P	K	Ca	Mg
(kg ha^{-1})	- - - - - - - - - - (kg ha^{-1}) - - - - - - - - - -			
L0 (0)	4.1 c	16 d	3.3 b	0.5
L1 (330)	7.7 b	31 c	3.4 b	1.0
L2 (670)	8.3 ab	36 b	4.5 b	1.1
L3 (1000)	8.9 ab	41 a	5.5 ab	1.2
L4 (1300)	9.7 a	44 a	7.2 a	2.8
F- test	**	**	*	ns
CV (%)	13.0	5.9	11.9	16.3

Note Means within a column followed by the same letter were not significantly at $\alpha = 0.05$ by Duncan's Multiple Range Test (DMRT)
* Significant at the 0.05 level, ** Significant at the 0.01 level
ns = Not significant

Table 16 Effect of lime on total P, K, Ca, and Mg uptake in haulm yield of soybean of Hoythakoune soil in the wet season 2006.

Lime rate	Nutrient uptake in haulm in Hk soil			
	P	K	Ca	Mg
(kg ha^{-1})	- - - - - - - - - - (kg ha^{-1}) - - - - - - - - - -			
L0 (0)	1.5 c	10 c	6.1 b	4.3 c
L1 (330)	2.1 ab	15 b	8.3 a	6.0 b
L2 (670)	2.4 ab	15 b	8.1 a	6.0 b
L3 (1000)	2.4 ab	16 b	9.0 a	6.2 b
L4 (1300)	2.7 a	18 a	9.0 a	8.2 a
F- test	**	***	**	***
CV (%)	12.4	7.4	13.1	12.8

Note Means within a column followed by the same letter were not significantly at $\alpha = 0.05$ by Duncan's Multiple Range Test (DMRT)

** Significant at the 0.01 level

*** Significant at the 0.001 level

3.2.3 Soil analyses after soybean harvest in the wet season 2006

Bachieng soil

Soil data of Bc indicated that pH was increased with the higher liming rates but there were no significant differences between various liming treatments (Table 17). The lack of significance may be due to the relatively small lime applications and the soils apparently high buffering against pH change. Wortmann *et al*. (2005) reported that it may take one to two years for the full effect of lime application to occur. Bray 2 extractable soils P content was slightly increased with liming treatments from 1.8 to 2.8 mg kg^{-1}, but remained deficient. The concentration of Ca increased (from 0.77 to 1.57 $cmol_c$ Ca kg^{-1}) as did the Mg concentration, and from 0.55 to 0.77 $cmol_c$ Mg kg^{-1} due to liming. Caires *et al.*

(2006) studied the effect of liming in acid soils and found that liming resulted in a significant increase in pH, and exchangeable Ca^{2+} and Mg^{2+} contents as long as 58 months after application. According to this result, KCl-extractable Al content in the soil decreased from 0.65 to 0.26 $cmol_c$ Al kg^{-1} in the highest liming treatments (Table 17)

Table 17 Some soil properties measured after soybean harvest in the Bachieng soil in the wet season 2006

Lime rate	Soil	Soil analysis in Bachieng soil				
	pH	P[£]	K[¥]	Ca[¥]	Mg[¥]	Al[$]
($kg\ ha^{-1}$)		($mg\ kg^{-1}$)	---------------------($cmol_c\ kg^{-1}$)-------------------			
L0 (0)	4.4b	1.8	0.20	0.57b	0.55c	0.65a
L1 (360)	5.1a	2.5	0.20	0.78ab	0.56c	0.51ab
L2 (730)	5.1a	2.7	0.20	1.15ab	0.67b	0.33ab
L3 (1600)	5.2a	2.8	0.20	1.36ab	0.72ab	0.33b
L4 (2160)	5.3a	2.8	0.20	1.57a	0.77a	0.26b
F- test	**	Ns	Ns	*	**	*
CV (%)	4.13	35.5	13.4	26.7	8.5	33.3

Note [£] Bray 2 extractions (Bray and Kurtz, 1945).

[¥] 1 *M* Ammonium acetate, pH 7 (Rhoades, 1982)

[$] 1 *M* KCl extraction (Barnhisel and Bertsch, 1982)

Means within a column followed by the same letter were not significantly at $\alpha = 0.05$ by Duncan's Multiple Range Test (DMRT)

** Significant at the 0.01 level

* Significant at the 0.05 level

ns = Not significant

Hoythakouane soil

In Hk soil, KCl-extractable Al decreased with increasing liming rates (Table 18). Soil toxic Al content in L0 was 0.59 $cmol_c\ kg^{-1}$ in contrast with 0.15 $cmol_c$ Al kg^{-1} at the liming rate of 1300 kg $CaCO_3$ ha^{-1} (L4). Extractable P of Hk soil was increased from 4.2 to 5.7 mg kg^{-1} with liming. Friesen *et al*. (1980) also reported that P increased when soils were limed to pH 6.0 or higher. Calcium and Mg content in soil were increased with liming 0.4 to 0.6 $cmol_c\ kg^{-1}$and 0.2 to 0.7 $cmol_c\ kg^{-1}$, respectively. This case was similar to that of Meng *et al*. (2004) who found that lime application to soil increased exchangeable Ca and Mg. The greatest benefits of liming acid soil are the reduction in solution of Al.

In Hk soil, the concentration of Ca and Mg increased from 0.42 to 0.62 $cmol_c$ Ca kg^{-1} and from 0.2 to 0.7 $cmol_c$ Mg kg^{-1} due to liming. Anjos and Rowell (1987) reported that the exchangeable Ca and Mg increased with lime application. The extractable soil P content was slightly increased with liming treatments from 4.2 to 5.7 mg kg^{-1}. Friesen *et al*. (1980) also reported that P increased when soils were limed to pH 6.0 or higher. Extractable Al decreased with increasing liming rates. Aluminum content decreased from 0.59 to 0.15 $cmol_c\ kg^{-1}$ at the liming rate of 1300 kg $CaCO_3$ ha^{-1}. The greatest benefits of liming acid soil are the reduction in solution of Al.

