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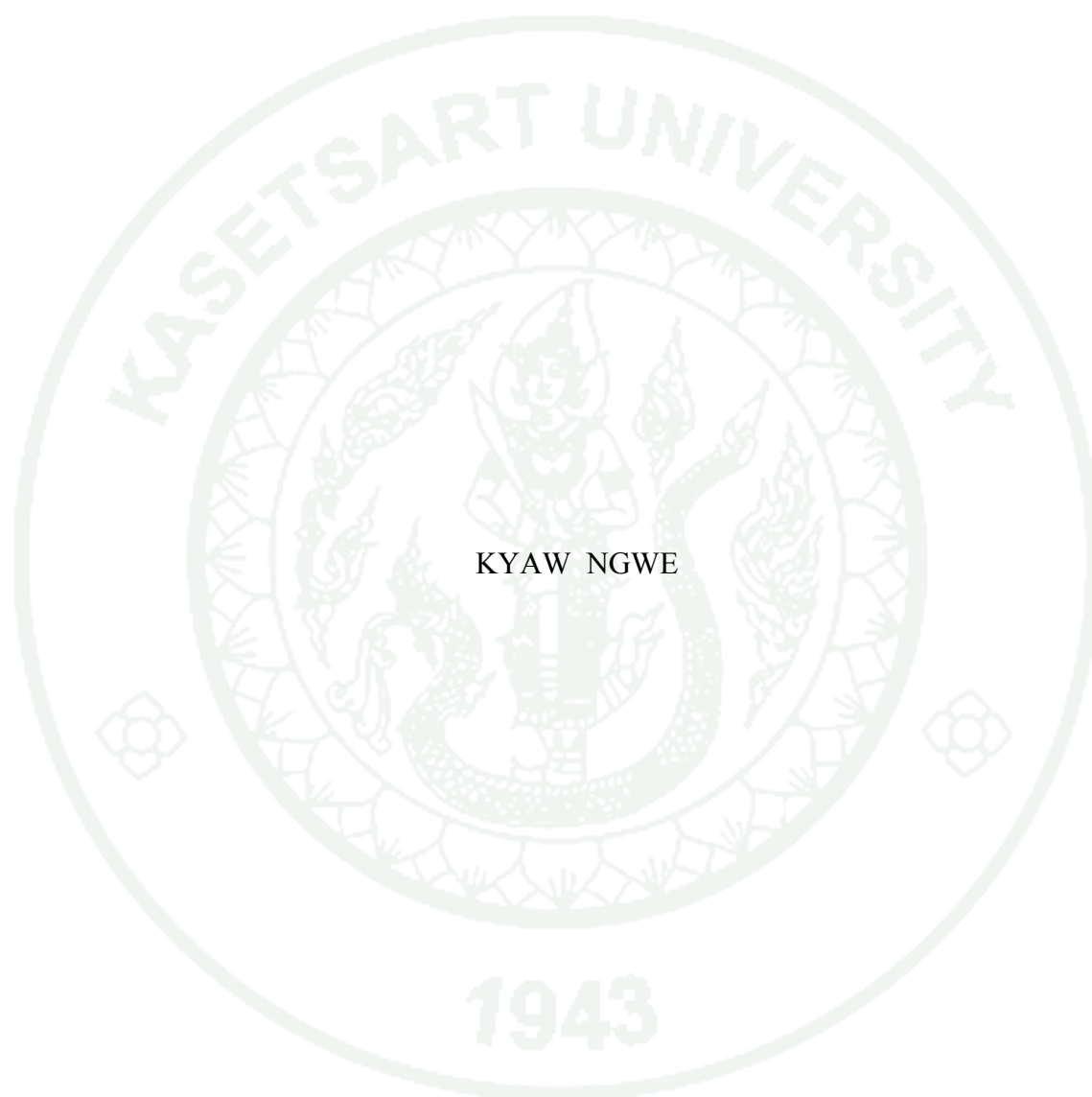
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THESIS

