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THESIS

ESTIMATING POTASSIUM SUPPLYING POWER OF SELECTED MAIZE SOILS OF THAILAND

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A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
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Maize is one of the important economic field crops in Thailand. In 2008, a production of approximately 4.3 million tons was harvested from an area of approximately 0.95 million ha and mean maize yield per ha was 4.5 tons. The one hectare of soil may contain several tonnes to several hundred tonnes of non-exchangeable K ($K_{\text{non-ex}}$) that is held in the structure of micas and K feldspars which is differentially available for plant growth. The objective of this study was to quantify the plant available $K_{\text{non-ex}}$ for intensive maize growing in eight kaolinitic and smectitic maize soils of Thailand. The release patterns and the availability of $K_{\text{non-ex}}$ was studied using successive the Ca-resin extraction method and described the pattern of release using a segmented regression model. The results indicated that there were two fractions of $K_{\text{non-ex}}$, which were released at distinctly different rates as fast and slow release rates. Estimating of plant available $K_{\text{non-ex}}$ in the soils was obtained using successive maize crops and selected extraction methods. This result indicates that the mixed acid and Ca-resin extraction methods were the most accurate methods to directly extract the total plant extractable K in both kaolinitic and smectitic soils, which included the exchangeable and non-exchangeable K pools in the soils. The mixed acid extraction method was used to determine the plant available $K_{\text{non-ex}}$ in the Pc and Lb soils at 0-20 cm depth that were exhaustively cropped with maize in the field conditions. The total plant available K of Pc and Lb soils in field experiment were 1,145 and 1,234 kg ha^{-1}, and the plant available $K_{\text{non-ex}}$ was release by different rates, the rapid K release rates of plant available $K_{\text{non-ex field}}$ were 4.86 and 6.67 kg $\text{ha}^{-1}\text{d}^{-1}$, and slow K release rates were 0 and 0.18 kg ha^{-1} d^{-1} in Pc and Lb soils, respectively. The K supplying power of Pc soil in field experiment was determined, and approximately 9 years, and the producing yield approximately 3,543 kg ha^{-1} for intensive maize growing in Thailand where only 2 crops per year are grown and only grain is removed from the field.

Student's signature	Thesis Advisor's signature	____ / ____ / ____

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Weena Nilawonk
February, 2009

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LIST OF ABBREVIATIONS

Ca-resin-K = Potassium extracted by Ca-resin

Cd soil = Chai Badan soil

CEC = Cation exchange capacity

HF-K = Potassium extracted by hydrofluoric acid

HNO_3-K = Potassium extracted by nitric acid

Il = Illite

Ka = Kaolinite

K_{ex} = Exchangeable potassium

$K_{non\text{-}ex}$ = Non-exchangeable potassium

$K_{removed}$ = Potassium removed by plant

Lb soil = Lop Buri soil

Ln soil = Lam Narai soil

Mixed acid-K = Potassium extracted by mixed acid

MSE = Mean square error

NH_4OAc-K = Potassium extracted by ammonium acetate

ns = Not significant

Pc soil = Pak Chong soil

Qu = Quartz

RMS = Residual mean square

SAS = Statistical Analysis System

Sm Smectite

Suk soil = Satuk soil

Tk soil = Takhli soil

Ve = Vermiculite

Wn soil = Warin soil

ESTIMATING POTASSIUM SUPPLYING POWER OF SELECTED MAIZE SOILS OF THAILAND

INTRODUCTION

Maize is one of the important economic field crops in Thailand. In 2008, a production of approximately 4.3 million tons was harvested from an area of approximately 0.95 million ha and mean maize yield per ha was 4.5 tons (Office of Agricultural Economics, 2008). This production was largely used for animal feed. Maize is widely produced in the North, Northeast, and Central parts of Thailand. The clay mineralogy of soils in these areas is dominated by smectite, kaolinite, and in some soils a small amount of illite was found (Land Development Department, 2008). Response of maize to K fertilizer was reported in the Phu Sana (Ps), Satuk (Suk) and Warin (Wn) soils, all of which were dominated by kaolinite (Attanandana and Teeraphorn, 2005). On the other hand, response was not found in Lop Buri (Lb), Chai Badan (Cd), Takhli (Tk) and Lam Narai (Ln) soils which were dominated by smectite (Attanandana *et al*., 2004). It is believed, in broad terms, that K is sufficient for plant growth in the smectitic soils, but insufficient in kaolinitic soils. The plant available K was measured by the 1 ***M*** NH_4OAc method which has been the soil test method used to establish K fertilizer recommendations in Thailand (Land Development Department, 2008). The 1 ***M*** NH_4OAc method, however, only measures the availability of solution and exchangeable K (Cox *et al*., 1999; Hosseinpour *et al*., 2004). McLean and Watson (1985) indicated that when the exchangeable K approached the critical level, the availability of K to plants tended to be regulated by the release of non-exchangeable K. Nair *et al*. (1997) and Wang *et al*. (2004) indicated that non-exchangeable K was more likely to control the overall buffering capacity of a low exchangeable K soil. The NH_4OAc extractant has been found to be inadequate to determine plant available K mostly in 2:1 clay soils, for example, illitic (Eckert and Watson, 1996), vermiculitic (Cassman *et al*., 1990) and smectitic (Schindler *et al*. 2002; Schindler, 2005) soils. Non-exchangeable K is held between adjacent tetrahedral layers of weathered dioctahedral and trioctahedral micas (Mengel *et al*., 1998) and released to plants by diffusion controlled processes (Dhillon and Dhillon, 1990; Jalali, 2005; Martin and Sparks, 1983). Therefore, the non-exchangeable K is important source of plant available K for long duration plant growth.

Large amounts of K chemical fertilizer are used in Thailand for maize production. However, K fertilizer is not recommended in the soils high in clay content *i.e.* Lop Buri (Typic Pellusterts; very fine, montmorillonitic), Lam Narai (Typic Haplustolls; fine, mixed), Chai Badan (Typic Chromusterts; fine, montmorillonitic), and Takhli (Typic Calciustolls; fine, montmorillonitic) soil series (Attanandana *et al*., 2004). The NH_4OAc-K soil test was an adequate measure of long term supply of plant available K in clayey soils (Havlin and Westfall, 1985). Maize yield gave no response to added K on high clay soils but gave significant response to K fertilizer at 31.25 kg ha^{-1} K_2O in the sandy loam or loamy sand soils (Meesawat *et al*., 1981). The high clay content soils did not respond to K fertilizer, probably because of the transformation of non-exchangeable to exchangeable K (release) and exchangeable K to water soluble K (desorption) which is available to plants (Havlin and Westfall, 1985). Non-exchangeable K has been used to characterize the K supplying power in specific soils. Consequently, a study of the accumulation and mechanisms of non-exchangeable K release was hypothesized to be useful to determine K supplying power and a way to increase the efficiency of K fertilizer management in high clay content maize soils of Thailand.

A hypothesis of this study is that the release of K from non-exchangeable K forms could provide plant available K and thus improve estimates of K supplying power in maize soils of Thailand.

OBJECTIVES

1. Characterize non-exchangeable K release from soil fractions using Ca-resin.

2. Describe, using selected K release models, the plant available non-exchangeable K release.

3. Estimate plant available non-exchangeable K using different extraction methods.

4. Field-test improved prediction of K supplying power of representative maize growth soils in field conditions.

LITERATURE REVIEW

1. Maize soils in Thailand

Maize is one of five major crops in Thailand, in addition to rice, cassava, sugarcane, and rubber. Maize occupies a major portion, approximately 33%, of Thailand upland farmlands. A production of approximately 4.3 million tons was harvested in 2006 for use by the animal feed industry, from an area of approximately 0.95 million ha (Office of Agricultural Economics, 2008). Maize is primarily produced in the North, Northeast, and Central parts of Thailand. The maize area of approximately 0.59(61.7%), 0.19(19.6%), and 0.15(15.3%) million ha was found in the North, Northeast, and Central parts of Thailand, respectively (Land Development Department, 2008). The clay mineralogy of soils in these areas is dominated by smectite, kaolinite, and in some soils a small amount of illite was found (Soil Survey Staff, 1999). The response of maize to K fertilizer in Phu Sana (Ps), Satuk (Suk) and Warin (Wn) soils (which are low clay soils and dominated by kaolinite) were found (Attanandana and Teeraphorn, 2005). On the other hand, the Lop Buri (Lb), Chai Badan (Cd), Takhli (Tk) and Lam Narai (Ln) soils (which are high clay soils and dominated by smectite) were not found response (Attanandana *et al*., 2004). It is believed, in broad terms, that K is sufficient for plant growth in the smectitic soils, but insufficient in kaolinitic soils. Maize yield typically does not increase with K fertilization of the high clay soils but often does give significant yield increases to K fertilizer applications of 31.25 kg K_2O on the sandy loam or loamy sand soils (Meesawat *et al*., 1981). Department of Agricultural Extension (2009), however, indicates that maize did not respond to K fertilizer applications in the Pc soil, a kaolinitic soil, and has not recommended K fertilizer in this soil.

2. Potassium forms

It is generally agreed that soils supply K to plants mainly from both the exchangeable and non-exchangeable K pools (Cox *et al*., 1999), while potassium in four soil pools varies in availability to plants.

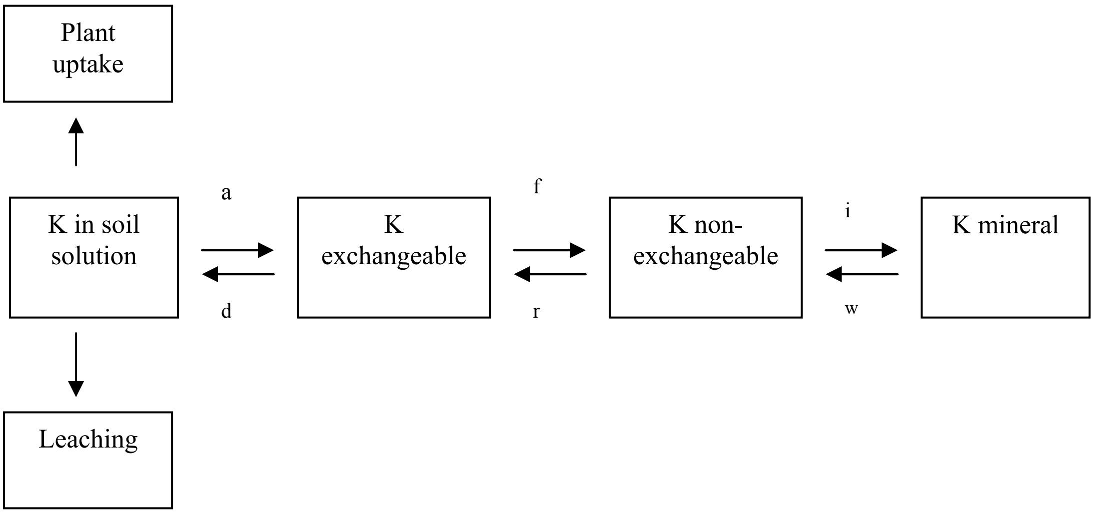


Figure 1 **The soil's K pools (Sparks and Huang, 1985).**

The changes among the four soil K pools depend on plant uptake, K fertilizer application and leaching. The plant uptake will be related to ability of soils to supply K to plants which depends on K in solution, exchangeable K and a substantial amount of non-exchangeable K (Rahmatullah and Mengel, 2000). Kinetic reactions between soil K pools has been referred to as adsorption (a), desorption (d), fixation (f), release (r) immobilization (i) and weathering (w) or mineralization (Sparks, 1987). Availability of K to plants depends on the initial amount of K, the release of non-exchangeable to exchangeable and transformations of exchangeable to soil solution K (Wang *et al.*, 2004).

One hectare of soil may have several megagrams to several hundred megagrams of K held in the structure of micas and K feldspars, which is located around rooting zone of plant (Sparks and Huang, 1985). The exchangeable K is available for plant in the short term. Amount of exchangeable K pool may be a few hundred kg ha^{-1}, for example, corresponding to the demand of just a few years of intensive cropping. Extraction K by plant was found to remove K from non-exchangeable pool on a time scale of only years (Singh *et al.,* 2002). The large amount of non-exchangeable K which was released caused a negative K balance (harvest>fertilizer+manure) for intensive cropping. Negative K balances in fields are found for mixed systems with both livestock and arable farming, especially in organic farming systems, which mainly rely on farm nutrient recycling and internal sources (Magnus *et al.*, 2007; Öbom *et al.*, 2005). The interaction between K in soil minerals and soil mineralogy, texture, and biological process was found to be complicated (Wang *et al.*, 2000; Hinsinger and Jaillard, 2006). There were several studies of K release kinetics which were conducted on both pure minerals and soils. The ability of soil K release followed the sequence: trioctahedral micas > dioctahedral micas > K feldspars (Huang, 2005; Sparks and Huang, 1985). The release of interlayer K seems to proceed near equilibrium and switches to fixation of K when the concentration in the ambient solution exceeds a critical value (Hinsinger and Jaillard, 2006). However, when K fertilizer is applied to the soils, some of dissolved K will be taken up by plant; some of dissolved K can be fixed by clay and become part of the non-exchangeable K pool. The changes in K pools depend on initial K in soil or amount of K fertilizer application, clay mineralogy, and equilibrium among different K pools, drying-wetting cycles (Hanway and Scott, 1957; Wiwutwongwana, 1977), and the amount of soil organic matter (Olk *et. al.*, 1995). Liu *et al.* (1997) showed that level of exchangeable K and K fixation capacities were influenced by long-term K fertilizer management.

3. Determination plant available K using chemical extraction

Potassium uptake during plant growth is a dynamic process with period of K depletion in the plant root zone and release of non-exchangeable to exchangeable K and solution fractions by K bearing soil minerals. Non-exchangeable K release is an important process and it has been examined and described by many researchers. The long term plant available K is evaluated by determining the amount of exchangeable and released plant available, non-exchangeable K. Ammonium acetate extractable K is the most widely used index of plant available K whereas, it has been shown to be inadequate in determining plant available K when the soils contain substantial amounts of K in phyllosilicates (e.g., vermiculite and hydrous mica). Cox *et al.* (1999) illustrated the limitations of the NH_4OAc extraction method to predict plant available K in soils where non-exchangeable K contributed to K available to wheat. The inability of the NH_4OAc method to estimate plant-available K and a 60% underestimation of plant-available K were both attributed to the release of non-exchangeable K to plant available K. Plant-available K has been determined from the total K removed by successive plant growing in pots (Askegaard *et al.*, 2005; Schindler *et al.*, 2002; Sherrod *et al.*, 2002) and predicted using different extraction methods. The most commonly used methods for determining availability to the plant of non-exchangeable K in soils, have been boiling HNO_3 (Helmke and Sparks, 1996), H_2SO_4 (Hunter and Pratt, 1957), $NaBPh_4$ (Cox *et al*, 1996; Cox *et al.*, 1999), HNO_3+$HClO_4$ (Blancher *et al.*, 1965), and Ca-resin (Jalai, 2005; Singh *et al.*, 2002; Srinivasarao *et al.*, 2006).

Mengel and Uhlenbecker (1993) suggested that a modified electro-ultrafiltration (EUF) technique was an appropriate tool for the determination of release patterns of interlayer K^+. A Ca-resin method was used to study non-exchangeable K release to alfalfa, and it showed that Ca-resin-extractable K was highly correlated with non-exchangeable K release to alfalfa (r=0.91; Y= -284+1.52x, where Y and x are K release to alfalfa and Ca-resin-extractable K, respectively (Havlin and Westfall, 1985). This extraction method was used to study the kinetics of K release from loamy sand and fine sandy loam. Potassium release from the whole soil to Ca-resin, ranged from 0.172 to 0.251 $cmol_c\ kg^{-1}$ over a 30 d period (Sadusky *et al.*, 1987). Martin and Sparks (1983) studied the kinetics of non-exchangeable K release using H-saturated resin on loamy soils. Calcium saturated soil samples were equilibrated with H-saturated resin from 0.5 to 960 h. Equilibrium in K release in soil was attained in about 960 h. Rahmatullah and Mengel (2000) used H-saturated resin to determine- K release from sand, silt and clay fractions.

Single extractions with a $NaOAc$-$NaBPh_4$ solution removed more non-exchangeable K than five successive NaCl-HCl extractions (Scott and Welch, 1961). They found that non-exchangeable K was also extracted from the undried soils by two chemical methods that tend to reduce the blocking effect of replaced K. Simard *et al.*, (1992) examined the K and Mg release from silt and clay fractions by using fifteen sequential extractions with $5x10^{-4}$ *M* citric acid, through a period of 32 h, and a single extraction with boiling 1.0 ***M*** HNO_3. They concluded that a citric acid extraction resulted in the dissolution of trioctahedral phyllosilicates from the sandy soil and the transformation of dioctahedral micas to vermiculite in the clay soils. The amounts of K released from the soil fractions in dilute citric acid solutions were significantly related to their amounts of HNO_3-extractable forms ($r = 0.76$, $P<0.01$) but not to the structural or total forms. Cox *et al*., (1996, 1999) used the modified sodium tetraphenylboron ($NaBPh_4$) method to estimate non-exchangeable K.

Sulfuric acid (Hunter and Pratt, 1957), 0.01 *M* $CaCl_2$, 1 ***M*** NH_4OAc, oxalic and citric acid (Song and Huang, 1988), Ca^{2+} or H^+ resin (Rahmatullah and Mengel, 2000) , boiling nitric acid, sodium tetraphenyl borate (Cox *et al*., 1996: Cox *et al*., 1999: Ngugen My Hoa, 2003), electro-ultrafiltration techniques (Mengel and Uhlenbecker, 1993) are commonly used for determining non-exchangeable K. The suitable methods for determining plant available K depend on many factors, such as, plant species, clay minerals, and soil properties.

4. Pattern of soil K release

The mechanism of K release was described by many mathematical equations. The equations are associated with parameters of non-exchangeable K release and indicate the reliability by the relationship between constant value of equation and K uptake by plant. Havlin *et al*.,(1985) and Rahmatullah and Mengel (2000) indicated that cumulative K release from soil extracted by Ca^{2+} resin could be mathematically described by a power function equation, diffusion equation and the empirical constants were related to yield, K uptake, and exchangeable K levels. Elovich equations were used for chemisorption kinetics, dissolution of hydroxypatite, and kinetics of phosphate release and sorption (Havlin *et al*., 1985). A power function equation has been applied to the dissolution of P by EDTA (McDowell and Sharpley, 2002). The first order and parabolic diffusion equations have been used to describe the kinetics of K release by Havlin and Westfall (1985).

The Elovich equation applied to K release is expressed as

$$y = a + b \ln t$$

where:; y = amount of K+ released, t = time, and a and b are constants. The constants *a* and *b* represent the intercept on the ordinate and the steepness of the slope, respectively (Mengel and Uhlenbecker, 1993).

The linear form of the power function, first-order and parabolic diffusion equations are expressed as

$$\ln y = \ln a + b \ln t$$

$$\ln y = \ln a - bt$$

$$y = a - bt^{½}$$

where;

y = the amount of K release (mg kg^{-1})

t = time (hours)

a, b = constants value

(Havlin and Westfall, 1985)

The parabolic diffusion equation was modified to reflect the initial condition as zero in the K release process, i.e. there was no K on the Ca-resin nor was there K uptake by the plants at time 0. This resulted in rewriting the equation as

$$y = bt^{1/2} \ (t \geq 0)$$

The power equation is sometimes written as

$$\ln(y) = b\ln(t) \text{ or } y = at^{b}$$

Mengel and Uhlenbecker (1993) showed that potassium uptake by ryegrass grown in Mitscherlich pots was correlated with the *b* values of the parabolic diffusion equation, the power function, and particularly the Elovich function. The latter finding shows that the *b* value represents a reliable indicator for the availability of non-exchangeable K. The same is true for the NH_4^+-exchangeable K, provided the soil is low in exchangeable K. Simard *et al.*, (1992) showed that the parabolic diffusion equation best represented the cumulative release of K to $5x10^{-4}$ ***M*** citric acid extraction. Martin and Spark (1983) examined the kinetics of K release in loamy soils using the Elovich, parabolic diffusion law, first-order diffusion, and zero-order equations. The first-order diffusion equation described the K release kinetics best as evidenced by the highest correlation coefficient and lowest value of the standard error of the estimate (SE).

The efficiency of the equations to describe the kinetics of K release depends on the methods for determining extractable K and soil characteristics. The pattern of K release was a simple reaction and is usually described by a linear regression form of the first-order, parabolic diffusion, power function, or Elovich equations. These equations have a straight-line and a slope (*b* constant value). The slope value often indicates a steady release rate of K in the soils. The reliability of the K release rate was examined by considering the relationship between the rate of K release with total plant K uptake and yields (Havlin *et al*., 1985; Simard *et al*., 1992). In contrast, Jalali (2005), and Srinivasarao *et al*., (2006) showed that the release of K to various successive extraction methods was not released by a single steady rate, but rather a rapid K release rate which was found at the initial time period, followed by a second time period during which the rate was slower than that of the initial time period. These results suggested that the release of K is probably a complex reaction in the soil possibly resulting from two distinct processes. A segmented regression model has been proposed to describe the complex reactions with different mechanisms in agricultural science (Shuai *et al*., 2003). The straight-lines with different slopes (*b*) and join points (*a*) of the segment regression model describe the different processes as different mechanisms (Anderson and Nelson, 1975; Cox *et al*., 1999; Cox and Barnes, 2002).