Table 18 Some soil properties after soybean harvesting of Hoythakoune soil in the wet season 2006

Lime rate	Soil	Soil analysis in Hoythakoune soil				
	pH	P[£]	K[¥]	Ca[¥]	Mg[¥]	Al[$]
(kg ha^{-1})		(mg kg^{-1})	--------------------(cmol$_c$ kg^{-1})-------------------			
L0 (0)	4.7b	4.2	0.20	0.42b	0.20b	0.59a
L1 (330)	5.3ab	5.0	0.20	0.50ab	0.20b	0.34b
L2 (670)	5.7ab	5.1	0.20	0.54ab	0.40ab	0.24b
L3 (1000)	5.7ab	5.6	0.20	0.59ab	0.60ab	0.21b
L4 (1300)	6.0a	5.7	0.20	0.62a	0.70a	0.15b
F- test	**	ns	ns	*	**	**
CV (%)	8.1	26.6	11.9	21.8	25.0	27.3

Note Means within a column followed by the same letter were not significantly at $\alpha = 0.05$ by Duncan's Multiple Range Test (DMRT)

[*] Walkley and Black, 1934

[£] Bray 2 extractions (Bray and Kurtz, 1945)

[¥] 1 *M* Ammonium acetate, pH 7 (Rhoades, 1982)

[$] 1 *M* KCl extraction (Barnhisel and Bertsch, 1982)

* Significant at the 0.05 level

** Significant at the 0.01 level

ns = Not significant

3.2.4 Economic analysis of the soybean yield in Bc and Hk soils, in 2006

An Economic dominance analysis (Harrington, 1998) of the soybean yield in Bachieng soil indicated that net return of soybean production on the Bc soil was extremely high in the treatment L3 (about \$ 500 ha^{-1}), with a benefit/cost ratio of 1.3. Lime application of 360 kg ha^{-1} (L1) gave a net return of \$402, with a benefit/cost ratio of 1.4. This suggested that the low investment farmers should apply the L1 treatment with a lower net return. In the case of higher investment farmers, liming at

1,600 kg ha^{-1} (L3) should be applied to achieve the highest net return. The maximum net return of the soybean on the Hoythakoune site was \$503 ha^{-1} for 1,000 kg ha^{-1} of lime application (L3) with a benefit/cost ratio of 1.6 (Table 19).

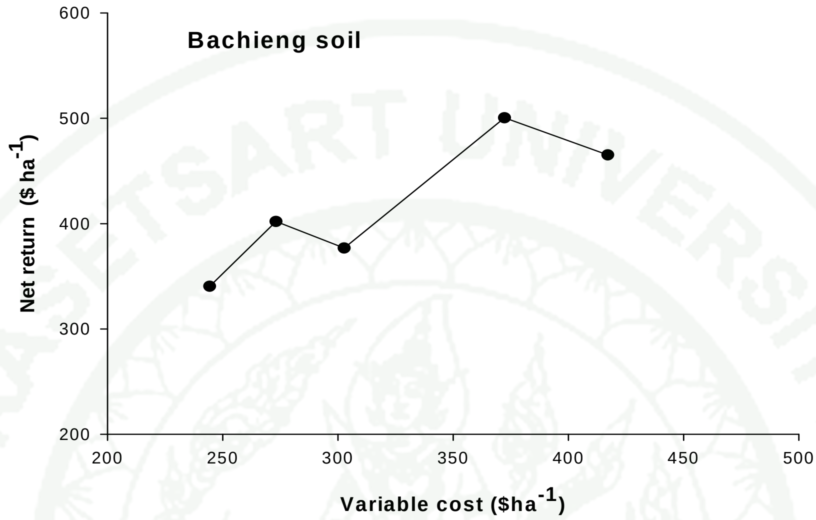

Figure 7 Relationship of net return and variable cost in Bachieng soil 2006.

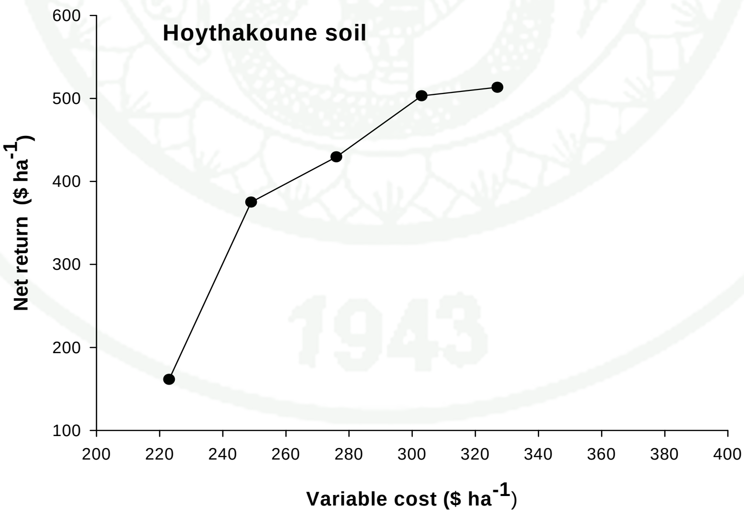

Figure 8 Relationship of net return and variable cost in Hoythakoune soil 2006.

Table 19 Variable cost and net return of soybean production with different lime treatments of Bachieng and Hoythakoune soils in 2006

Bachieng soil				Hoythakoune soil			
Lime rate	Variable cost	Net return	Benefit/ Cost	Lime rate	Variable cost	Net return	Benefit/ Cost
(kg ha^{-1})	- - - - ($US ha^{-1}) - - - -			(kg ha^{-1})	- - - - ($US ha^{-1}) - - - -		
L0 (0)	244	340c	1.3	L0 (0)	223	161c	0.6
L1 (360)	273	402b	1.4	L1 (330)	249	374b	1.5
L2 (730)	302	376ab	1.2	L2 (670)	276	429ab	1.5
L3 (1600)	372	500a	1.3	L3 (1000)	303	503a	1.6
L4 (2160)	417	465ab	1.1	L4 (1300)	327	513a	1.5
F- test		*				***	
CV (%)		19.4				5.5	

Note Means within a column followed by the same letter were not significantly at $\alpha = 0.05$ by Duncan's Multiple Range Test (DMRT)

* Significant at the 0.05 level

*** Significant at the 0.001 level

3.3 Field experiments in the wet season 2007

3.3.1 Soybean yield in Bachieng and Hoythakoune soils, in 2007.

In both Bc and Hk soils, the grain and haulm yields were significantly increased by increasing rates of lime compared with the control treatment, but grain yields of 2170, 2190 and 2194 kg ha^{-1} were not significantly different (Table 20). However, grain yield reached a maximum with the application of an additional 1125 kg $CaCO_3$ ha^{-1} in the second year (2007), with the yield of about 2170 kg ha^{-1} (Figure 9). Grain yield increased with liming rate, and there were no differences yield in various liming treatments.