POTASSIUM CHEMISTRY IN PADDY SOILS UNDER
TROPICAL SAVANNA CLIMATE



KYAW NGWE

A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
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The purposes of the study on potassium chemistry of paddy soils developed under a tropical savanna climate were to determine different forms of potassium and to ascertain the influence of soil physical and chemical properties on their chemistry. Pedon analysis, field morphological and physicochemical and mineralogical properties were determined for five Vertisols including Ban Mi1 (Bm1), Ban Mi2 (Bm2), Chong Khae (Ck), Lop Buri (Lb) and Wattana(Wa) series; three Alfisols including Ubon (Ub), Tha Tum (Tt) and Doem Bang(Db) series; four Ultisols as Roi Et (Re), Phen (Pn), Renu (Rn) and Nakhon Phanom (Nn) series and one Inceptisol including Samut Prakan (Sm) series representative paddy soils in Thailand.

These paddy soils are acid to slightly alkaline and all soils have various textures which included clayey to sandy. They developed on local alluvium derived from limestone, wash and local alluvium from weathered sedimentary rocks, alluvium over marine deposits, mixed marine and local alluvium from metasedimentary rocks and recent alluvium on residuum from fine grained clastic sedimentary rocks.

The available K (soluble K + exchangeable K) was “very low” of Re, Pn, Rn (Ultisols), “low” in Ub, Tt, Db (Alfisols), Nn (Ultisols) and Sm (Inceptisol), “high” in Wa and Ck (Vertisols) and “very high” available K in Bm1 (Vertisol). Based on profile average, there was a high content of non-exchangeable K $671.63 \text{ mg kg}^{-1}$ and $545.70 \text{ mg kg}^{-1}$ in Ck (Vertisol) and Sm (Inceptisol) respectively. The lowest content of non-exchangeable K was found in Db (Alfisol) (11.76 mg kg^{-1}). The highest reserved K was found in subsoil of Sm compared with that in other soil profiles.

The highest total K with a profile average of 21729 mg kg^{-1} was found in the soil derived from alluvium over marine deposits Sm, while the lowest average of 172 mg kg^{-1} and 176 mg kg^{-1} were found in the soils derived from local alluvium partially derived from limestone, Wa and Bm2 respectively.

The content of available K (soluble K + exchangeable K) was observed from high to low in the order of Vertisols > Inceptisols > Alfisols > Ultisols. However, the total K content in the soils was as follows: Inceptisols > Ultisols > Alfisols > Vertisols. The clay content and organic matter and cation exchange capacity positively and significantly correlated with the soluble K plus exchangeable K in these soils, more than any other soil properties. Non-exchangeable K was significantly correlated with soluble K plus exchangeable K ($r=0.502^{***}$), reserved K ($r=0.635^{***}$) and total K ($r=0.654^{***}$) indicating that different forms of potassium along with organic matter maintenance should be carefully considered for management of potassium fertility in rice production.