MATERIALS AND METHODS

This study consists of four experiments:

1. Experiment 1. A study of non-exchangeable K release models in soil fractions using Ca-resin.

2. Experiment 2. Estimating plant available non-exchangeable K release using plant exhaustion and K release equations.

3. Experiment 3. Estimating plant available non-exchangeable K using different extraction methods.

4. Experiment 4. Testing the prediction of K supplying power for maize growth in field conditions.

1. Experiment 1 A laboratory study of non-exchangeable K release models in soil fractions using Ca-resin

1.1 Soils

Samples from eight representative maize soils were collected from farmer fields at 0-20 cm depth, in the Central Plain and Northeast regions of Thailand. There were Phu Sana (Ps), Satuk (Suk), Warin (Wn), Pak Chong (Pc), Lop Buri (Lb), Chai Badan (Cd), Takhli (Tk), and Lam Narai (Ln) soils. The taxonomy, chemical and physical properties are presented in Table 1. Soil pH was determined by a 1:1; water: soil ratio. Exchangeable K, Ca and Mg were extracted by 1 ***M*** NH_4OAc. Non-exchangeable K was determined by boiling 1 ***M*** HNO_3. Total K was determined by HF digestion (Helmke and Sparks, 1996). Cation exchange capacity (CEC) was measured by the saturation method (Summer and Miller, 1996). Particle size analysis was determined by the pipette method (Gee and Bauder, 1986). A mineralogical analysis of the clay fraction was carried out using X-ray diffraction. The soil samples were prepared for clay mineralogy analysis following the procedure given by Kunze and Dixon (1986).

1.2 Soil potassium release to Ca-resin

Soil fractions were prepared by removing $CaCO_3$ with dilute HCl and organic matter with H_2O_2 (Kunze and Dixon, 1986). The iron oxides were removed by the Na dithionite-citrate-bicarbonate method. The sand fraction was separated by wet sieving. Silt and clay fractions were separated by the pipette method.

Potassium release from the soil fractions was determined by successive extraction with Ca-saturated cation exchange resin. Calcium saturated resin was prepared by slowly leaching Na-resin with 1 ***M*** $CaCl_2$ pH 7.0 (Havlin *et al*., 1985). Two grams of air-dry soil fraction from each sample was placed in a 120 ml bottle with 1.0 ml deionized water and allowed to reach equilibrium over night. Four grams of moist Ca-resin and 10 ml deionized water were then added to each soil sample.

The soil:resin:water mixture was equilibrated at 25 ^{0}C for 0 to 600 hours (0, 60, 120, 240, 360, 480, and 600 h). At the end of each reaction period the resin was separated from the soil on a 0.50 mm sieve with 25 ml deionized water. The soil suspension was centrifuged for 10 minutes. Twenty five ml of the supernatant solution was removed and analyzed for K by atomic absorption spectrophotometry. A fresh charge of Ca-resin was added to the reaction flask and soil, and incubated for the subsequent time period. The separated resin was leached with 150 ml of 0.01 ***M*** $CaCl_2$ and the leachate was analyzed for K by atomic absorption spectrophotometry. The cumulative K release in a given time period was calculated as the sum of the K adsorbed on the resin and the K in the supernatant solution. Blank samples were treated the same as the soil samples. The total cumulative K of each soil was the summation of the K released per gram of sand, silt, and clay fractions from each soil

1.3 Statistical analyses

The K release to Ca-saturated exchange resin was described by a linear form of the parabolic diffusion equation (1), a linear form of the power function equation (2) and a nonlinear segmented linear equation (4):

Parabolic diffusion equation;

$$y = a + bt^{1/2} \ (t \geq 0) \tag{1}$$

Power function equation;

$$\ln(y) = b\ln(t) \tag{2}$$

Segmented straight-line equation;

$$y = b_1\min(\text{node}, x) + b_2\max(\text{node}, x) - c \tag{3}$$

where y = cumulative K release (mg kg^{-1}), t = time, a and b are estimated parameter values, b_1 is the slope of the first segment, node = the x value corresponding to the join point between the two straight-lines, and b_2 = slope of the second segment and c is the y intercept of the segmented straight-line equation.

Equation (3) is a more general form of the linear response plateau equation sometimes used to fit response and plateau responses of the type described by Anderson and Nelson (1975).

$$y = b_0 + b_1 * \min(\text{time}, \text{node}) \tag{4}$$

where b_0 is the y intercept, b_1 is the slope of the response below the join point (node) of the plateau.

All equations were rewritten or modified to reflect conditions of this study as follows: The parabolic diffusion equation was modified to reflect the initial condition as zero in the K release process, i.e. there was no K on the Ca-resin nor was there K uptake by the plants at time 0. This resulted in rewriting equation (1) as

$$y = bt^{1/2} \ (t \geq 0) \tag{5}$$

The power equation is sometimes written as

$$\ln(y) = b\ln(t) \tag{6}$$

We chose to rewrite it and fit it as

$$y = at^{b} \tag{7}$$

so that the residuals would not need the back transformation that would otherwise be required to compare the residual mean squares (RMS) of equation (6) fits with the other non-transformed equations. To also reflect the constraint that the equation should pass through the origin, the segmented straight-line equation was modified and fitted as

$$y = b_1 * \min(\text{node}, x) + b_2 * \max(\text{node}, x) - b_2 * \text{node} \tag{8}$$

where, the coefficients remain as defined earlier.

The revised models (5), (7), and (8) were fitted with the same statistical routine (SAS routine PROC NLIN, SAS Institute, 1985). This was necessary since the method of estimating the parameters and calculating the residual mean square and parameters may differ for routines designed for models that are linear rather than nonlinear in their parameters. The parabolic diffusion model (5) and the power function model (7) remain linear in the parameters, but were, nonetheless, fitted using the SAS routine for consistency. The residual mean square (RMS) resulting from fitting the equations, thus, could be used as one of several criteria to evaluate the fit of the equations for describing the release of K.

The coefficients of the fitted models can be used to interpret the release rates of $K_{non\text{-}ex}$. In the case of the segmented straight-line equation, the coefficients b_1 and b_2 quantify the slopes of the initial and subsequent straight-lines, representing fast and slow rates of release, respectively, of K to the Ca-resin.

2. Experiment 2 Estimating plant available non-exchangeable K release using K release equations.

2.1 Potassium exhaustion pot experiment

A pot experiment was carried out with the eight soils (Ps, Suk, Wn, Pc, Lb, Cd, Tk, and Ln soils) using a randomized complete block experimental design that consisted of a no-K fertilizer treatment and a 200 mg kg^{-1} treatment in four replications. Soils were air-dried and ground to pass a 6-mm sieve, and 10 kilograms of each soil were weighed into each pot. The ten maize seeds were placed about 2 cm below the soil surface and 5 d after emergence, each pot was thinned to 2 seedlings. Nitrogen fertilizer, at 100 mg N kg^{-1}, as ammonium nitrate, and 56 mg P kg^{-1} as $Ca(H_2PO_4)_2.2H_2O$ were applied to the soil at 10 d after emergence. All fertilizers were added in liquid form to facilitate distribution. The aboveground part of the maize plant was cut at the soil surface at tasselling stage (55 d after emergence) because more than 90% of the total K uptake is usually accumulated by that stage (Ritchie *et al.*, 1997). The maize tissue was dried at 70°C for 48 h, crushed and ground to pass a 0.5-mm sieve. A 0.5-g subsample was digested by a nitric-perchloric acid mixture at 180-200° C (Jones, 2001) and the K concentration determined. The roots of the maize plant were crushed and remixed with the soil. Soil samples were taken before and after cropping for NH_4OAc-extractable K determination (Helmke and Sparks, 1996). Up to four maize (*Zea mays* L.) crops were grown successively in each pot. The data of the K exhaustion experiment were used to quantify the release of non-exchangeable K from the soil to maize. The quantity of $K_{non\text{-}ex}$ released to the maize was calculated by the following K balance equation (Havlin and Westfall, 1985):

$$K_{non\text{-}ex} = K_{removed} - (K_{ex\ before} - K_{ex\ after}) \qquad (9)$$

where, $K_{non\text{-}ex}$ is the quantity of the K as released from the non-exchangeable pool to the plant (mg kg^{-1}), $K_{removed}$ is the cumulative K uptake by maize (mg kg^{-1}), and $K_{ex\ before}$ and $K_{ex\ after}$ are the NH_4OAc- K before and after each maize crop (mg kg^{-1}).

2.2 Statistical analyses

The cumulative K release resulting from the exhaustion cropping by maize was described by a segmented straight-line equation (8). The multiple regression analysis was used to relate the rapid and slow release rates of $K_{non\text{-}ex}$ with selected soil properties. The statistical analysis of all data was performed using SAS, version 5 (SAS, 1985).

3. Experiment 3 Estimating plant available non-exchangeable K using different extraction methods.

3.1 Soil K fractions determination

The methods for determination of soil K fractions before maize planting were 1 ***M*** NH_4OAc pH 7, Boiling 1 ***M*** HNO_3 (Helmke and Sparks, 1996), mixed acid in a 5:2 v/v ratio of 8 ***M*** HNO_3 and 10 ***M*** $HClO_4$ (soil: mixed acid ratio was 1:10) and successive Ca-resin extraction methods at 0-600 h (Havlin *et al.*, 1985). The K concentration was measured by an atomic absorption spectrophotometer.

3.2 Data analysis

The relationships between plant extracted K and extractable K in all soils were determined the accuracy of extraction method to extract plant available K_{non-ex}, was analyze using simple linear regression procedure in SAS program and a 1:1 line was used to determine the accuracy of extraction method in predicting total plant available K_{non-ex}. The statistical analysis of all data was performed using SAS, version 5 (SAS, 1985).

4. Experiment 4 Testing the prediction of K supplying power for maize growth in the field condition.

4.1 Field experiments

Two field experiments were conducted on the Lb and Pc soils (2005-2006). A commercial corn hybrid (CP.DK.888) was planted. The treatments were 0 and 125 kg K_2O ha^{-1}. The treatments were arranged in a randomized complete block design with four replications. The individual plot size was 6x5 meters, the plant spacing was 0.75x0.25 meter and each plot consisted of eight rows. The selected K fertilizer rates were band-applied and 43.75 kg P_2O_5 ha^{-1} as triple superphosphate were applied in Pc and Lb soils prior to planting. Urea, 40.63 kg N ha^{-1} and 56.25 kg N ha^{-1} for 1st and 2nd crop was placed at 0-20 cm depth prior to planting in Pc soil, and 25 kg N ha^{-1} and 40.63 kg N ha^{-1} for the 1st and 2nd crops in Lb soil. Fifteen days after planting, 40.63 and 56.25 kg N ha^{-1} were applied as a top dressing for all treatments for 1st and 2nd crop in Pc soil, 25 and 40.63 kg N ha^{-1} for the 1st and 2nd crops in Lb soil.

4.2 Soil and plant data collection

Soil samples were collected before maize planting and after harvest at 0-20 cm depth and exchangeable K was determined using ammonium acetate pH 7 (McLean and Watson, 1985). The K concentration was determined by AAS. Grain yield was harvested from six rows at maturity (120 d) and the yields were adjusted to 15% moisture. At harvest, the above ground part was collected from six rows in each plot to determine the dry matter yield, and subsamples were secured for total K content. Grain and stover were oven-dried at 70 ^{o}C for 48 h to determine dry weight and K content. The plant samples were analyzed using a concentrated nitric and perchloric acid mixture digestion (Jones, 2001).

4.3 Statistical analysis

The mean comparisons of grain yield, stover, and total K uptake were analyzed using the Duncan Multiple Range Test. The cumulative $K_{\text{non-ex}}$ release resulting from the exhaustion cropping by maize in both Pc and Lb field experiments was described by a segmented straight-line equation (8). The statistical analysis of all data was performed using SAS, version 5 (SAS, 1985).

RESULTS AND DISCUSSION

1. Experiment 1 A study of non-exchangeable K release equations in soil fractions using Ca-resin.

The release of K_{non-ex} in soil fractions probably regulated the availability of K to plant, which is usually influenced by the amounts and mineralogy of the clay and silt fractions (Jalali, 2005; Srinivasarao *et al*., 2006). The release of K_{non-ex} has been described by a linear regression of the parabolic diffusion and power function equations (Cox *et al*., 1996; Havlin and Westfall, 1985). These regression equations indicated a steady release rate of K_{non-ex}, whereas some research has indicated that the release of K_{non-ex} in soil was probably a complex reaction possibly resulting from two distinct processes (Mengel *et al*., 1998; Benipal *et al*. 2006), therefore, a segmented regression model was proposed to describe the complex reactions with different mechanisms found in soil (Anderson and Nelson, 1975; Shuai *et al*., 2003). Therefore, the linear and segmented equations were used to describe the release of K_{non-ex} in the studied soils.

A hypothesis of this study is that the difference of amount of plant available non-exchangeable K released to plants is controlled by the rate of K release which depends on the amount and type of clay minerals in each soil. The extraction methods and the various mathematical equations are thus important for precise determination and description of the release rate of K in soils that contain various clay minerals. The objectives of this study were (i) to describe the K release pattern in some representative maize soils and, (ii) to determine the amount and rate of non-exchangeable K release to plants so that predictions of plant K sufficiency can be more accurate.

The discussion of this study can be simplified by grouping the soils based on the mineralogy of the clay fraction (< 2mm) (Table 1).

Kaolinitic soils: This group consisted of Ps, Suk, Wn, and Pc soils. The dominant clay mineral of these soils was kaolinite with small amounts of vermiculite, illite, and quartz. A small amount of smectite was found in the Pc soil. Clay content and CEC ranged from 232 to 464 g kg^{-1} and 2.4 to 11.0 $cmol_c$ kg^{-1}, respectively (Table 1). The total K content in the clay fraction of these soils ranged from 210 to 1,591 mg kg^{-1}, it represented the higher content of the total K than the silt and sand fractions (Table 2).

Smectitic soils: This group consisted of Lop Buri (Lb), Chai Badan (Cd), Takhli (Tk), and Lam Narai (Ln) soils. Smectite was the dominant clay mineral of these soils. A small amount of vermiculite was found in the Lb soil. The Cd soil contained small amount of illite, kaolinite, and quartz. Clay content and CEC ranged from 380 - 802 g kg^{-1} and 29.2 - 57.2 $cmol_c$ kg^{-1}, respectively (Table 1). The total K in the clay fraction of these soils ranged from 211 to 1,269 mg kg^{-1}. The content of the total K in the clay fraction was smaller than the silt or sand fractions in the Lb, Cd, and Ln soils (Table 2).

Table 1 Soil taxonomy, selected chemical and physical properties, and mineralogy of the eight soils studied.

Soil series	Subgroup†	pH	Silt	Clay	CEC	NH_4OAc-K	HNO_3-K	HF-K	Mineralogy‡
			---(g kg^{-1})---		($cmol_c$ kg^{-1})	-----------------mg kg^{-1}---------------			
		Kaolinitic soils							
Phu Sana; Ps	Kanhaplic Haplustults	4.5	255	262	5.9	39	52	1,899	Ka, Ve, Il, Qu
Satuk; Suk	Typic Paleustults	4.6	49	232	3.1	34	57	862	Ka, Il, Qu
Warin; Wn	Typic Kandiustults	4.6	42	247	2.4	18	63	1,273	Ka, Il, Qu
Pak Chong; Pc	Rhodic Kandiustox	5.3	331	464	11.0	107	126	2,146	Ka, Sm, Il, Qu
		Smectitic soils							
Lop Buri; Lb	Typic Haplusterts	6.6	132	802	53.5	139	170	6,577	Sm, Ve
Chai Badan; Cd	Leptic Haplusterts	7.3	129	759	57.2	375	431	5,036	Sm, Il, Ka, Qu
Takhli; Tk	Entic Haplustolls	7.7	510	380	29.2	85	123	1,629	Sm
Lam Narai; Ln	Vertic Haplustolls	7.5	111	802	46.9	60	102	1,041	Sm, Ka

†Soil Survey Staff (1999)

‡ Ka = Kaolinite, Ve = Vermiculite, Il = Illite, Qu = Quartz, Sm = Smectite

Table 2 Total K (HF-K) in sand, silt, and clay fractions in eight soils.

Soils	Sand	Silt	Clay
	(mg K kg^{-1} soil)		
	Kaolinitic soils		
Ps	178	503	210
Suk	67	577	1,591
Wn	167	611	1,214
Pc	497	525	1,077
	Smectitic soils		
Lb	1,850	2,377	476
Cd	1,725	1,180	1,078
Tk	235	71	1,269
Ln	335	611	211

1.1 Release of Potassium in Soil Fractions to Ca-resin

The cumulative release of $K_{non\text{-}ex}$ from the clay-size fraction between 0 to 600 h was greater than that from the silt and sand fractions in all the soils. Ninety-six percent of the total K release was from the clay fraction and approximately 4% was from sand and silt fractions. Benipal *et al.* (2006) and Havlin and Westfall (1985) also showed that the cumulative K release from the clay fraction was larger than from silt and sand fractions. The results indicated that about 50% of the cumulative $K_{non\text{-}ex}$ released by all soils was released by the end of the initial reaction period (0-60 h) (Figure 2), which was consistent with the findings of Askegaard *et al.* (2005), which indicated that large amount of $K_{non\text{-}ex}$ was released during the initial time period of Ca-resin extraction. The total cumulative K release (sum of sand, silt, and clay fractions) from kaolinitic soils was lower than that from smectitic soils (Figure 2), ranging from 11 to 27 mg kg^{-1} in kaolinitic soils and 29 to 137 mg kg^{-1} in smectitic soils. The amount of cumulative K release in Pc and Cd soils was higher than from other soils in their respective groups. This was most probably the result of the large amount of K_{non-ex} pools as indicated by the content of boiling HNO_3-K in these soils (Table 1).

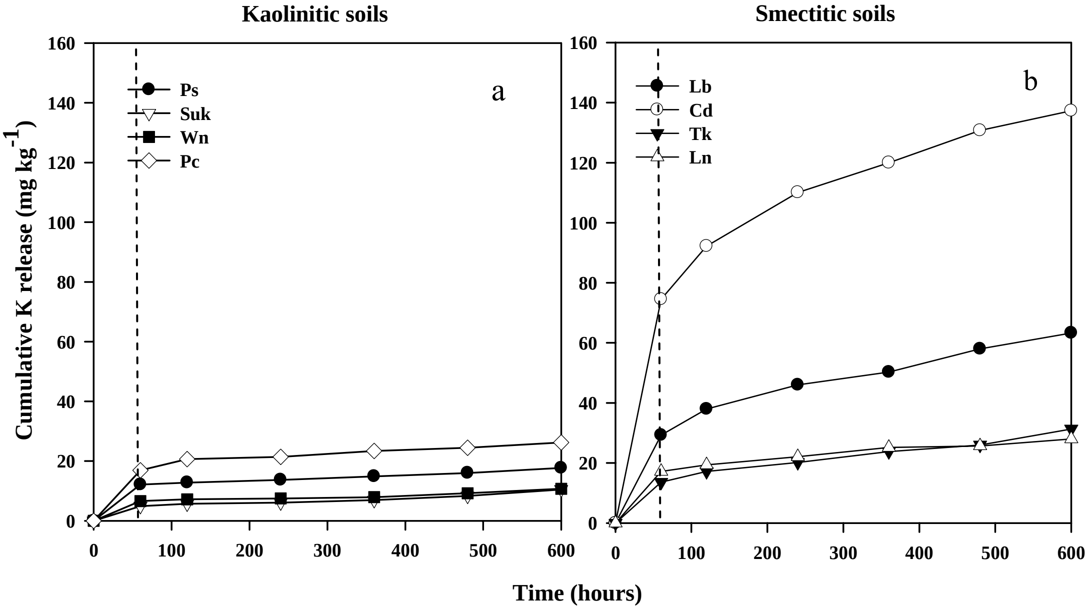
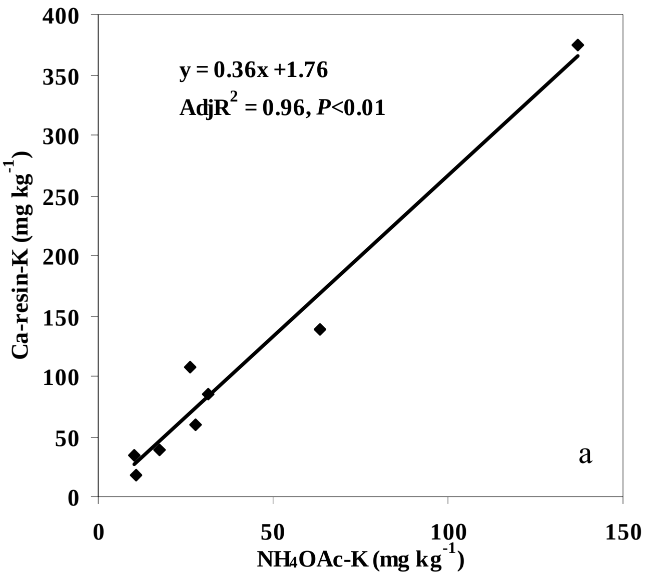


Figure 2 Cumulative non-exchangeable K release from soil fractions (sum of clay, silt, and sand fractions) of the eight soils to Ca-resin from 0 to 600 hours (approximately 25 days).