In Hoythakoune soil, grain and haulm yields of soybean at higher liming rates were increased (Table 20). Grain yield of L3 was 2170 kg ha^{-1} which was higher compared to the control treatment yield of 1340 kg ha^{-1}. While the grain yields of 2020, 2058, and 2179 kg ha^{-1} were not significantly different. Soybean responded to second year lime applications of 1013kg $CaCO_3$ kg ha^{-1} with the yield of 2100 kg ha^{-1} (Figure 9). Lime application at the different rates had a significant effect compared to control treatment. Lime applications on sandy soils may be as high as 4 tons ha^{-1} (Lim and Shen, 1978). Response to the second lime application on the Hk soil was less than that of the first liming, as the soil data analysis shown Ca and Mg content in soil was higher than in 2006 (Tables 25, 26).

Table 20 Grain and haulm yield of soybean of Bachieng and Hoythakoune soils under different lime rates in the wet season 2007.

Grain and haulm yield of Bc soil			Grain and haulm yield of Hk soil		
Lime rate	Grain	Haulm	Lime rate	Grain	Haulm
(kg ha^{-1})	- - - - - (kg ha^{-1}) - - - -		(kg ha^{-1})	- - - - - (kg ha^{-1}) - - - -	
L0 (0)	1500 b	1760 b	L0 (0)	1340 b	1496 b
L1 (990)	2107 a	2930 a	L1 (500)	2020 a	2242 ab
L2 (2990)	2190 a	2999 a	L2 (1000)	2058 a	2318 ab
L3 (4590)	2194 a	3010a	L3 (2250)	2171 a	2595 a
L4 (6480)	2401 a	3080 a	L4 (3000)	2179 a	3212 a
F- test	*	*	F- test	*	*
CV (%)	14.8	16.7	CV (%)	17.4	26.1

Note Means within a column followed by the same letter were not significantly Different at $\alpha = 0.05$ by Duncan's Multiple Range Test (DMRT)

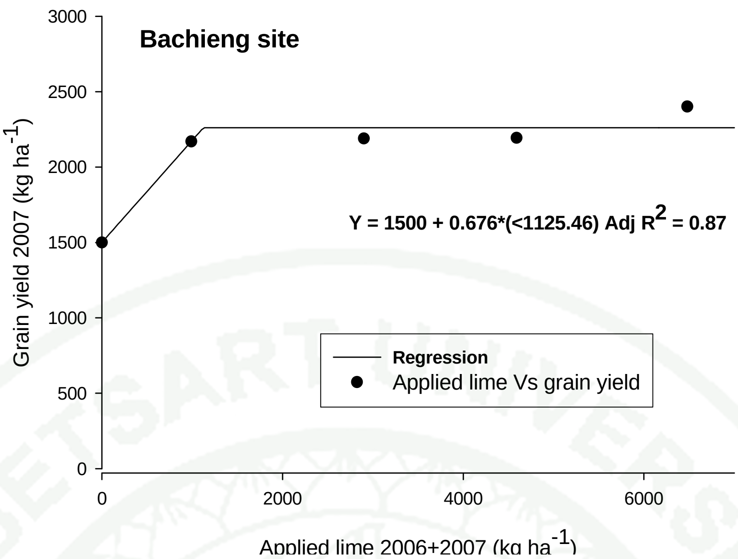

Figure 9 Soybean yield response to additional lime application to the Bc soil in 2007.

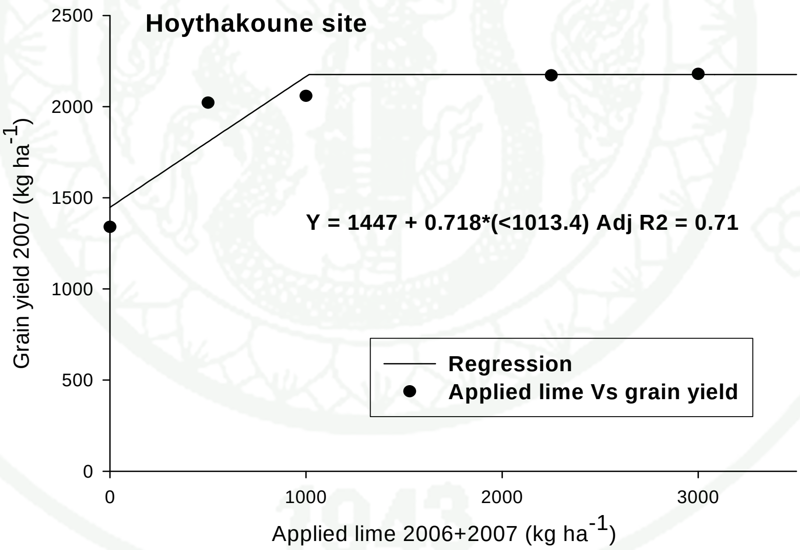

Figure 10 Soybean yield response to additional lime application to the Hk soil in 2007.

3.3.2 Total P, K, Ca and Mg uptake in grain yield of soybean of Bachieng and Hoythakoune soils in the wet season 2007.

Total P uptake by grain and haulm of Bc soil in the wet season 2007 was not different from that of previous season (2006). Total P content in grain and haulm ranged from 6.0-11.0 and 0.9-2.0 kg ha^{-1}, respectively; however, there were significant differences between the control and the application of high lime rates (4590 and 6480 kg $CaCO_3$ ha^{-1}). Obviously, the P uptake by grain and haulm all treatments was low (<11.1 and 2.1 kg P ha^{-1}) (Tables 21, 22). Total K uptake by grain and haulm of Bc soil in 2007 was different. Total K uptake by grain in 2007 was lower than in 2006 (20-33 and 34-52 kg K ha^{-1}), in the case of K in haulm was not much different (10 to 18 and 11 to 24 kg ha^{-1} for 2007 and 2006, respectively). The lower K uptake by grain in 2007 was probably due to lime added. The K uptake by grain and haulm was significantly different from the control treatment.

