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THESIS

PHOSPHORUS REQUIREMENTS FOR MAIZE IN ULTISOLS OF XIENGKHOUANG PROVINCE, LAO PDR.

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A Thesis Submitted in Partial Fulfilment of
the Requirements for the Degree of
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The Ultisols of Xiengkhouang Province are very strong acid soils, so the phosphorus (P) deficiency is the serious problem in this area. The P requirements for maize in Ultisols of Xiengkhouang Province, Lao PDR were quantified based on the terms in the Phosphorus Decision Support System (PDSS) equation. The Phosphorus Buffer Coefficient (PBC), an important factor in this equation, quantifies the reactivity of the soil with P that has been added to the soil. Based on data from South America, the PBC is estimated by its relationship with percent clay. This estimation might not be appropriate for different soils in Laos. This study was comprised of 3 experiments: 1) Determine the Phosphorus Buffer Coefficient (PBC) of 15 representative maize soils of Laos from which P was extracted by three different methods; Bray 2 ($PBC_{Bray\ 2}$), Mehlich 1 ($PBC_{Mehlich\ 1}$) and the Pi test ($PBC_{Pi\ test}$). The soils were incubated with KH_2PO_4 at the rate of 0, 25, 50, 100, 200 and 400 mg P kg^{-1} for two weeks, the amount of P extracted was plotted against added P and the slope of the curve (the PBC) was determined. The results showed that the PBC_{Bray2} values were higher than those of $PBC_{Mehlich1}$ and $PBC_{Pi\ test}$ for all soils. $PBC_{Bray\ 2}$ and $PBC_{Mehlich\ 1}$ were highly correlated with organic carbon, Fe_d and clay and could be predicted with an $AdjR^2$ of 0.79** and 0.86**, respectively. The $PBC_{Pi\ test}$ was correlated with Al_o, clay and organic carbon and could be predicted with an $AdjR^2$ of 0.80**. 2) Quantify the P sorption of potential maize soils of Laos. The results indicated that soils with higher clay, Fe and Al contents sorbed higher amounts of P and desorbed lower amounts of P. The P requirement determined by P sorption isotherms using P in soil solution at equilibrium points of 0.06 and 0.2 mg P L^{-1}($PS_{0.06}$ and $PS_{0.2}$) was very high compared to the P requirement estimated from the PDSS equation for Bray 2, Mehlich 1 and the Pi methods. The third thesis component (3) Determine the necessary amounts of P and Zn needed for commercial maize production in Xiengkhouang province. A field experiment was conducted in an Ultisol near Mee village, Pek district of Xiengkhouang province. The soil was very acid, and P deficiency severely restricted maize growth in the soil as indicated by a diagnostic greenhouse experiment. The field study revealed that after the application of 3.8 T ha^{-1} of $Ca(OH)_2$ lime, and P application at the highest rate of 56 kg P ha^{-1} with 4.72 kg ha^{-1} $ZnSO_4.7H_2O$ gave the highest yield of 5,735 kg ha^{-1} and gave a net return of US$ 290 ha^{-1}. With only the application of lime and the highest P application, (without Zn) yields were 4,418 kg ha^{-1} and the net return was US$ 88 ha^{-1}. The P fertilizer might have been inadequate for this area at the highest rate of application, because maize showed P deficiency symptoms during growth. The PDSS equation predicted the P requirement of the Pek soil at the site may be higher than 56 kg P ha^{-1} when compare to the result of field experiment.

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Student’s signature Thesis Advisor’s signature

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Xaysatith Souliyavongsa
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LIST OF ABBREVIATIONS

ADP = Adenosine Di-Phosphate
Al_d = Aluminum extracted by citrate bicarbonate dithionite
Al_o = Aluminum extracted by acid ammonium oxalate
ATP = Adenosine Tri-Phosphate
Bc = Bachieng soil
Bt = Bortaen soil
CEC = Cation Exchange Capacity
Cm = Centimeter
CV = Coefficient of variation
FAO = Food and Agriculture Organization of United Nation
Fe_d = Iron extracted by citrate bicarbonate dithionite
Fe_o = Iron extracted by acid ammonium oxalate
G = Gram
Kg = Kilogram
Kha = Kham soil
Kn = Koon soil
Ks = Kasi soil
Kt = Kaentao soil
GDP = Gross Domestic Product
M = Meter
Mm = Millimeter
NS = Not significant
OC = Organic carbon
OM = Organic matter
P_0 = Initial soil level of extractable phosphorus
PBC = Phosphorus Buffer Coefficient
PBC_{Bray2} = PBC in Bray2 extractable phosphorus
$PBC_{Mehlich1}$ = PBC in Mehlich1 extractable phosphorus
$PBC_{Pi\ test}$ = PBC in Pi test extractable phosphorus

LIST OF ABBREVIATIONS **(Continued)**

P_{cl} = Phosphorus critical level

PDSS = Phosphorus Decision Support System

Pe = Pek soil

Pkd = Pookood soil

Pkn = Pookoon soil

Pl = Paklay soil

$PS_{0.06}$ = Phosphorus required to obtain soil solution P concentration of 0.06 mg L^{-1}

$PS_{0.2}$ = Phosphorus required to obtain soil solution P concentration of 0.2 mg L^{-1}

Psi = Pasai soil

Pso = Paksong soil

Sk = Sekong soil

Sv = Salavanh soil

Tb = Tabok soil

USDA = United States Department of Agriculture

PHOSPHORUS REQUIREMENTS FOR MAIZE IN ULTISOLS OF XIENGKHOUANG PROVINCE, LAO PDR.

INTRODUCTION

The agricultural sector is the backbone of Laos's economy and will be the basis for increasing farmer's income, currently accounting for about 56% of the Lao GDP. After rice, maize is considered as the most important cereal crop and is now playing a major role in the food security of Lao people (Bouahom *et al*., 2001).

Soil is one of the most important natural resources contributing to a nation's values. It is a key base for agriculture and forestry. For the Lao PDR, a large area of about 80% is covered by mountains. The major areas are Acrisols and Alisols in the FAO UNESCO system (FAO, 1990) similar to Ultisols in soil taxonomy (USDA and NRCS, 2006). The native P content of Ultisols is usually low and the soils tend to fix fertilizer P rapidly (Ruaysoongnern and Keerati-kasikorn, 1996).

The Ultisols cover about 68% of the agricultural area in Laos (Phommasack, 2001). About 97% of the soils contain extractable P less than 10 mg kg^{-1}. Soils with extractable K less than 40 mg kg^{-1} cover about 71 % of the soils while soils with a pH of 4.1 to 5 cover 78%. Soils in which the organic matter content is less than 2 g kg^{-1} cover 87% of the total area (Vonghachack, 2000).

The major problems of maize production in Laos are thus infertile soils with high soil acidity and low P. Beside the soil problem, farmers are still lacking of nutrient management and fertilizer application knowledge. These factors have resulted in low yields. Fertilizer applications for maize production are very different in the production area depending on the economy of the farmers rather than on the nutrient needs of the soils (Lathvilayvong, 2000).

Xiengkhouang province is located on the central part of Laos and it has potential in maize production, but this area is covered by acid, infertile savanna grassland with pine trees, and only 5% of the total areas is cultivated (Lienhard *et al.*, 2005). In the vicinity of the provincial capital of Xiengkhouang, it is estimated that more than 60,000 ha of acid, infertile savanna grassland are under-utilized by small holders (Tivet *et al*., 2005). Phosphorus deficiency is a serious problem in this area. A new technology for P fertilizer prediction using Phosphorus Decision Support System (PDSS) program has been developed by Yost *et al*. (1992). This software has been successfully used for maize production in Thailand. The use of the decision-aid has worked well, and resulted in reducing P fertilizer applications, and the farmers accepted the recommendations (Attanandana *et al*., 2000). Dounphady (2009) found that P fertilizer applied at 56 kg P_2O_5 ha^{-1} and a 3800 kg ha^{-1} lime application in an Ultisol of Xiengkhouang permitted maize yields of up to 6,254 kg ha^{-1}, while the control treatment yielded only 632 kg ha^{-1}. However, strong Zn deficiency symptoms occurred. Consequently, additional study to assess methods of correcting the zinc deficiency was needed.

Phosphorus Buffer Coefficients (PBC), the slope of regression line of extractable P versus P added is an important factor in the P requirement prediction in the PDSS program (Chen *et al*., 1997). Beside the PBC, P sorption by soils is an important parameter for understanding soil fertility problems, as well as for determining the environmental fate of P (Graetz and Nair, 2000). Consequently, the study proposed herein was to determine the PBC and factors affecting PBC of some representative maize soils of Laos. The study on estimating P fertilizer requirements for maize production by the algorithm in the PDSS programs will be a great benefit to the farmers of Laos.

The P sorption of representative upland soils is also studied for P fertilizer recommendation and management. The response of maize to P and zinc in the Ultisol of Xiengkhouang province is also included in the studies.

OBJECTIVES

1. Determine the PBC of 15 representative maize soils of Laos using three extractant methods: Bray 2; Mehlich 1; and Pi test.

2. Predict P requirement for 15 representative maize soils in the Lao PDR

3. Determine phosphorus sorption in 15 soils of Laos by phosphorus sorption isotherm technique

4. Determine the economics of phosphorus and zinc response to maize in an Ultisol of Xiengkhouang Province

LITERATURE REVIEW

1. The importance of P for maize.

Phosphorus is an essential macronutrient that is needed by plants. It is a component of adenosine diphosphate (ADP) and adenosine triphosphate (ATP), the two compounds involved in most significant energy transformations in plants. ATP, synthesized from ADP through both respiration and photosynthesis, contains a high energy phosphate group that drives most biochemical processes requiring energy (Brady, 1990). Furthermore, Troeh and Thompson (2005) added that P is directly involved in most life processes. It is an essential component of living cells as a part of the nucleoproteins that carry the genetic code of living things. When fertilizer is applied, P and nitrogen are nearly always considered.

Plants, especially maize when receiving inadequate amounts of P will grow slowly, produce short thin stems, exhibit stem and leave margins or tips of leaves that are purple, and mature slowly. Plants might not produce flowers and ears on time, and roots grow incompletely in low phosphorus soils. Phosphorus deficiency can occur in both low and high pH soils (Rattanarat *et al.*, 2000)

2. Forms of P in soils

Soil P can be generally classified into organic and inorganic forms (Sauchelli, 1965). The organic fraction is found in humus and organic materials which may or may not be associated with humus.

Inorganic compounds were classified into two types (1) those containing calcium and (2) those containing iron and aluminum (Tisdale *et al.*, 1985). The solubility of these compounds in water varies from sparingly soluble to very insoluble. Phosphate also reacts with clays to form generally insoluble phosphate complexes. The important process involved is the P sorption process.

3. Phosphorus sorption

Phosphorus sorption is the process by which P is adsorbed on the surfaces of soil constituents. After the initial surface reaction, the adsorbed P diffuses slowly towards the interior of the particle and so becomes ever less available to plants. The whole reaction, adsorption plus penetration are called sorption (Bolland *et al*., 2003). So P sorption involves to inner sphere ligand exchange between P ions and soil constituents (Bolland *et al*., 2003). When P is added to soil, P sorption rate on the solid phase is fast at the initial stage and declines until reaching equilibrium (Frossard *et al*., 1995). There are many physical and chemical properties of soil that influence P sorption including the following:

3.1 Soil clay mineralogy

Havlin *et al*. (2005) indicated that adsorption and desorption reactions are affected by the type of mineral surfaces in contact with solution. Iron and Al oxides are abundant in acid soils and have the capacity to adsorb large amounts of solution P. Iron and Al oxides occur as discrete particles in soils or as coatings or film on other soil particles. They also exist as amorphous Al hydroxyl compounds between the layers of expandable Al silicates. In soils with significant Fe and Al oxide contents, the less crystalline or the more amorphous the oxides, the larger their P fixation capacity because of greater surface area.

Phosphorus is adsorbed to a greater extent by 1:1 clays (e.g.,kaolinite) than by 2:1 clays (e.g., smectite) because of the higher amount of Fe and Al oxides associated with kaolinitic clays that predominate in highly weathered soils. The greater amount of P fixed by 1:1 clays is probably largely due to the higher amount of hydrated oxides of Fe and Al associated with Kaolinitic clays. In addition, kaolinite develops pH dependent charges on its edges which can enter into sorption reaction with phosphorus (Tisdale *et al*., 1985).

However, Ryan *et al*., (1985) reported that P sorption in related to their Fe oxide more than $CaCO_3$ content in the soils. Phosphorus sorption capacity of soil is highly correlated with Fe oxide and clay contents while $CaCO_3$ plays a less important role in P sorption (Solis and Torrent, 1989).

To maintain a given level of solution P in soils with a high fixation capacity, it is necessary to add large quantities of P fertilizer. In any one soil, solution P concentration increases with increasing P additions. Larger additions of P are required to reach a given solution P concentration in fine textured soils compared with coarse textured soils. This often is the consequence of greater surface area in clay soils than in sandy soils.

3.2 Soil pH

Prasad and Power (1997); Jones (1979) explained that pH has a profound influence on the availability of P and other ions in soil solution. Phosphorus availability in soils is greatest in the pH range of 6 to 6.5. At lower pH, the increased solubility of Fe and Al resulted in greater retention of applied P, while at higher pH, Ca plays a dominant role in P retention.

3.3 Cation effects

Divalent and trivalent cations on the soil exchange complex enhance P adsorption more than do monovalent cations (Havlin *et al*., 2005). For example, clay saturated with Ca^{+2} retain greater amounts of P than those saturated with Na^{+} or other monovalent ions. Divalent cations increase the accessibility of (+) charged edges of clay minerals to P and this occurs at pH <6.5, because at higher soil pH, Ca-P minerals would be precipitated (Havlin *et al*., 2005).

In addition, Fe, Al, Ca and other cations in soils are directly involved in P retention and can also influence the retention of P in the soils (Prasad and Power, 1997).

3.4 Anion effects

Tisdale *et al*. (1985) suggested that both inorganic and organic anions can compete with P for adsorption sites, resulting in decreased P adsorption. Weakly held inorganic anions such as NO_3^- and Cl^- are of little consequence, whereas specifically sorbed anions and acids such as OH^-, $H_3SiO_4^-$, SO_4^{-2}, and MoO_4^{-2} can be competitive. The strength of bonding of the anion with the sorption surface determines the competitive ability of that anion.

Organic anions from sources such as organic waste materials and wastewater treatment can affect the P adsorption–desorption reactions in soils. The impact of organic anions on the reduction of adsorbed P is related to their molecular structure and pH. Organic anions form stable complexes with Fe and Al, which reduces adsorbed P. Oxalate and citrate, can be adsorbed on soil surfaces similarly to $H_2PO_4^-$. Some of the effect of organic anions on P adsorption is also partially responsible for the beneficial action of OM on P availability.

3.5 Extent of P saturation

Havlin *et al*, (2005) indicated that in general, P adsorption is greater in soils with little P adsorbed to mineral surfaces. As fertilizer P is added and the quantity of P adsorption increases, the potential for additional P adsorption decreases. When all adsorption sites are saturated with $H_2PO_4^-$, further adsorption will not occur and recovery of applied fertilizer P should increase.

3.6 Soil OM

Humus, since it is normally negatively charged, is not thought to retain much P by itself; however in association with cations such as Fe^{3+}, Al^{3+}, and Ca^{2+} it is able to retain significant amounts of phosphate (Wild, 1950). Appelt *et al*. (1975) prepared a hydroxyl-Al-humic acid complex that was capable of adsorbing P. The amount of P adsorbed increased as the Al:OH ratio decreased, which led them to believe that the P was absorbed by ligand exchange of phosphate for a hydroxyl group. They reasoned that humic acid could react with Al from soil minerals to form these complexes, which would give rise to new surfaces for P adsorption.

3.7 Time and temperature

Tisdale *et al*. (1985) reported that P adsorption in soil follows two distinct patterns: an initial rapid reaction followed by a much slower reaction. Adsorption reactions involving exchange of P for anions on Fe and Al oxide surface are rapid. The slower reactions involve (1) formation of covalent Fe-P or Al-P bonds on Fe and Al oxide surfaces and (2) precipitation of a P compound for which the solubility product has been exceeded. These slow reactions involve a transition from more loosely bound to more tightly bound adsorbed P, which is less accessible by plants.