A close relationship was found between cumulative K release to Ca-resin in all soils and the amount of K extracted by NH_4OAc ($AdjR^2 = 0.96$; $P = 0.01$) and boiling HNO_3 ($AdjR^2 = 0.97$; $P = 0.01$) from the initial samples (Figure 3). Because the soils prepared for the Ca-resin extraction are expected to be Na-saturated given the high concentrations of Na from the dithionite and citrate treatments, these results suggest that the release of K from soil fractions to Ca-resin was regulated by the K_{non-ex} in both kaolinitic and smectitic soils. Wang *et al.* (2004) suggested that the release of K near the threshold of critical K would be controlled by the amount of K_{ex} and K_{non-ex} and indicated the ease of K release increased with a high content of exchangeable K in the soil. As indicated in equation (1), the plant removal of K was corrected for the changes in exchangeable K before and after each plant growth period, and reported as cumulative K_{non-ex} release.



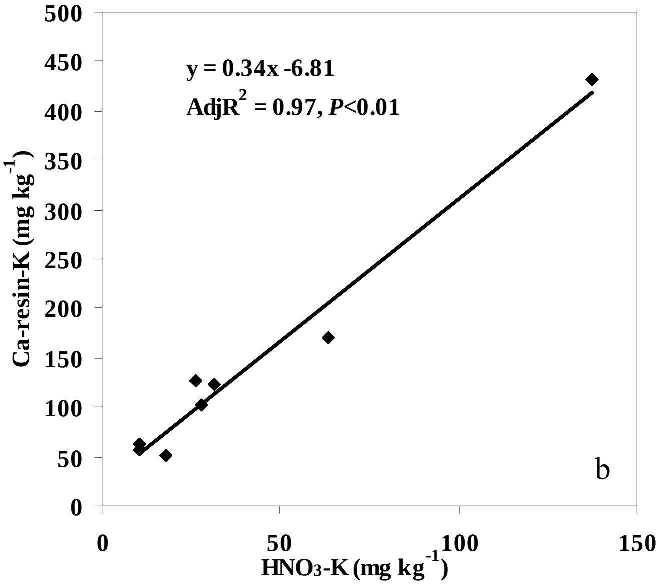


Figure 3 The linear regression between cumulative K release to Ca-resin in all soils and the amount of K extracted by NH_4OAc and boiling HNO_3 in initial soil samples.

1.2 Modeling Potassium Release from Soil Fractions to Ca-resin

The estimated parameters of the equations describing the rate of release of K from each of the experimental soils are shown in Table 3. The fitted coefficient b of the diffusion equation and coefficients *a* and *b* of the power function also appear to have little physical or chemical significance other than that of the statistical fit. The coefficients of the segmented straight-line, however, might be a quantification of the two phase release of K reported by Mengel *et al.* (1998) and Benipal *et al.* (2006). We suspect that the coefficients might be proportional to the K release that occurs to plants since the model seemed to fit both the release of K to Ca-resin and to plants of the K exhaustion studies. Our results show that the power function and segmented straight-line equations more reliably described the release of K in the soils studied than did the parabolic diffusion function. The better fit of the power function and segmented straight-line equations to the experimental data is indicated by the lower residual mean square (RMS) in Table 3. The segmented straight-line equation gave the lowest RMS among the equations, except for the Cd, and possibly the Ln soils. The inadequate description of K release by the power function probably was a result of the short time (0-600 h) of this laboratory study. Jalali (2005) and Havlin *et al.* (1985) represented that the power function equation adequately described for the release of K to Ca-resin between 0 to 7000 hours. It is unclear whether a segmented straight-line might assist in the interpretation of those data.

The reliability of the K release rate has been examined by considering its relationship with total plant K uptake and yields (Havlin *et al.*, 1985; Mengel and Uhlenbecker, 1993). In addition, the cumulative Ca-resin extracted K (at 600 h) by all equations and total plant K uptake were closely related as indicated by a linear regression (Table 4). This laboratory study indicated that the segmented straight-line equation generally provided the best fit equation describing the release of K and different patterns of K release in kaolinitic and smectitic soils. In addition, the equation provides estimates of a slow and fast release rate as postulated by others.

Table 3 The release of K in eight soils to Ca-resin as fitted by the parabolic diffusion, power function and the segmented straight-line equations and residual mean square (RMS).

Soils	Parabolic diffusion ($y = bt^{1/2}$)		Power function ($y = at^{b}$)			Segmented straight-line ($y = b_1$*min(node, x) + b_2*max(node, x) $-b_2$*node)			
	b	RMS	a	b	RMS	node	b_1	b_2	RMS
Kaolinitic soils									
Ps	0.81	9.70	5.84	0.16	0.49	60.0	0.200	0.010	0.037
Suk	0.41	0.99	1.05	0.34	0.87	60.0	0.078	0.009	0.270
Wn	0.46	2.61	2.67	0.20	0.57	60.0	0.107	0.007	0.160
Pc	1.24	22.2	8.63	0.17	0.59	74.0	0.282	0.012	0.097
Smectitic soils									
Lb	2.76	27.1	7.77	0.32	2.04	74.1	0.489	0.052	0.711
Cd	6.34	28.3	26.4	0.26	1.68	74.7	1.240	0.092	9.600
Tk	1.29	4.62	2.96	0.36	1.83	68.1	0.226	0.028	0.500
Ln	1.30	17.2	7.01	0.21	0.32	68.2	0.286	0.017	0.440

Table 4 Linear regression between cumulative non-exchangeable K release at 220 days in the pot experiment of eight soils (x) and predicted Ca-resin extractable K (y) at 600 h by the parabolic diffusion, power function, and segmented straight-line equations.

	Parabolic diffusion ($y = bt^{1/2}$)	Power function ($y = at^{b}$)	Segmented straight-line ($y=b_1*\min(time,a)+b_2*\max(a, time) - a*b_2$)
Linear regression	y = 56.0+3.42x	y = 77.6+2.51x	y = 61.43+3.48x
AdjR^2	0.950**	0.944**	0.959**
RMS	1,253	1,474	1,056

** Significant at P=0.01

1.3 Summary

The segmented straight line equation was the appropriate equation for describing the release of K from soil fractions (sand, silt, and clay) to Ca-resin, and it represented that the two fractions of $K_{\text{non-ex}}$ were released at distinctly different rates, as rapid and slow release rates.

2. Experiment 2 Estimating plant available non-exchangeable K release using different K release equations.

Availability of K_{non-ex} to maize was determined using successive crops of maize grown in a pot experiment. The release of plant available K_{non-ex} was described using a segmented straight-line equation which was the result from experiment 1. This experiment was conducted to determine amount of plant available K_{non-ex} and to estimate the release rate of plant available K_{non-ex} in studied soils using the segmented straight-line equation. The release rate of plant available K_{non-ex} as obtained from segmented regression equation was related to selected soil properties in order to predict the effect of soil properties on the release of plant available K_{non-ex}.

2.1 Non-exchangeable Potassium Release from Soil to Maize

The data of the K exhaustion experiment was used to quantify the release of K_{non-ex} from soil to maize. The result indicated that > 40% of the total plant available K was released from the K_{non-ex} pool. The quantity of K_{non-ex} released to the maize was calculated by the K balance equation (Eq. 9).

The K_{ex} after planting and K removed in each crop declined when the number of crops increased in all soils (Table 5). The kaolinitic soils showed classic K deficiency symptoms beginning with the 2nd crop (Ps, Wn, and Suk soils) and 3rd crop (Pc soil), while smectitic soils only showed deficiency symptoms beginning with the 4th crop (Lb, Cd, Tk, and Ln soils). The amount of cumulative K_{non-ex} release (sum of first crop to final crop) in kaolinitic soil (48 to 91 mg kg^{-1}) was much less than that from smectitic soils (163 to 225 mg kg^{-1}). The cumulative K_{non-ex} release of Pc and Cd soils was higher than that of other kaolinitic and smectitic soils, respectively. These results were consistent with the laboratory experiment, in addition, nearly same amount of cumulative K_{non-ex} release was found in Lb, Tk, and Ln soils. The Ln and Lb soils contained high clay content, while low clay and high silt contents were found in Tk soil (Table 1). Therefore, the K_{non-ex} of the Tk soil appears to be released from the weathering of mica in the silt fractions. Benipal *et al*., (2006), Sadusky *et al*., (1987), Schindler, (2005) showed that plant available K was readily released from silt fractions, which probably occurred because of its high mica concentration. The cumulative K_{non-ex} released from soil to plant and K released from soil to Ca-resin could be predicted for all soils using the following regression equation: ($y = 74.82 + 1.235x$; $AdjR^2 = 0.661^{**}$, where x and y are the cumulative K release from soil to Ca-resin and the K_{non-ex} release to maize, respectively). The results indicated that the successive Ca^{2+}-resin extraction method appears to be an accurate method to determine the K_{non-ex} release in the soil

2.2 Estimating Rate of Non-exchangeable Potassium Release to Maize by the Segmented Regression Model

The result of the study on the release of K from soil fractions to Ca^{2+}-resin indicated that the segmented straight-line equation provided a good fit to the data. This equation provided coefficients that were meaningful in describing the patterns of K release and for estimating the rate and cumulative K_{non-ex} release in both kaolinitic and smectitic soils. The amounts of K_{non-ex} released to the plant in each crop (mg kg^{-1}) as calculated by the equation (9) (Table 5) and the time (day) were fitted by the segmented straight-line equation (Figure 4), while the amount of K_{non-ex} released after the occurrence of K deficiency symptoms was assumed to indicate zero additional plant available K_{non-ex}.

Table 5 The amount of plant K uptake, NH_4OAc-K after cropping, and non-exchangeable K released to maize in each crop of the eight soils.

Soil series	Number of crops	Plant K uptake				Exchangeable K (NH_4OAc-K)				Non-exchangeable K released to maize[†]			
		Crop1	Crop2	Crop3	Crop4	Crop1	Crop2	Crop3	Crop4	Crop1	Crop2	Crop3	Crop4
		(mg kg^{-1})											
		Kaolinitic soils											
Ps	2	54±11[††]	27±3	-	-	21±3	20±1	-	-	36±20	26±8	-	-
Suk	2	45±10	23±5	-	-	14±2	14±2	-	-	25±10	23±7	-	-
Wn	2	48±20	30±14	-	-	17±2	16±2	-	-	47±21	29±14	-	-
Pc	3	101±26	43±17	22±2	-	43±11	34±4	32±4	-	37±31	34±4	20±2	-
		Smectitic soils											
Lb	4	125±13	78±11	34±28	21±12	102±7	60±7	53±3	52±3	88±26	36±8	27±22	20±11
Cd	4	237±41	182±30	89±31	55±10	247±32	124±5	64±6	37±4	109±60	59±48	29±34	28±18
Tk	4	89±15	71±18	36±5	18±4	90±11	54±5	38±3	35±5	94±24	35±13	20±4	15±7
Ln	4	102±8	44±8	32±9	23±9	47±3	47±4	31±2	22±5	89±9	44±7	16±6	14±13

[†] Calculated using equation 9; $K_{non\text{-}ex} = K_{removed} - (K_{ex\ before} - K_{ex\ after})$

[††] Standard deviation

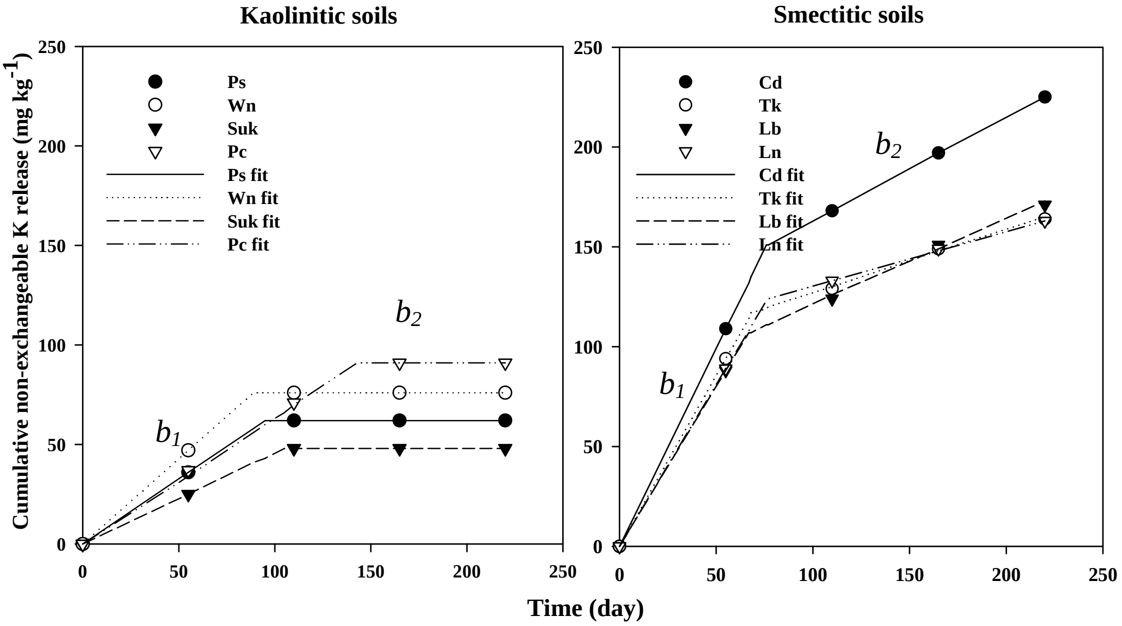


Figure 4 Cumulative non-exchangeable K release from the eight soils to maize plants at 0 to 220 days as fitted by segment straight-line equation.

The segmented straight-line equation fit to $K_{\text{non-ex}}$ release from kaolinitic soils fit better than the same equation fit to data from smectitic soils as indicated by the RMS in Table 5. This equation provides two straight-lines which showed different slopes (b_1 and b_2), and were connected by join point (a) which indicated a cut-off time (a time which the rate of $K_{\text{non-ex}}$ release changed substantially). The first straight-line appears to represent the cumulative $K_{\text{non-ex}}$ and the rapid release rate of $K_{\text{non-ex}}$ (b_1) during the first time period (initial time to cut-off time), and the second line presented the cumulative $K_{\text{non-ex}}$ and the slow release rate of $K_{\text{non-ex}}$ (b_2) during the final time period (after cut-off time to final time). The results of this study are consistent with the findings by Dhillon and Dhillon (1990), Benipal *et al.*, (2006), and Jalali (2005), which suggested that the study of K release by successive extraction methods indicated two fractions of K, which were rapidly and slowly released at the initial and final time periods of the reaction, respectively. The results of these studies showed that the cut-off time of $K_{\text{non-ex}}$ in the kaolinitic soils occurred much later than in smectitic soils. Both the rapid and slow release rates of $K_{\text{non-ex}}$ in smectitic soils were higher than those in kaolinitic soils. The rapid (b_1) and slow (b_2) K release rates of plant available $K_{non\text{-}ex}$ range from 0.45 to 0.85 and 0 mg kg^{-1} day^{-1} in kaolinitic soils, and 1.60 to 1.98 and 0.27 to 0.52 mg kg^{-1} day^{-1} in smectitic soils, respectively (Table 6). The release of $K_{non\text{-}ex}$ in this study probably was a result of the equilibration between the interlattice K and the soil solution, which was caused by the continuing release of interlattice K to solutions in which the K concentration was kept at a low level (Hanway and Scott, 1957).

Table 6 Parameter estimates and residual mean squares of the segmented straight-line equations fitted to the release of K to maize in eight soils.

Soil series	Segmented straight-line equation ($y = b_1\text{median}(A_L, t, a_1) + b_2\text{median}(A_R, t, a_1) - c$)				
	a_1, transition fast to slow	*b_1, slope- fast*	*b_2, slope - slow*	*c, (y intercept)*	RMS
	Days		mg kg^{-1} d^{-1}		
	Kaolinitic soils				
Ps	94.70	0.65	0.00	0.00	0.00
Suk	105.60	0.45	0.00	0.00	0.00
Wn	88.93	0.85	0.00	0.00	0.00
Pc	143.3	0.65	0.00	-1.5	13.5
	Smectitic soils				
Lb	66.65	1.60	0.43	-28.48	8.17
Cd	75.95	1.98	0.52	-39.36	0.17
Tk	68.18	1.71	0.32	-21.69	4.17
Ln	76.80	1.62	0.27	-20.95	0.67

Non-exchangeable K release in kaolinitic soils The rapid release (b_1) of $K_{non\text{-}ex}$ in kaolinitic soils may have been the release of some K from trace amounts of illite or vermiculite in the clay fractions (Cox *et al*., 1999). The slow release (b_2) of $K_{non\text{-}ex}$ in kaolinitic soils was zero (Table 6), which was expected because these soils are highly weathered and contain no primary minerals such as feldspars.

Non-exchangeable K release in smectitic soils In the smectitic soils, the rapid release (*b_1*) of $K_{\text{non-ex}}$ may have been the release of K from the illite or vermiculite in the clay fractions. The slow release rate in the smectitic soils appears to have been the result of release from clay fraction K and that resulting from K release from K-feldspar weathering in sand and silt fractions (Simard *et al.*, 1992 and Sadusky *et al.*, 1987), both of which were absent in the kaolinitic soils. The marked differences in slow K release rate in smectitic soils (Cd and Lb soils, for example) probably occur because of the distribution of total K in these two soils. The Lb soil, for example, contained most K in the silt fraction (50.6% of the total K in the silt fraction) while the Cd soil contained 29.6% of its K in this fraction. The higher release in the Cd soil in slow release (b_2) portion of the curve probably resulted from the high K content in the clay fraction (27%), while the Lb soil contained only 10.1% of its K in the clay fraction (Table 2).

The relationship between the slow and rapid release rates of K with selected soil properties and total plant K removed is presented in Table 7. The results indicated that increasing CEC and clay content increased the release rates of $K_{\text{non-ex}}$ in all soils. The quantities of NH_4OAc-K and HNO_3-K tended to indicate the difference between the slow (b_2) and rapid (b_1) release rates in all soils. In addition, the quantity of HF-K was highly significantly correlated with the b_2 release rate of $K_{\text{non-ex}}$. This result suggested that the slow release rate is probably regulated by the quantity of mineral K in the soil. The highly significant correlation between the rates of K release and total plant K removed provided evidence that the segmented straight-line equation adequately described the release of $K_{\text{non-ex}}$ in the selected soils.

Table 7 Correlation coefficient (*r*) of the relationship between some soil properties, total plant K removed in eight soils, and the rates of non exchangeable K release (b_1 and b_2) as fitted by segmented straight-line equation.

	Segmented straight-line equation (y = $b_1$median(A_L, t,a_1) + $b_2$median(A_R,t,a_1)-c)	
	(b_1)	(b_2)
Silt (g kg^{-1})	0.154	0.068
Clay (g kg^{-1})	0.775*	0.812*
CEC ($cmol_c$ kg^{-1})	0.919**	0.957**
NH_4OAc-K (mg kg^{-1})	0.650	0.754*
HNO_3-K (mg kg^{-1})	0.693	0.778*
HF (mg kg^{-1})	0.542	0.722*
Total plant K removed (mg kg^{-1})	0.799*	0.861**

* Significant at P=0.05

** Significant at P=0.01

Multiple regression analysis was used to relate the rapid (b_1) and slow (b_2) release rates of $K_{non\text{-}ex}$ with selected soil properties and the result provided following equations;

$$b_1 = 0.380 + 0.023CEC + 0.00008NH_4OAc\text{-}K \quad AdjR^2 = 0.834^{**} \qquad (10)$$

$$b_2 = -0.045 + 0.008CEC + 0.0003\ NH_4OAc\text{-}K \quad AdjR^2 = 0.925^{**} \qquad (11)$$

The rapid and slow release rates of $K_{non\text{-}ex}$ in these soils (mg $kg^{-1}d^{-1}$) indicate the critical release rates in the kaolinitic (b_1) and smectitic soils (b_2), eqs. (10) and (11). Interestingly K deficiency symptom occurred when the release rate of $K_{non\text{-}ex}$ was low in these soils. The occurrence of K deficiency symptoms was found in the 2nd and 3rd crops for the Ps, Wn, Suk, and Pc soils when the release rate of $K_{non\text{-}ex}$ less than 0.65, 0.45, 0.85, and 0.65 mg $kg^{-1}d^{-1}$ (b_1 in kaolinitic soils), respectively, and less than 0.43, 0.52, 0.32, 0.27 mg $kg^{-1}d^{-1}$ (b_1 in smectitic soils) in Lb, Cd, Tk, Ln soils, respectively. Thus it seems that in greenhouse conditions, that K deficiency symptom occurred in maize when K_{non-ex} release rates were less than about 1.00 mg $kg^{-1}d^{-1}$. The critical release rates were predicted by the equations (10) and (11), respectively. The results suggested that the release of K_{non-ex} from the soil was accompanied by the uptake of K by the plant. When taken over a long time period, the decreasing K_{non-ex} release rate may result in insufficient K for optimum yield. Therefore, there may be a critical release rate for K_{non-ex} to effectively be considered as a replacement for K fertilizer. Most probably fertilizer K will be needed for plant production when the release rate of K_{non-ex} in the soil is less than such a critical release rate of K_{non-ex}. A proposed research objective thus would be to estimate such a critical release rate of K_{non-ex}.

2.3 Summary

The slow and rapid release rates of K_{non-ex} in kaolinitic and smectitic soils appear to be released from the different pools in each soil. In kaolinitic soils, the rapid release rate probably was the release of some K from illite or vermiculite in the clay fractions, and the slow release rate was expected because the kaolinitic soils are highly weathered and contain no primary minerals such as K feldspars. The rapid release rate of K_{non-ex} in smectitic soils may have been the release of K from the illite or vermiculite in the clay fractions, and the slow release rate probably was a result of K release from clay fraction and K-feldspar weathering in sand and silt fractions. The rapid and slow release rates of K_{non-ex} in both kaolinitic and smectitic soils were affected by the clay content and CEC, and the release rates were predicted by the initial NH_4OAc-K and CEC in these soils.