Total Ca and Mg uptake by plants in the high lime rate was higher than control and low lime rate treatments. There were significant differences between lime rates Table 21). The additional application of lime to the Bc soil in 2007 not only increased soil pH but increased Ca and Mg uptake by grain, which ranged from 3.2 to 6.5 and 2.2 to 3.8 kg Ca and Mg ha^{-1}, respectively (Table 21). In the case of haulm, uptake was higher of these elements (from 6.9 to 14.0 and 5.6 to 10.3 kg Ca and Mg ha^{-1}, respectively) (Table 22).

Table 21 Effect of lime on P, K, Ca and Mg uptake with grain yield of Bachieng soil in the wet season 2007.

Lime rate	Nutrient uptake in grain in Bc soil			
	P	K	Ca	Mg
(kg ha^{-1})	- - - - - - - - - - (kg ha^{-1}) - - - - - - - - - -			
L0 (0)	6.1 c	20 b	3.2 b	2.2 b
L1 (990)	6.3 c	31 ab	3.2 b	3.2 b
L2 (2990)	7.4 bc	31 ab	4.3 ab	3.5 b
L3 (4590)	8.2 ab	31 ab	5.2 ab	3.5 a
L4 (6480)	11.1 a	33 a	6.5 a	3.8 a
F- test	***	*	*	**
CV (%)	11.1	14.5	13.4	14.8

Table 21 (Continued)

Note Means within a column followed by the same letter were not significantly at $\alpha = 0.05$ by Duncan's Multiple Range Test (DMRT)

* Significant at the 0.05 level, ** Significant at the 0.01 level

*** Significant at the 0.001 level

Table 22 Effect of lime on P, K, Ca and Mg uptake in haulm of Bachieng soil in the wet season 2007

Lime rate	Nutrient uptake in haulm in Bc soil			
	P	K	Ca	Mg
(kg ha^{-1})	- - - - - - - - - -	(kg ha^{-1})	- - - - - - - - - -	
L0 (0)	0.9 d	11 c	6.9 b	5.6 c
L1 (990)	1.7 c	17 b	9.5 a	6.4 b
L2 (2990)	1.7 bc	17 b	13.3a	7.8 b
L3 (4590)	1.8 ab	23 b	14.0 a	8.9 b
L4 (6480)	2.1 a	24 a	14.0 a	10.3 a
F- test	**	**	**	**
CV (%)	12.4	7.4	13.1	12.8

Note Means within a column followed by the same letter were not significantly at $\alpha = 0.05$ by Duncan's Multiple Range Test (DMRT)

* Significant at the 0.05 level, ** Significant at the 0.01 level

*** Significant at the 0.001 level

In the Hoythakouane soil, total P, K, Ca and Mg uptake in grain and in haulm are given in tables 23-24. Nutrient uptake was significantly different between higher and low lime rates and control treatment. Total P uptake ranged from 4.5 to 10 and 1.7 to 3.4 kg P ha^{-1}, for grain and haulm, respectively. The results revealed that higher lime rates had significantly increased P uptake. Higher P uptake in grain was found in L2, L3 and L4 (9.1, 9.6 and 10 kg ha^{-1}) while in for haulm yields L3 & L4 rates were similar (3.2 and 3.4 kg ha^{-1}). However, the P uptake by haulm was lower than removed in the grain.

The level of K uptake by soybean grain and haulm in lime treatments of both soils in 2006-2007 was higher in 2006. The K uptake by grain was twice as high as in haulm except for the control treatments. There were significant differences in total K uptake of both grain and haulm under different lime treatments. The K removed by grain and haulm of Hk soil varied from 18 to 51 and 14 to 23 kg K ha^{-1}, respectively (Tables 23, 24). The higher K uptake in grain probably occurred because K was added and crop residues were incorporated into the soils. The highest lime rates resulted in more Ca, and Mg uptake. There was a significant increase in Ca and Mg uptake at all lime treatments compared to the control treatment. This was probably because grain and haulm yield was increased (Table 23).

Table 23 Effect of lime on P, K, Ca and Mg uptake in grain yield of Hoythakoune soil in the wet season 2007

Lime rate	Nutrient uptake in grain in Hk soil			
	P	K	Ca	Mg
(kg ha^{-1})	- - - - - - - - - - - (kg ha^{-1})	- - - - - - - - - - -		
L0 (0)	4.5 c	18 d	2.3 d	2.6 c
L1 (500)	8.3 b	41 c	4.0 bc	4.0 ab
L2 (1000)	9.1 ab	42 b	5.5 b	6.1 a
L3 (2250)	9.6 ab	45 a	5.7 b	6.5 a
L4 (3000)	10.0 a	51 a	9.3 a	6.5 a
F- test	**	***	**	***
CV (%)	14.2	16.3	11.4	15.4

Note Means within a column followed by the same letter were not significantly at $\alpha = 0.05$ by Duncan's Multiple Range Test (DMRT)

** Significant at the 0.01 level

*** Significant at the 0.001 level

Table 24 Effect of lime on P, K, Ca and Mg uptake in haulm of Hoythakoune soil in the wet season 2007

Lime rate	Nutrient uptake in haulm in Hk soil			
	P	K	Ca	Mg
(kg ha^{-1})	- - - - - - - - - - (kg ha^{-1}) - - - - - - - - - -			
L0 (0)	1.7 c	14 ab	6.7 c	2.2 c
L1 (500)	2.5 bc	20 ab	10.1 ab	4.3 ab
L2 (1000)	3.0 ab	20 ab	10.2 ab	5.2 ab
L3 (2250)	3.2 ab	22 a	13.0 ab	6.5 ab
L4 (3000)	3.4 a	23 a	13.3 a	7.7 a
F- test	***	**	***	*
CV (%)	12.3	16.5	11.7	15.4