Certain climates also give rise to soils with higher Fe and Al oxide contents. Mineralization of P from soil OM or crop residues depends on soil biological activity, which increases with increasing temperature. Usually, mineralization rates and chemical reactions in general double with each 10˚C increase in temperature (Havlin *et al*., 2005).

Singh and Jones (1977) reported the influence of temperature and available P on lettuce growth. They found that cold temperatures reduced plant P uptake, the use of equilibrium solution P as a predictor was useful for estimating P requirement.

4. Interactions between P and zinc

The suggestion that P induced zinc deficiency results from precipitation of $Zn_3(PO_4)_2$ in the soils or on the roots was convincingly demonstrated by solubility experiments (Boawn *et al*., 1954; Jurinak and Inoye, 1962). Furthermore Boawn *et al*., (1954) stressed another puzzling aspect of the Zn-P relationship, i.e., Zn content of leaves is not always an indicator of Zn deficiency. Verma and Minhas (1987) however, found that the concentration of Zn in maize decreased when increased P application.

5. Extractable soil P analysis

Presently, there are numerous soil tests that assess the availability of soil P (Peverill *et al*., 1999) (Table 1). Each extractant was specifically developed to assess plant available P in different soils with different conditions, for example, as in acid soils, Al-P and Fe-P are usually found, whereas in calcareous soils, Ca-P is found.

Table 1 Extracting methods frequently used to determine plant-available P.

Method	Extractant	Soil/extractant ratio	Shaking time	Reference
Ammonium lactate acetate acid	0.1 *M* ammonium lactate + 0.4 *M* acetic acid	1:20	30 min	Egner *et al*., 1960
Bray 1	0.03 *M* NH_4F in 0.025M HCl	1:7	60 s	Bray and Kurtz 1945
Bray 2	0.03 *M* NH_4F in 0.1M HCl	1:7	40 s	Bray and Kurtz 1945
BSES	0.005 *M* H_2SO_4	1:200	16 h	Kerr and von Stieglitz 1938
Calcium chloride	0.005 *M* $CaCl_2$	1:5	18 h	Moody *et al*., 1983
Water	Water	1:10	5 min	Kuo, 1996
Calcium acetate lactate	0.1 *M* calcium lactate + 0.01 *M* calcium acetate + 0.3 M acetic acid	1:20	2 h	Schuller, 1969
Colwell	0.5 *M* $NaHCO_3$, pH8.5	1:100	16 h	Colwell, 1963
Equilibrium P concentration	0.01 *M* $CaCl_2$	1:10	18 h	Moody *et al*., 1983
Fluoride	0.5 *M* NH4F	1:50	2 h	Holford *et al*., 1985
Lactate	0.02 *M* calcium lactate in 0.01*M* HCl	1:50	16 h	Holford *et al*., 1985
Mehlich-1	0.05 *M* HCl + 0.05 M H_2SO_4	1:4	18 h	Mehlich, 1953
Olsen	0.5 *M* $NaHCO_3$, pH 8.5	1:20	30 min	Olsen *et al*., 1954
P*i*	Iron oxide impregnated paper in 0.01*M* $CaCl_2$	1:40	16 h	Menon *et al*., 1990
Truog	0.001*M* H_2SO_4+ 0.3%$(NH_4)_2SO_4$	1:200	30 min	Truog, 1930

In Laos, the Bray 2 method is usually used for P extraction. However, there seems to be no study identifying the most appropriate method for assessing plant available P soils of Laos. There are, however, no indications that soils of Laos will require different methods from those already in used. Recently, Dounphady (2009) found that maize yield was most highly correlated with P extracted by Mehlich 1 than with Bray 2 and Pi extraction methods.

In addition, Sissingh (1983) proposed the iron oxide impregnated filter paper method (Pi test). This method attempts to mimic P uptake by plant roots.

Menon *et al*., (1989) found that P extracted by the Pi test was highly correlated with maize growth in 4 soils that varied in pH from 4.5-8.2. The correlation was 0.87 between P uptakes by plant dry matter yield. The Pi method is thus an efficient method in P determination in soils.

Hosseinpur and Ghanee (2006) compared P extractant methods for maize in 16 soil samples, they included the Pi test; Olsen; Colwell; Mehlich1; 0.1*M* $CaCl_2$; AB-DTPA and 0.1*M* HCl. They found that P extracted by the Pi test was significantly correlated with P uptake by plant.

6. The study of Phosphorus Buffer Coefficient

Phosphorus Buffer Coefficient (PBC) is an index for quantifying the reactivity of soil with added P. It can be obtained from the slope of regression between P added in the soils and soil extractable P (Figure 1). This figure illustrates that the PBC of soil from PooKood District was 0.2134.

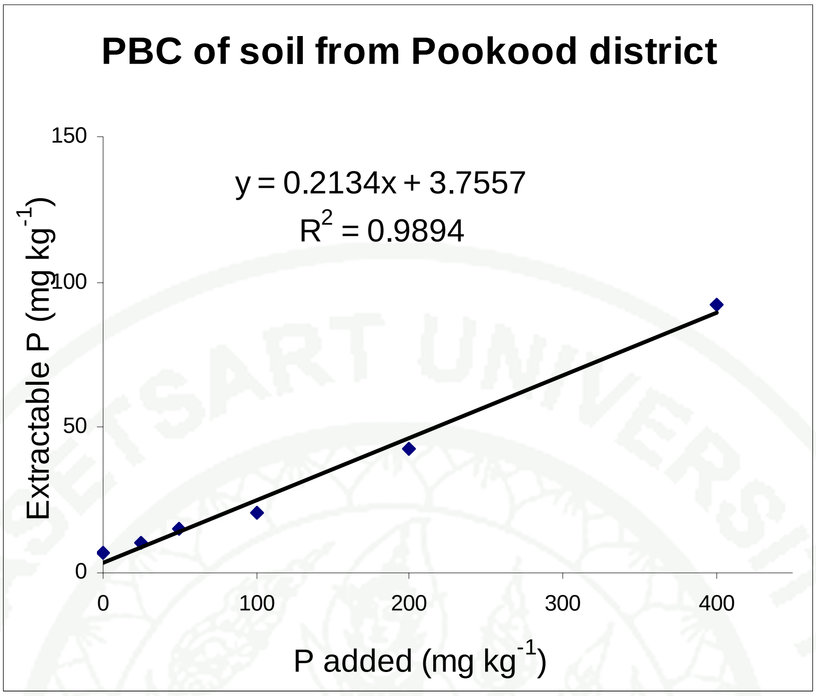

Figure 1 An example of obtaining PBC of soil from Pookood District

Presently, the PDSS software determines PBC using related equation between PBC and percent of clay (Cox, 1994; Lins and Cox, 1989). George *et al*. (1999) presented PBC values from some soil samples of Philippine and Indonesia estimated by PDSS software and found that PBC in soil contained 35% clay was 0.22., 0.10 in 54%clay and 0.07 in a soil with 63% clay. These estimates, however, differed somewhat from both field experiment and PDSS prediction. There was a lack of consistency in the ranking in this limited range of sites and clay content. A much larger set of site and comparisons would be needed to further refine the prediction of PBC.

Wang *et al*. (2000) used potential sorption site density and soil aggregation to predict PBC of soils. They found that soils which had large differences in equilibrium points of P were not different with regard to PBC values. They suggested that the PBC prediction should include other soil characteristics in addition to P sorption potential or P sorption site density.

Hongthana (2007) evaluated the correlation between soil properties and PBC of 10 submerged soil series extracted by Mehlich 1; Bray 2 and Pi test and found that the Pi test was a suitable method for PBC determination in submerged soil. Alcantara *et al*. (2008) reported that the PBC is strongly dependent on clay and soil organic matter content, and that the classification and grouping of soils according to their P buffer capacity improved the correlations between extractable P and plant response for Mehlich 1 and Bray 1 extractants.

7. Phosphorus requirement prediction

The P requirement of the soils could be predicted by Phosphorus Decision Support System (PDSS) program (Yost *et al*., 1992). The PDSS is the software on a CD-ROM and can be used with computers that use the Windows operating system. The P requirement can be obtained using eq. 1.

P requirement = {(P_{CL}-Po)/PBC+0.8 x PBC x P uptake x 0.8 x 1/2 x Placement factor x App Depth/10

Where: P_{CL} = P critical level of the crop using a specific extractant
Po = Initial soil level of extractable P, obtained using the same extractant as used to determine the P_{CL}
PBC = Phosphorus Buffer Coefficient, also obtained using the same extractant as used to obtain the P_{CL}
P uptake = Yield of crop component removed*% P in removed tissue/100
Application depth = Depth to which the fertilizer is incorporated
Placement factor = A factor that represents the relative efficiency of localized placement in reducing the P fertilizer requirement

8. The study of P sorption and desorption in soil

Kamprath and Watson (1980) reported that the P sorption isotherm is a technique to estimate P requirements of plants, because it gives details of intensity and sorbed P by soil in equilibrium point. The method is based on mixing an amount of soils with P solution, shaking for 24 hours at a certain temperature, to estimate the equilibrium point of P in solution with sorbed P (Nair *et al*., 1984). Phosphorus lost from solution after equilibrium is considered P sorbed by soil. Kamprath and Watson (1980) reported that the concentration 0.2 mg L^{-1} of P in soil solution at equilibrium point was an index of optimum plant growth. The amount of sorbed P at this equilibrium point was called P buffer capacity, in contrast to the Phosphorus Buffer Coefficient (PBC), which was proposed for P recommendation. Ozanne and Shaw (1967) used this technique to determine the P requirement for pasture growth. They found a good linear correlation between the amount of phosphate sorbed and phosphate required on different soils, which accounted for over 85% of the variability in phosphate requirement. This method was also used as a standard method to estimate P sorption in Western Australia (Bolland *et al*., 2003). Fox and Kamprath (1970) also conducted an experiment with wheat in greenhouse pots and reported that a P concentration of 0.2 mg P kg^{-1} in soil solution was adequate for a plant yield of 90% maximum. They concluded that P estimated by this method was suitable for P recommendations.

9. Characteristics of Ultisols

Kyuma (1984) suggested that there were three problems of Ultisols in fertility characteristics as follows:

9.1 Acidity and aluminum toxicity is implied in the term “acid infertile soils”. Oxisols and Ultisols are invariably acid, as a result of long term weathering and leaching under humid climatic conditions. The paucity of nutrients in soils with low pH and low negative charge is a more generally recognized problem associated with soil acidity in the humid tropics.

9.2 Soils dominated by low activity clay have, by definition, a low cation retention capacity. For variable charge components it is evident that the cation retention capacity or effective CEC can be increased by raising the medium pH.

9.3 Phosphorus sorption by Al and Fe oxides is a widely noted agronomic problem in the tropics.

Driessen and Dudal (1991) summarized the chemical characteristics of Acrisols (FAO/Unesco) or Ultisols (USDA and NRCS, 2006) indicating that Acrisols have poor chemical characteristics; their nutritional limitations include widespread Al toxicity and strong P sorption as in Ferrasols. The pH (H_2O) is often close to 5.5. Because Acrisols are soils with little biological activity and low activity clay, natural regeneration of the surface soil, e.g. degraded by mechanized agriculture, is very slow.

In addition, Brady and Weil (2008) described Ultisols as typically formed on old land surfaces, under forest vegetation, although savanna or swamp vegetation is common. Clay mineral weathering is a principal process involved in forming highly weathered Ultisols. Ultisols commonly have both an epipedon and subsoil that are quite acid and low in plant nutrients.

MATERIALS AND METHODS

1. Soil sampling

Fifteen representative upland maize soils were selected from different sites in 7 provinces of Laos for this study (Table 2).

Table 2 List of soil samples selected to represent upland soils of Laos.

No.	District Name	Province	Bulk density (Mg m^{-3})	Soil family
1	Pasai	Xiengkhuang	1.01	Ultisols: fine, kaolinitic, isohyperthermic Typic Paleustults
2	Pek	Xiengkhuang	1.24	Ultisols: fine, kaolinitic, isohyperthermic Typic Paleustults
3	Kham	Xiengkhuang	1.54	Ultisol: fine, kaolinitic, isohyperthermic Typic Paleustults
4	Pookood	Xiengkhuang	1.18	Ultisols: fine, kaolinitic, isohyperthermic Typic Paleustults
5	Salavanh	Salavanh	1.06	Ultisols: very fine, mixed, isohyperthermic Typic Paleustults
6	Pookoon	Luangpabang	0.82	Ultisols: very fine, mixed, isohyperthermic Typic Paleustults
7	Borten	Saiyabuly	1.38	Ultisols: fine, mixed, isohyperthermic Typic Haplustults
8	Bachieng	Champasak	1.24	Ultisols: very fine, kaolinitic, isohyperthermic Kanhaplic Haplustults
9	Tabok	Champasak	1.16	Ultisols: very fine, mixed, isohyperthermic Typic Paleustults
10	Paksong	Salavanh	1.11	Ultisols: fine, mixed, isohyperthermic Typic Paleustults
11	Kasi	Vientiane	0.89	Alfisols: fine, kaolinitic, isohyperthermic Kandic Paleustalfs
12	Paklay	Saiyabuly	1.19	Alfisols: fine, mixed, isohyperthermic Ultic Paleustalfs
13	Sekong	Sekong	1.08	Alfisols: very fine, mixed, isohyperthermic Ultic Paleustalfs
14	Koon	Xiengkhuang	1.40	Alfisols: fine, mixed, isohyperthermic Kandic Paleustalfs
15	Kentao	Saiyabuly	1.16	Alfisols: very fine, mixed, isohyperthermic Ultic Paleustalfs

2. Soil preparation

The fifteen upland soil samples were air dried ground and sieved to 2 mm and 0.5 mm particles (for organic matter analysis).

3. Experiments

This study consisted of 3 experiments:

3.1 Experiment 1: Quantify the correlation of the PBC and soil properties

3.1.1 Soil properties analysis

Some soil properties were analyzed. Soil pH was determined by glass electrode in a soil : water ratio of 1:1 (Black *et al*., 1965), field capacity was determined by the pressure plate method (Tan, 2005), soil texture was determined by the pipette method (Gee and Bauder, 1986), total N and P was determined by Kjeldahl analysis (Kjeldahl, 1883), available P was extracted by Bray 2 (Bray and Kurtz, 1945), Mehlich 1 (Mehlich, 1953), and by the Fe-strip Pi (Chardon, 2000) methods, extractable K, Ca, Mg, Na were analyzed by NH_4OAc, pH 7 (Yoshida *et al*., 1972), cation exchange capacity (CEC) was measured by NH_4OAc, pH 7 (Yoshida *et al*., 1972), organic matter (OM) was determined by the method of Walkley and Black, 1934; Fe, Mn, Zn were extracted by the DTPA pH 7.3 method (Lindsay and Norwell, 1978), extractable Al and Fe were measured by two methods as acid ammonium oxalate pH 3 and the citrate bicarbonate dithionite method (Loeppert and Inskeep, 1996).

3.1.2 Phosphorus Buffer Coefficient study

A. Phosphorus Buffer Coefficient by Bray 2

Five gram of 2 mm-sieved soil was amended with potassium dihydrogen phosphate (KH_2PO_4) at the rates of 0, 25, 50, 100, 200 and 400 mg P kg^{-1}. Deionized water was added to maintain the soil moisture at field capacity. Samples were incubated at 30˚C for two weeks. Phosphorus was extracted by the Bray 2 extractant solution (0.1 M HCl + 0.03 M NH_4F) then shaken for 60 seconds. The extractable P was determined using the ascorbic acid method (Murphy and Riley, 1962). The extractable P was plotted against added P and the slope of the plot was recorded as the Phosphorus Buffer Coefficient.

B. Phosphorus Buffer Coefficients by Mehlich 1

Each sample of 5 g of 2 mm-sieved soil was amended with potassium dihydrogen phosphate (KH_2PO_4) at the rates of 0, 25, 50, 100, 200 and 400 mg P kg^{-1}. Deionized water was added to maintain the soil moisture at field capacity. Samples then were incubated at 30˚C for two weeks. Phosphorus was extracted by Mehlich 1 extractant solution (0.05 M HCl + 0.0125 M H_2SO_4) and then shaken for 5 minutes. Extractable P was determined using the ascorbic acid method (Murphy and Riley, 1962). The extractable P was plotted against added P and the slope of the graph was recorded as the Phosphorus Buffer Coefficient.