3. Experiment 3 Estimating plant available non-exchangeable K using different extraction methods.

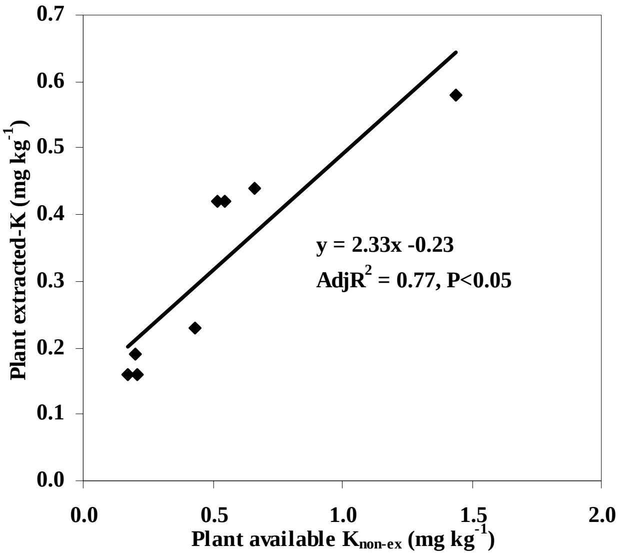
The amount of plant available K in maize soil was determined using successive crops of maize together with measurements of K_{ex} and $K_{non\text{-}ex}$ forms. In Thailand, plant available K is determined using 1 ***M*** NH_4OAc, which extracts only exchangeable K (Cox *et al*., 1999). Consequently, the NH_4OAc-K will probably not be adequate to determine the availability of $K_{non\text{-}ex}$ in smectitic soils. Therefore, an alternative chemical extraction method is needed for estimating plant available K from K_{ex} and $K_{non\text{-}ex}$ forms.

3.1 Plant extracted K and non-exchangeable available K

Potassium deficiency symptoms began appearing in the 2nd 3rd or 4th crops in the control treatment, and in the 3rd or 4th crops where K had been applied (Table 5). The kaolinitic soils showed classic K deficiency symptoms beginning with the 2nd crop (Ps, Wn, and Suk soils) or the 3rd crop (Pc soil), while smectitic soils only showed deficiency symptoms beginning with the 4th crop (Lb, Cd, Tk, and Ln soils). The cumulative dry matter of the control was less than the dry matter yield where K had been applied in all soils. The plant extracted K in kaolinitic soils ranged from 0.17 to 0.43 $cmol_c$ K kg^{-1} in control soils and 0.54 to 0.93 $cmol_c$ K kg^{-1} in K added soils, and smectitic soils ranged from 0.52 to 1.44 $cmol_c$ K kg^{-1} in control soils and 0.88 to 1.92 $cmol_c$ K kg^{-1} in K added soils. The plant extracted K in kaolinitic soils was much less than that extracted from smectitic soils in the control treatment. The plant extracted K in the Cd soil was highest of all soils, which was probably the result of the large content of both K_{ex} and $K_{non\text{-}ex}$ in this soil (Table 1). Güzel *et al.* (2001) indicated that high levels of K_{ex} were usually correlated with a large content of $K_{non\text{-}ex}$ in soil, which is evidence that $K_{non\text{-}ex}$ tends to supply or sustain levels of K_{ex}. Plant extracted available $K_{non\text{-}ex}$ was estimated as total plant K minus initial exchangeable minus final exchangeable and represents the contribution from $K_{non\text{-}ex}$ pools by the following K balance equation (9) (Havlin and Westfall, 1985; Havlin *et al*., 1985).

The cumulative $K_{non\text{-}ex}$ release in kaolinitic soils ranged from 0.16 to 0.23 $cmol_c$ K kg^{-1} (approximately 55-97% of the plant extracted K) in the control soil, and ranged from 0.05 to 0.47 $cmol_c$ K kg^{-1} (approximately 11-51% of the plant extractd K in the K fertilizer soil (Table 8). The cumulative $K_{non\text{-}ex}$ release in kaolinitic soils was lower than smectitic soils, which ranged from 0.42 to 0.58 $cmol_c$ K kg^{-1} (approximately 40-81% of the plant extracted K) in the control soil, and ranged from 0.31 to 0.79 $cmol_c$ K kg^{-1} (35-68% of the plant extracted K) in the K added soil.

The amount of $K_{non\text{-}ex}$ released to plants extract K in kaolinitic soils was smaller than smectitic soils. The consistent result was found in the successive Ca-resin extraction study, which showed the larger amount of $K_{non\text{-}ex}$ was released to Ca-resin from smectitic soils than from kaolinitic soils. The percentage of $K_{non\text{-}ex}$ released to plants from the control soil was higher than K added soil in both kaolinitic and smectitic soils, it indicated that most of the plant extracted K resulted from the release of the $K_{non\text{-}ex}$ pool. The contribution of $K_{non\text{-}ex}$ to total plant extracted K in the selected soils has been attributed to K release from illite or vermiculite in the clay fractions (Cox *et al.,* 1999; Nilawonk *et al.* 2008), and the silt or sand fraction, probably because of its high mica concentration (Sadusky *et al*., 1987; and Schindler 2002). The correlation between plant extracted K, plant available $K_{non\text{-}ex}$, and initial clay content of these soils was found. The total plant extracted K was positively correlated with the clay content ($AdjR^2$= 0.43, $P< 0.05$) and plant available $K_{non\text{-}ex}$ ($AdjR^2 = 0.77$, $P<0.05$) in the control treatment of the eight studied soils (Figure 5). The results indicated that increasing soil clay was associated with higher contents of total plant extractable K, which was derived largely from the $K_{non\text{-}ex}$ form in these soils. This result is consistent with that of Cox *et al*. (1999). The clay minerals illite and vermiculite were the major sources of plant available $K_{non\text{-}ex}$ in the soils (Güzel *et al*., 2001; Surapaneni *et a*l., 2002).



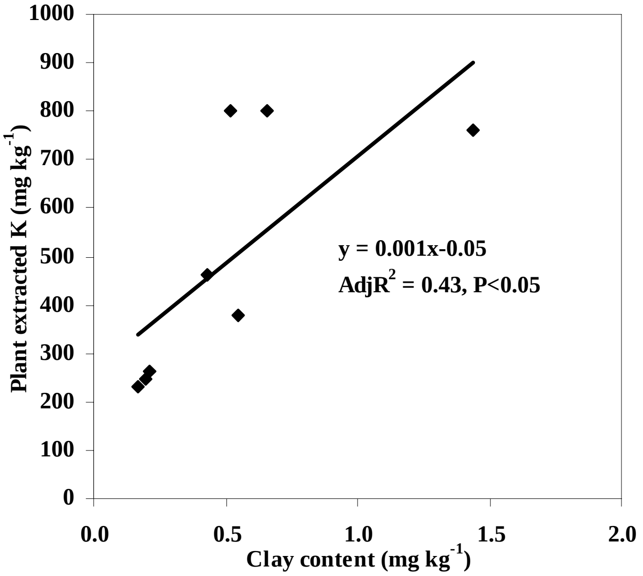


Figure 5 The relationship between the plant extracted K and plant available K$_{non\text{-}ex}$ (a) and clay content (b) in control treatment of eight studied soils.

3.2 The relationship between plant available K and soil K extraction methods

The fractions of soil K that were extracted using NH_4OAc, HNO_3, Mixed-acid, and Ca-resin extraction methods are presented in Table 9. The average quantity of soil K fractions in control soils was in the following increasing order NH_4OAc < Ca-resin < HNO_3 < Mixed-acid extractable K, these extraction methods extracted approximately 46%, 47%, 70%, and 99% of total plant extracted K, respectively (calculated from total plant extracted K in Table 8 and soil K fractions as extracted by different extraction methods in the Table 9). The NH_4OAc-K was approximately 66% of the HNO_3-K, this result was similar to the study of Dhaliwal *et al.* (2006). Cox *et al.* (1996) also indicated that large amounts of K^+ were released by HNO_3 in highly fixing soils where K^+ was held strongly. All K fractions were related to plant extracted K in all soils and were described by linear regression equations (Table 10). The linear relationship between extractable K and total plant extracted K indicated that mixed acid and Ca-resin extracted K were more highly correlated with total plant available K than other methods in kaolinitic and smectitic soils, respectively. However, the correlation between extractable K using different extraction methods and total plant available K did not significantly vary in all soils. The coefficient of determination ($AdjR^2$ ranged from 0.89 to 0.96 in kaolinitic soils and 0.82 to 0.97 in smectitic soils) and Mean Square Error (MSE ranged from 0.003 to 0.007 in kaolinitic soils and 0.007 to 0.040 in smectitic soils) were very similar. The plant available K_{non-ex} was significantly related to all K fractions, which were extracted by different extraction methods (Table 11). This result suggested that all of extraction methods were related to the plant availability of K_{non-ex} in these studied soils.

Table 8 Cumulative dry matter yield and plant-extracted K during exhaustive maize cropping in the greenhouse. Cropping continued until K deficiency symptoms occurred.

Soil series	Addition K (mg K kg^{-1})	Number of crop cycles	Cumulative dry matter (g kg soil^{-1})	Plant extracted K[§]	Non-exchangeable available K[‡]
				(cmol$_c$ K kg^{-1})	
	Kaolinitic soils				
Ps	0	2	12.1±1[††]	0.21±0.01[††]	0.16±0.02[††](77)[†]
	200	3	22.5±2	0.61±0.02	0.12±0.01 (19)
Suk	0	2	12.5±1	0.17±0.01	0.16±0.02 (71)
	200	3	18.9±1	0.54±0.01	0.05±0.01 (11)
Wn	0	2	10.1±1	0.20±0.01	0.19±0.01 (97)
	200	3	18.7±2	0.57±0.02	0.09±0.03 (17)
Pc	0	3	19.5±2	0.43±0.05	0.23±0.05 (55)
	200	4	30.5±1	0.93±0.03	0.47±0.02 (51)
	Smectitic soils				
Lb	0	4	28.8±1	0.66±0.01	0.44±0.04 (66)
	200	4	37.2±3	1.16±0.18	0.79±0.18 (68)
Cd	0	4	35.4±3	1.44±0.08	0.58±0.13 (40)
	200	4	39.1±4	1.92±0.17	0.68±0.18 (35)
Tk	0	4	23.8±1	0.55±0.06	0.42±0.07 (77)
	200	4	28.3±2	0.88±0.03	0.31±0.06 (35)
Ln	0	4	27.1±3	0.52±0.12	0.42±0.12 (81)
	200	4	29.1±4	1.06±0.05	0.65±0.12 (61)

[§] The plant extracted K refers to the total plant K removed by successive maize crops.

[‡] Plant extracted K – (initial NH_4OAc K – final NH_4OAc K).

[†] Numbers in parentheses indicate percentage of plant extracted K in non-exchangeable K form [(non-exchangeable available/plant extracted) *100] [††] Standard deviation

The NH_4OAc extracted K was highly correlated with the total plant available K, which was released from exchangeable and non-exchangeable pools. This results appears to be consistent with the successive Ca-resin extraction in experiment 1, which showed that NH_4OAc-K was sufficient to determine plant available K in kaolinitic soils, and a successive Ca-resin extraction characterization plus NH_4OAc-K was required to determine plant available K in smectitic soils. The NH_4OAc extraction method only extracted K_{ex}, which was approximately 46% of the total plant available K in these soils. Therefore, the NH_4OAc extraction method can not estimate the K supplying power of all of these soils, which included the smectitic soils K that released K from the non-exchangeable pools. Consequently, the HNO_3, mixed-acid, and Ca-resin extraction methods were used to determine the plant available K, which consisted of K_{ex} and $K_{non\text{-}ex}$.

Table 9 **Soil K fractions before successive crops of maize in the eight selected soils.**

Soil series	NH_4OAc-K[#]	HNO_3-K[##]	Mixed acid-K[§]	Ca-resin[¶]
	cmol$_c$ kg^{-1}			
Kaolinitic soils				
Ps	0.10	0.13	0.17	0.15
Suk	0.09	0.15	0.22	0.12
Wn	0.05	0.16	0.19	0.08
Pc	0.27	0.32	0.51	0.34
Smectitic soils				
Lb	0.36	0.44	0.80	0.52
Cd	0.96	1.11	1.31	1.31
Tk	0.22	0.32	0.59	0.30
Ln	0.15	0.26	0.25	0.20

[#] Ammonium acetate pH 7

[##] Boiling 1***M*** HNO_3

[§] Extracted by Mixed acid (8 ***M*** HNO_3+10 ***M*** $HClO_4$)

[¶] Ca-resin extraction**.**

The 1:1 line relationship provides a more precise indication than correlation analysis of the relationship between the K extraction method and total plant extracted K (Figure 6). The result indicated that the mixed acid and Ca-resin extractable K approximated the total plant extracted K in all soils of this study. Sherrod *et al.* (2002) reported that resin was the most appropriate extraction method for the study of plant-available nutrients, a result consistent with the conclusions of Sadusky *et al.* (1987). They suggested that Ca-resin was a suitable method to determine K release that occurred from the sand fractions that was plant available.

Table 10 Simple linear regression equations describing the relationship of plant extracted K and extractable K using different extraction methods.

Extraction methods	Linear regression equations	AdjR$^{2\ \#¶}$	MSE§	N
Kaolinitic soils				
NH_4OAc	y = 0.12+0.87x	0.90	0.006	8
HNO_3	y = 0.07+0.87x	0.89	0.007	8
Mixed-acid	y = 0.02+0.83x	0.96	0.003	8
Ca-resin	y = 0.09+0.87x	0.93	0.005	8
Smectitic soils				
NH_4OAc	y = 0.29+1.08x	0.95	0.011	8
HNO_3	y = 0.20+1.04x	0.96	0.009	8
Mixed-acid	y = 0.13+0.89x	0.82	0.040	8
Ca-resin	y = 0.27+0.89x	0.97	0.007	8

[#] Adj.R^2 of all linear regression equations was significant at the 0.01 probability level.

[§] MSE = Mean Square Error

[¶] 8 ***M*** HNO_3+10 ***M*** $HClO_4$

Table 11 Correlation coefficients (*r*) between the plant extracted $K_{non\text{-}ex}$ and K fractions which was extracted using different extraction methods in studied soils.

	Available $K_{non\text{-}ex}$ ‡	NH_4OAc-K	HNO_3-K	Mixed acid-K	Ca-resin-K
Available $K_{non\text{-}ex}$ ‡	1.000	0.581*	0.603*	0.665**	0.626**
NH_4OAc-K		1.000	0.997**	0.965**	0.988**
HNO_3-K			1.000	0.966**	0.991**
Mixed acid-K¶				1.000	0.974**
Ca-resin-K					1.000

¶8 ***M*** HNO_3+10 ***M*** $HClO_4$

§ The plant extracted K refers to the total plant K removed by successive maize crop.

‡ Plant extracted K – (initial NH_4OAc K – final NH_4OAc)

*, ** Significant at ***P***<0.05, 0.01

3.3 Summary

The mixed-acid and Ca-resin extraction methods were the best methods for direct estimating K supplying power of kaolinitic and smectitic soils, respectively. The plant available K consisted of both exchangeable and non-exchangeable pools in both kaolinitic and smectitic soils. Because of the short time and the simplicity of the mixed-acid procedure it was used to determine the release of $K_{non\text{-}ex}$ in field experiment.

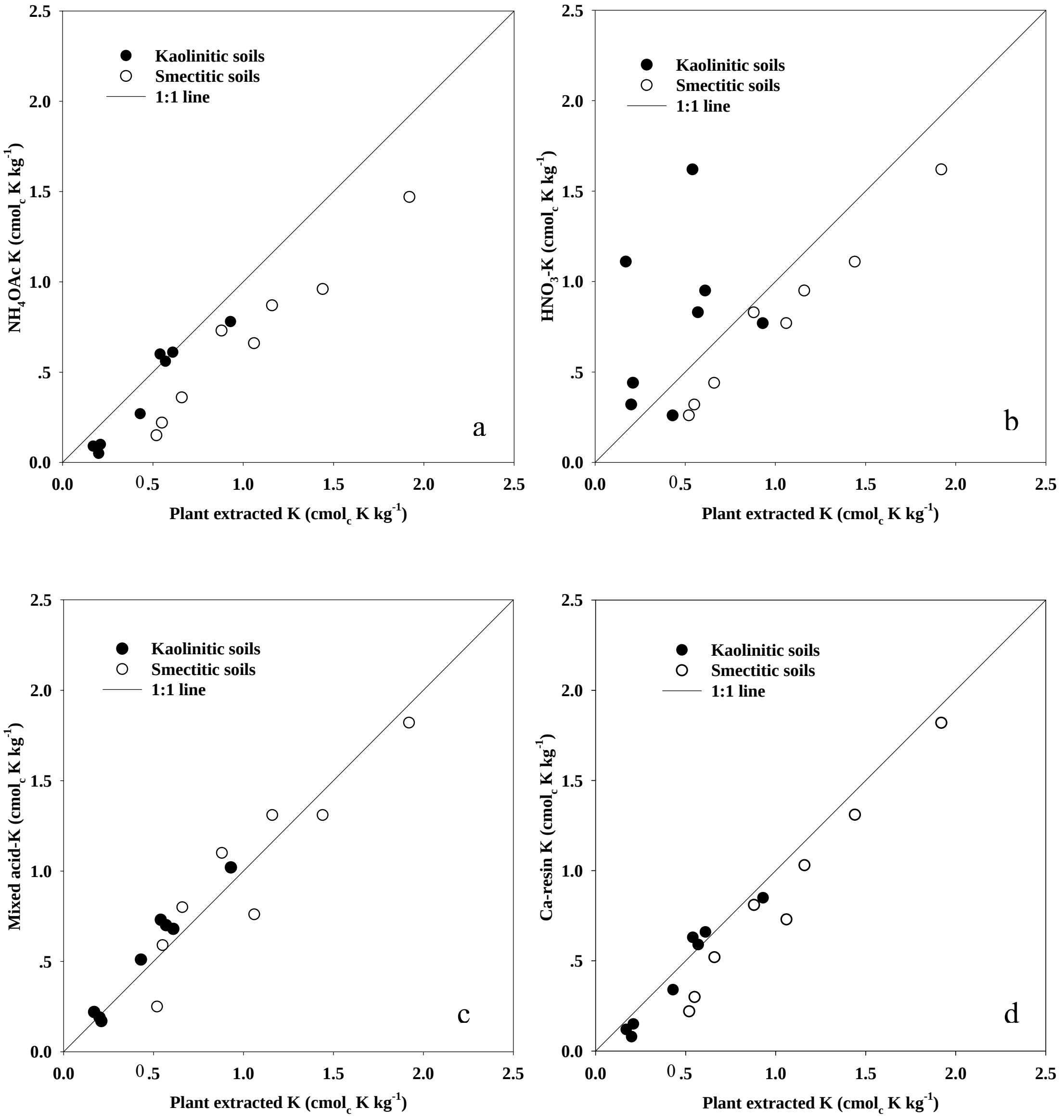


Figure 6 Relationships between plant extracted K and initial extractable K using different extraction methods in all soils.

4. Experiment 4 Testing the prediction of K supplying power for maize growth in field conditions.

The objective of this experiment was to estimate the K supplying power of Pc and Lb soils under field conditions. The segmented straight-line equation was a suitable equation to describe and estimate the release rate of non-exchangeable K as a result of experiment 2. Therefore, the cumulative $K_{non\text{-}ex}$ release in field experiment of Pc and Lb soils was fitted using this equation. The changes of $K_{non\text{-}ex}$ by each crop was estimated using the mixed acid extraction method which was one of the best extraction methods to determine $K_{non\text{-}ex}$ in Pc and Lb soils as a result of experiment 3.

4.1 Change in exchangeable (NH_4OAc-K) and non-exchangeable K (mixed-acid-K) during the growth of maize in the Pc and Lb soils

The amount of K_{ex} in Pc soil (Figure 7a) after each crop in the control was lower than in the added K treatment, which may be a result of the residual of K fertilizer in the soil. The amount of K_{ex} in Lb soil before the 1st crop was 125 mg kg^{-1} decreasing to 92, 80 and 72 mg kg^{-1} after each crop in the control soils, while the significant variation of K_{ex} among 1st to 3rdcrop in the added K application treatment was found. The K_{ex} of added K fertilizer treatment decreased to 130 mg kg^{-1} after 1st and increased to 157 and 292 mg kg^{-1} after 2nd and 3rd crop. The decrease of K_{ex} after the 1st 2nd and 3rd crop in the control soil both in Pc and Lb soils was a result of maize K uptake. Whereas, the large amount of residue K_{ex} after 2nd and 3rd crops in added K fertilizer treatment Lb soil was found (Figure 7a). This is probably a result of residue of K fertilizer and $K_{non\text{-}ex}$ in the clay fraction which could not be taken up by maize because the effect of dry season crop that may have caused a rapid rate of $K_{non\text{-}ex}$ in 2nd and 3rd crop in Lb soils. Attoe (1946) found that fixation of the added K from fertilizer occurred when the soils were dried. The fixation percentage ranged from 11 to 52% of the total added K fertilizer. The profile distribution of K_{ex} depended upon the moisture content of the soil (Hanway and Scott, 1957). Consequently, the large amount of $K_{non\text{-}ex}$ was found after harvested in Lb soil (Figure 7b).