Note Means within a column followed by the same letter were not significantly at α = 0.05 by Duncan's Multiple Range Test (DMRT)

* Significant at the 0.05 level

** Significant at the 0.01 level

*** Significant at the 0.001 level

3.3.3 Soil analyses after soybean harvest in the wet season 2007

Soil pH was increased with the higher liming rates of both Bc and Hk soils but there were no significant differences between the two highest application rates (Table 25 and 26). Brooke *et al*. (1989) found that lime 2.5 t per ha^{-1} substantially reduced the level of exchangeable A1 raising soil pH by about 1.0 unit. Liming treatment increased soil P, with the high lime rates resulting in more extractable P in soil. Holford, 1985 found that in the former soils, lime increased the levels of exchangeable phosphate, phosphate concentration in solution, and uptake of soil phosphate, but generally depressed the uptake of fertilizer phosphate. In Bc and Hk soils soil P was increased with increasing lime rates which ranged from 1.8 to 3.1 and 4.2 to 6.2, respectively. Friesen *et al*. (1980) reported that P increased when soils were limed to pH 6.1. The comparison of two soils found that Hk soil had higher soil P than in Bc as well as previous year (2006).

The Hk soil had higher native soil pH than Bc soil, and after liming soil pH increased further. Turan *et al*. (2002) reported that soil pH, exchangeable Ca, Mg and available P content of soil increased with increasing rates of lime doses but exchangeable Al contents decreased with increasing doses. Also Rahman *et al*. (2002 found that soil pH, available P, exchangeable Ca and Mg content in the soil were gradually increased with increasing lime levels to 2.0 ton ha^{-1}. After first year of liming the amount of P increase was about 3.1 mg kg^{-1}, but P content was slightly increased with liming treatments from 1.8 to 3.1 mg kg^{-1}, which remained deficient (Table 28). Soil Ca and Mg of Bc soil of liming treatments were doubled compared to 2006; in contrast for the control treatment of 2007 the amount of Ca and Mg declined (0.60 and 0.5 $cmol_c$ kg^{-1}). Liming had significant effect to increase soil Ca and Mg. This case was similar to Rahman *et al*. (2002); Caires *et al*. (2005) who found that lime application to soil increased exchangeable Ca and Mg.

Extractable Al content in both soils declined with increasing lime rate (Tables 25, 26). Aluminum declined from 0.65 to 0.12 and from 0.58 to 0.12 $cmol_c$ $kg^{-1}$for Bc and Hk soils, respectively. The soil Al in 2007 on all lime treatments was lower in 2006 for both soils; especially, the minimum of Al content in L4 treatments was about 0.26 to 0.15 $cmol_c$ Al kg^{-1}. The decline of Al in higher lime rates treatments improved plant growth and helped result in higher yields in both Bc and Hk soils.

Table 25 Some soil properties after soybean harvest of Bachieng soil in the wet season 2007

Lime rate	Soil	Soil analysis in Bachieng soil				
	pH	P[£]	K[¥]	Ca[¥]	Mg[¥]	Al[$]
(kg ha^{-1})		(mg kg^{-1})	--------------------(cmol$_c$ kg^{-1})-------------------			
L0 (0)	4.5b	1.8b	0.2b	0.6c	0.5c	0.65a
L1 (990)	5.1a	2.7a	0.3a	1.4b	0.7bc	0.39b
L2 (2990)	5.3a	2.9a	0.3a	1.6b	0.9ab	0.37b
L3 (4590)	5.8a	3.1a	0.3a	1.7b	1.1ab	0.18c
L4 (6480)	5.8a	3.1a	0.3a	3.0a	1.1ab	0.12c
F- test	**	*	*	***	**	**
CV (%)	7.9	22.9	8.8	16.3	23.5	27.3

Note Means within a column followed by the same letter were not significantly at $\alpha = 0.05$ by Duncan's Multiple Range Test (DMRT)

* Significant at the 0.05 probability level

** Significant at the 0.01 probability level

*** Significant at the 0.001 probability level

ns = Not significant

[*] Walkley and Black, 1934

[£] Bray 2 extractions (Bray and Kurtz, 1945)

[¥] 1 *M* Ammonium acetate, pH 7 (Rhoades, 1982)

[$] Al by 1 *M* KCl extraction (Barnhisel and Bertsch, 1982)

Table 26 Some soil properties after soybean harvest, Hoythakoune soil in the wet season 2007

Lime rate	Soil	Soil analysis in Hoythakoune soil				
	pH	P	K	Ca	Mg	Al
(kg ha^{-1})		(mg kg^{-1})	------------------(cmol$_c$ kg^{-1})-------------------			
L0 (0)	4.7c	4.2b	0.20	0.52b	0.23c	0.58a
L1 (500)	5.3 bc	4.9ab	0.20	1.52a	0.48b	0.42b
L2 (1000)	5.7ab	4.9ab	0.30	1.62a	0.52b	0.20c
L3 (2250)	5.7ab	5.6ab	0.30	1.77a	0.67ab	0.14c
L4 (3000)	6.1a	6.2a	0.30	2.01a	0.88a	0.12c
F- test	**	*	ns	**	**	**
CV (%)	5.8	16.8	11.9	19.6	28.5	21.2

Note Means within a column followed by the same letter were not significantly at $\alpha = 0.05$ by Duncan's Multiple Range Test (DMRT)

* Significant at the 0.05 probability level

** Significant at the 0.01 probability level

ns = Not significant

In situations where soil pH is extremely low, it required a large amount of lime for recommendation it depends on the type of soil and crop being grown. In Bc and Hk soils after growing continuous soybean for two years the amount of lime that appears necessary for maintaining pH at or above 5.5 was 3720 (L2) and 900 (L3) kg ha^{-1} and can raise soil pH up to 5.8 and 5.7 for Bc and Hk soils, respectively.