C. Phosphorus Buffer Coefficients by Pi test

One g of 2 mm-sieved soil was amended with potassium dihydrogen phosphate (KH_2PO_4) at the rates of 0, 25, 50, 100, 200 and 400 mg P kg^{-1}. Deionized water was added to maintain the soil moisture at field capacity. Samples were incubated at 30˚C for two weeks. Phosphorus was extracted for the Pi test using FeO paper. The FeO paper was covered with a nylon net then put into a bottle containing soil and 0.01 M $CaCl_2$, and shaken for 16 hours.

After removing the FeO paper from the bottle, it was washed with deionized water to remove soil particles, then the FeO paper was shaken with 0.1 *M* H_2SO_4 for one hour. Finally, all extractable P was determined using the ascorbic acid method. The Phosphorus Buffer Coefficient was obtained as the slope of linear equation, determined by a linear regression of extracted P (Y axis) versus the added P. The PBCs obtained from each of the three extracting methods were examined and tested for correlation with soil properties by multiple regression.

3.2 Experiment 2: Determine phosphorus sorption of selected soils by the P sorption isotherm technique

The method of P sorption isotherm followed the method of Nair *et al.* (1984). Fifteen soil samples were ground and sieved to pass a 2 mm sieve, and then 2 g of soil was weighed into plastic bottles. Potassium dihydrogen phosphate at the rates of 0, 25, 50, 100, 200 and 400 mg P kg^{-1} was applied (the P rates applied to each soil were different depending on the P sorption capacity of the soil). Forty ml of $0.01M$ $CaCl_2$ and three drops of toluene were added to the bottles to control activity of microorganisms. The soil and solution were shaken for 24 hours, and then centrifuged at 3000 R min^{-1}. The P that remained in solution was determined by the ascorbic acid method.

The Phosphorus adsorbed by soil was calculated as the amount of P added in to soils minus the P that remained in soil solution. The P sorption was obtained by plotting P remaining in soil solution against P sorption by soils.

3.3 Experiment 3: Determine the appropriate rates of P and Zn application for maize production in an Ultisol of Xiengkhouang Province

A field experiment had been earlier established on grasslands of Mee village, Pek District, Xiengkhouang province, by another student (Dounphady, 2009). This previous experiment was continued for additional study of P and Zn applications. The soil of the area is a fine, kaolinitic, isohyperthermic Typic Paleustult that was very acid, pH 4.5, high Al and Fe, and also P deficient.

The study in wet season 2006 and 2007 in this area (Dounphady, 2009), revealed that the maize yield in 2006 was very low, only 1,600 kg ha^{-1}, at a rate of P application of 56 kg P_2O_5 ha^{-1} and with 3,500 kg ha^{-1} of $Ca(OH)_2$ lime. An additional 300 kg ha^{-1} of $Ca(OH)_2$ lime was added in 2007, and P was re-applied as elemental P rather than as P_2O_5 as previously. Zn deficiency symptoms were observed, however.

Consequently, the experiment reported here was the third crop. Nitrogen and K were applied at the same rate as Dounphady (2009) (Table 3), and $ZnSO_4.7H_2O$ was applied at the rate of 4.78 kg ha^{-1}. Phosphorus had been applied for Crops 1 and 2 as the indicated amounts, but as P_2O_5 ha^{-1}, rather than as kg P ha^{-1}.

Table 3 Fertilizer rates of field experiment in 2008.

Treatment	N (kg ha^{-1})	P (kg ha^{-1})^1	K (kg ha^{-1})	$ZnSO_4.7H_2O$ (kg ha^{-1})
1	110	0	82	4.78
2	110	7	82	4.78
3	110	14	82	4.78
4	110	28	82	4.78
5	110	56	82	4.78

Note ^{1}These rates of P were applied as P_2O_5 ha^{-1} in crops 1 (in 2006) and 2 (in 2007) but were applied as kg P ha^{-1} for crops 3 (in 2008) and subsequently.

The field experiment was an RCB with Zn application as strip-plot design (Appendix 1). The main plot size was 5 x 6 m with 8 rows and 200 plants. Each main plot was divided into two subplots comprised of 4 rows. Each subplot either received or did not receive zinc sulfate. The spacing between plots was 1 meter, and the plant spacing was 25cm x 75cm.

Maize variety LVN10 was chosen because this variety is adapted to Xiengkhouang conditions. Phosphorus and K were applied at the planting time and N was split-applied two times, at 10 days as a basal dressing and at 30 days after planting as a top dressing. Zinc was applied as a coating of the grain using a gum arabic solution. The solution was prepared by dissolved 75 g of gum arabic in 250 ml boiling, deionized water, after cooling, 143.43g of $ZnSO_4.7H_2O$ (4.78 kg ha^{-1}) was added to the gum arabic solution and 937.5 g of maize seed (30 kg ha^{-1}) was put into the solution and mixed thoroughly (Rattanarat *et al*., 1983).

RESULTS AND DISCUSSION

1. **Experiment 1:** Quantify the correlation of the PBC and soil properties

1.1 Characteristics of the selected soils

The fifteen upland maize soils in this study were Ultisols (Psi, Pe, Kha, Pkd, Pkn, Bt, Sv, Bc, Tb, Pso), and Alfisols (Kn, Ks, Pl, Kt, Sk). The soils were predominantly acidic with soil pH values ranging from 4.5-5.9, soil textures were clay, silty clay, clay loam, silty clay loam, loam and sandy loam. All soils had low contents of organic carbon (7.0-22.9 g kg^{-1}); low available P ranging from 0.68-4.62 mg kg^{-1} by Bray 2, except the Pkd soil which contained high levels of available P according to all extracting methods (Table 4). Soil samples were divided into two groups as follows: (1) Soils containing a high percent clay, ranging from 363-709 g kg^{-1}, high Fe and Al as determined by the citrate bicarbonate dithionite method (Fe_d and Al_d) ranging from 26.8-125.5 and 2.56-30.56 g kg^{-1} respectively, and high levels of Fe and Al extracted by ammonium oxalate (Fe_o and Al_o) ranging from 2.64-7.96 and 0.88-6.88 g kg^{-1} respectively. This group of soils included Tb, Pso, Sv, Sk, Pkn, Kn, Kt, Ks and Bc. The second group of soils (2) contained low clay content ranging from 179-363 g kg^{-1}, generally low Fe_d and Al_d in the range of 10.0-23.8 and 1.09-8.3 g kg^{-1} respectively, and generally low Fe_o and Al_o in the range of 2.26-8.52 and 0.76-8.26 g kg^{-1} respectively. This group of soils included Bt, Psi, Pe, Kha, Pkd, and Pl.

Table 4 Some properties of selected soils.

Group	Soil name	Soil properties											
		Texture^{1}	Clay^{1} (g kg^{-1})	pH^{2}	OC^{3} (g kg^{-1})	CEC^{4} (cmol$_c$ kg^{-1})	P^{5} (mg kg^{-1})	P^{6} (mg kg^{-1})	P^{7} (mg kg^{-1})	Fe$_d$^{8} (g kg^{-1})	Fe$_o$^{9} (g kg^{1})	Al$_d$^{8} (g kg^{-1})	Al$_0$^{9} (g kg^{-1})
1	Koon (Kn)	Clay	430	5.3	14.5	14.2	0.52	0.31	0.40	31.8	2.64	6.24	1.05
	Pookoon (Pkn)	Clay	553	4.9	22.4	31.7	1.19	0.61	0.40	61.8	5.09	17.46	6.08
	Kentao (Kt)	Silty clay	456	5.9	21.9	28.3	1.35	0.88	1.12	51.0	5.28	2.56	0.88
	Kasi (Ks)	Clay loam	363	5.9	19.6	22.1	1.04	0.61	1.62	125.5	5.44	12.35	5.88
	Bachieng (Bc)	Clay	669	4.6	14.1	17.5	4.54	1.17	1.01	26.8	2.78	4.88	2.38
	Tabok (Tb)	Clay	582	5.8	19.4	14.2	4.62	1.29	3.84	66.1	6.25	11.42	6.12
	Paksong (Pso)	Silty clay	426	4.8	22.9	25.4	3.52	0.82	2.81	99.6	7.62	30.56	9.45
	Salavanh (Sv)	Clay	709	4.6	18.7	25.0	2.11	0.87	2.15	97.0	5.92	12.28	4.50
	Sekong (Sk)	Silty clay loam	513	5.3	21.5	32.1	0.68	0.16	0.87	88.0	7.96	19.22	6.88
2	Pasai (Psi)	Loam	222	4.8	19.1	18.8	3.04	0.87	0.78	10.0	2.87	8.30	8.26
	Pek (Pek)	Clay loam	323	4.5	22.4	12.1	1.46	0.85	0.60	21.8	3.91	7.65	3.07
	Kham (Kha)	Sandy loam	179	5.4	7.0	4.3	3.04	1.69	1.87	12.8	2.26	3.33	0.96
	Pookood (Pkd)	Loam	245	4.8	21.8	12.1	24.32	8.89	7.22	18.2	8.52	4.61	2.26
	Paklay (Pl)	Silty clay loam	344	5.8	19.8	23.8	2.80	1.49	1.66	23.8	4.52	1.97	0.76
	Botaen (Bt)	Silty clay loam	363	4.8	10.6	16.3	1.24	0.72	0.90	16.7	3.03	1.09	1.47

Note [1] Pipette method (Day, 1965)

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

Table 4 (Continued)

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

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

[5] Bray 2 (Bray and Kurtz, 1945)

[6] Mehlich 1 (Mehlich, 1953)

[7] Pi test (Myers *et al*., 1995; Chardon *et al*., 1996; Chardon, 2000)

[8] Citrate bicarbonate dithionite method (Loeppert and Inskeep, 1996)

[9] Ammonium oxalate pH 3 in darkness (Loeppert and Inskeep, 1996)

1.2 Phosphorus Buffer Coefficient (PBC) studies

The soils of the first group was the soils from Bc, Tb, Ps, Sv, Sk, Ks, Pkn, Kn and Kt Districts were low in PBC with all extracting methods indicating high sorption of P (Table 5). The high P sorption is probably the result of the high amount of clay and Fe_d Al_d, Fe_o, Al_o observed in these soils. As the amount of clay increased in the soils, the P-sorption capacity increased, a result expected due to increased surface area. As the proportion of clay increases and its constituents of Fe and Al also increase, resulting in a tremendous amount of surface area for phosphate sorption. High amounts of Fe_d, Al_d, Fe_o, Al_o in the soils could sorbs more P, resulting in high P sorption (Brady, 1990).

The PBC study showed that percent clay was not the only factor affecting PBC values in the soils. For example, the soil from Kham District (17.93 % clay) and Psi district (22.15% clay), had approximately similar amounts of clay but different PBC values for all extractants was observed. The same was true for the soils from Ks and Bt District (Table 5). The relationship between PBC and clay alone was low with Adj R^2 of 0.32, 0.34 and 0.20 for Bray 2, Mehlich 1 and Pi test respectively (Figures 2, 3 and 4). Further study indicated that in addition to the amount of clay, the PBC values of soils appear related to the amount of Fe and Al, OM, CEC or pH.

As expected the PBC was different among soils and soil P testing methods (Table 5). The PBC values of the low-clay soils were generally higher than those of the high-clay first group indicating less P sorption, likely reflecting the lower amounts of clay, Fe and Al oxides, and less amorphous Fe and Al. The $PBC_{Bray\ 2}$, $PBC_{Mehlich\ 1}$ and $PBC_{Pi\ test}$ were in the range of 0.11-0.76, 0.06-0.56 and 0.05-0.34, respectively (Table 5).

1.2.1 Extractants of P

The PBC_{Bray2} gave the highest values among the three extractant methods (Table 5). The Bray 2 extractant is higher in acid concentration than either the Mehlich 1 or the Pi methods. The $PBC_{Pi\ test}$ of all soils was the lowest values among the extractants indicating that this method removed less P than the other extractants. The study of Hongthana (2007) in submerged Thai soils and Dounphady (2009) in seven upland Laotian soils also reported that PBC_{Bray2} was higher than $PBC_{Mehlich1}$ and $PBC_{Pi\ test}$. Among soil samples, soils from Kham, and Pookood Districts provided the highest PBC for all methods; these soils had the lowest amount of clay (179 and 245 g kg^{-1}), respectively. Also, these soils had low amounts of Fe and Al, with the soil from Kham District having Fe_d of 12.8 g kg^{-1}, Fe_o 2.2 g kg^{-1} and Al_d 3.3 g kg^{-1}, and Al_o 0.96 g kg^{-1}. The amount of Fe_d, Fe_d, Al_d and Al_o of soil from Pookood district was slightly higher than soil from Kham District. Additionally, the Pookood was higher in initial P compared to other soils (Table 4). Consequently, they might have less capacity to adsorb P.

Table 5 The Phosphorus Buffer Coefficients of the selected soils.

Group	Soil order	District name	% clay	Phosphorus Buffer Coefficients (PBC)		
				Bray 2	Mehlich 1	Pi test
1	Alfisols	Koon	43.04	0.22	0.16	0.14
	Ultisols	Pookoon	55.27	0.19	0.11	0.05
	Alfisols	Kentao	45.57	0.17	0.13	0.11
	Alfisols	Kasi	36.29	0.11	0.08	0.06
	Ultisols	Bachieng	66.88	0.32	0.23	0.14
	Ultisols	Tabok	58.23	0.14	0.06	0.08
	Ultisols	Paksong	42.62	0.05	0.02	0.03
	Ultisols	Salavanh	70.89	0.10	0.02	0.06
	Alfisols	Sekong	51.27	0.07	0.02	0.03
2	Ultisols	Pasai	22.15	0.38	0.19	0.07
	Ultisols	Pek	32.28	0.46	0.24	0.11
	Ultisols	Kham	17.93	0.76	0.56	0.34
	Ultisols	Pookood	24.47	0.42	0.25	0.21
	Alfisols	Paklay	34.39	0.33	0.22	0.28
	Ultisols	Botaen	36.29	0.40	0.39	0.28