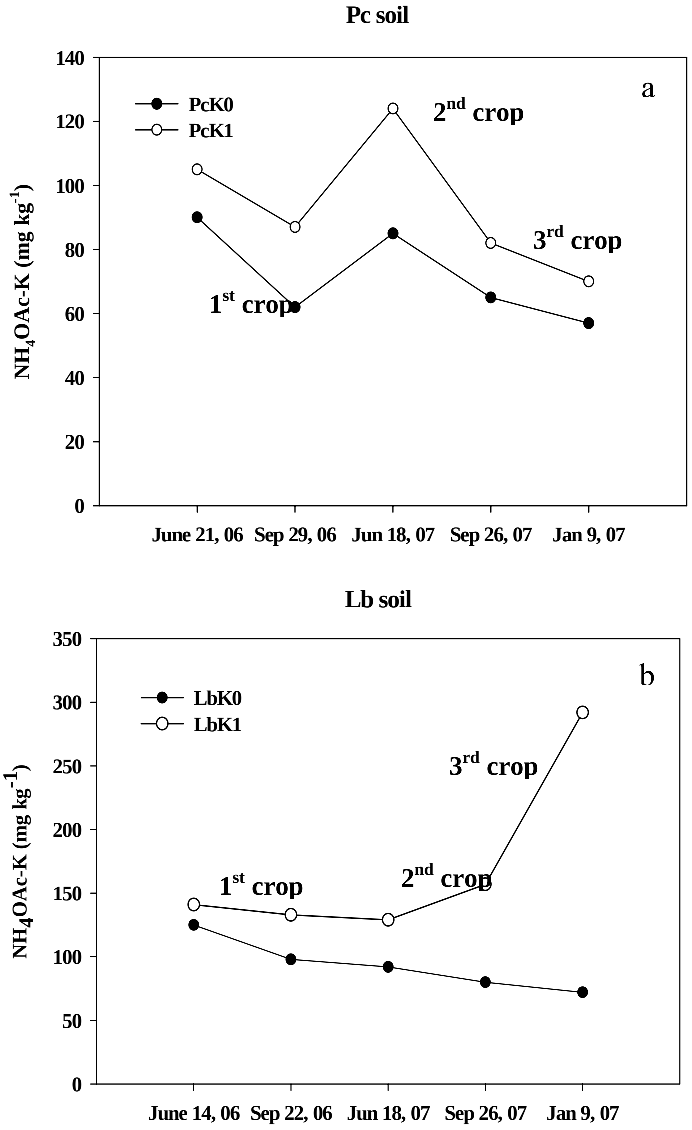


Figure 7 Change in exchangeable K (NH_4OAc-K) during maize exhaustion field experiments in Pak Chong and Lop Buri soils (1st to 3rd crop).

The K_{non-ex} was measured as the subtraction of NH_4OAc-K from mixed acid-K. The mean of K_{non-ex} in Pc soil (Figure 8a) before 1st crop was 50 mg kg^{-1} and decreased to 28, 35 and 26 mg kg^{-1} in the control soil, while K_{non-ex} of K fertilizer application treatment decreased to 27, 24 and 25 mg kg^{-1} after 1st, 2nd and 3rd crops, respectively. The decrease of K_{non-ex} after each crop in the control soil was similar to added K fertilizer treatment. The K_{non-ex} of the Lb soil (Figure 8b) before 1st crop was 75 mg kg^{-1} and decreased to 32, 29 and 12 mg kg^{-1} after each crop in the control soil, while K_{non-ex} of the added K fertilizer soil increased to 165 mg kg^{-1} after 1st and decreased to 93 and 125 mg kg^{-1} after 2nd and 3rd crops. The decrease of K_{non-ex} after the 1st, 2nd and 3rd crops in the control soil was a result of plant K uptake. Whereas, the amount of K_{non-ex} after the 1st, 2nd and 3rd crops in added K fertilizer treatment soil tended to increase, which apparently was the result of residue K fertilizer which was transformed into K_{non-ex} form. Residual K fertilizer as indicated by the large amount of NH_4OAc-K after 2nd crop was found in the Lb soil. This increase may be a result of soils drying during cropping, which increased K fixation. Consequently, the slow release of K_{non-ex} from soils was found and it decreased the exchangeable K level over the total cropping period (Dowdy and Hutcheson, 1963).

The relationship between K_{ex} and K_{non-ex} was analyzed using the linear regression. The linear regression equations of Pc and Lb soils (Figure 9a, b) were $y = -6.6+0.6x$; $AdjR^2=0.58^{**}$, and $y=-37.9+0.8x$; $AdjR^2=0.56^{**}$; where x and y are K_{ex} and K_{non-ex} (mg kg^{-1}), respectively. The result indicates that NH_4OAc extraction method could be indicated the amount of K_{non-ex} in Pc and Lb soils which were the kaolinitic and smectitic soils, respectively, in this specific case.

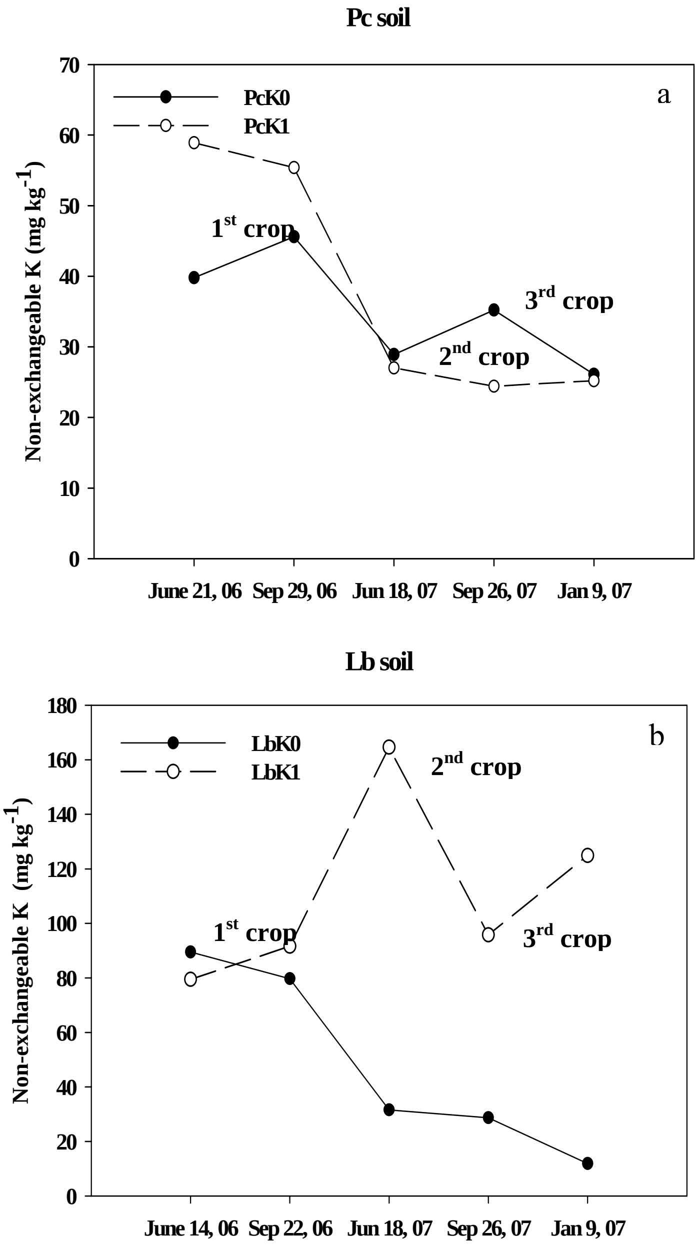
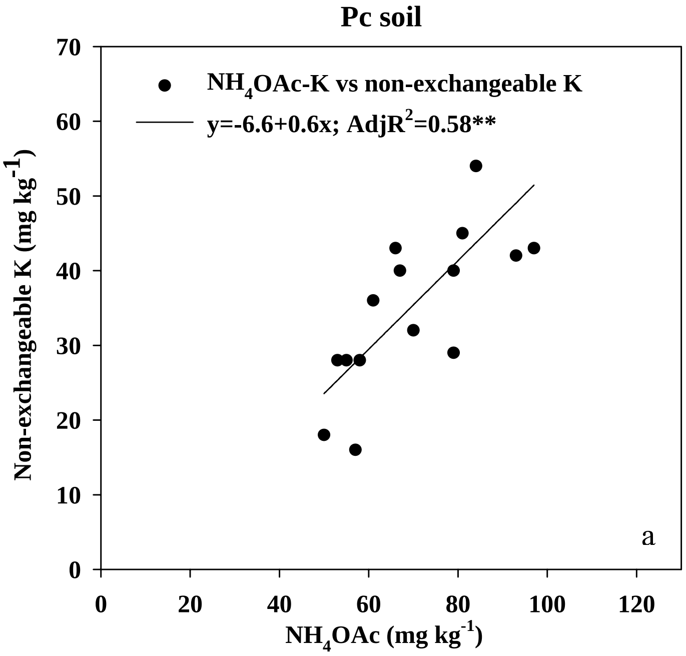


Figure 8 Change in non-exchangeable K (subtraction NH_4OAc-K from mixed-acid-K) during maize growth in Pak Chong and Lop Buri soils (1st to 3rd crop).



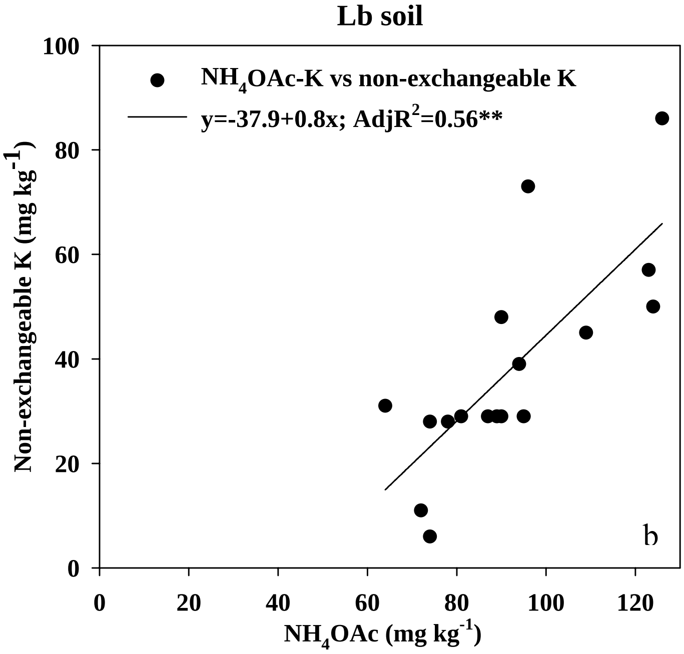


Figure 9 The relationship between exchangeable and non-exchangeable K in Pak Chong and Lop Buri soils under maize field condition.

4.2 Response of maize to K fertilizer in Pak Chong and Lop Buri soils

The response of maize to K fertilizer was found in the Pc and Lb soils in the 2nd and 3 rd crops in the field condition. The addition of K fertilizer increased maize grain and especially stover yields as well as K uptake. The effect of K fertilizer on dry matter (grain, stover, and cob) and total K uptake which were harvested from Pc and Lb soils is presented in Tables 12, 13, 14, and 15. Most of the stover increase was obtained with the added K fertilizer in the 1st crop in both Pc and Lb soils. The large amount of stover in 1st crop and significant decreased in stover weight observed in the 2nd and 3rd crops in the Lb soil, was probably a result of the large amount of exchangeable K and chicken manure applied and the soybean rotation by the farmer prior to the first crop. Mengel *et al*., (2002) found that chicken manure applications to a maize field increased soil organic matter content, which led to a positive long term effect on maize yield. In addition, the severely limitating rainfall during the 2nd and 3rd crops in Lb soil probably decreased yield. A higher proportion of the total dry matter in the 1st crop of Lb soil was partitioned to the grain compared with the 2nd and 3rd crop (Table 10). The application of K fertilizer enhanced photosynthesis so that less carbohydrate stored in the vegetative tissue was utilized to produce grain (Hanway, 1962). The mean comparisons of dry matter and total K uptake also indicated that a significant response of maize yield to fertilizer in both Lb and Pc soils occurred in the 2nd and 3rd crops and that there was a significant decrease of dry matter and total K uptake in both the added K fertilizer and control soils. Grain yield was not increased by the added K fertilizer for the 1st crop, in contrast, it increased as the result of K fertilization for the 2nd and 3rd crop in Pc and Lb soils. The decreases in grain yield were consistent with the decrease in exchangeable K, which affected the decline in grain yield where no K was added to the soil.

Table 12 Dry weight of grain yield, stover, and cob in the Pak Chong soil.

	Treatment		F-test		
	Mean (kg ha^{-1})				
	0 kg K_2O ha^{-1}	125 kg K_2O ha^{-1}	Block	Treatment	CV
1^{st} crop					
Grain yield	4,358	4,513	ns	ns	8.2
Stover	6,506	7,331	ns	ns	6.2
Cob	1,350	1,469	ns	ns	6.8
2^{nd} crop					
Grain yield	3,313b	4,290a	ns	*	12.0
Stover	5,430b	6,650a	ns	*	10.0
Cob	1,021b	1,194a	ns	*	25.8
3^{rd} crop					
Grain yield	2,959b	3,801a	ns	*	5.9
Stover	5,048b	6,007a	ns	*	8.0
Cob	758	823	ns	ns	3.5

Note: Means within a row followed by the same letter were not significantly different at α=0.05 by Duncan's Multiple Range Test.

*, ** Significant at α =0.05, 0.01 ns = not significant

Table 13 Dry weight of grain yield, stover, and cob in the Lop Buri soil.

	Treatment				
	Mean (kg K ha^{-1})		F-test		
	0 kg K_2O ha^{-1}	125 kg K_2O ha^{-1}	Block	Treatment	CV
1st crop					
Grain yield	7,050	6,874	ns	ns	9.8
Stover	15,136	15,844	ns	ns	6.6
Cob	1,630	1,686	ns	ns	39.0
2nd crop					
Grain yield	3,224b	4,648a	ns	*	8.4
Stover	4,164b	5,433a	*	**	3.1
Cob	828	969	ns	*	20.0
3rd crop					
Grain yield	2,996b	3,965a	ns	*	12.5
Stover	4,074	5,994	ns	ns	14.9
Cob	829b	1,080a	ns	*	16.8

Note: Means within a row followed by the same letter were not significantly different at α=0.05 by the Duncan's Multiple Range Test.

*, ** Significant at α =0.05, 0.01   ns = not significant

Table 14 Potassium uptake by maize in the Pak Chong soil.

	Treatment				
	Mean (kg K ha^{-1})		F-test		
	0 kg K_2O ha^{-1}	125 kg K_2O ha^{-1}	Block	Treatment	CV
1st crop					
Grain	41b	63a	ns	*	6.1
Stover	84	103	ns	ns	10.4
Cob	17b	20a	ns	*	6.7
Total	142b	186a	ns	*	6.3
2nd crop					
Grain	32b	60a	ns	*	11.8
Stover	67	68	ns	ns	8.3
Cob	13	15	ns	ns	26.5
Total	112b	143a	ns	*	8.5
3rd crop					
Grain	28b	44a	ns	*	5.3
Stover	46	48	ns	ns	6.0
Cob	9b	11a	ns	*	3.7
Total	83b	104a	ns	*	

Note: Means within a row followed by the same letter were not significantly different at α=0.05 by the Duncan's Multiple Range Test.

*, ** Significant at α =0.05, 0.01   ns = not significant

Table 15 Potassium uptake by maize in the Lop Buri soil.

	Treatment				
	Mean (kg ha^{-1})		F-test		
	0 kg K_2O ha^{-1}	125 kg K_2O ha^{-1}	Block	Treatment	CV
1st crop					
Grain	80	82	*	ns	9.8
Stover	221	244	ns	ns	6.5
Cob	16	18	ns	ns	38.4
Total	321	342	ns	ns	6.8
2nd crop					
Grain	38b	58a	ns	*	16.4
Stover	74	103	ns	ns	18.7
Cob	9	10	ns	ns	20.0
Total	121	172	ns	ns	16
3rd crop					
Grain	35b	69a	ns	*	15.0
Stover	61b	84a	*	**	3.23
Cob	8	11	ns	ns	17.4
Total	104b	164a	ns	*	7.9

Note:

Means within a row followed by the same letter were not significantly different at α=0.05 by the Duncan's Multiple Range Test.

*, ** Significant at α =0.05, 0.01   ns = not significant

4.3 Soil K balance and rate of release

Soil K balance was established as the change in K $_{\text{non-ex}}$ according equation (Magnus *et al*., 2007)

$$K_{\text{fertilizer}} + (K_{\text{exch}} + K_{\text{non-ex}})_{\text{before}} = K_{\text{harvest}} + (K_{\text{ex}} + K_{\text{non-ex}})_{\text{after}} \qquad (12)$$

Where;

$K_{\text{fertilizer}}$ = amount of added K fertilizer as converted to kg ha^{-1} using bulk density of 1.53 in the Pc soil and 1.38 g cm^{-3} in the Lb soil with 0-20 cm depth

K_{harvest} = amount of K in dry matter (grain, stover, and cob) that was removed from the soil (kg ha^{-1})

$(K_{\text{exch}} + K_{\text{non-ex}})_{\text{before}}$ = amount of NH_4OAc-K (K_{ex}) and subtraction of NH_4OAc-K from the mixed acid-K ($K_{\text{non-ex}}$) before each crop (kg ha^{-1})

$(K_{\text{exch}} + K_{\text{non-ex}})_{\text{after}}$ = amount of NH_4OAc-K (K_{ex}) and subtraction of NH_4OAc-K from the mixed acid-K ($K_{\text{non-ex}}$) after each crop (kg ha^{-1})

The net K balance in Pc and Lb soils is presented in table 16, a negative net K balance was interpreted as a net release of $K_{\text{non-ex}}$ in the field, whereas a positive value indicated that net fixation of K had taken place. Positive net K balances were not found in this study. The negative net K balance was found in both Pc and Lb soils and this result was similar with the research of Bhattacharyya *et al*. (2006). They indicated that a negative net K balance and the decrease in K_{ex} and $K_{\text{non-ex}}$ pools were found in a Typic Haplaquept soil, which was cropped continuously and plant residues were removed.

Table 16 Mean of soil inputs ($K_{fertilizer}$, K_{ex} and K_{non-ex} before planting), outputs ($K_{harvest}$, K_{ex} and K_{non-ex} after planting), and soil net K balance (input-output) in the Pak Chong and Lop Buri soils.

Soil	Crop	K fertilizer application (kg K_2O ha^{-1})	K input (kg ha^{-1} crop^{-1})			K output (kg ha^{-1} crop^{-1})			net K balance (kg ha^{-1} crop^{-1})
			K fertilizer	K_{ex}	$K_{non-ex\ mixed\ acid}$ #	K harvest	K_{ex}	$K_{non-ex\ mixed\ acid}$	
Pc	1st	0	0	277±42##	122±48	142±14	191±46	139±23	-342±65
		125	104	322±84	180±23	186±9	267±63	170±23	-354±53
	2nd	0	0	260±22	88±51	112±16	199±37	108±28	-304±56
		125	104	378±68	83±21	143±3	249±46	75±24	-212±46
	3rd	0	0	199±37	108±28	83±6	174±20	80±38	-237±45
		125	104	249±46	75±25	104±4	214±34	77±26	-185±14
Lb	1st	0	0	344±35	247±144	321±45	272±21	220±140	-221±56
		125	104	390±20	219±57	342±15	253±99	253±99	-248±54
	2nd	0	0	254±18	87±14	121±11	221±15	79±18	-81±17
		125	104	357±47	454±126	172±24	264±156	50±15	-547±172
	3rd	0	0	221±15	79±18	104±5	198±16	87±91	-185±14
		125	104	434±63	264±156	164±16	344±209	345±209	-68±84

$K_{non-ex\ mixed\ acid} = K_{mixed\ acid} - K_{ex}$ ## Standard deviation.

The average of net K balances in the present study decreased with an increasing number of crops in both Pc and Lb soils. The most negative net K balance was found in the 1st crop, which then decreased in the 2nd and 3rd crops. There clearly was a difference between net K balance of control and added K fertilizer soils in both soils. This result was clearly consistent with the simultaneous decline of NH_4OAc-K and mixed acid-K after each crop harvest. The decrease of K_{ex} and K_{non-ex} concentration clearly indicated that most of K uptake by the crops has come from the K_{ex} and K_{non-ex} forms, which were probably the result from the equilibrium between interlattice K and soil solution K (Mengel and Rahmatullah, 1994; Singh *et al.*, 2002). The source of K_{non-ex} in the Lb soil was most probably from vermiculite clay minerals (Cox *et al.*, 1999) in the clay fraction, whereas K_{non-ex} in Pc soil was probably released from the trace amount of illite and most amounts from K-feldspar weathering in the sand and silt fractions (Simard *et al.*, 1992; Sadusky *et al.*, 1987), which probably contained a larger amount than clay fraction according to mineralogical analysis. The K-feldspar weathering was a result of the H^+ ions replacement in the interlayer in which K is tightly held by electrostatic forces, and the transformation of micas into expansible 2:1 layer silicates or by dissolution particularly through the acidification of the rhizosphere by the excretion of H^+ ions from plant roots (Singh and Goulding, 1997).