3.3.4 Economic analysis of the soybean yield in Bc and Hk soils, in 2007

Economic analysis was undertaken to determine the profitability of lime in these soils (Bachieng and Hoythakoune). Over one year since application, lime increased annual gross by an average of $ 323 per hectare (relative to the adjacent unlimed soybean). However, despite this excellent long-term result, it must also be noted that it took two years for full cost recovery to be realized at this two soils. Soybean yield in Bachieng soil indicated that benefit cost of Bc soil was obtained extremely high in the treatment L1 (about \$519 ha^{-1}), with a benefit/cost ratio of 1.6 the benefit was considerably higher than that for control and low lime rates treatments. The economic analysis of grain yield Bc soil revealed that lime application at 990 $CaCO_3$ kg ha^{-1} resulted in a highly significant net return. The maximum net benefit of the soybean of Hoythakoune soil was \$ 544 ha^{-1}, for L1 (500 kg $CaCO_3$), with a benefit/cost ratio of 2.0 (Figures 11-12). This indicated that high liming rate (500 kg $CaCO_3$ ha^{-1}) gave high benefit.

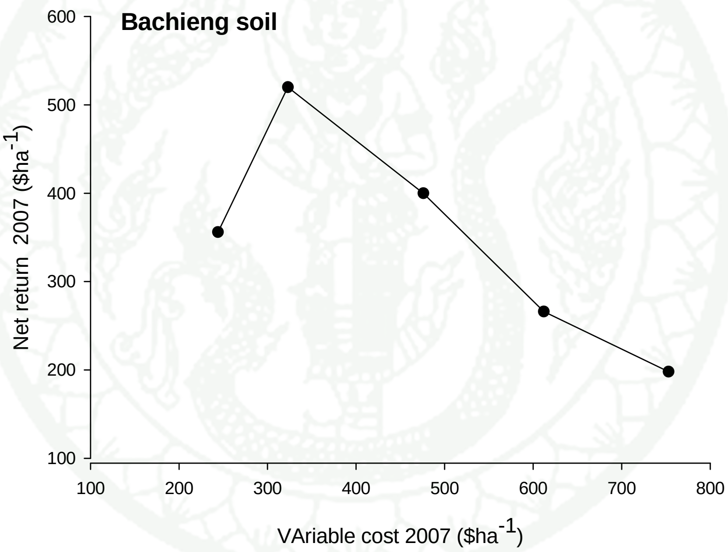

Figure 11 Relationship of net return and variable cost in Bachieng soil in 2007.

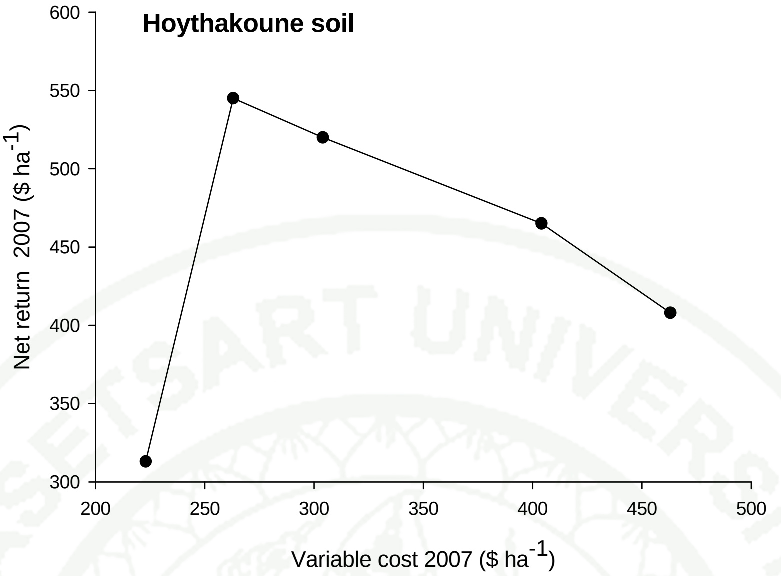

Figure 12 Relationship of net return and variable cost in Hoythakoune soil 2007.

Table 27 Variable cost and net return of Soybean production with different lime treatments of Bachieng and Hoythakoune soils in 2007

Bachieng soil				Hoythakoune soil			
Lime rate	Variable cost	Net return	Benefit/ Cost	Lime rate	Variable cost	Net return	Benefit/ Cost
($kg\ ha^{-1}$)	- - - - ($US ha^{-1}) - - - -			($kg\ ha^{-1}$)	- - - - ($US ha^{-1}) - - - -		
L0 (0)	244	355b	1.4	L0(0)	243	312b	1.3
L1 (990)	323	519a	1.6	L1(500)	263	544a	2.0
L2 (2990)	476	400ab	0.8	L2(1000)	303	519a	1.7
L3 (4590)	612	266c	0.4	L3 (2250)	403	464a	1.1
L4 (6480)	762	198d	0.2	L4 (3000)	463	408a	0.8
F- test		*				*	
CV (%)		22.4				20.2	

Note Means within a column followed by the same letter were not significantly different at $\alpha = 0.05$ by Duncan's Multiple Range Test (DMRT)

CONCLUSION AND RECOMMENDATION

The particle size analysis of three lime materials revealed that calcium hydroxide ($Ca(OH)_2$ has a smaller particle size than calcium carbonate ($CaCO_3$) and marl. The percentage of the liming materials that passed a 60 (<0.25) mm sieve were 93.8 and 88.8 % for calcium hydroxide and calcium carbonate, respectively. In contrast, only 33.96 % of the marl liming material passed a 60 mesh sieve. The fineness of the calcium hydroxide and carbonate is very important because it governs how quickly acidity will be corrected when the lime is incorporated into soil. The amount of the liming materials that was retained on a 35 mesh sieve differed among materials (0.73, 0.8 and 30.02 % of $Ca(OH)_2$,$CaCO_3$ and marl, respectively). The large particle size of marl would probably lead to slow reaction when applied to the soil, and thus this material may not be best suited as a liming material. The high percent of calcium carbonate equivalent in these three liming materials indicated that all materials have acid neutralization capacity necessary to increase soil pH

The analysis of percent of calcium carbonate equivalent (CCE) revealed that the chemical purity of three agriculture limes were different and ranged from 95 to 107%. As expected the CCE of calcium hydroxide was higher than 100 %, reflecting its lower molecular weight. In the case of calcium carbonate and marl both contained a lower percent of CCE. These results similar to Tisdale *et al*. (1975) who reported that the CCE expected percent of “calcium carbonate” and “marl” was 100 and 70-90, respectively. The marl CCE measurement was 95 percent which was less than that of both $Ca(OH)_2$ and $CaCO_3$. This lower CCE may have been the result of the inclusion of clay in the marl.