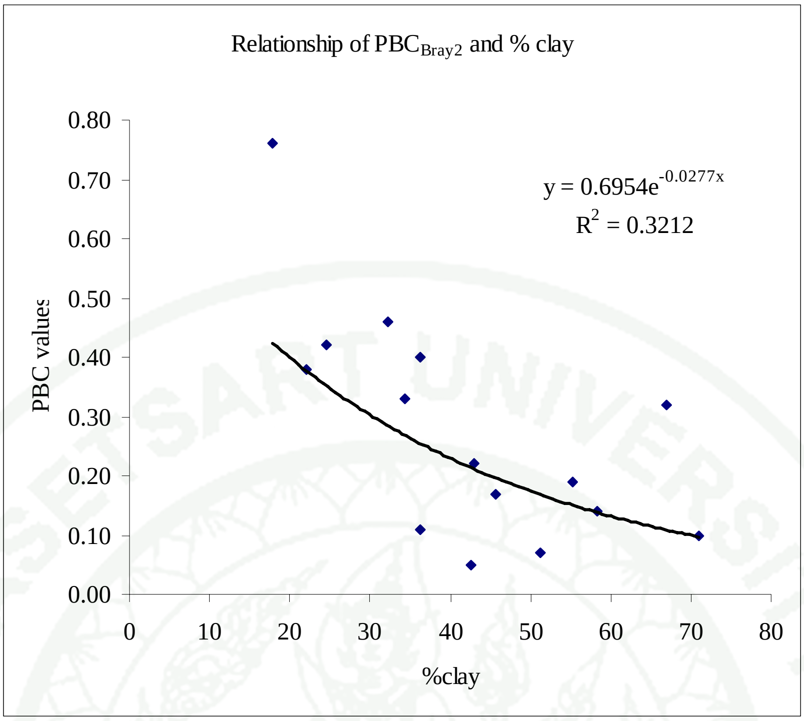

Figure 2 Relationship of PBC$_{Bray2}$ and % clay

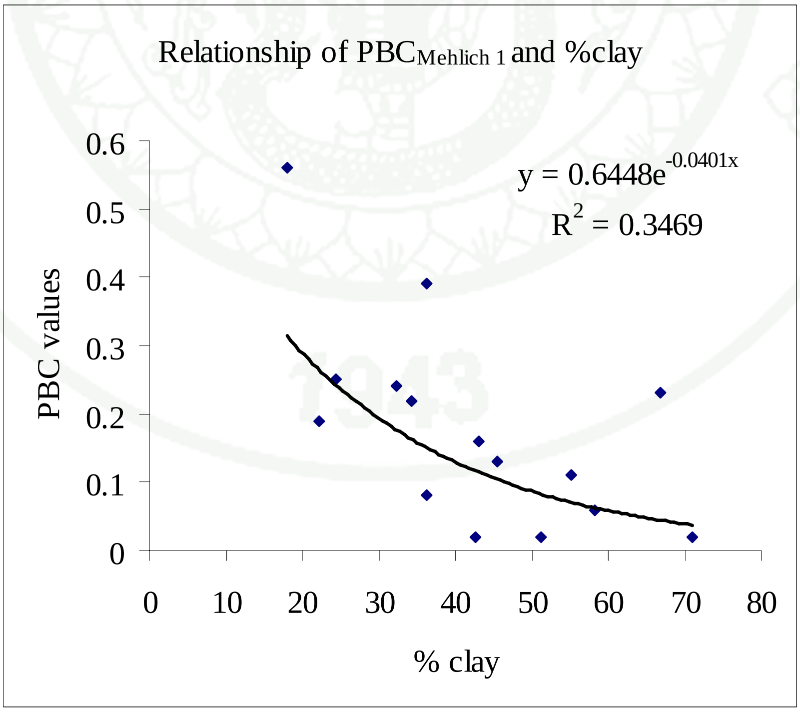

Figure 3 Relationship of PBC$_{Mehlich1}$ and % clay

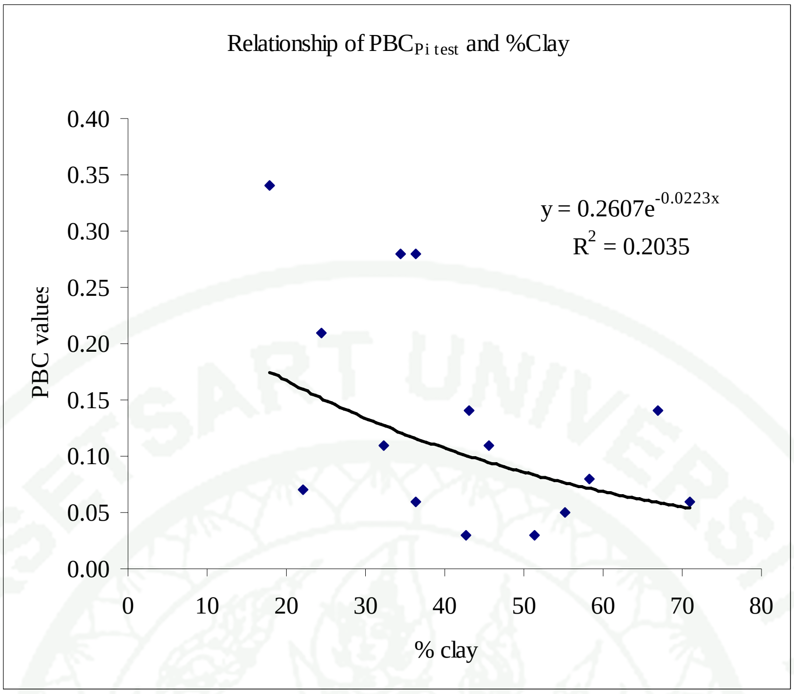

Figure 4 Relationship of $PBC_{Pi\ test}$ and % clay

1.3 The relationship of PBC with soil properties

Statistical models of PBC estimated by the three extraction methods indicated that different independent variables were important in predicting the PBC of different extractants (Table 6). The different soil factors probably reflect the differing chemical constituents of the extractants. The Pi test differs from the chemical extractants, because it is a desorption rather than a dissolution reaction that assesses the soil P. For $PBC_{Bray\ 2}$ (model 1) and $PBC_{Mehlich\ 1}$ (model 2), the OC, Fe_d and amount of clay could explain 79% and 86% of the variability, respectively. On the other hand, Al_o, OC and amount of clay could explain 80% of the variability in the $PBC_{\ Pi\text{-}test}$ (model 3). So, the $PBC_{Mehlich\ 1}$ showed the highest correlation with some soil properties, the explanation of these variables in model 2 and is discussed below.

Table 6 Models and coefficients for predicting the PBC of maize soils of Laos.

Statistical model	AdjR^2	SSR
(1)$PBC_{Bray\ 2}$ = 0.837-0.004clay-0.002Fe_d-0.137OC	0.79**	0.08
(2)$PBC_{Mehlich\ 1}$ = 0.695-0.003clay-0.001Fe_d-0.17OC	0.86**	0.02
(3)$PBC_{Pi\ test}$ = 0.440-0.002clay-0.017Al_o-0.076OC	0.80**	0.03

Note **significant at the 0.01 level

1.3.1 Effects of soil organic carbon

Tisdale *et al*. (1985) suggested that certain organic anions arising from the decomposition of organic matter will form stable complexes with Fe and Al thus preventing their reaction with P and increase the available P to plants, but in some instances P sorption has been found to correlate with OC content of soils. At the first it was believed that this adsorption involved an exchange of P anions with OH groups in the organic matter. Other results indicated that it is the Al and to a lesser extent the Fe adsorbed by the organic colloids which are active in P adsorption.

Wild (1950) reasoned that humus, since it is normally negatively charged, is not thought to retain much P by itself; however in association with cations such as Fe^{3+}, Al^{3+}, and Ca^{2+} it is able to retain significant amounts of phosphate. Appelt *et al*., (1975) prepared a hydroxyl-Al-humic acid complex that was capable of adsorbing P. The amount of P adsorbed increased as the Al:OH ratio decreased, which led them to believe that the P was absorbed by ligand exchange of phosphate for a hydroxyl group. They reasoned that humic acid could react with Al from soil minerals to form these complexes, which would give rise to new surfaces for P adsorption.

1.3.2 Amounts of Fe, Al, and clay

Since phosphate is an anion, any particle of clay that generates an anion exchange capacity such as Al_2O_3 and Fe_2O_3 under acidic conditions, highly weathered kaolinitic clay and amorphous materials will form strong bonds with phosphate (Brady, 1990).

Bear (1964) stated that the anion adsorption was intimately connected with the nature of the soil colloids and with the pH of the system. All of the soils were acidic, and as the amount of Fe increased, more P was sorbed, thus decreasing PBC values.

Wiriyakitnateekul *et al*. (2005) reported that variability in P sorption by Thai soils could be explained by a combination of Fe_d, Fe_o, Al_d and Al_o. Zhang *et al*., (2003) have confirmed that P availability of flooded rice soils was largely controlled by the transformation of Fe, from crystalline to amorphous form, indicating that poorly crystalline and amorphous forms of Fe play a primary role in P sorption of Thai soils. The greater surface area of amorphous Fe was responsible for more soil P sorption. In addition, soil containing large quantities of clay will fix more P than soils with small amounts of clay (Tisdale *et al*., 1985). However, P sorption also depends on clay mineral type, for example kaolinite, which contains hydroxyl groups, would be able to adsorb the P ion in large amounts (Millar, 1955). Phosphate adsorption takes place by replacing hydroxyl ions exposed at the edges or other surfaces of silicate clays minerals or of oxide minerals (Troeh and Thompson, 2005), especially if the soil colloids are primarily Fe and Al oxides. Wang *et al*. (2000) studied PBC using potential sorption site density and soil aggregate size and found that in some case, soils with different P sorption site density were not different in PBC values. So, they suggested that the PBC prediction should include other soil characteristics.

The study of Atbandit *et al*., (2005) found that the phosphorus sorption of Ferric and Haplic Acrisols (Ultisols) of Laos were high correlated with Fe_d and Fe_o at 0.01 level of probability. At lower pH soils sorbed higher amount of P with high relation of 0.01 levels, the P sorption of Laotian soils were also correlated with organic matter and clay at 0.05 level of probability. A study on rice soils (Hongthana *et al*., 2007) showed that the $PBC_{Bray\ 2}$ and $PBC_{Mehlich\ 1}$ were highly correlated with organic matter and Fe_d.

1.4 PBC prediction from soil properties

Specific soil properties were substituted into model (1), (2) and (3) of Table 6 to predict the $PBC_{Bray\ 2}$, $PBC_{Mehlich\ 1}$ and $PBC_{Pi\ test}$, respectively. The predicted PBC was plotted against observed PBC to quantify the prediction of PBC using 1:1 line relationship (Figure 5). The relationship depicted in Figure 5 indicated that the predicted and observed PBC by Mehlich 1 and Pi test were very similar. The sum square residual of the variation between predicted and observed PBC of the three extractants was calculated.

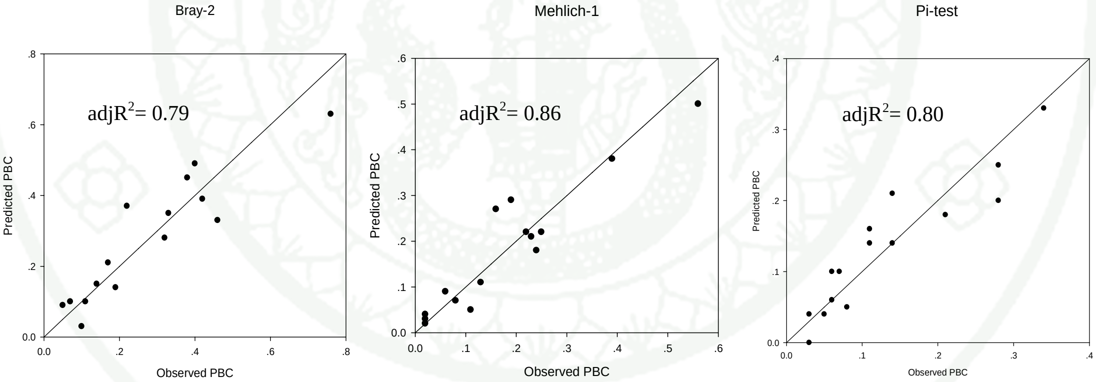

Figure 5 The 1:1 relationship of predicted and observed PBC by three extractant methods

The results showed that sum square residual of predicted and observed PBC by Bray 2, Mehlich 1 and Pi test were 0.08, 0.02 and 0.03, respectively. The two extractants Mehlich 1 and Pi test were similar in AdjR^2 and SSR. A comparison of Mehlich 1 and Pi test methods reveals that Mehlich 1 is the simpler and more rapid extractant method. Consequently, Mehlich 1 is proposed as the best extractant method for PBC prediction for maize soils of Laos.

2. Experiment 2: Determine phosphorus sorption of selected soils by the P sorption isotherm technique

2.1 Phosphorus sorption of selected Lao upland soils

Water soluble P readily reacts with aluminum and iron, to form less soluble, more stable compounds. The reactions mostly take place on the surfaces of soil constituents (clay; oxides of iron and aluminum; organic matter and iron and aluminum compounds coating surface of sands). After the initial surface reaction, the adsorbed P diffuses slowly towards the interior of the particle and so becomes less available to plants. The combined reactions, adsorption plus penetration, is called sorption (Bolland *et al*., 2003).

The experimental results indicated that soils differed in P sorption (Figure 6). In general, the fifteen soils were high in P sorption, except soil from Kham district, probably because this soil had lowest amount of clay compared to other soils. The P sorption characteristics of the fifteen soils could be divided in to two groups:

2.1.1 Soils with higher P sorption, the higher amount of clay, Fe and Al contents were observed in these soils such as the soil from Paksong, Sekong, Pookoon, Tabok, Salavanh, Pek, Bachieng and Kasi Districts. Havlin *et al*. (2005) observed that soil containing large quantities of clay will fix more P than soils with low clay content. In other words, the more surface area exposed with a given type of clay, the greater the tendency to adsorb P. Juo and Fox (1977) said that many soils in humid topics, the P sorption capacity was mainly related to soil mineralogy, which in turn was related to soil parent materials and free iron oxide content of the soils. Tisdale *et al*. (1985) also reported that P was retained to greater extent by 1:1 than by 2:1 clays. Soils high in kaolinitic clays, such as those found in areas of high rain fall and high temperature will fix or retain larger quantities of added P than those containing the 2:1 type. The greater amount of P fixed 1:1 clays is probably largely due to the higher amounts of hydrated oxides of Fe and Al associated with kaolinitic clays. In addition kaolinite developed pH dependent charges on its edges which could enter into sorption reactions with P. So, these might be reasons for the high P sorption of soils from Paksong, Sekong, Pookoon, Tabok, Salavanh, Pek, Bachieng and Kasi Districts.

Cox (1994) predicted increases in extractable P from fertilizing soils in six field experiment Ultisols that varied in clay content and found that the extractable P increased per unit of applied P for soils with 10% clay, and it decreased exponentially for soils with less than 50% clay. The results of this study were similar to the P incubation study in Natal, South Africa (Bainbridge *et al.*, 1995), on 54 soils from five U.S. taxonomic orders, including Ultisols and Oxisols.

According to the classification of Fox and Kamprath (1970), the soil from Pasai, Pookoon, Paksong, Salavanh, Sekong Districts were grouped in the high P sorption soils, category because these soils sorbed P ranging from 550-800 mg kg^{-1} at a P concentration at equilibrium of 0.2 mg P L^{-1} (Table 7), the high amount of clay, OC, Fe and Al were observed in these soils. Even the soil from Pasai District had low clay but this soil had high Al so it might be a reason of high P sorption in this soil. The soil from Pek, Pookood, Koon, Kentao, Bortaen, Kasi, Bachieng and Tabok Districts were grouped in the medium P sorption soils, these soils sorbed P in the range of 130-390 mg P kg^{-1} because these soils had lower clay, OC, Fe and Al content. The lowest P sorption were soils from Kham and Paklay District because low clay, OC, Fe and Al in these soils.

The fifteen maize soils were all strongly acid soils with only four soils with pH above 5.5. Furthermore, some soils were comprised of predominantly kaolinitic clay e.g: Pe, Psi, Ksi soils. Sanchez and Uehara (1980) indicated that Ultisols that are high in clay fix more P, especially if the clays are primarily Fe, Al oxides and with amorphous rather than crystalline form.

2.1.2 Soils from Koon, Bortaen, Kaentao, Paklay, Kham and Pookood sites sorbed lower amounts of P than the first group, these soils were also acidic but contained lower amounts of clay and Fe and Al, which probably explains the lower P sorption. The characteristics of P sorption of soils are shown in Figure 6.

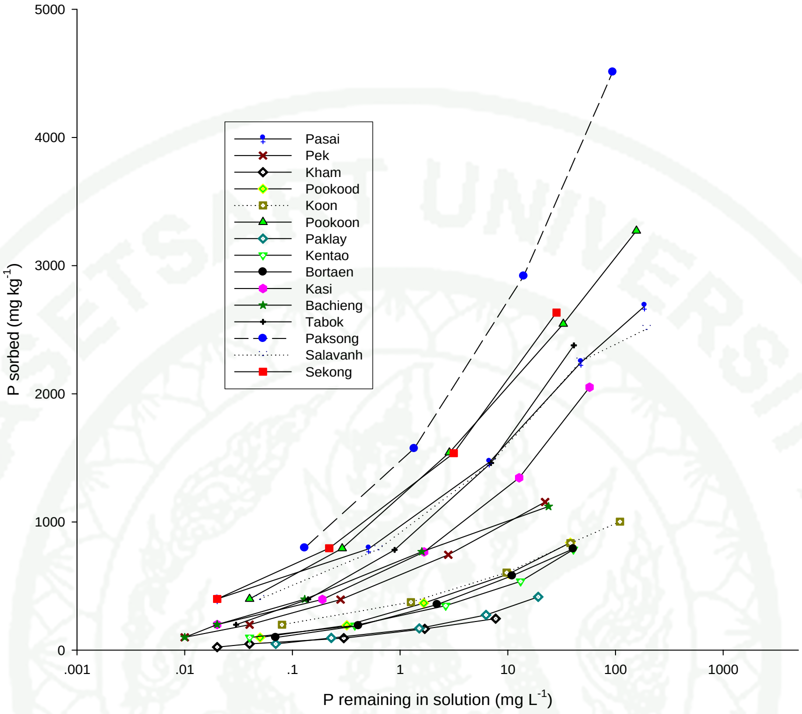

Figure 6 Characteristics of P sorption in selected soils.