The study of net K balance also indicated that the mixed acid extraction method did not extract all of plant available K_{non-ex} in field experiment in either the Pc or Lb soils. Therefore, the total of plant available $K_{non-ex\ field}$ should be the summation of net K_{non-ex} release (calculated from the net K balance in the field in table 16) and $K_{non-ex\ mixed-acid}$ in field experiment of Pc and Lb soils

The total amount of plant available $K_{non-ex\ field}$ released to each crop of maize (mg kg^{-1}) was fitted using segmented regression equation (equation 4) which was the best fitting equation for describing the release of K_{non-ex} of the maize soil in greenhouse (Experiment 2) based on RMS criteria. Where y = total plant available K_{non-ex} release in field ($K_{non-ex\ field}$) which is the summation of net K_{non-ex} release (the net K balance in field in Table 13) and $K_{non-ex\ mixed-acid}$ (kg ha^{-1}), and t = time (day).

The length of time for each crop planting was 100 days, because 100% of the total K uptake is usually accumulated by 100 days after emergence (Ritchie *et al.*, 1997).

Table 17 The release of total plant available $K_{\text{non-ex}}$ ($K_{\text{non-ex field}}$) in units of kg ha^{-1} d^{-1} in field experiments on Lb and Pc soils at 0-20 cm soil depth as fitted by the segmented straight-line equation (no-intercept).

Soil	K fertilizer application (kg K_2O ha^{-1})	Segmented straight-line ($y= b_1$*min(node, x) + b_2*max(node, x) $-b_2$*node)		
		node	b_1	b_2
Pc	0	277.8	4.32	-0.04
	125	179.6	5.34	0.00
Lb	0	100.0	6.36	0.00
	125	257.3	7.00	0.35

The release of $K_{\text{non-ex field}}$ to each crop of maize as a function of time (day) is shown in Figure 10. The estimated parameters of the equations describing the rate of release of $K_{\text{non-ex field}}$ (kg ha^{-1} d^{-1}) are shown in Table 17. The amount of plant available $K_{\text{non-ex field}}$ released after the occurrence of the response of maize yield to K fertilizer was assumed to be zero. Therefore, the exhaustive maize cropping after 3rd crop was discontinued. The mean of rapid K release rates of plant available $K_{\text{non-ex field}}$ were 4.83 and 6.68 kg ha^{-1}d^{-1}, and slow K release rates were 0 and 0.18 kg ha^{-1} d^{-1} in Pc and Lb soils, respectively. The slow release rates of Pc and Lb soils were both zero and nearly zero. The $K_{\text{non-ex}}$ release pattern of Pc soil under field condition is consistent with the release pattern of $K_{\text{non-ex}}$ in pot experiment. The $K_{\text{non-ex}}$ release pattern between pot and field experiment in Lb soil was not consistent. The low, near zero estimate of b_2 in Lb soil in the field was possibly the result of a small amount of plant available $K_{\text{non-ex}}$ release in the field (Table 13), which was affected from the dry season during the 2nd and 3rd crop. Therefore, the release of $K_{\text{non-ex}}$ in field experiment of Lb soil was not inadequately determined in this study. The rapid release (b_1) and the slow release (b_2) rates of

$K_{non\text{-}ex\ field}$ in the Pc soil are believed to be the release of K from trace amounts of illite in the clay fraction (Cox *et al.*, 1999) and K feldspar in the silt and sand fraction (Simard *et al.*, 1992; Sadusky *et al.,* 1987).

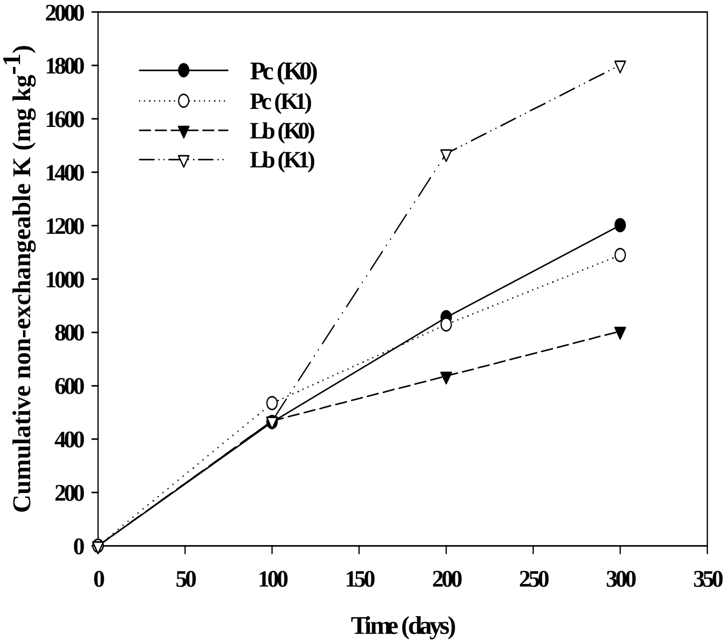


Figure 10 Cumulative non-exchangeable K release (summation of $K_{non\text{-}ex\ field}$ and $K_{non\text{-}ex\ mixed\text{-}acid}$) from Pc and Lb soils which no K (K0) and added K fertilizer (K1) during 1st to 3rd crop (approximately 300 days).

The relationship between NH_4OAc-K and mixed acid-K (mg kg^{-1}) before each crop planting and the amount of total plant available $K_{non\text{-}ex}$ release in the field (total $K_{non\text{-}ex\ field}$) (mg kg^{-1}) of each crop in field experiments on Pc soils is summarized by the following equations;

Pc soil;

total $K_{non\text{-}ex\ field}$ = 39+1.2*NH_4OAc-K AdjR^2=0.31* n=12 (13)

total $K_{non\text{-}ex\ field}$ = 6.8+1.1*Mixed acid-K AdjR^2=0.66** n=12 (14)

The results suggest that amount of total plant available K_{non-ex} (total $K_{non-ex\ field}$) from the field experimental soils can be predicted from the initial soil NH_4OAc-K and mixed acid-K values with reasonably good results. The difference between the two equations was the more precise determination of total $K_{non-ex\ field}$ using mixed acid than NH_4OAc extraction methods. If we only consider the $AdjR^2$ value, it indicates that the mixed acid-K is the better method than NH_4OAc for estimation of the total K_{non-ex} release in Pc soil. That the mixed acid predicted the plant available K_{non-ex} so well is because it extracts some of the phyllosilicate K which is held between interlayers of illite clay mineral and micas (Huang, 2005), whereas the NH_4OAc extraction method probably extracted only the portion of the soil K_{ex} that is electrostatically bond as an outer-sphere complex to the surfaces of clay mineral (Sparks and Huang, 1985). Andrist-Rangel *et al.* (2007) indicated that the release of K_{non-ex} was influenced by the actual pool size of K_{non-ex}, which was extracted by HCl (HCl-K). Simonsson *et al.* (2007) also indicated that release and fixation of K_{non-ex} in the long term had a significant an effect on K_{non-ex}, which is a large amount compared to the annual uptake of K.

4.4 Estimating K supplying power in Pc soil

The results of the study on the release of $K_{non\text{-}ex}$ in the field experiment at 0-20 cm soil depth was calculated in order to estimate the number of year for maize cropping in only Pc soils. Such estimates were not possible for the Lb soil because of the severe drought that occurred during the field experiment in the 2nd and 3rd crops.

The number of years for maize cropping was estimated using the following simple equation (Chunyanuwat, 1981);

$$\text{Number of years} = \frac{\text{Total plant available K}}{\text{Total plant removed per crop}} \times \frac{1}{\text{Number of crops per year}} \qquad (15)$$

Where:

Number of years = the number of year for maize cropping that may be grown until a response of maize to K is expected.

Total plant available K = the summation of plant available K_{ex} and plant available $K_{non\text{-}ex}$ in the soil (mg K kg^{-1}) at 0-20 cm depth

Total plant removed per crop = amount of K that was removed with each crop (mg K kg^{-1}) at 0-20 cm depth

Number of crops per year = number of maize crops usually grown in Thailand (= 2 for maize cultivation in Pc soil with irrigation system).

The mean of total plant available K (calculated from the total plant K uptake in Table 14) was 1,145 kg ha^{-1} or 376 mg K kg^{-1} in Pc soil. This was approximately 17.5% of the total K (HF-K) in Pc soil (2,146 mg kg^{-1}). The approximate number of maize crops was calculated using equation 15, where; total plant available K of Pc soil was 1,145 kg ha^{-1} and total plant K removed per crop was

128 kg ha^{-1}. The estimated number of maize crops that could be growth without a response to additional K was approximately 9 crops in the Pc soils, under the unusual conditions that all of crop residues are removed from the soils. In Thailand, only the grain is removed from the soil thus leaving the stover and root K in the field. Therefore, the number of maize crops was determined by dividing the total K total plant available K in the soils by grain K removed per crop (Table 14) . The number of maize crops in Pc soil increased to 19 crops under the assumed conditions that only K in the grain is removed from the field. The result indicates that the K supplying power of the Pc soil was approximately 9 years, while producing a yield of approximately 3,543 kg ha^{-1} (using the mean grain yield in control treatment in Table 12) for intensive maize growth in Thailand where only 2 crops per year are grown and only grain is removed from the field.

Andrist-Rangel *et al.* (2007) determined the K supplying power in mixed crop rotation and organic cropping system by using three long-term field experiments on sandy loam soils. The results indicated that these soils supply 20 kg ha^{-1} yr^{-1}, and the main long term source of soil K (dioctahedral phyllosilicates and K feldspars) would be 150-500 years. Whereas, the maximum K supplying power in an organic cropping system on clay soil was 35-70 kg ha^{-1} yr^{-1} (Simonsson *et al*., 2007). The K supplying power for continuous cropping with the removal of crop residues in a rainfed soybean-wheat system in sandy soil was approximately 39.9 kg ha^{-1} yr^{-1} (Bhattacharyya *et al*., 2006). The study indicated that the K supplying power is controlled by crop K demand or type of crop, soil texture, and type of clay minerals. The crop K demand was controlled by factors other than K availability, for example, the supply of N and P or other soil fertility factors (Alfaro *et al*., 2003; Andrist-Rangel *et al*., 2007).

4.5 Summary

The total $K_{\text{non-ex field}}$ was more precisely determined by mixed acid than by NH_4OAc extraction methods in the Pc soil. The total plant available K of Pc and Lb soils was 1,145 and 1,234 kg ha^{-1}, and the plant available $K_{\text{non-ex}}$ was released at different rates, the rapid K release rates of plant available $K_{\text{non-ex field}}$ were 4.86 and 6.67 kg ha^{-1}d^{-1}, and slow K release rates were 0 and 0.18 kg ha^{-1} d^{-1} in Pc and Lb soils, respectively. The K supplying power was only determined in the Pc soil due to drought at the Lb site for the 2nd and 3rd crops. The K-supplying power was estimated sufficient for approximately 9 years while producing a yield of approximately 3,543 kg ha^{-1}, where 2 crops per year are grown and only grain is removed from the field.

CONCLUSION

The study on K release by successive equilibration with Ca-resin indicated that a larger quantity of available K was found in smectitic compared to kaolinitic soils. A segmented regression model gave the best characterization of soil K release to Ca-resin and of K_{non-ex} release to plants in the K exhaustion greenhouse studies. It provided estimates of two fractions of plant available K_{non-ex} which were released in different patterns and rates in kaolinitic and smectitic soils. The rapid and slow K release rates of plant available K_{non-ex} in the greenhouse K exhaustion study were 0.45 - 0.85 and 0 mg kg^{-1} day^{-1} for kaolinitic soils, and 1.60 - 1.98 and 0.27 - 0.52 mg kg^{-1} day^{-1} for smectitic soils, respectively. The release rates of plant available K_{non-ex} was affected by clay mineral type, clay content and CEC. These studies clearly showed that with kaolinitic soils exchangeable K methods such as NH_4OAc were adequate to assess K reserves and to predict K fertilizer requirements. In contrast, NH_4OAc and Ca-resin and possibly mixed acid extractions appear to be necessary to assess K reserves in smectitic soils.

Estimates of plant available K in kaolinitic and smectitic soils was obtained using successive maize crops and selected extraction methods. Total plant extracted K included more K_{non-ex} in the control soils than in K fertilized application soils. The regression analysis indicated that the correlation between extractable K using different extraction methods and total plant available K did not significantly vary among soils. Therefore all extraction methods were able to estimate total plant extracted K to some extent in the selected soils. However, figures with a 1:1 line relationship revealed that the mixed acid and Ca-resin extractable K were most closely correlated with total plant available K in all soils. This result indicates that the mixed acid and Ca-resin extraction methods were the most accurate methods to directly extract the total plant extractable K, which included the K_{ex} and K_{non-ex} pools in the soils. Therefore, the mixed acid and Ca-resin extraction methods were the best methods to estimate the total plant extractable K for the intensive maize growth in these soils.

A field experiment revealed that the total plant available K of Pc and Lb soils were 1,145 and 1,234 kg ha^{-1}, although there was drought at the Lb soil site. The rapid K release rates of plant available $K_{non\text{-}ex\ field}$ were 4.86 and 6.67 kg ha^{-1}d^{-1} in Pc and Lb soils, and slow K release rates were 0 and 0.18 kg ha^{-1} d^{-1} in Pc and Lb soils, respectively. Based on a only two crops, it was estimated that 19 crops could be grown on the Pc soil, under the conditions that all of crop residue is removed from the soil. The K supplying power of Pc soil might be different in other provinces due to variation in soil properties and presence of an irrigation system for intensive maize cultivation in this soil.

RECOMMENDATIONS

This study revealed that most of the plant available K in two representative soils for intensive maize growth soils was from the pools of $K_{non\text{-}ex}$. The plant available $K_{non\text{-}ex}$ was released at different rates depending on the type of clay mineral and clay content in the soils. The results suggest that based on a only two crops, the Pc soil at this site might be used for continuously maize growth under irrigation system and no K fertilizer application, for approximately 9 years

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APPENDIX

Appendix Table 1 Characterization of Phu Sana (Ps) soil series.

Characterization	Description
Distribution	Occupies small extent in Northeast and North Thailand.
Setting:	Phu Sana soils are residuum from granitic rock and occur on erosion surface or peneplain remnant. Relief is undulating to rolling which slopes range from 3 to 8 percent. Elevation is from 200 to 450 m above sea level. The climate is Tropical Savanna. Average annual precipitation varies from 1,100 to 1,500 mm. Mean annual air temperature is from 26 to 28 ^{o}C.
Drainage, Permeability and Runoff:	Well drained. Ground water table falls below 5 m all year round. Permeability is rapid over moderate. Surface runoff is rapid.
Vegetation and Land Use:	Low open dipterocarp forest. Part are cleared for upland crops such as kenaf, maize, water melon and some upland rice.
Characteristic Profile Features:	Phu Sana series is a member of the fine-loamy, mixed,isohyperthermic Kanhaplic Haplustults. They are shallow to gravels and are characterized by a very dark grayish brown to dark brown sandy loam or loamy sand a horizon overlying a yellowish red, reddish yellow or strong brown very gravelly sandy clay loam or very gravelly clay loam argillic B horizon. Weathered granitic rock fragments occur below 80 cm depth from the surface. Reaction is slightly acid to medium acid over medium to strongly acid.
Location:	Amphoe Muang Changwat Loei.
Parent material:	residuum and colluvium derived from granite
Drainage:	well drained
Annual rainfall:	1,238.1 mm
Mean temp.:	25.5 ^{o}C
Climate type:	Tropical Savannah
Natural vegetation or land use:	Maize

Source: Land Development Department (2008)

Appendix Table 2 Characterization of Satuk (Suk) soil series.

Characterization	Description
Distribution	Occupies moderate extent in Northeast Thailand and small extent in Western part of Central Plain and in North Thailand.
Setting:	Satuk soils are formed from wash deposit from sandstone and occur on the middle part of peneplain Relief is undulating which range of slope is 2 to 8 percent. Elevation above sea level is 160 to 220 m. The climate is Tropical Savanna. Average annual precipitation is from 1,100 mm up to 2,200 mm. Mean annual air temperature varies from 26 to 28°C.
Drainage, Permeability and Runoff:	Well drained. Ground water table falls below 1.50 m most of the years. Permeability is moderate and surface runoff is medium to rapid.
Vegetation and Land Use:	Mainly dipterocarp and mixed deciduous forest with parts cleared for the cultivation of upland crops such as kenaf, water melon, cassava, beans corn, etc.
Characteristic Profile Features:	Satuk series is a member of the fine-loamy, siliceous,subactive, isohyperthermic Typic Paleustults. They are very deep soils and are characterized by a very dark grayish brown, dark grayish brown or dark brown sandy loam A horizon overlying a strong brown or yellowish brown or reddish yellow sandy clay loam or clay loam argillic B horizon. Reaction is slightly acid to medium over strongly acid to very strongly acid.
Location:	Amphoe Wat Bod, Changwat Phitsanulok.
Parent material:	Washed deposit from sandstone
Drainage:	Well drained
Annual rainfall:	1,207.6 mm
Mean temp.:	26.7 °C
Climate type:	Tropical Savannah
Natural vegetation or land use:	Mainly dipterocarp and mixed deciduous forest with parts cleared for upland crops such as kenaf, cassava etc

Source: Land Development Department (2008)

Appendix Table 3 Characterization of Warin (Wn) soil series.

Characterization	Description
Distribution	Occupies moderate extent in Northeast Thailand.
Setting:	Warin soils are formed from washed deposit from sandstone and occur on the upper part of peneplain. Relief is undulating. Slopes range from 2 to 8 percent. Elevation is from 180 to 250 m above sea level. The climate is Tropical Savanna. Average annual precipitation is from, 1,100 to 2,200 mm. Mean annual air temperature varies from 26 to 28°C.
Drainage, Permeability and Runoff:	Well drained soils. Permeability is moderate. Surface runoff is medium to rapid. Ground water table falls below 5 meters during the peak of the dry period.
Vegetation and Land Use:	Originally mixed deciduous forest and dipterocarp forest. Parts are cleared for upland crops such as corn, cotton, sugar cane, kenaf, water melon and some fruit crops such as pineapple, custard apple and kapok.
Characteristic Profile Features:	The Warin series are a member of fine-loamy, siliceous,isohyperthermic Typic Kandiustults. They are deep soils which are characterized by a dark brown, brown or dark grayish brown sandy loam or loamy sand A horizon overlying a yellowish red or reddish yellow sandy clay loam B horizon. Reaction is medium to strongly acid over strongly acid to very strong acid.
Location:	Amphoe Wat Bod, Changwat Pisanuloke.
Parent material:	Washed deposit from sandstone
Drainage:	Well drained
Annual rainfall:	2,163.3 mm
Mean temp.:	25.9 ^{0}C
Climate type:	Tropical Savannah
Natural vegetation or land use:	Mixed deciduous forest and dipterocarp forest. Parts are cleared for upland crops such as corn, cotton, sugar cane, casava etc

Source: Land Development Department (2008)

Appendix Table 4 Characterization of Pak Chong (Pc) soil series.

Characterization	Description
Distribution	Occupies moderate extent in Central Highlands and small extent in North Thailand
Setting:	Pak Chong soils are formed from residuum and local colluvium from limestone and occur on the karst topography. Relief is undulating which slopes range from 2 to 8 percent. Elevation is variable above sea level, but mainly not above 400 m. The climate is Tropical Savanna. Average annual precipitation varies from 1,100 to 1,400 mm. Mean annual air temperature is from 26 to 28°C.
Drainage, Permeability and Runoff:	Well drained soils. Permeability is moderate. Runoff is rapid to medium.
Vegetation and Land Use:	Originally mixed deciduous forest, but mainly cleared for upland crop cultivation such as corn, cotton, beans, sorghum, castor bean and some fruit crops.
Characteristic Profile Features:	The Pak Chong series is a member of the very fine, kaolinitic, isohyperthermic Rhodic Kandiustox; They are very deep soils and are characterized by a dark reddish brown clay or silty clay A horizon overlies red or dark red clay lower kandic B horizon. Reaction is slightly acid to neutral over strongly to very strongly acid.
Location:	Amphoe Pak Chong Changwat Nakhon Ratchasima.
Parent material:	Residuum and colluvium from limestone
Drainage:	Well drained
Annual rainfall:	1,100-1,400 mm
Mean temp.:	26-28 ^{0}C
Climate type:	Tropical Savannah
Natural vegetation or land use:	Upland crops and some fruit trees

Source: Land Development Department (2008)

Appendix Table 5 Characterization of Lop Buri (Lb) soil series.

Characterization	Description
Distribution	Occupies moderate extent along the borders of the Central Plain and in the Central Highlands, mainly in Changwat Lop Buri, Saraburi and Amphoe Pak Chong, Changwat Nakhon Ratchasima.
Setting:	Lop Buri soils are formed from alluvium which is rich in montmorillonitic clay, underlying marl layer and occur on terraces adjacent to limestone hills. Relief is nearly flat to slightly undulating. Slopes are 1-5%. They have a 'gilgai' micro-relief. The climate is Tropical Savannah. Mean annual precipitation is approximately 1,400 mm. Mean annual temperature is 27 ^{o}C.
Drainage, Permeability and Runoff:	Well drained. Permeability is slow and runoff is slow to moderate. The soil dries and cracks deeply during the dry season.
Vegetation and Land Use:	Originally mixed deciduous forest, now mainly cleared for upland crops, such as, maize, sorghum, beans and rice.
Characteristic Profile Features:	Lop Buri series is a member of the Very-fine, smectitic,isohyperthermic Typic Haplusterts.They are deep neutral to moderately alkaline soils and are characterized by a very thick black or very dark gray clay A horizon overlying a black or very dark gray coloured B horizon. Slickensides and pressure faces are characteristic of the dark coloured B horizon. The marl layer has its upper boundary at some depth below 80 cm from the soil surface and scattered secondary lime nodules occur throughout. Cracks 1 cm or more wide at 50 cm depth open for long periods during the dry season.
Location:	Amphoe Wang Mueang Changwat Saraburi.
Parent material:	Alluvium
Drainage:	Well drained
Annual rainfall:	1,211.9 mm
Mean temp.:	28.1 °C
Climate type:	Tropical Savannah
Natural vegetation or land use:	Upland crops; sorghum, sugarcane, corn

Source: Land Development Department (2008)

Appendix Table 6 Characterization of Chai Badan (Cd) soil series.