Lime requirement using different methods of analysis of a target pH of 5.5 of eight soils were widely different. The lowest and highest lime requirements were of the Sv and Xk soils, for Dunn method. The amount of lime requirement using the Kissel and extractable aluminum method were lower for Hk and Pt soils, these soils probably had lower lime requirements because they contained lower clay and organic matter. The highest estimated lime requirement occurred on soils with low soil pH and high clay such as: the Bc, Xk and Ls soils. The Adams-Evans method predicted higher amounts of lime that the other methods and seems generally inappropriate for these soils. Lime requirement of Laos's soils can be estimated by the Kissel and extractable Al methods.

The amount of lime needed based on the field experiments on Bc and Hk soils was about 1125 and 1013 kg ha^{-1} in first and second year with the pH 5.2 and 5.7, respectively. In both Bc and Hk soils, the grain yields were significantly increased by increasing rates of lime compared with the control treatment, but grain yields (L1,2107), (L2,2190) and (L3,2194) kg ha^{-1} were not significantly different between liming treatments . However, grain yield reached a maximum at 1125 kg CaCO3 ha^{-1} with the yield of about 2170 kg ha^{-1}. Grain yield increased with liming rate, and there were no differences yield in various liming treatments. In the Hk soil, grain yields of soybean increased at higher liming rates. The grain yield of L3 was 2170 kg ha^{-1} which was higher than the control treatment of 1340 kg ha^{-1}. Soybean responded to lime application of 1013 kg CaCO3 ha^{-1} with the yield of about 2100 kg ha^{-1}

A field experiment was conducted in the wet seasons of 2006 and 2007 in Bachieng and Hoythakouane soils. The grain and haulm yields were highly significantly increased by increasing liming rates. The data indicated that pH was increased a both years from 4.4 to 5.8 and 4.7 to 6.1 respectively. Apart from pH, lime increased concentration of P, Ca, Mg and decreased Al and Mg in these two soils.

The economic dominance analysis of the soybean yields in Bachieng and Hoythakouane soils indicated very high net returns to the addition of lime in both years. The dominance analysis of the soybean yields at the Bachieng and Hoythakoune sites indicated gave high net returns from the addition of lime the application rate resulted in a decline in soil acidity and an increase in yield.

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APPENDIX

Appendix: Analytical method

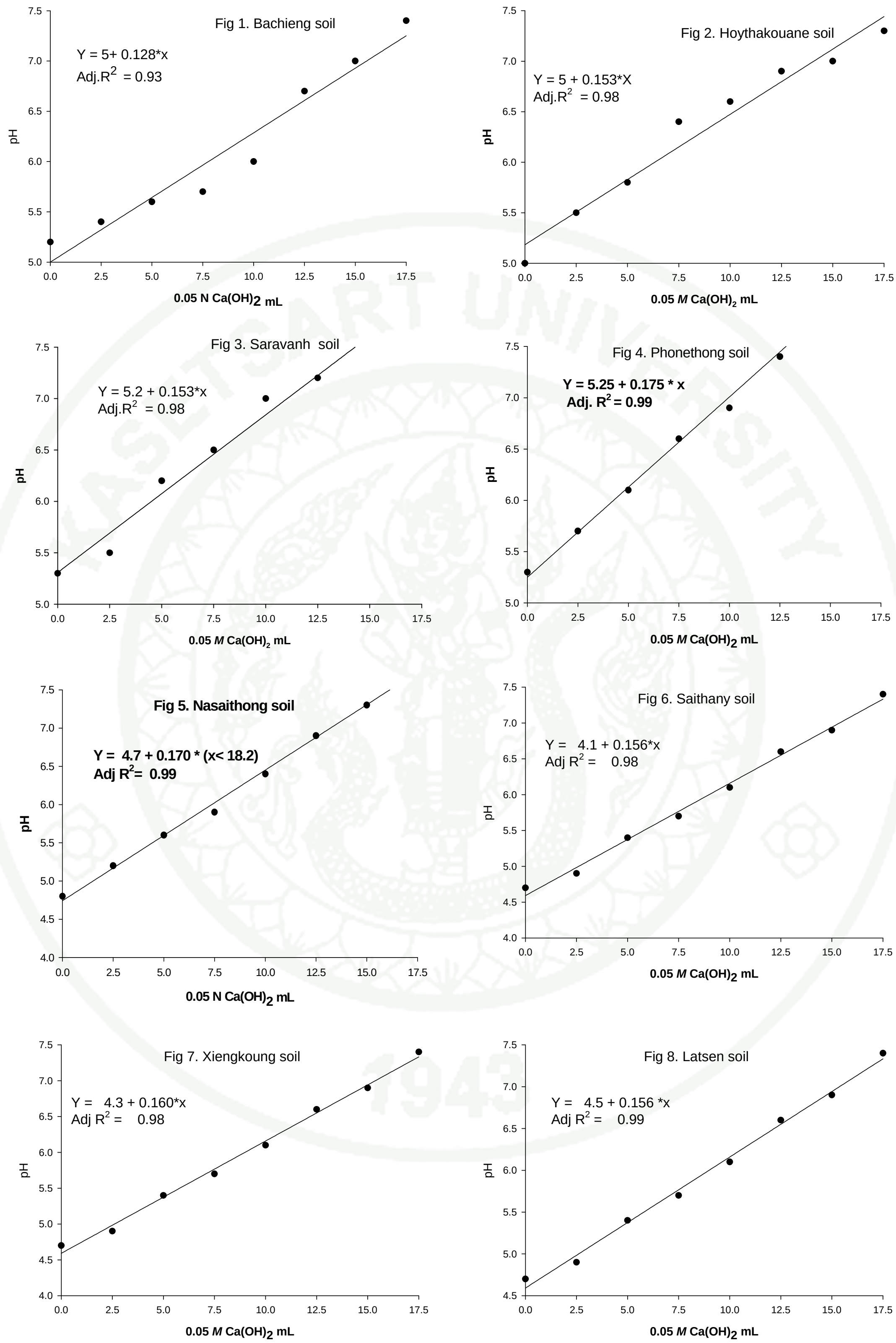
Materials for the field experiments

1. Fertilizer (Triple super phosphate, potassium chloride, urea)
2. Soybean seed, Rhizobia inoculums
3. Auger
4. Lime
5. Balance

Materials and equipments used the laboratory

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

The three experiments were conducted of which one experiment was done in the laboratory and two experiments were conducted in the fields.