2.2 Phosphorus recommendation for maize by phosphorus sorption isotherm technique.

Phosphorus sorption isotherm has been used in estimating plant P requirement. Ozanne and Shaw (1967) found that P concentration in equilibrium of 0.2 mg P L^{-1} (PS$_{0.2}$) in soil solution was adequate for pasture and increased yields to 85% of maximum yield but the recommendation based on PS$_{0.2}$ were quite high and might result in higher levels of P than that the plants need. Fox and Kamprath (1970) found that millet (*Pennesitum typhoides*, Var. Gahi-1) grew in silty clay loam approached 95% of maximum yield when phosphate in soil solution was adjusted to 0.07 mg L^{-1}.

The study of Jones and Benson (1975) indicated that sweet corn responded to P in soil solution up to 0.13 mg L^{-1}. Fox *et al.* (1974) reported that maize in Hawaii responded to P in soil solution up to 0.06 mg L^{-1}. In addition, P requirements estimated by concentrations are general recommendation for field crops but might not be suitable for soils having different properties. So, in this study, the P requirement by PDSS estimation was compared with P requirement using P sorption at equilibrium of 0.06 and 0.2 mg P L^{-1} ($PS_{0.06}$ and $PS_{0.2}$).

Table 7 Phosphorus recommendation by $PS_{0.06}$ and $PS_{0.2}$

District name	Bulk density (Mg m^{-3})	$PS_{0.06}$ (mg P kg^{-1})	$PS_{0.2}$ (mg P kg^{-1})	$PS_{0.06}$ P (kg ha^{-1})	$PS_{0.2}$ P (kg ha^{-1})
Pasai	1.01	500	620	1,006	1,535
Pek*	1.24	210	320	520	792
Kham	1.54	50	78	154	193
Pookood	1.18	90	140	212	347
Koon	1.40	175	225	488	557
Pookoon	0.82	400	630	658	1,559
Paklay	1.19	38	75	90.1	186
Kentao	1.16	105	140	243	347
Bortaen	1.38	80	130	221	322
Kasi	0.89	260	350	465	866
Bachieng	1.24	270	390	675	965
Tabok	1.16	250	390	581	965
paksong	1.11	650	800	1,442	1,980
Salavanh	1.06	390	550	826	1,3461
Sekong	1.08	540	710	1,165	1,757

Note Calculated at 20 cm depth of soils.

The P sorption at $PS_{0.2}$ was higher than $PS_{0.06}$, but in the case of soil from Kham District the P sorption at $PS_{0.06}$ was 50 mg kg^{-1} and increased to 78 mg kg^{-1}at PS$_{0.2}$ (Table7). The increase of 28 mg P kg^{-1} in soil from Kham District soil between the two levels of P in solution was very low when compared to other soils. This is probably because Kham soil has the lowest amount of clay (179 g kg^{-1}).

2.3 Phosphorus recommendation by PDSS equation

The P requirement calculated by the PDSS equation was compared with P sorption isotherm technique. The P critical level of soil in an Ultisol of Xiengkhouang was needed. The P critical level (P$_{cl}$) is the minimum extractable soil P level that plant needs for optimum yield. This study used the P critical levels of Dounphady (2009), P$_{cl}$ of soil from Pek District was 15.2, 5.01 and 16.2 mg kg^{-1} for Bray 2, Mehlich 1 and Pi test respectively. In order to estimate P fertilizer requirements of upland Lao soils known values were used in the PDSS equation. Except the Pek soil, the P$_{cl}$ of other soils were estimated by PDSS software (Table 8, 9 and 10).

P requirement = {(P$_{CL}$-Po)/PBC+0.8 x PBC x P uptake x 0.8 x 1/2 x Placement factor x App Depth/10

Illustrating the use of PDSS equation for the Pek soil:

- P$_{cl}$ (Bray2) = 15.2 mg kg^{-1}, P$_0$ = 1.46 mg kg^{-1}, PBC= 0.46
- P$_{cl}$ (Mehlich 1) =19.31, P$_0$ = 0.84, PBC= 0.24
- P$_{cl}$ (Pi test) =16.2, P$_0$ = 2.03, PBC= 0.11
- P uptake= 5.42 mg kg^{-1}
- Placement factor= 0.13 (for banding application 10 cm along plant, and 75cm between plant row or 10/75cm)
- Application depth=10 cm

Table 8 Estimated P requirements using Bray 2 extractable P.

Soil name	P_{cl} (mg L^{-1})	P_0 (mg kg^{-1})	PBC	P uptake (mg kg^{-1})	P requirement (kg P ha^{-1})
Pasai	17.00	3.04	0.38	5.42	36.8
Pek*	15.20	1.46	0.46	5.42	29.9
Kham	17.00	3.04	0.76	5.42	18.5
Pookood	17.00	24.32	0.42	5.42	0
Koon	17.00	0.52	0.22	5.42	74.9
Pookoon	17.00	1.19	0.19	5.42	83.2
Paklay	17.00	2.80	0.33	5.42	43.1
Kentao	17.00	1.35	0.17	5.42	92.1
Borten	17.00	1.24	0.40	5.42	39.5
Kasi	17.00	1.04	0.11	5.42	145.2
Bachieng	17.00	4.54	0.32	5.42	38.9
Tabok	17.00	4.62	0.14	5.42	88.4
Paksong	17.00	3.52	0.05	5.42	270
Salavanh	17.00	2.11	0.10	5.42	149
Sekong	17.00	0.68	0.07	5.42	233

Note * = field study site

Table 9 Estimated P requirements using Mehlich 1 extractable P.

Soil name	P_{cl} (mg L^{-1})	P_0 (mg kg^{-1})	PBC	P uptake (mg kg^{-1})	P requirement (kg P ha^{-1})
Pasai	14.60	0.87	0.19	5.42	72.27
Pek*	5.01	0.84	0.24	5.42	17.38
Kham	17.30	1.69	0.56	5.42	27.96
Pookood	13.00	8.88	0.25	5.42	16.49
Koon	7.49	0.30	0.16	5.42	44.91
Pookoon	7.49	0.61	0.11	5.42	62.55
Paklay	7.49	1.48	0.22	5.42	27.31
Kentao	7.49	0.87	0.13	5.42	50.91
Borten	7.49	0.71	0.39	5.42	17.44
Kasi	7.49	0.61	0.08	5.42	85.99
Bachieng	7.49	1.17	0.23	5.42	27.50
Tabok	7.49	1.28	0.06	5.42	103.36
Paksong	7.49	0.82	0.02	5.42	333.43
Salavanh	7.49	0.87	0.02	5.42	330.78
Sekong	7.49	0.16	0.02	5.42	366.36

Note * = study site

Table 10 Estimated P requirements using Pi test extractable P.

Soil name	P_{cl} (mg L^{-1})	P_0 (mg kg^{-1})	PBC	P uptake (mg kg^{-1})	P requirement (kg P ha^{-1})
Pasai	15.00	1.46	0.07	5.42	193
Pek*	16.20	2.03	0.11	5.42	128
Kham	15.00	2.60	0.34	5.42	36.5
Pookood	15.00	11.33	0.21	5.42	17.5
Koon	15.00	0.90	0.14	5.42	100
Pookoon	15.00	0.90	0.05	5.42	282
Paklay	15.00	4.36	0.28	5.42	38.1
Kentao	15.00	2.03	0.11	5.42	118
Borten	15.00	4.36	0.28	5.42	38.1
Kasi	15.00	2.60	0.06	5.42	207
Bachieng	15.00	2.03	0.14	5.42	92.6
Tabok	15.00	2.60	0.08	5.42	155
Paksong	15.00	3.77	0.03	5.42	374
Salavanh	15.00	3.77	0.06	5.42	187
Sekong	15.00	2.03	0.03	5.42	432

Note * = study site

The P requirements of soils differed depending on PBC and P_{cl} values. If soils had low PBC, more P was needed for maize, e.g. soils such as Paksong, Salavanh and Sekong. In contrast, if soils had higher PBC, little P was needed. The P requirement of Pookood soil was the lowest 0, 40.89 and 17.53 kg P ha^{-1} for Bray 2, Mehlich1 and Pi tests, respectively because this soil has a high P_0. The P requirement of Pek soil was high because this soil had low PBC and medium P sorption. The P requirement of Pek soil using PDSS equation was 29.95, 17.38, and 128.83 kg P ha^{-1} for Bray 2, Mehlich 1 and Pi test extractant methods respectively. While the P recommendation for this soil from $PS_{0.06}$ and $PS_{0.2}$ was 520 and 792 kg P ha^{-1} respectively.

The P requirement from PDSS equation of 15 soils (Yost *et al.*, 1992) was compared with P sorption isotherm technique. The P requirement observed from both $PS_{0.06}$ and $PS_{0.2}$ were higher than P requirements as determined by the PDSS equation in all studied soils, and probably exceed the needs of maize (Table 11). The P requirement for $PS_{0.06}$ ranged from 90.09-1442.48 kg P ha^{-1} and $PS_{0.2}$ was in the range of 185.64 - 1980.16 kg P ha^{-1}. The study of Hongtana (2007) in submerged soils of Thailand also showed that P requirement calculated from both $PS_{0.1}$ and $PS_{0.2}$ was higher than P requirement that calculated from PDSS equation.

Table 11 Phosphorus recommendation from PDSS, $PS_{0.06}$ and $PS_{0.2}$

Soil name	Bray 2 P (kg ha^{-1})	Mehlich1 P (kg ha^{-1})	Pi test P (kg ha^{-1})	$PS_{0.06}$ P (kg ha^{-1})	$PS_{0.2}$ P (kg ha^{-1})
Pasai	36.8	72.2	193	1,006	1,535
Pek*	29.9	17.4	128	520	792
Kham	18.5	27.9	36.5	154	193
Pookood	0	16.4	17.5	212	347
Koon	74.9	44.9	100	488	557
Pookoon	83.2	62.5	282	658	1,559
Paklay	43.1	27.3	38.1	90.1	186
Kentao	92.1	50.9	118	243	347
Bortaen	39.5	17.4	38.1	221	322
Kasi	145	85.9	207	465	866
Bachieng	38.9	27.5	92.6	675	965
Tabok	88.4	103.3	155	581	965
paksong	270	333.4	374	1,442	1,980
Salavanh	149	330.7	187	826	1,3461
Sekong	233	366.3	432	1,165	1,757

Note * = study site

3. Experiment 3: Determine appropriate rates of P and Zn application for maize production in an Ultisol of Xiengkhouang province

3.1 Growth of maize

Phosphorus applications in the soil from Pek District clearly increased yields and reduced visual deficiency symptoms of P (Figure 7). However, the growth of maize was observed by measuring the maize height after 30 and 60 days of planting because this period maize was most sensitive to nutrient absorption. The height of maize at 30 days in treatment with Zn and without Zn applications was not significantly different, and the height of maize increased with increasing of P and was significantly different at ($P < 0.01$) level (Table 12). The height of maize in the 0 kg P ha^{-1} treatment was 17.83 cm with Zn application and 20.66 cm without Zn application. The height of maize in 0 kg P ha^{-1} application was shortest when compared to P application at 7, 14, 28 and 56 kg P ha^{-1} in both Zn and without Zn applications (Figure 8).

A comparison of treatments with Zn and without Zn applications indicated that the height at 60 days after planting was significantly different at $P < 0.05$ level, and among P application rates, the height of maize was significantly different at $P < 0.05$ level. The P application at the rate of 56 kg P ha^{-1} showed the highest maize height of 146 and 117 cm for Zn application and without Zn application respectively (Figure 9). The height of maize in this crop was higher than in the wet season 2007 (Dounphady, 2009).

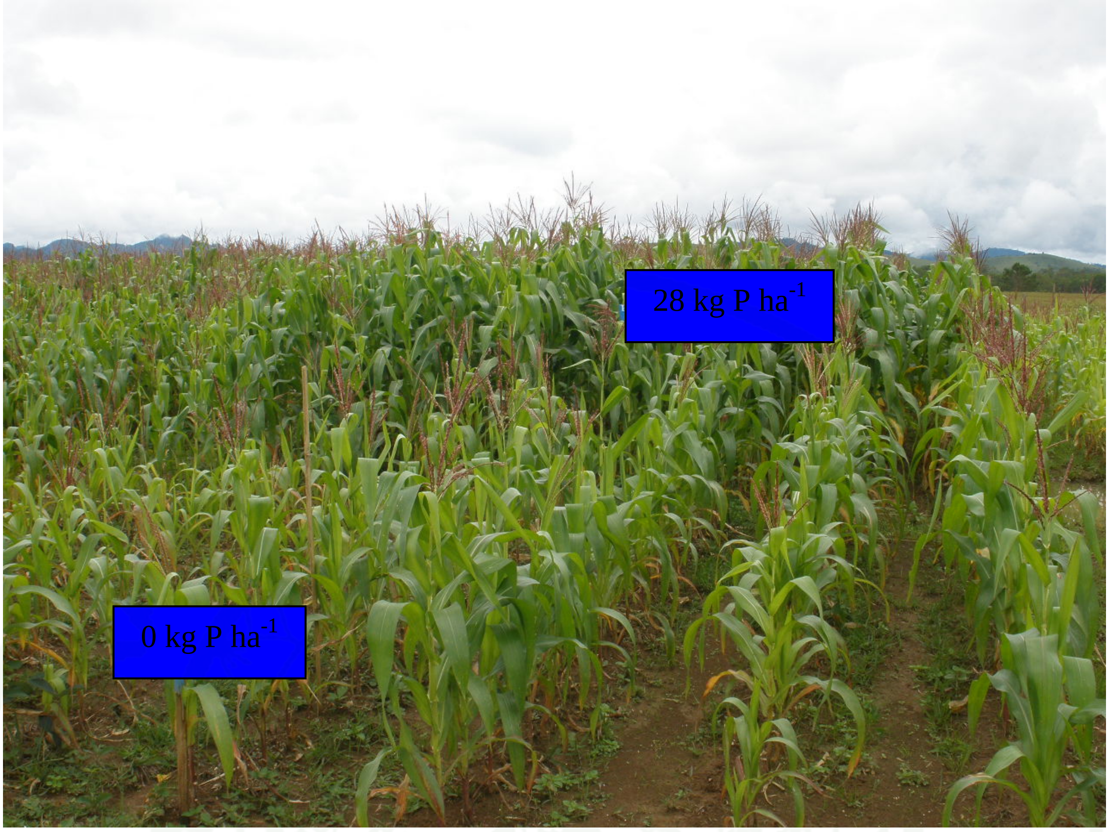

Figure 7 The effect of P on increasing maize growth, Xiengkhouang Province, Laos.

Table 12 Maize height at 30 and 60 days after planting.

P rates (kg ha^{-1})	Height at 30 days (cm)		Height at 60 days (cm)	
	Zn	No Zn	Zn	No Zn
0	17.83	20.66	37.83	49.72
7	26.92	29.57	89.55	87.10
14	30.3	27.01	100.7	87.46
28	31.82	25.15	115.51	99.08
56	37.74	30.56	146.98	117.18
Zn applied	NS		*	
P applied	**		**	
Zn applied*P applied	*		NS	
CV%	14.41		15.39	
F-test for Zn applied	3.4		6.56	
F-test for P applied	14.35		36.04	

Table 12 (Continued)

Note * = Significantly different at 95%

** = Significantly different at 99%

NS = Not significant

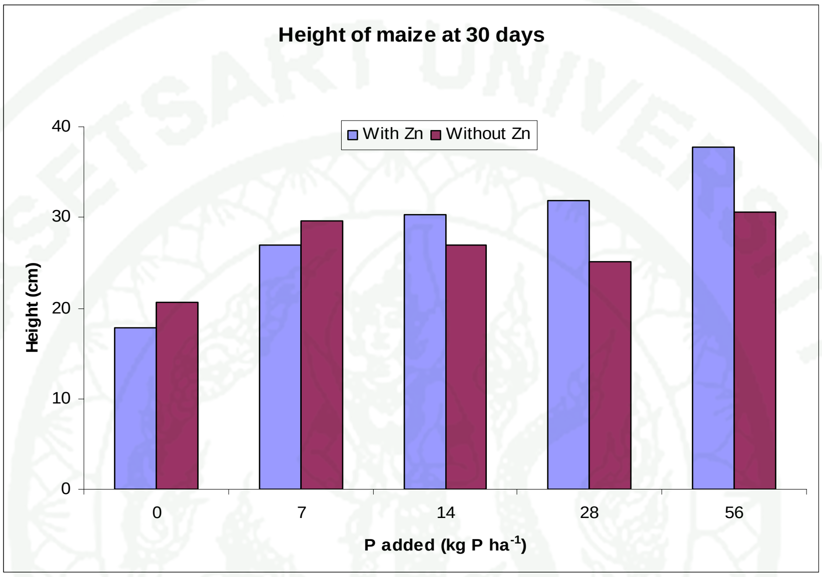

Figure 8 Height of maize at 30 days after planting in Pek District.