Characterization	Description
Distribution	Occupies moderate extent in the Central Highlands.
Setting:	Chai Badan soils are on gently undulating to rolling slopes of dissected lava flows. Slopes range from 3 to 16 percent. They are derived from residuum and colluvium from basalt,andesite and occasionally rhyolite. The climate is Tropical Savanna. The annual precipitation ranges from 1,100 to 1,600 mm. Elevation ranges from 60 to 150 m above sea level.
Drainage, Permeability and Runoff:	Moderately well drained. Runoff is slow to rapid. Permeability is estimated to be moderate to slow.
Vegetation and Land Use:	Mixed deciduous and dry evergreen forest. Parts are cleared for upland crops such as corn, sorghum, soy bean, peanuts and sunflower etc.
Characteristic Profile Features:	Chai Badan series is a member of the fine, smectitic,isohyperthermic Leptic Haplusterts. They are moderately deep soils. Weathered parent rocks usually occur lower than 50 cm but within 100 cm from the soil surface. These soils are characterized by a very dark gray or very dark grayish brown silty clay or clay. A horizon overlying a dark grayish brown, dark brown or brown silty clay or clay cambic B horizon. Cracks occur deeply from the surfaces to C horizon during the dry season. Slickensides can be observed in the profile. Some secondary lime nodules are usually present in the C horizon.
Location:	Amphoe Pharbhudabaht Changwat Saraburi
Parent material:	Colluvium from basalt and/or andesite
Drainage:	Moderately well drained
Annual rainfall:	1,247 mm
Mean temp.:	27.2 ^{0}C
Climate type:	Tropical Savannah
Natural vegetation or land use:	Maize

Source: Land Development Department (2008)

Appendix Table 7 Characterization of Takhli (Tk) soil series.

Characterization	Description
Distribution	Occupies moderate extend in the Central Highlands, North East and small extent in South West Thailand.
Setting:	Takhli soils are formed from transported material over marly beds and occur on gently undulating to undulating terrains with slopes ranging from 2 to 12%. The climate is Tropical Savanna.
Drainage, Permeability and Runoff:	Well drained. Permeability is estimated to be moderate. Runoff is slow to medium.
Vegetation and Land Use:	Mixed deciduous and dry evergreen forest. Parts are cultivated to corn, cotton, beans and orchards of custard apples and other fruits.
Characteristic Profile Features:	Takhli series is a member of the loamy-skeletal, carbonatic, isohyperthermic, Entic Haplustolls. They are shallow and calcareous soils. They are characterized by a black, very dark gray, very dark grayish brown or very dark brown(gravelly) clay loam or silty clay loam A horizon overlying a dark brown or brown, with some whitish marl nodules, silty clay loam, clay loam B horizon. The C horizon with many secondary lime nodules or marl occur as a layer within 50 cm from the surface. The reaction is neutral to moderately alkaline in the surface and moderately alkaline in the subsoils.
Location:	Amphoe Phayuha Khiri, Changwat Nakhon Sawan.
Parent material:	Transported materials over secondary lime and marl.
Drainage:	Well drained
Annual rainfall:	1,119 mm
Mean temp.:	28.3 ^{o}C
Climate type:	Tropical Savannah
Natural vegetation or land use:	Upland crops; sorghum, sugarcane, corn

Source: Land Development Department (2008)

Appendix Table 8 Characterization of Lam Narai (Ln) soil series.

Characterization	Description
Distribution	Occupies moderate extent in the Central Highlands.
Setting:	Lam Narai soils are formed from mixed predominantly basic rocks (basalt, limestone and andesite) and occur on undulating to rolling dissected lava flows and erosion surfaces. Slopes range from 3 to 6%. Elevation varies from 50 to 160 m above sea level. The climate is Tropical Savanna. Mean annual precipitation ranges from 1,100 to 1,600 mm.
Drainage, Permeability and Runoff:	Well drained. Permeability is estimated to be moderate and runoff is estimated to be medium. Ground water table is below 1.5 m.
Vegetation and Land Use:	Natural forests are mixed deciduous or dry evergreen. These soils are mainly used for the cultivation of upland crops, e.g. corn, cotton, sorghum and beans.
Characteristic Profile Features:	Lam Narai series is a member of the fine, smectitic, isohyperthermic Vertic Haplustolls. They are moderately deep soils to a layer of lime concretions that may occur between 50 and 80 cm below which weathered parent rocks are found. They are characterized by a dark brown or dark reddish brown clay loam or clay. A horizon overlying a dark reddish brown, reddish brown or dusky red silty clay or clay weakly developed B horizon. Lime nodules are few in the surface and become many in the subsoil. The reaction is neutral to moderately alkaline.
Location:	Tambon Lam Narai, Amphoe Chai Badan Changwat Lop Buri
Parent material:	Material: resdiuum and colluvium derived from basalt, limestone, calcareous sandstone and andesite
Drainage:	well drained
Annual rainfall:	1,211.9 mm
Mean temp.:	25.6 ^{o}C
Climate type:	Tropical Savannah
Natural vegetation or land use:	Maize

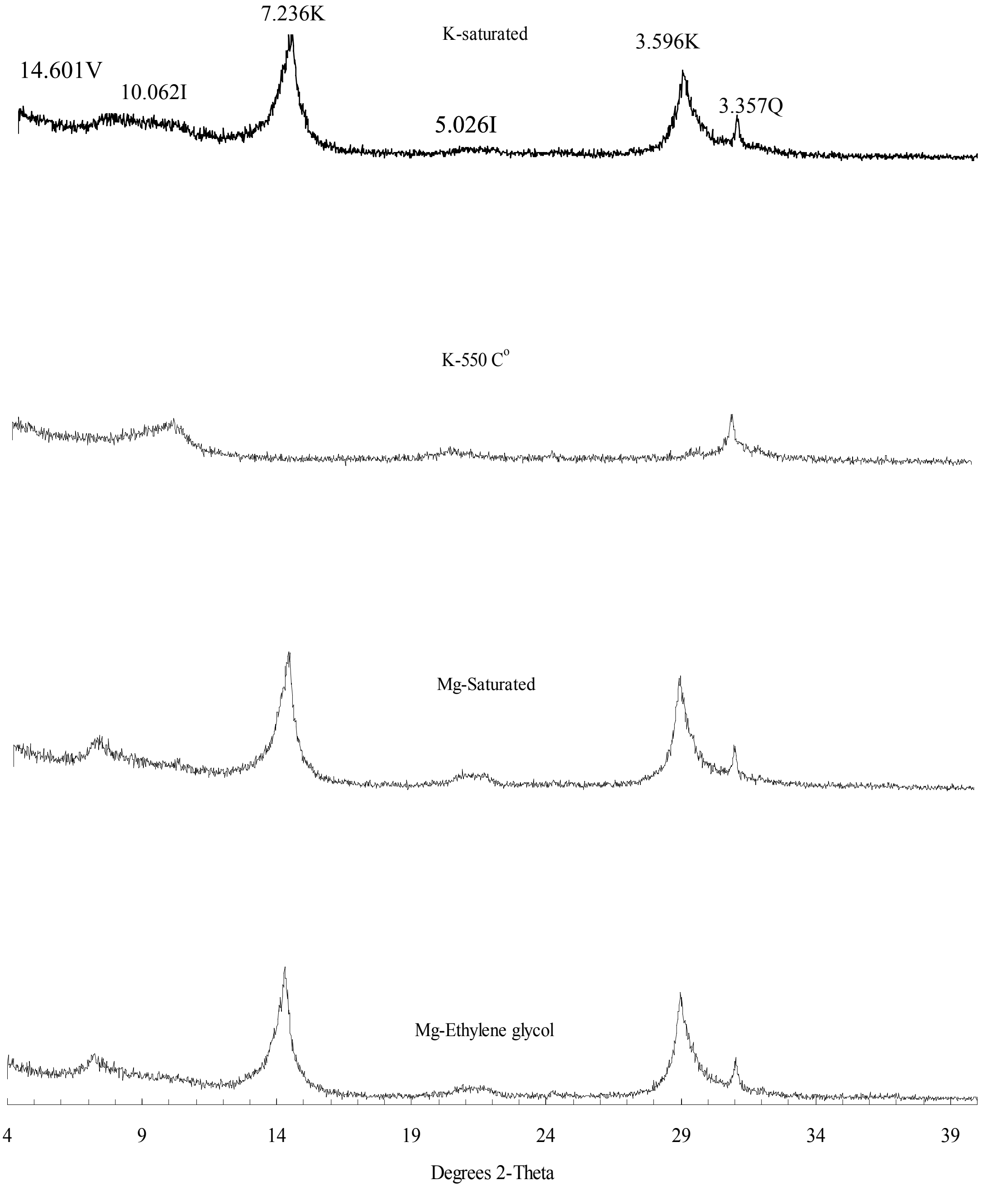
Source: Land Development Department (2008)

Appendix Table 9 Dates of maize planting in Pak Chong and Lop Buri soils.

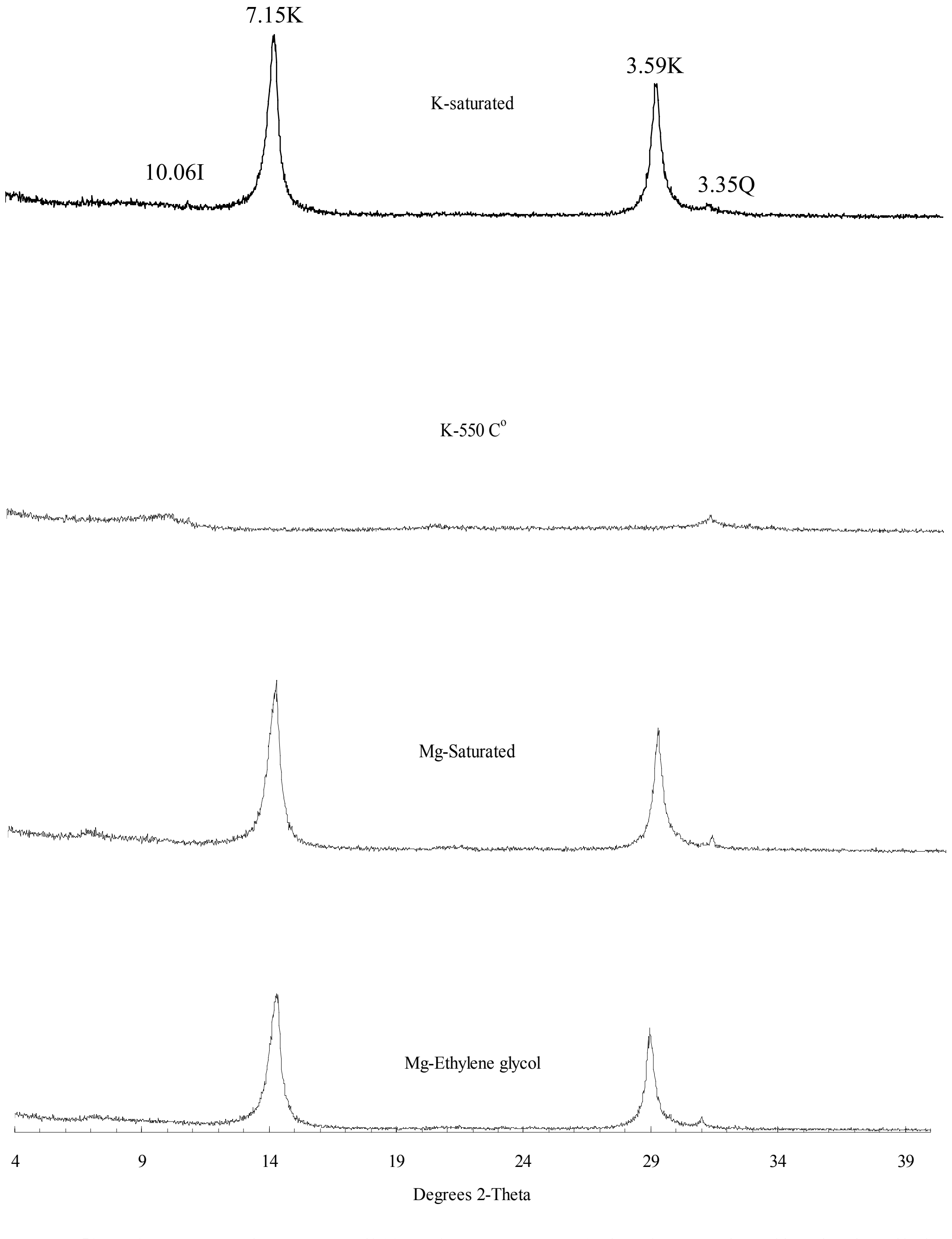
Soil	1^{st}crop planting	1^{st}crop harvested	2^{nd}crop planting	2^{nd}crop harvested	2^{nd}crop planting	2^{nd}crop harvested
Pc	June 21, 05	Sep 29, 05	June 18, 06	Sep 26, 06	Sep 26, 06	Jan 9, 07
Lb	June 14, 05	Sep 22, 05	June 18, 06	Sep 26, 06	Sep 26, 06	Jan 9, 07

Appendix Table 10 Exchangeable K (NH_4OAc-K) and mixed acid-K during maize growth in Pak Chong and Lop Buri soils.

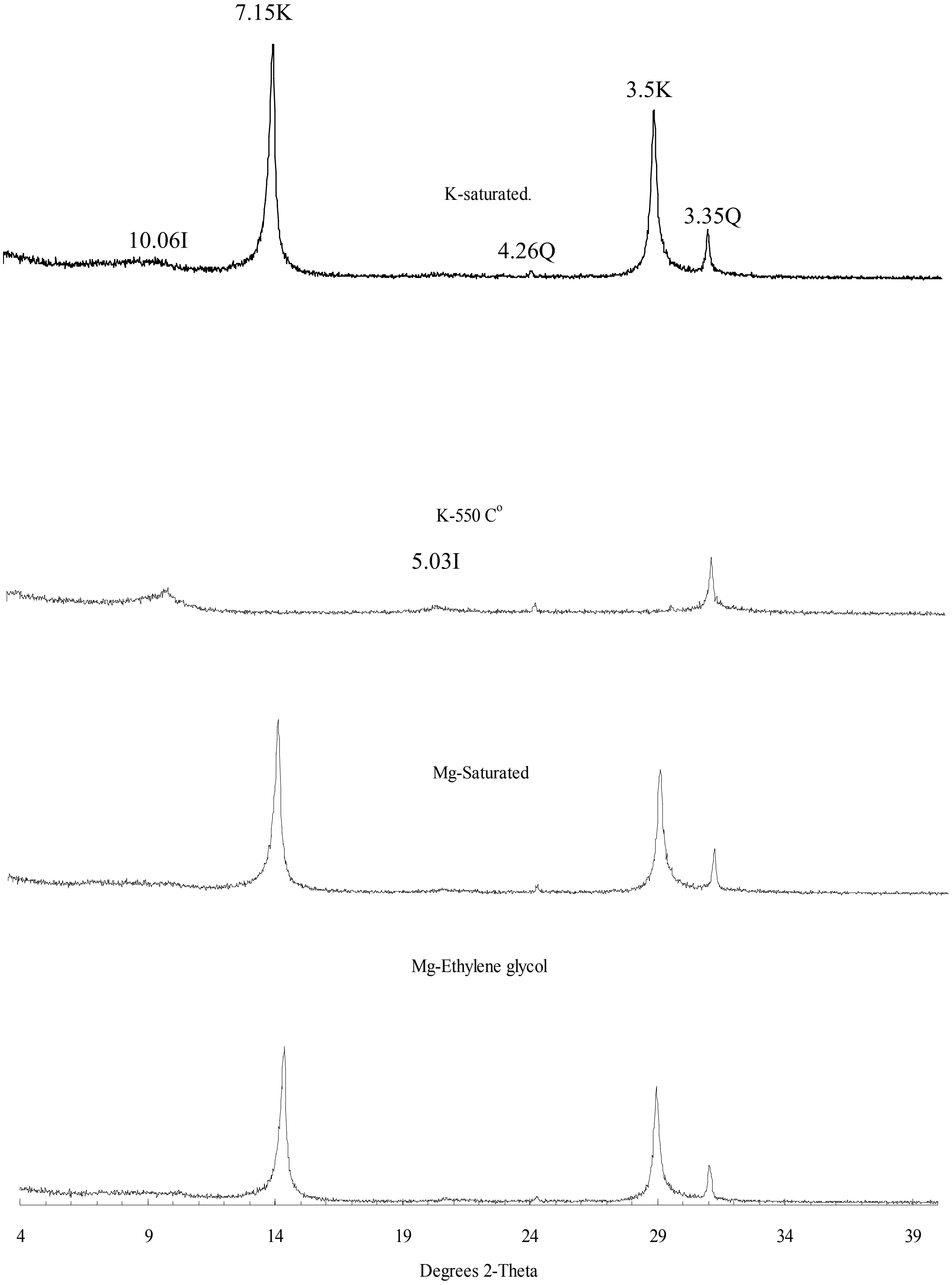
Treatment	Before 1^{st}	After 1^{st}	Before 2^{nd}	After 2^{nd}	After 3^{rd}
		Pc soil			
NH_4OAc-K (mg kg^{-1})					
0 kg K_2O ha^{-1}	91	62	85	65	57
125 kg K_2O ha^{-1}	105	87	124	82	70
Mixed acid-K (mg kg^{-1})					
0 kg K_2O ha^{-1}	130	108	114	100	83
125 kg K_2O ha^{-1}	164	143	151	106	95
		Lb soil			
NH_4OAc-K (mg kg^{-1})					
0 kg K_2O ha^{-1}	125	98	92	80	72
125 kg K_2O ha^{-1}	141	133	130	157	292
Mixed acid-K (mg kg^{-1})					
0 kg K_2O ha^{-1}	214	178	124	109	84
125 kg K_2O ha^{-1}	221	224	294	253	416



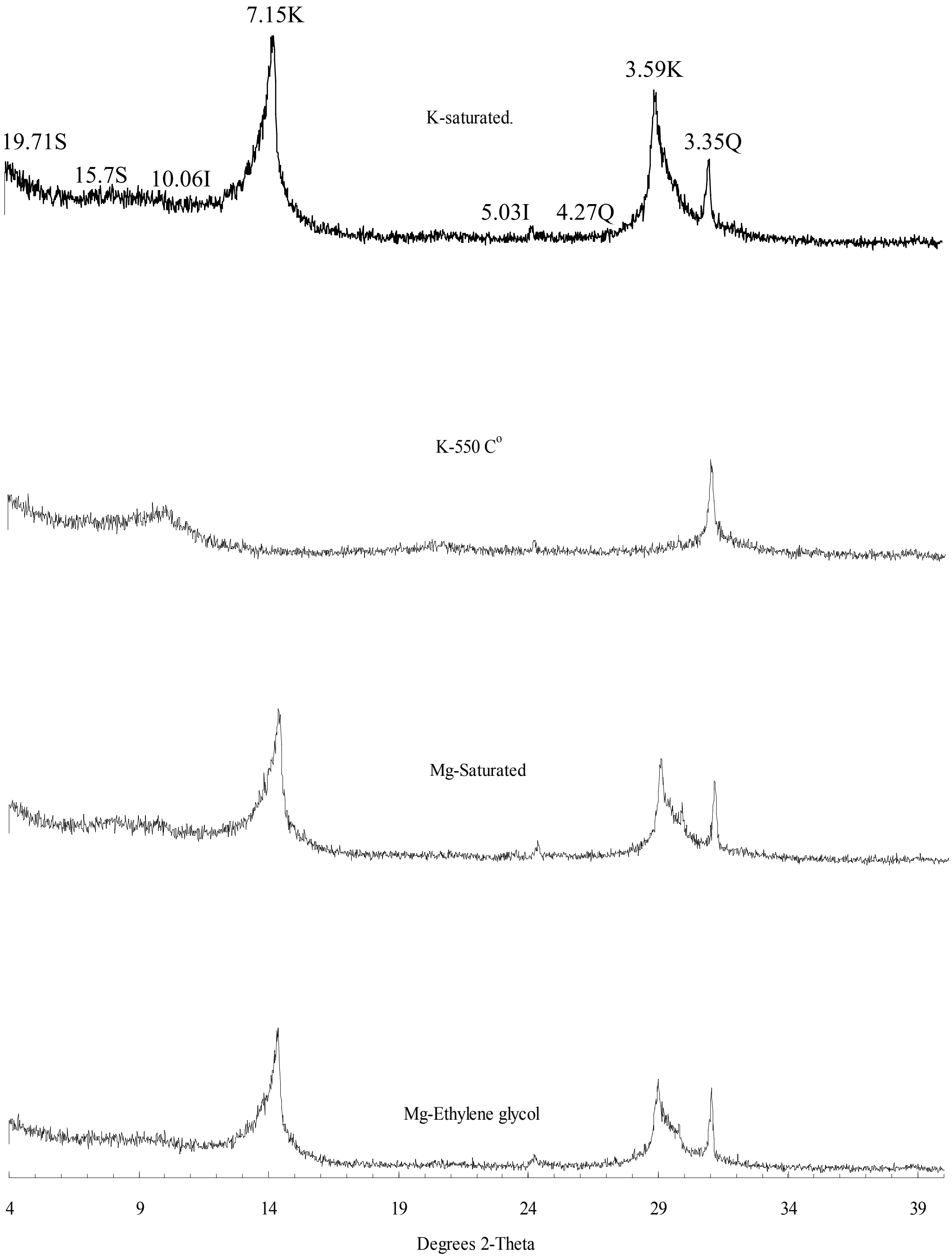
Appendix Figure 1 The X-ray diffraction pattern of clay in Phu Sana soil. The kaolinite was the dominant clay mineral (K=Kaolinite, V=Vermiculite, I= Illite, Q=Quartz).