Appendix Figure 1 Titration of eight soils with 0.05 *M* $Ca(OH)_2$ were calculated from mL of $Ca(OH)_2$.

Determination of lime buffer capacity (LBC) in routine Laboratory Practice (Kissel lime requirement method)

In routine laboratory practice, sequentially, the soil was dipped with a 20-mL scoop, 20 mL of 0.01 M calcium chloride ($CaCl_2$) was added, the mixture was equilibrated for at least 15 min, and pH (referred to as pH1) was measured using a specially a glass electrodes meter. This was followed by the addition of $Ca(OH)_2$ while stirring [currently 1.8 mL saturated $Ca(OH)_2$],the mixture was equilibrated for an additional 30 min, and a second measurement of pH (referred to as pH2) was done. The following equation is used for calculation of the LBC:

$$LBC = \frac{mL \times N \times EWCaCO_3}{\text{soil weight} \times (pH_2 - pH_1)}$$

for which mL is the volume of $Ca(OH)_2$ added, N is the normality of the saturated $Ca(OH)_2$ (0.046 N), EW is the equivalent weight of $CaCO_3$ (50 mg meq^1), the soil weight (20. g for each soils) is adjusted according to soil province based on an average bulk density (BD), and pH1 and pH2 are the measured values of soil pH before and after the addition of $Ca(OH)_2$, respectively. For the LBC to be directly expressed as mg CaCO3 kg^1 pH1, the soil weight for Equation (2) is entered as kg (20 g 0.020 kg).

Factor 2 in Equation (2) converts LBC units of ppm pure $CaCO_3$ to parts per 2 million (pp2m) pure $CaCO_3$ or lbs. of pure $CaCO_3$ per acre 6-inch depth of soil (assumes BD= 1.5 g cm^{-3}). The factor of 1.5 converts pure $CaCO_3$ to Ag lime. The factor 1.5 has been used previously by both Auburn University and the University of Georgia to compensate for poorly reactive large particles and $CaCO_3$ equivalents less than 100% of Ag lime. The depth conversion is for depths other than 15 cm.

Preparation of Saturated Calcium Hydroxide

Reagents

a. *0.05 N $KHC_8H_4O_4$ (KHP) solution:* Crush 15 to 20 g primary standard $KHC_8H_4O_4$ to about 100 mesh and dry at 120^{o}C for 2 hours. Cool in a desiccators. Weigh 10.00 g (to the nearest milligram), transfer to 1-L volumetric flask and dilute to 1000 mL.

b. *Saturated $Ca(OH)_2$ solution:* Weigh about 42 g $Ca(OH)_2$ powder and place it in 20-L carboy. Add distilled water halfway up, shake vigorously, then fill up to the 20-L mark.

c.*1% Phenolphthalein Indicator:* Pre-prepared concentration available from any chemical vendor.

Method on Standardization of saturated $Ca(OH)_2$ solution

1. Place 5 mL of 0.05 N $KHC_8H_4O_4$ solutions into 100 mL beaker.

2. Add 5 drops of 1% phenolphthalein indicator to the beaker.

3. Obtain a burette. Rinse a small portion of $Ca(OH)_2$ solution through the burette.

4. Fill the burette with saturated $Ca(OH)_2$ solution. Set the burette in a burette clamp.

5. Measure the initial volume of $Ca(OH)_2$ in the burette.

6. Slowly titrate the base ($Ca(OH)_2$) against the acid (KHP). When the OH^- from $Ca(OH)_2$ has neutralized the hydrogen of potassium acid phthalate, the pink

color of phenolphthalein appears. Stop the addition of calcium hydroxide when only the faintest pink appears and remains for two minutes.

7. Measure the final volume of calcium hydroxide ($Ca(OH)_2$).Calculate the normality of $Ca(OH)_2$ following the example below

Dissolve 720 g of calcium acetate $Ca(CH_2OH)_2H_2O$, 11.25 g of magnesium oxide (MgO) and 144 g of para-nitrophenol into 18-L of deionized water. While stirring, continuously bubble air into the solution for 24 hours. Let the solution stand for 48 hours. Siphon through a glass wool filter to another 18-L container to remove undesired precipitates.

Adams-Evans Buffer Solution, pH 8.0±0.1

Dissolve 20 g of *p*-Nitrophenol, 15 g of boric acid (H_3BO_3), 74 g of potassium chloride and 10.5 g potassium hydroxide in 750 ml and dilute to l0-fold with deionized water. Adjust pH to 8.0 with potassium hydroxide.

Adams-Evans and buffer procedure

The A-E procedure was used to predict the lime requirement of each soil sample. Ten milliliters of deionized water was added to 10 g of each soil. After 5 min, the pH was measured while stirred. Then, 10 ml of Adam-Evans and buffer was added to each soil. The soil were shaken for ten min and then allowed to stand for 30 min. The buffer pH was then measured while being stirred. The Adams-Evans procedure was duplicated for each soil and the mean value was used in the analysis. The following equation is used for Adams-Evans

$$\text{Equation} = \frac{(\text{mL V} * \text{M HCl})*(\text{CaCO3} * \text{Soil Kg ha}^{-1})*(\text{pH unit})}{\text{Weight soil (g)} * \text{mL buffer solution}}$$

CIRRICULUM VITAE

NAME	: Mr. Vongvilay Phengsouvana		
DATE OF BIRTH	: June 02, 1962		
PLACE OF BIRTH	: Saravanh province		
EDUCATION	: <u>YEAR</u>	<u>INSTITUTION</u>	<u>DEGREE</u>
	1980	Vsetin Agriculture University, Czechoslovakia	B.Sc. (Agriculture)
SCHOLARSHIP	: Agriculture and Forestry Champasack province, PhoneNgam Rice Research center of Champasack province, Laos PDR, 1985-2005		