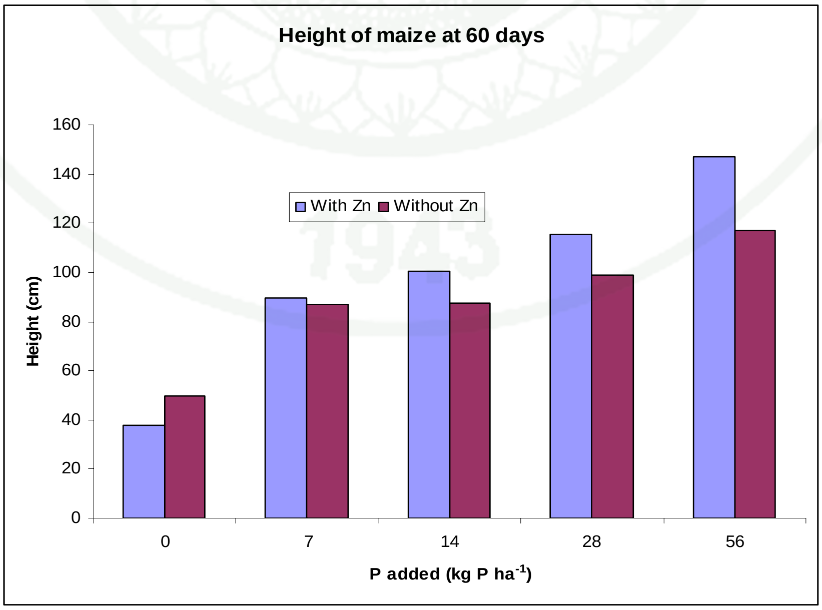

Figure 9 Height of maize at 60 days after plantining in Pek District.

3.2 Grain yield and Stover yield

The first two year’s results of the field experiment in Pek District, Xiengkhouang province, and described herein, have been reported by Dounphady (2009). Those results indicated that maize yield increased with increasing P fertilizer rates. The repeated application P at the rate of 56 kg P_2O_5 ha^{-1} corresponded to the highest maize yield of over 6 t ha^{-1} . However, extreme Zn deficiency was observed in the maize leaves during early growth.

For the following year, 2008, the field experiment was modified to test the effects of applying Zn fertilizer. For the Zn experiment, all plots were divided in to two strips, with Zn applied to the first strip and no Zn applied to the second strip to quantify the effect of Zn on maize yield.

The experimental results indicated as in other years maize yield increased with increasing P fertilizer. In addition, the treatment of P with zinc application gave higher yields than that without Zn application. Phosphorus was applied on the basis of kg P ha^{-1} rather than as P_2O_5 ha^{-1} as in the first two years (2006 and 2007). The maize yield in P and Zn applications at the rates of 0, 7, 14, 28 and 56 kg P ha^{-1} + 4.72 kg ha^{-1} of $ZnSO_4.7H_2O$ were 1,382; 3,382; 4,169 and 5,735 kg ha^{-1} respectively. Phosphorus and Zn application at the rate of 56 kg P ha^{-1} + 4.72 kg ha^{-1} $ZnSO_4.7H_2O$ kg ha^{-1} gave about 5 times of yield compared to 0 kg P ha^{-1} + 4.72 kg ha^{-1} $ZnSO_4.7H_2O$ kg ha^{-1} (Figure 10). The without Zn application treatments gave yields of 1,302; 2,945; 3,246; 4,213 and 4,418 kg ha^{-1} respectively. The statistical analysis showed the effect of Zn application increased grain yield when compared with the no Zn application at 0.01 level of probability.

Stover yield data display a similar trend as did the grain yield. Stover yields where both P and Zn were applied were in the range of 2,593-12,197 kg ha^{-1} which was higher than without Zn applications, which ranged from 1,893 to 11,063 kg ha^{-1} (Table 13). From the statistical analysis, Zn application increased stover yield with a significant difference at the 95% level. Phosphorus application increased stover yield significantly at the 99% level. The stover yield was highest with highest rate of P application (56 kg P ha^{-1}) (Figure 11).

Table 13 Grain and Stover yield of Xiengkhouang in 2008.

P rates (kg ha^{-1})	Grain yield (kg ha^{-1})		Stover yield (kg ha^{-1})	
	Zn	No Zn	Zn	No Zn
0	1,382	1,302	2,593	1,893
7	3,382	2,945	5,276	5,078
14	4,169	3,246	6,732	6,189
28	4,991	4,213	10,462	9,577
56	5,735	4,418	12,197	11,063
Zn applied	**		*	
P applied	**		**	
Zn applied*P applied	NS		NS	
CV%	15.26		14.31	
F-test	67.02	17.78	94.67	100.81
Intercept	1,584.80	1,302.01	2,921.00	2,489.90
Slope	199.1	234.74	273.1	260.8
Node	18.98	11.33	33.97	32.87

Note * = Significantly different at 95%

** = Significantly different at 99%

NS = Not significant

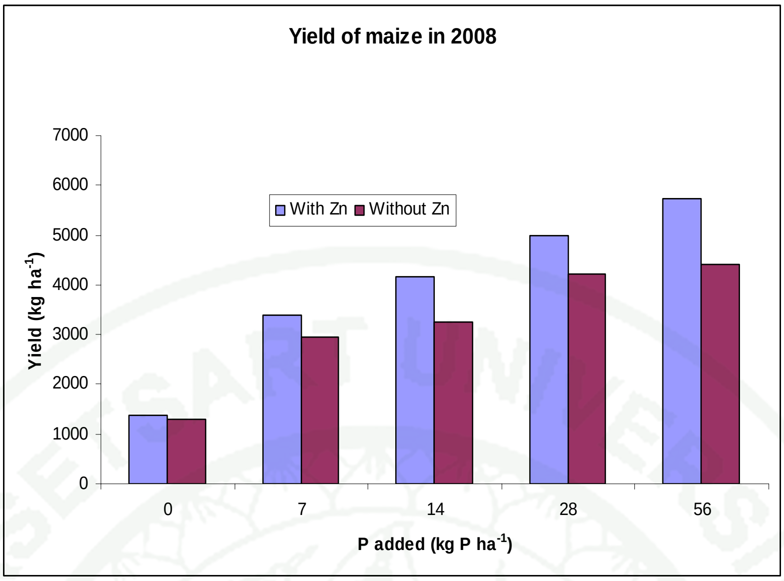

Figure 10 Yield of maize as affected by increasing applications of P in the presence or absence of Zn.

Note Fertilizer had been applied in 2006 and 2007 at the specified levels, except the P rates were applied as 0, 7, 14, 28, and 56 kg P_2O_5 ha^{-1}. Applications prior to the 2008 crop were applied as kg P ha^{-1}.

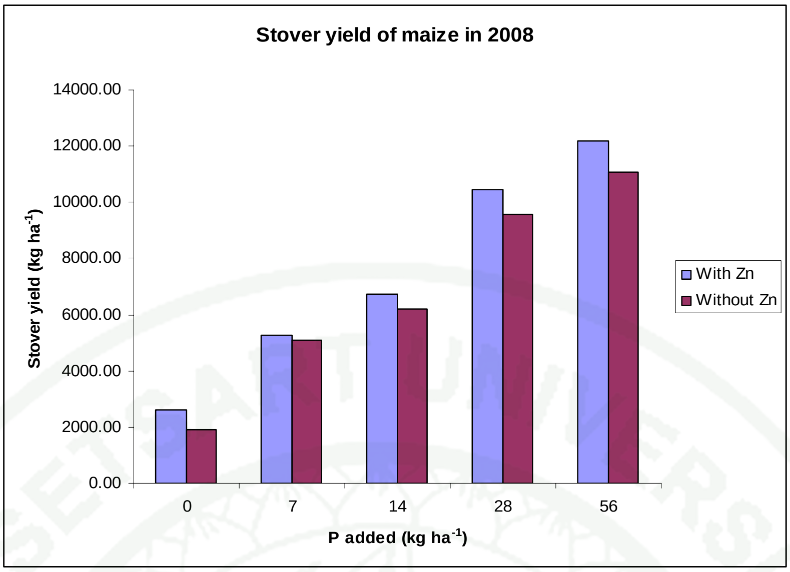

Figure 11 Stover yield of maize of soil from Pek District, Xiengkhouang Province.

Note Fertilizer had been applied in 2006 and 2007 at the specified levels, except the P rates were applied as 0, 7, 14, 28, and 56 kg P_2O_5 ha^{-1}. Applications prior to the 2008 crop were applied as kg P ha^{-1}.

Adams (1980) cited many studies that high rates of P application reduced the availability of Zn to plants and induced Zn deficiency symptoms. In those studies when Zn was applied, the yield of maize was higher than when only P was applied. The result of soil Zn analysis using DTPA method after harvest showed that treatments with Zn application remained (0.47 mg kg^{-1}) compared to the without Zn application treatment in which only 0.24 mg kg^{-1} of soil Zn was measured (Table 14).

In the treatment without Zn applications and with the high rate of P application (56 kg P ha^{-1}) soil Zn was inadequate for maize (0.17 mg kg^{-1}) while the lower P rates contained higher amount of Zn, illustrating the negative effect of fertilizer P on Zn nutrition of plants. Verma and Minhas (1987), reported that the concentration of Zn in maize decreased when increased P application. Jones (2001) reported that the Zn critical level by DTPA extractant method for maize production was about 0.2-2 mg kg^{-1}. Boawn *et al*. (1954); Jurinak and Inouye (1962) reported that P induced Zn deficiency occurred by precipitation of $Zn_3(PO_4)_2$ in the soils or on the roots.

Table 14 Zinc in soil after harvest as measured by DTPA chelate.

treatment	Zn (mg kg^{-1}) ^{1} in Zn application treatments	Zn (mg kg^{-1}) in no Zn application treatments
1	0.52	0.23
2	0.63	0.21
3	0.36	0.23
4	0.20	0.38
5	0.64	0.17
Average	0.47	0.24

However, the maize yield of highest rate of P application (56 kg P ha^{-1}) in 2008 was lower than the yield of the same treatment in wet season 2007, even with $ZnSO_4.7H_2O$ application. Phosphorus deficiency symptoms were observed at 21 days after planting as in earlier crops despite the application of additional P (Figure 12). This P rate might not be enough for maize in this area because of the productivity of LVN10 variety is about 7- 8 t ha^{-1}. The varieties testing of Vanthanouvong and Nguyenthe (2009) in Vientiane delta, Lao PDR found that when applied fertilizer at the rates of 150 N - 60 P_2O_5 -60 K_2O kg ha^{-1}, the LVN10 variety gave the yield of 7.38 T ha^{-1} in wet season, and 8.97 T ha^{-1} in dry season although soils in this area were also strongly acid soils (pH = 4.8-5.3).

3.3 Seasonal differences

Maize yields, although very high by local standards, varied considerably between seasons. One hypothesis was that there might have been more rainfall in one year than in another. Meteorological data from 2006, 2007 and 2008, however, indicate that the total rain in 2008 was higher than in 2006 and 2007. The mean temperature during the period of May to September was in the same range of 21-29^{o}C among years (Appendix table 2). Consequently, the weather might not be the main reason for the lower yield in 2008.

Figure 12 The P deficiency symptoms remained in the highest rate of applied P, treatment 5 (56 kg P ha^{-1}).

Soil analysis after the 2008 harvest indicated that pH (1:1) decreased from 5.3 to 4.6 in both P and Zn application and without Zn application compared to soil before planting (Table 15). The soil pH in the wet season 2007 was 5.2 (Dounphady, 2009), the decrease in pH might be the cause of lower yield in 2008 of this experiment. The lower pH might also explain the continued observation of P deficiency symptoms in spite of large applications of P (Figure 12). Many soil scientists explained that lower pH or strong acid, the phosphate ions are mostly precipitated or fixed by Fe and Al ions (Brady, 1990; Jones, 1979; Tisdale *et al*., 1985; Troeh and Thompson, 2005).

The liming material applied in wet season 2006 and 2007 in total amount of 3,800 kg ha^{-1} was burned lime. This lime material is very fine and is known to react rapidly with soil acidity. Because the lime material is very fine, it also tends to have less residual effect than lime with a distribution of both fine and coarser fractions. The lime which was added in 2006 might be neutralized allowing soil acidity to increase. This might be one reason that the yield in 2008 was lower than the yield in 2007.

The total nitrogen and organic matter in soil after harvest was not different in 2008 as compared with values from the wet season 2007. The amount of Fe and Al extracted by citrate bicarbonate dithionite and ammonium oxalate pH 3 in darkness methods were slightly higher than 2007. The available P extracted by Bray 2, Mehlich 1 and Pi test methods increased with increasing rates of P fertilizer.

Table 15 Soil chemical analysis after harvest in 2008

P rates	$ZnSO_4.7H_2O$	pH	P_{Bray2}	$P_{Mehlich1}$	$P_{Pi\ test}$
(kg P ha^{-1})	(kg ha^{-1})	(1:1)	------------------(mg kg^{-1})-----------------		
0	4.72	4.5	3.12	2.86	1.33
7	4.72	4.7	5.44	3.85	1.89
14	4.72	4.6	12.88	8.24	5.55
28	4.72	4.6	25.32	21.05	16.24
56	4.72	4.7	32.25	28.20	22.45
0	0	4.6	3.34	3.19	1.45
7	0	4.9	5.94	3.96	2.04
14	0	4.4	13.45	4.81	5.34
28	0	4.8	29.23	15.24	13.55
56	0	4.8	37.52	32.00	22.86

The plant analysis revealed that the N, P and K uptake in maize grain of the 2008 crop increased with increasing yield. Nitrogen uptake was in the range of 14.33-55.45 kg ha^{-1}, P was 1.8-11.29 kg ha^{-1} and potassium was 2.82-14.82 kg ha^{-1}

(Table 16). The N and K uptake was lower than in 2007, probably because in 2007 the nitrogen and potassium uptake was in range of 14.30-150 kg ha^{-1} and 2.4-24.6 kg ha^{-1} respectively. In contrast, the P uptake of maize grain in 2008 was higher than 2007. The stover analysis indicated that nitrogen uptake was in range of 10.48-54.97 kg ha^{-1} and lower than 2007, but the P and potassium uptake in stover was higher than in 2007, and in range of 0.68-5.34 kg P ha^{-1} and 24.67-119.14 kg K ha^{-1}.

Table 16 Nutrient uptake of maize grain and stover in 2008

P level	$ZnSO_4.7H_2O$	Grain			Stover		
		N	P	K	N	P	K
-- (kg ha^{-1}) --							
0	4.72	14.33	2.1	3.18	14.92	1.04	31.5
7	4.72	36.85	5.74	8.08	24.47	1.48	61.94
14	4.72	41.5	6.32	9.3	31.37	1.96	79.27
28	4.72	54.59	11.29	14.82	55.84	5.34	119.14
56	4.72	55.45	10.62	11.86	58.97	4.61	109.09
0	0	14.3	1.8	2.82	10.48	0.68	24.67
7	0	29.38	4.19	5.43	25.55	1.59	55.55
14	0	35.58	6.25	9.11	32.9	2.05	67
28	0	44.06	8.39	9.53	52.38	3.64	96.97
56	0	48.42	11.07	12.15	52.76	5.2	107.31

3.4 Economic dominance analysis of fertilization for maize in Xiengkhouang Province.

Although statistical analysis indicated a significant increase in maize yield with the application of lime, phosphorus, and zinc, it was not clear that the benefits of this practice were greater than the costs of the purchase and applications. Xiengkhouang province is quite remote and costs of transportation of fertilizer into the region may be high. An economic dominance analysis provides a quantitative estimate of the economic benefits of fertilization in relation to the costs incurred in the purchase and application of fertilizer and amendments.