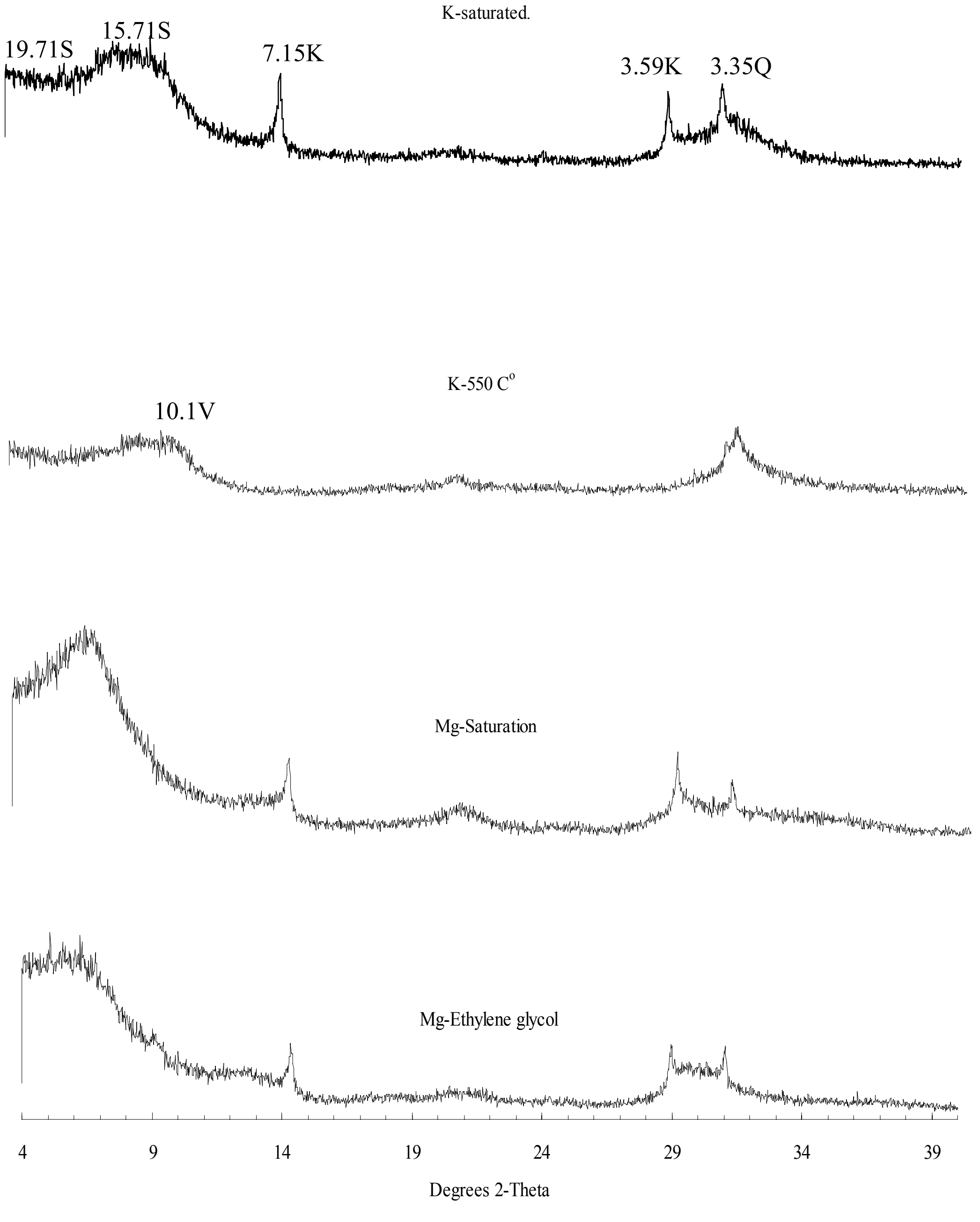
Appendix Figure 2 The X-ray diffraction pattern of clay in Satuk soil. The kaolinite was the dominant clay mineral (K=Kaolinite, I= Illite, Q=Quartz).



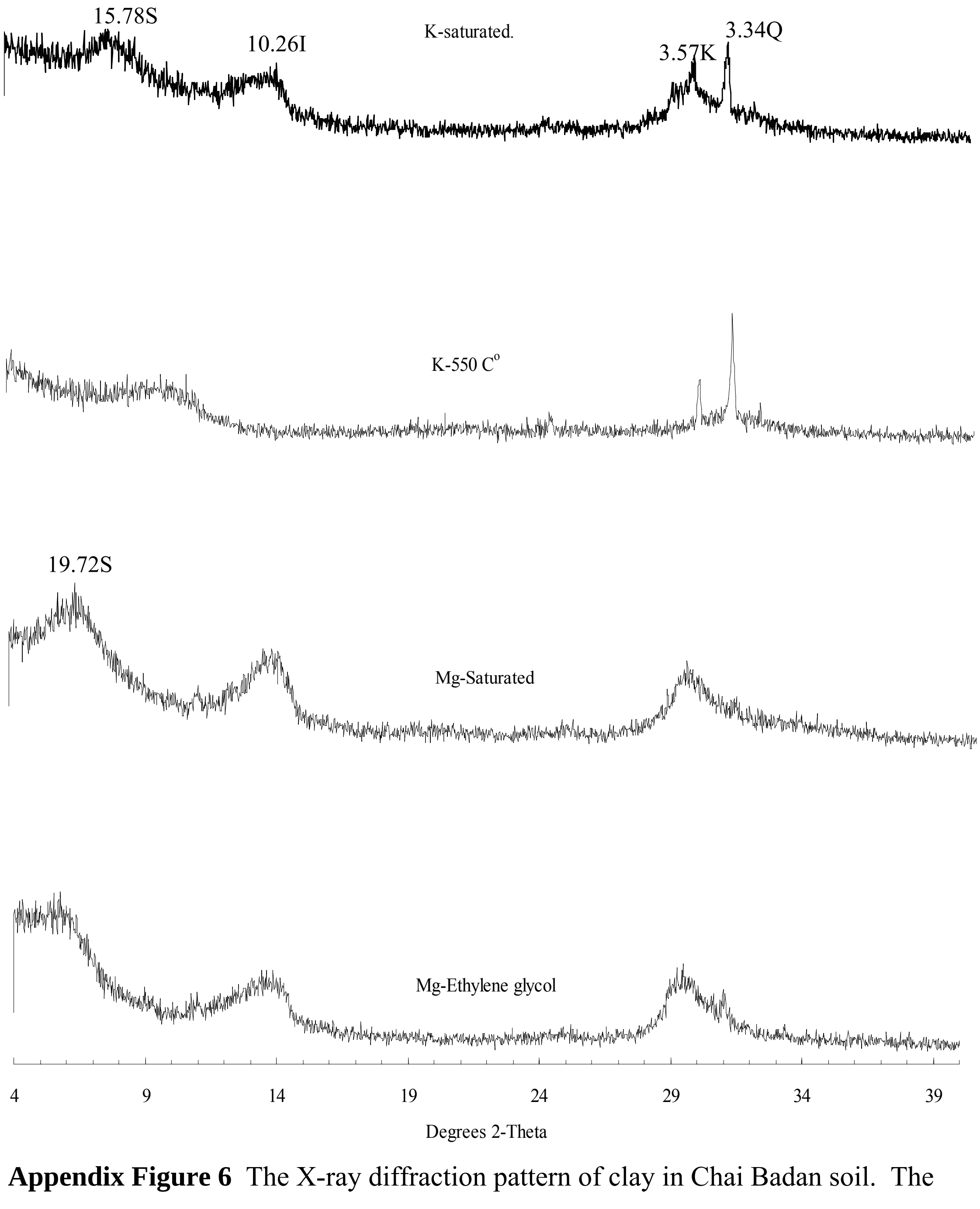
Appendix Figure 3 The X-ray diffraction pattern of clay in Warin soil. The kaolinite was the dominant clay mineral (K=Kaolinite, I= Illite, Q=Quartz).



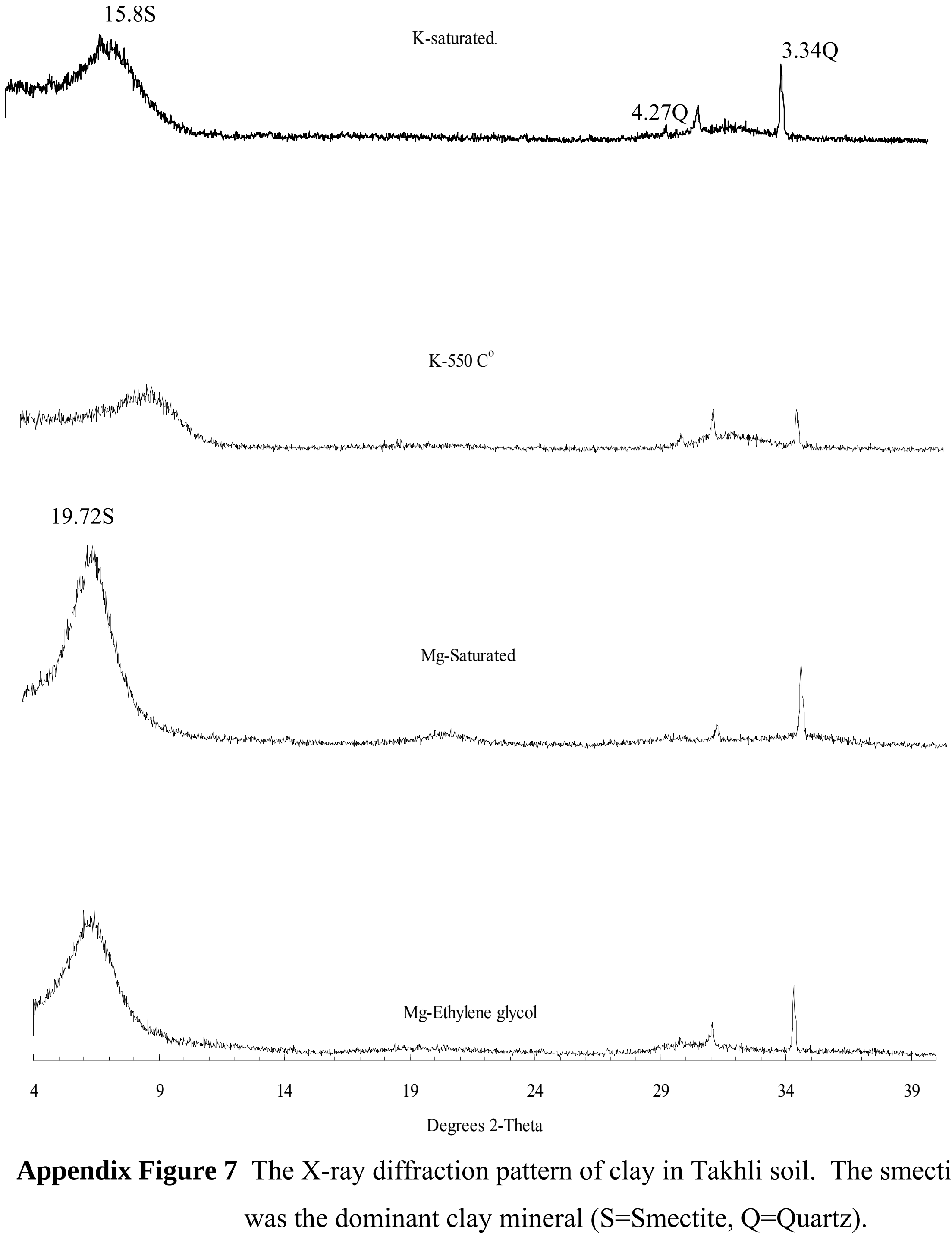
Appendix Figure 4 The X-ray diffraction pattern of clay in Pak Chong soil. The kaolinite was the dominant clay mineral (S=Smectite, K=Kaolinite, I= Illite, Q=Quartz).



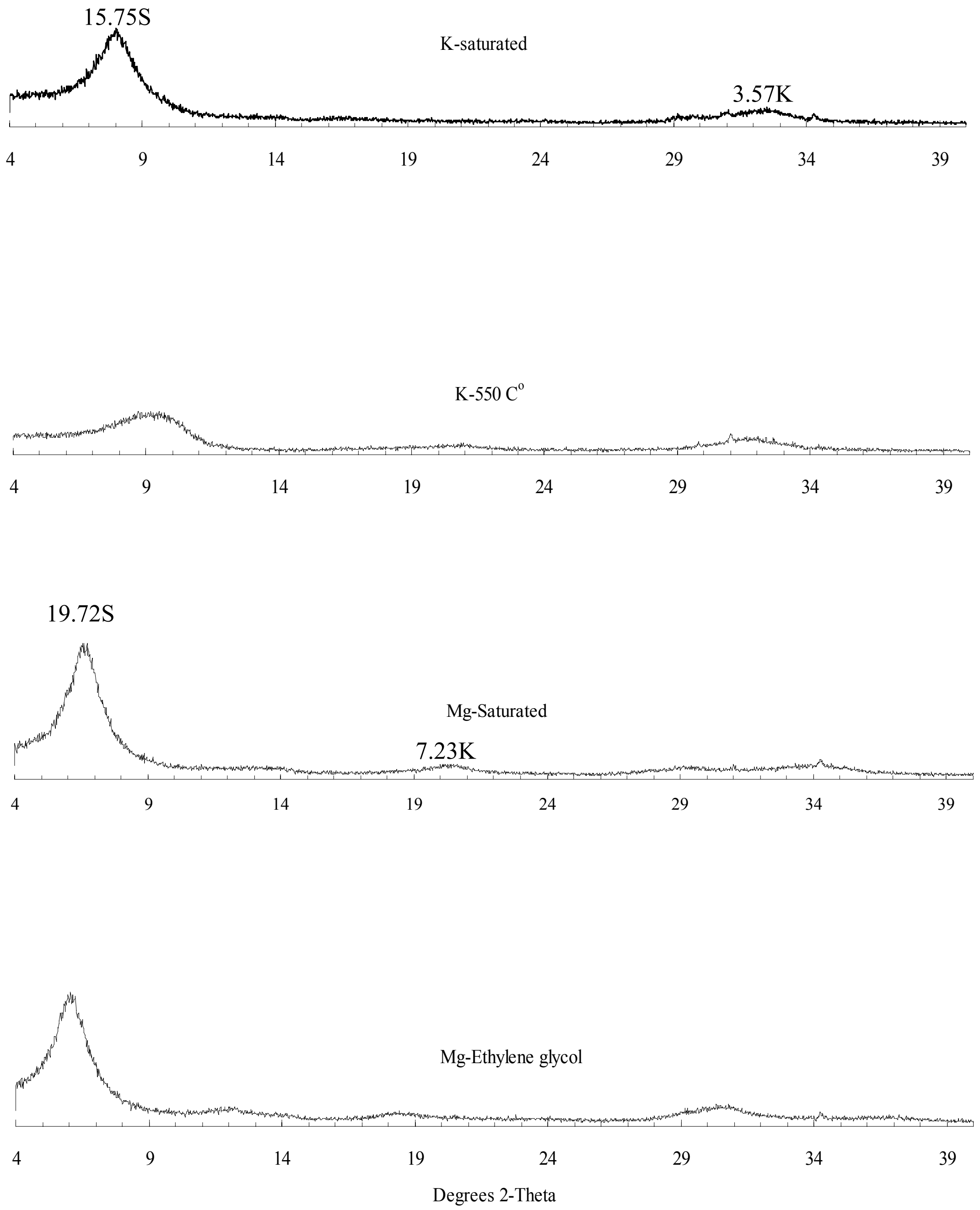
Appendix Figure 5 The X-ray diffraction pattern of clay in Lop Buri soil. The smectite was the dominant clay mineral (S=Smectite, V=Vermiculite, K=Kaolinite, Q=Quartz).



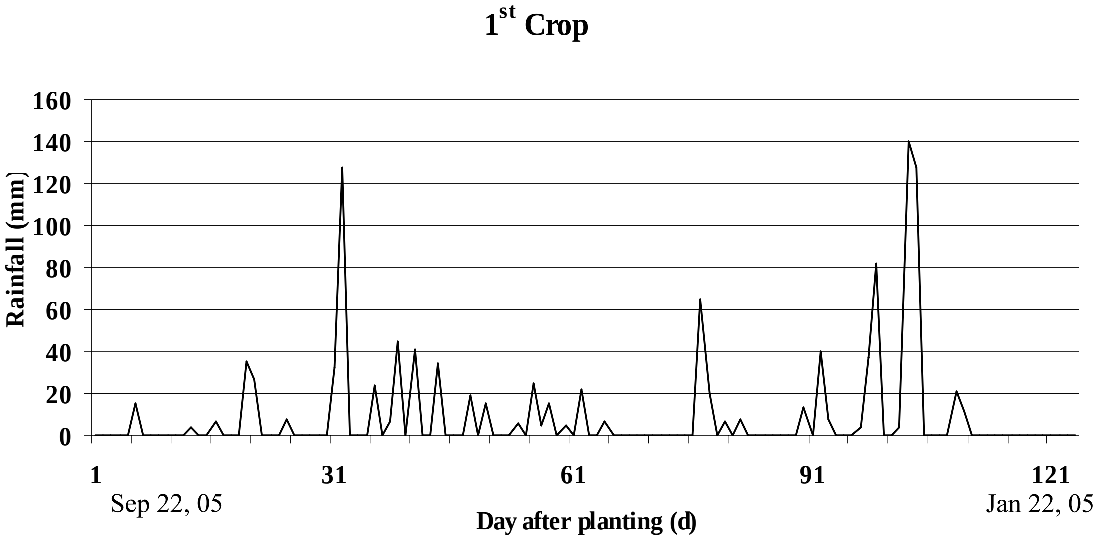
Appendix Figure 6 The X-ray diffraction pattern of clay in Chai Badan soil. The smectite was the dominant clay mineral (S=Smectite, I=Illite, K=Kaolinite, Q=Quartz).



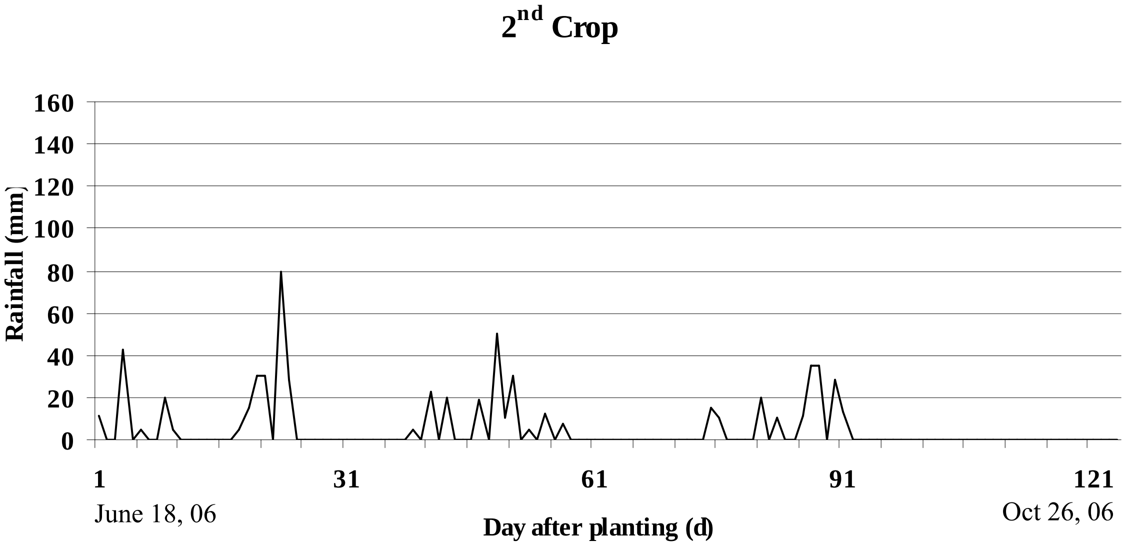
Appendix Figure 7 The X-ray diffraction pattern of clay in Takhli soil. The smectite was the dominant clay mineral (S=Smectite, Q=Quartz).



Appendix Figure 8 The X-ray diffraction pattern of clay in Lam Narai soil. The smectite was the dominant clay mineral (S=Smectite, K=Kaolinite).



Appendix Figure 9 Rainfall data during maize planting in Pak Chong and Lop Buri soils during 1st Crop.



Appendix Figure 10 Rainfall data during maize planting in Pak Chong and Lop Buri soils during 2nd crop.

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PUBLICATIONS :

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2) Nilawonk, W., T. Attanandana., A. Phonphoem., X Shuai and Y. Russell. 2008. Potassium Release in Representative Maize-producing Soils of Thailand. Soil Sci. Soc. Amer. J. 72: 791-797.