Phosphorus applications at the rate of 56 kg P ha^{-1} and 4.78 kg ha^{-1} of $ZnSO_4.7H_2O$ gave the highest profit than all treatments which was US$ 290.75 ha^{-1}. The control treatment (0 kg P ha^{-1}) and P application at the rate of 7 kg P ha^{-1}, the profit was US$ -352 and -39 ha^{-1} respectively, because of lower grain yield of these two treatments (Table 17) and the high cost of applying limestone. The economic dominance calculation showed that P and Zn applications provided more benefit than without Zn application treatment even if lime cost from 2006 and 2007 was included.

Table 17 Economic dominance analysis

P rates (kg ha^{-1})	$ZnSO_4.7H_2O$ (kg ha^{-1})	Yield (kg ha^{-1})	Yield value (US$)	Variable cost (US$)	Net return (US$)	Benefit/ Cost
0	4.72	1,382	240	592	-352	-0.59
7	4.72	3,382	587	626	-39	-0.06
14	4.72	4,169	723	644	79	0.12
28	4.72	4,991	866	668	197	0.29
56	4.72	5,735	995	704	290	0.41
0	0	1,302	226	583	-357	-0.61
7	0	2,945	511	612	-101	-0.17
14	0	3,246	563	623	-60	-0.10
28	0	4,213	731	649	82	0.13
56	0	4,418	766	678	89	0.13

The lowest benefit (Net Return) occurred when lime and P were applied but no Zn was applied. Yields were low and costs were high in these treatments. Where no Zn was applied, the lime and P applications at the rate of 0, 7 and 14 kg P ha^{-1} gave a Net Return of US$ -357, -101 and -60 ha^{-1}, respectively (Table 17). Only at the higher rate of P applications of 28 and 56 kg P ha^{-1}, did the net return become positive US$ 82, and 89 ha^{-1} respectively.

However, the benefit/cost ratio in both P with Zn and without Zn application treatments were lower than 2.0, that means the P and Zn application for maize in an Ultisol of Pek District, Xiengkhouang Province was not accepted in economics, because some reasons present before. But this study was very useful for farmers in this area and also Lao government. Because, this area have never utilized for crop production, so this information will be utilized in the future for food security.

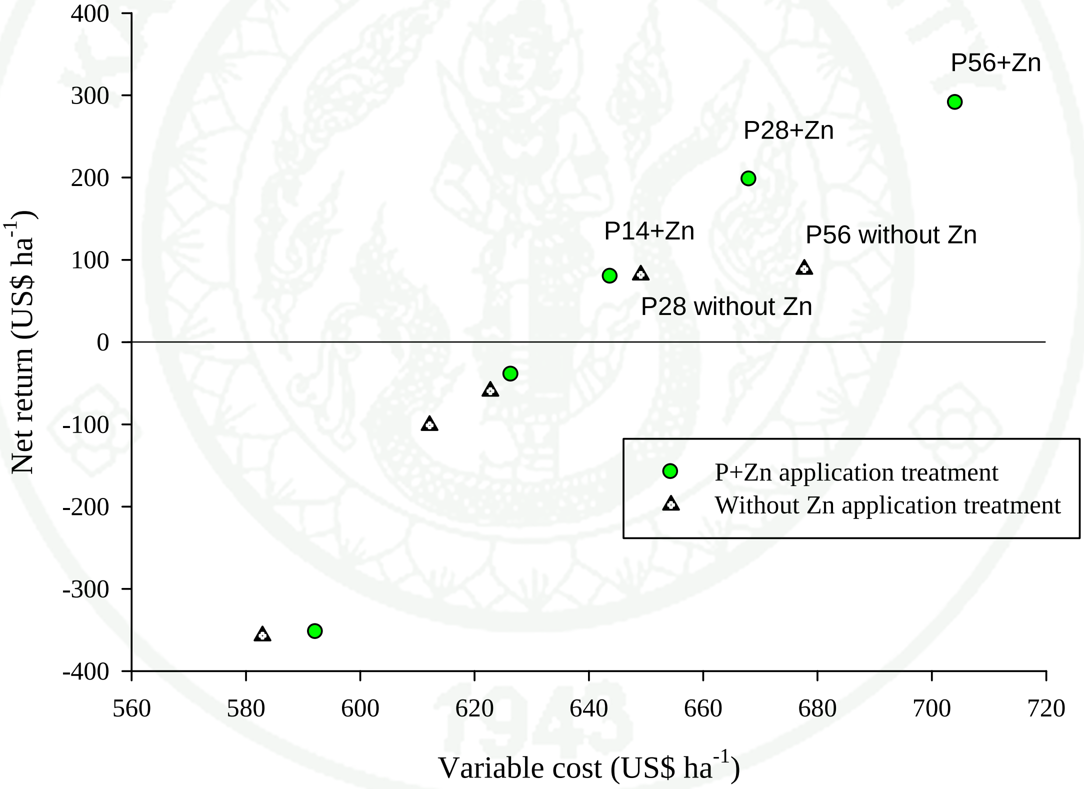

Figure 13 Economic dominance analysis of P and Zn applications to maize, Xiengkhouang Province, Laos.

The variable cost was plotted against net return (Figure 13). The graph showed the P application at the rate of 56 kg ha^{-1} and $ZnSO_4.7H_2O$ 4.78 kg ha^{-1} had dominant value, i.e. returned the highest net benefit for the costs involved in fertilization. Phosphorus application at the rate of 14 kg ha^{-1}and $ZnSO_4.7H_2O$ of 4.78 kg ha^{-1} gave the net return in the same level as the P application at the rate 28 and 56 kg ha^{-1}, but no Zn application. The low rate of P application at 0 and 7 kg ha^{-1} with 4.78 kg ha^{-1} $ZnSO_4.7H_2O$ and application of 7 and 14 kg P ha^{-1}, without Zn, was not economically commercial for maize production in Pek soil, Xiengkhouang province.

So, the commercial maize production in soil from Pek District, Xiengkhouang province, the application of lime and P application without Zn should be at 28 kg ha^{-1} or greater However, if $ZnSO_4.7H_2O$ was applied at the rate of 4.78 kg ha^{-1}, P became profitable at 14 kg ha^{-1}. Net return increased with higher rates of P application.

The results from the field experiment indicated that the P requirements of the soil in Xiengkhouang province appeared to be greater than 56 kg P ha^{-1} and possibly as high as 128 kg P ha^{-1} , which was predicted from the PDSS equation (Table 11).

CONCLUSION AND RECOMMENDATION

The fifteen representative maize soils of Laos were sampled, and their chemical properties were determined, and tentatively classified. These soils were classified as Ultisols and Alfisols according to Soil Taxonomy. Soils from Pasai, Pek, Kham, Pookood, Pookoon, Boten, Bachieng, Tabok, Paksong, Salavanh and Sekong soils were Ultisols. Soils from Koon, Paklay, Kentao and Kasi were Alfisols. Most of the soils were finely textured, except soil from Kham district had a rather coarse texture. Furthermore, the high Fe and Al reduced the availability of P fertilizer. These soils were low in P content, except the soil from Pookood district which contained high P and low organic carbon. The results show that these soils were both infertile and acid and will require substantial inputs, but could become quite productive if properly managed. Soils of these orders are highly productive elsewhere in the tropics.

The Phosphorus Buffer Coefficient (PBC) of the selected soils varied with the different extracting methods and chemical content and concentration, and method of extraction. The soils could be grouped into two categories according to PBC data and Fe_d, Al_o, percent of clay content and soil organic carbon (OC). The $PBC_{Bray\ 2}$ and $PBC_{Mehlich\ 1}$ were correlated with Fe_d, clay and organic carbon with $AdjR^2$ of 0.79** and 0.86**, respectively. The $PBC_{Pi\ test}$ was correlated with Al_o, clay content and organic carbon with $AdjR^2$ of 0.80**. The result of the study suggested that the PBC of selected Laotian soils should be estimated by Mehlich 1 because the PBC by this method had the highest correlation with soil properties and lower sum squares residual. The 1:1 line relationship indicated a close correspondence between predicted and observed PBC by the Mehlich 1 method. Furthermore, this method is simple and inexpensive for routine analysis in Laotian laboratories.

The results of P sorption study of 15 selected maize soils from Laos showed high P sorption. Some Ultisols of Xiengkhouang province and some representative maize soils of Laos sorbed high P and desorbed low P. The high acidity, high clay content and high contents of Fe and Al oxide played the important role in high P sorption and low desorption in these soils. Soils from Pasai, Pookoon, Kasi, Tabok, Paksong, Salavanh and Sekong sorbed the highest amount of P and the lowest desorption. Soils from Pek and Bachieng sorbed P in medium amount when compared with all soils. The soils from Kham, Pookood, Koon, Paklay, Kentao and Borten districts sorbed the least amounts of P.

The predicted P requirement by the PDSS equation predicts that Bray 2 extractant gave the lowest P requirement because of high values of PBC , high P critical level and high initial P contents. The Pi test predicted higher P requirements, probably because of high P critical level. Mehlich 1 gave the lowest amount of P requirement except some soils which contained very low amount of initial P.

The results of the PDSS predictions indicated that the Ultisol of Pek District, Xiengkouang Province have a P requirement of about 30; 17 and 128 kg P ha^{-1} for Bray 2, Mehlich 1 and Pi test extractant methods respectively. The P requirement estimated by $PS_{0.06}$ and $PS_{0.2}$ was 520 and 792 kg P ha^{-1} , which might be excessive for maize. The three field experiments included repeated applications of highest P treatment, initially of 56 kg P_2O_5 ha^{-1} to each of the first two crops and finally with an application of 56 kg P ha^{-1}. For the final crop a P application at the highest rate of 56 kg P ha^{-1} with 4.72 kg ha^{-1} of $ZnSO_4.7H_2O$ gave a maize grain yield of 5.7 t ha^{-1}, but P deficiency symptoms were again observed. The expected productivity of LVN10 variety was about 6-7 t ha^{-1}. The result of field experiment revealed that P requirement of this area might be greater than 56 kg P ha^{-1}.

Besides the lime and P applications, it was shown that Zn is necessary for maize production in Xiengkhouang province. Because of Ultisols of Xiengkhouang are highly weathered, the macro and micronutrients were leached out of the soil.

Because of Pek soils are very strongly acid soils, the availability of P and other nutrients appears to be highly limited. To increase the availability of all nutrients including P, lime should be applied and further studies on rates of lime are needed to assess the availability of nutrients in the soil from Pek District. A burned lime application of 3.5 t ha^{-1} in 2006 and an additional 0.3 t ha^{-1} in 2007 was applied, the results showed that maize yield was increased when pH increased from 4.5 to 5.2. However, pH was rapidly decreased in 2008, which was the third crop after lime application. The lime used in this experiment was calcium hydroxide which reacts quite readily but does not maintain soil pH as well as ground limestone resulting in pH drop and rather low yield.

The economic dominance analysis revealed that the rates of N, P, K of 110, 56 and 86 kg ha^{-1}, respectively with 4.78 kg ha^{-1} of $ZnSO_4.7H_2O$ provided the highest net return of US$ 290 per hectare. However, the commercial maize production in an Ultisol of Pek District is not recommended, because the benefit/cost ratio is lower than 2.0 which is not accepted in economics, but the maize production in this area is possible for food security.

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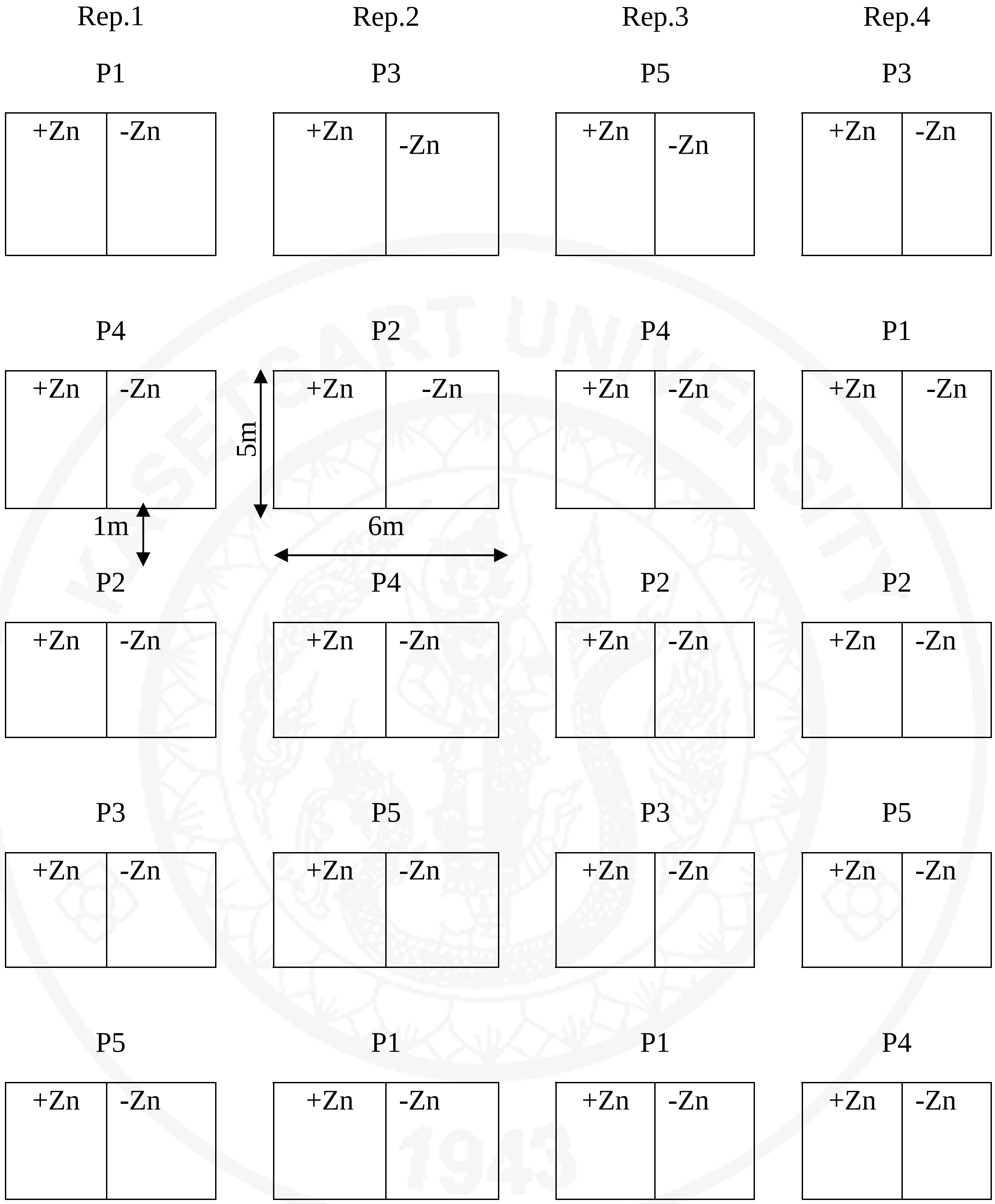
APPENDIX



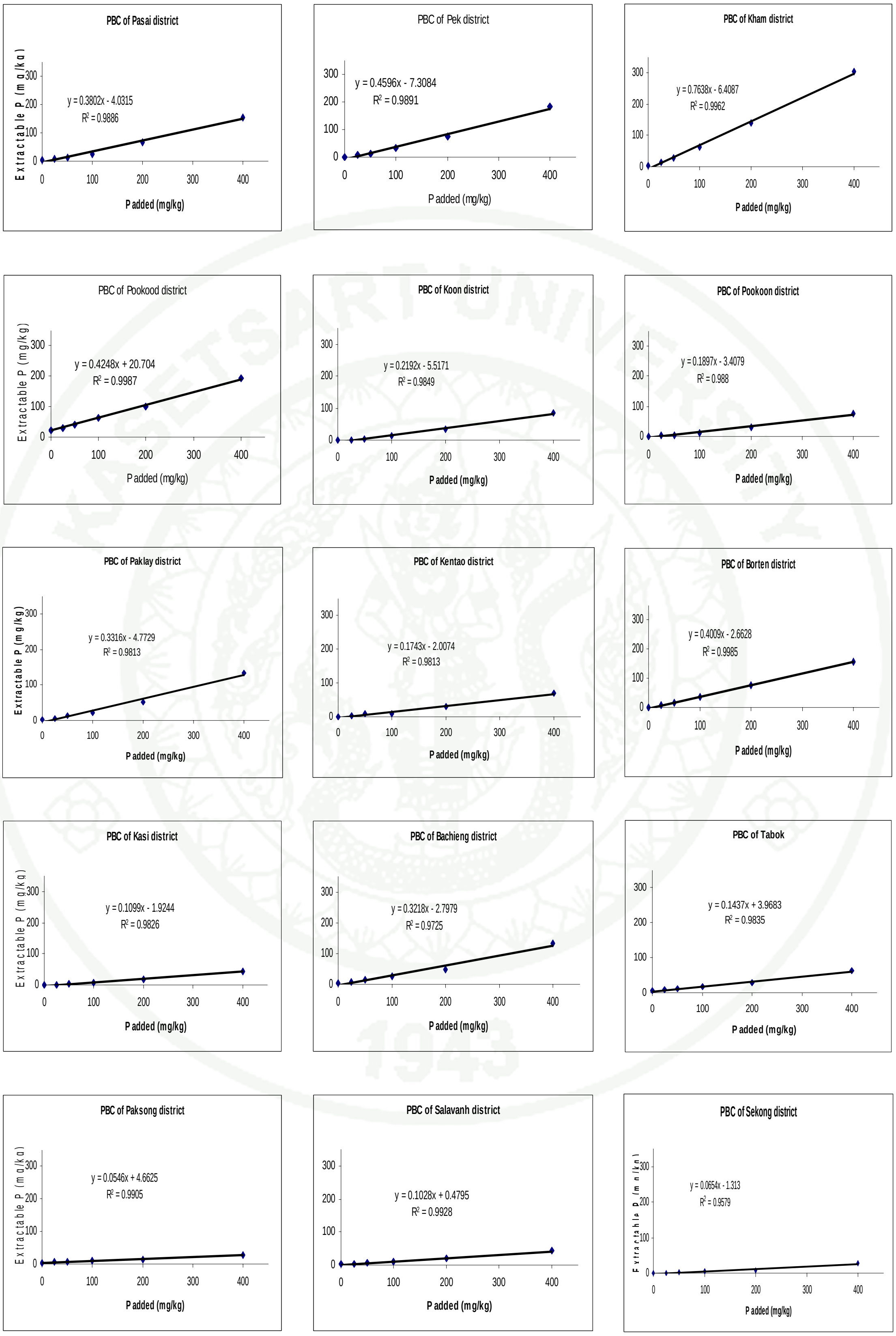
Appendix Figure 1 Diagram of field experiment.

Appendix Table 1 Meteorological data for 2008.

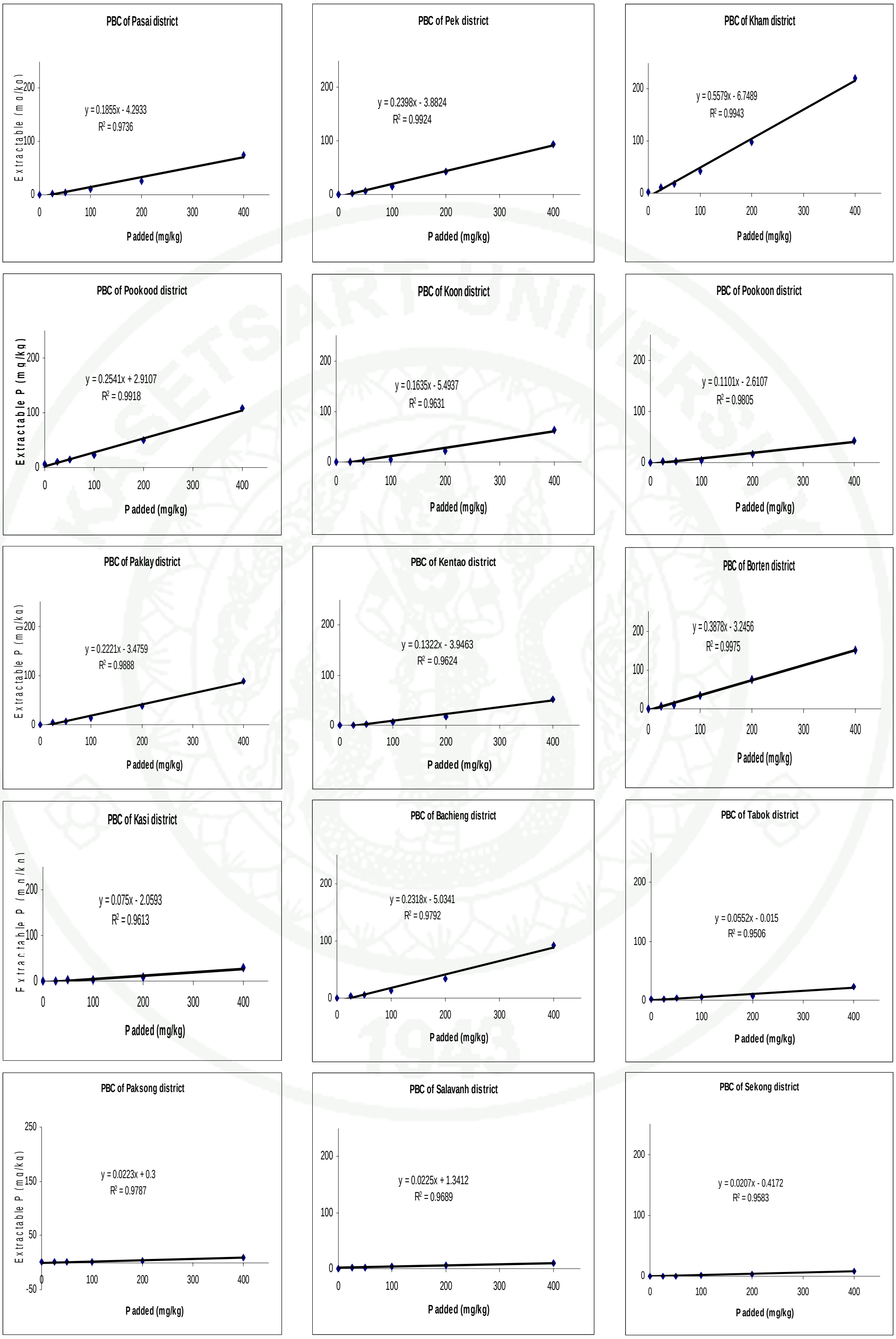
Month	Jan	Fre	Mar	App	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	mean
Relative humidity (%)	65	71	66	71	76	80	78	77	74	75	68	66	867	72
Mean of temperature (C)	16.2	14.4	19.8	22.8	23	23.6	23	23.5	23.2	21.6	16.8	14	241.9	20.1
Rain (mm)	22.3	23.8	81.7	264.8	159.7	278.4	372.9	455.4	135.8	34.4	54.5	12.9	1896.6	158
Speed of wind (m/s)	2	7	2	2	2	1	1	2	2	2	2	1	26	2
Sun light (hrs)	238.5	169.7	210.3	186.5	168.7	79.8	78.6	121.7	137.5	144.6	205.9	227.5	1969.2	164.1
Direction of wind	NE	NE	NE	E	NE	S	SW	S	NE	NE	NE	NE		
Evaporation	2.6	2.3	3.2	2.6	2.2	1.8	1.7	1.17	1.9	2.2	2.9	2.7	27.8	2.3
Minimum temperature	-0.6	5.5	5.8	15.8	15.4	18.4	18	18.8	17.2	14.6	3.3	0	132.2	11
Maximum temperature	28.8	28.2	31.2	31.5	29.6	30	29.8	29.5	30.3	29	27	24.6	349.5	29.1
Raining days	3	2	8	17	20	23	26	24	14	13	7	3	160	13

Appendix Table 2 Meteorological data in 2007.

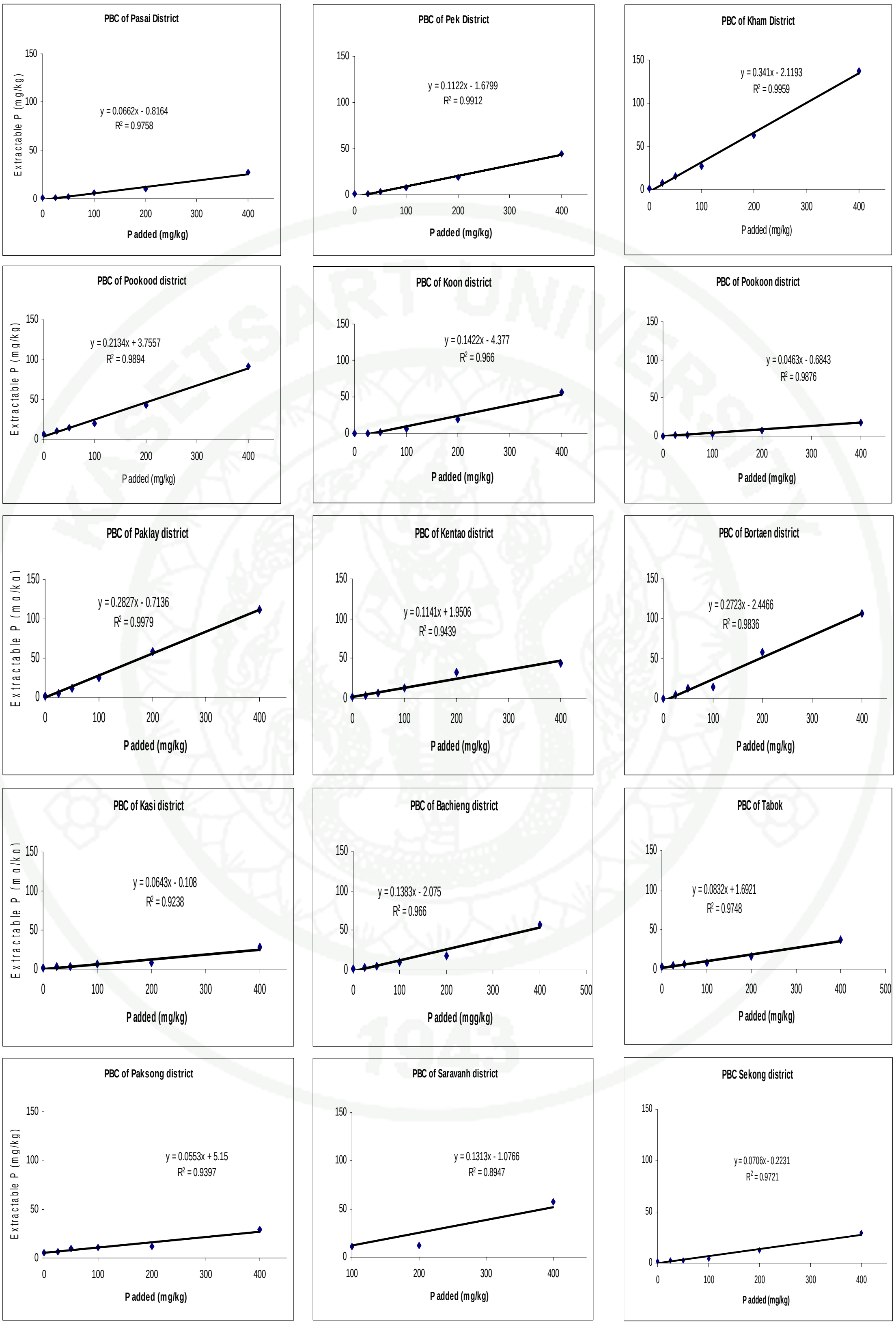
Month	Jan	Fre	Mar	App	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Mean
Minimum temperature(C)	1.4	2.0	8.8	11.0	11.8	17.8	16.0	17.8	11.4	8.7	0.7	1.8	109.2	9.1
Maximum temperature(C)	27.2	30.7	33.4	34.2	32.0	31.8	30.2	29.9	30.5	26.8	25.4	27.6	359.7	29.9
Mean of temperature(C)	15.0	17.8	21.9	22.0	22.7	24.2	23.5	23.4	20.9	17.7	13.0	14.7	234.4	19.5
Rain (mm)	0.0	4.6	18.6	37.0	15.4	9.54	122.5	182.4	219.3	122.5	1.4	0.0	733.3	61.1
Moisture (%)	67.0	56.0	62.0	68.0	68.0	71.0	73.0	74.0	74.0	75.0	68.0	68.0	824.0	68.6
Sun light (hrs)	236.0	251.6	235.0	177.5	205.8	180.8	145.2	139.9	134.5	156.7	213.9	200.9	2277.8	189.8



Appendix Figure 2 PBC of Lao soils using Bray 2 extractant method.



Appendix Figure 3 PBC of Lao soils using the Mehlich 1 extractant method.



Appendix Figure 4 PBC of Lao soils using the Pi extractant method.

Appendix Table 3 Phosphorus sorption of fifteen soils representative of Lao uplands.

No.	Soil name	P added (mg P kg^{-1})	P remaining in solution (mg P L^{-1})	P sorbed (mg P kg^{-1})
1	Pasai	0	0.00	0.00
		400	0.02	399.69
		800	0.51	789.73
		1600	6.71	1465.75
		3200	47.80	2244.02
		6400	185.83	2683.35
2	Pek	0	0.00	0.00
		100	0.01	99.85
		200	0.04	199.22
		400	0.28	394.36
		800	2.80	743.95
		1600	22.20	1155.90
3	Kham	0	0.00	0.00
		25	0.02	24.62
		50	0.04	49.27
		100	0.30	94.08
		200	1.69	166.14
		400	7.72	245.61
4	Pookood	0	0.00	0.00
		100	0.05	98.90
		200	0.32	193.52
		400	1.66	366.85
		800	10.24	595.25
		1600	38.05	839.05
5	Koon	0	0.00	0.00
		200	0.08	198.46
		400	1.26	374.75
		800	9.75	605.00
		1600	38.23	835.32
		3200	109.89	1002.24
6	Pookoon	0	0.00	0.00
		400	0.04	399.18
		800	0.29	794.27
		1600	2.87	1542.53
		3200	32.74	2545.14
		6400	156.38	3272.45
7	Paklay	0	0.00	0.00
		50	0.07	48.70
		100	0.23	95.46
		200	1.51	169.85
		400	6.27	274.53
		800	19.21	415.87

Appendix Table 3 (Continued)

No.	Soil name	P added (mg P kg^{-1})	P remaining in solution (mg P L^{-1})	P sorbed (mg P kg^{-1})
8	Kentao	0	0.00	0.00
		100	0.04	99.29
		200	0.38	192.37
		400	2.65	346.96
		800	13.16	536.71
		1600	40.74	785.15
9	Borten	0	0.00	0.00
		100	0.07	98.54
		200	0.41	191.77
		400	2.21	355.77
		800	10.99	580.22
		1600	40.50	790.09
10	Kasi	0	0.00	0.00
		200	0.02	199.61
		400	0.19	396.20
		800	1.67	766.61
		1600	12.74	1345.12
		3200	57.44	2051.19
11	Bachieng	0	0.00	0.00
		100	0.01	99.77
		200	0.02	199.53
		400	0.13	397.32
		800	1.59	768.15
		1600	23.95	1120.95
12	Tabok	0	0.00	0.00
		200	0.03	199.45
		400	0.14	397.14
		800	0.89	782.25
		1600	6.99	1460.22
		3200	41.09	2378.13
13	paksong	0	0.00	0.00
		400	0.00	399.93
		800	0.13	797.34
		1600	1.35	1573.00
		3200	14.06	2918.77
		6400	94.48	4510.40
14	Salavanh	0	0.00	0.00
		400	0.05	399.05
		800	0.63	787.39
		1600	7.02	1459.65
		3200	47.42	2251.67
		6400	194.72	2505.68

Appendix Table 3 (Continued)

No.	Soil name	P added (mg P kg^{-1})	P remaining in solution (mg P L^{-1})	P sorbed (mg P kg^{-1})
15	Sekong	0	0.00	0.00
		200	0.00	199.97
		400	0.02	399.68
		800	0.22	795.60
		1600	3.15	1536.93
		3200	28.33	2633.40

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