Student's signature

Thesis Advisor's signature

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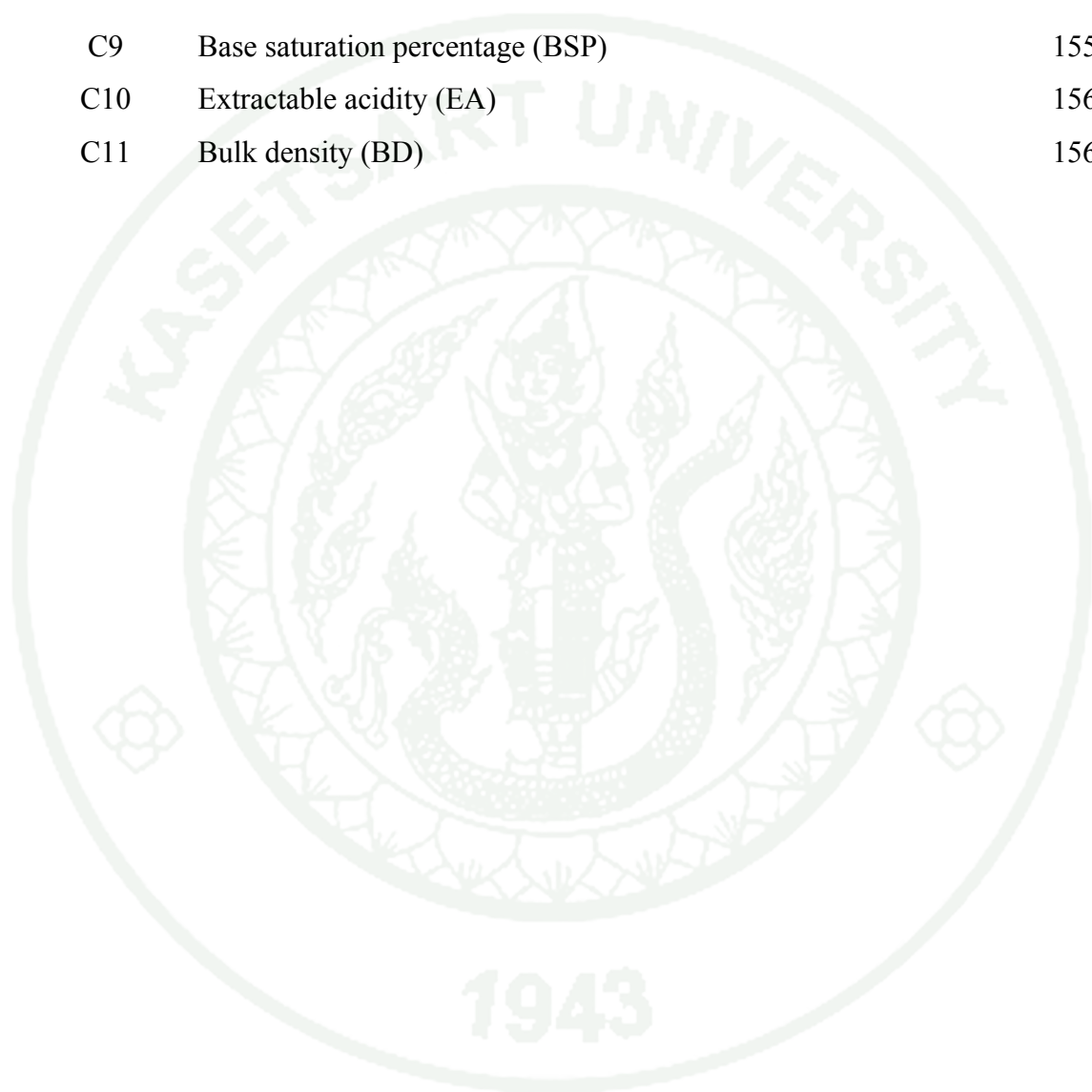
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POTASSIUM CHEMISTRY IN PADDY SOILS UNDER TROPICAL SAVANNA CLIMATE

INTRODUCTION

The combination of the climatic and physiographic conditions has made Thailand one of the most important rice-growing countries in the world (Wijnhoud *et al.*, 2003; Haefele and Konboon, 2009). Thailand has a total land area of about 51.4 million hectares of which 25 percent is lowlands where rice, the staple food crop, has been dominantly grown (Changprai, 1987). The total area for rice cultivation is estimated to be approximately 10 million hectares of which 9 million hectares are in lowlands (Kupkanchanakul *et al.*, 2001; Prakongkep *et al.*, 2007). The Central Plain is the main rice growing area of Thailand. Total K is high in central region lowland soils (Phetchawee *et al.*, 1985). However, the soils of Northeast Thailand are often described as universally infertile because of their light texture and low inherent nutrient contents (Kheoruenromne *et al.*, 1998; Haefele *et al.*, 2005).

Potassium is an essential element for plant growth, with its importance in agriculture well accepted (Kilmer *et al.*, 1968; Sparks and Huang, 1985). Potassium availability to plants is governed by the forms of K in the soils: water-soluble K, which is taken up directly by plants, exchangeable K, which is held by negative charges on clay particles and is available to plants, fixed K or non-exchangeable K, which is trapped between layers of expanding lattice clays, and lattice K or total K, which is an integral part of primary K-bearing minerals (Sparks and Huang, 1985; Shanwal and Dahiya, 2006). The distribution of K forms in the soil and the equilibrium between them determine the K status and K chemistry of the soil and potential of K supply to plants (Pavlov, 2007).

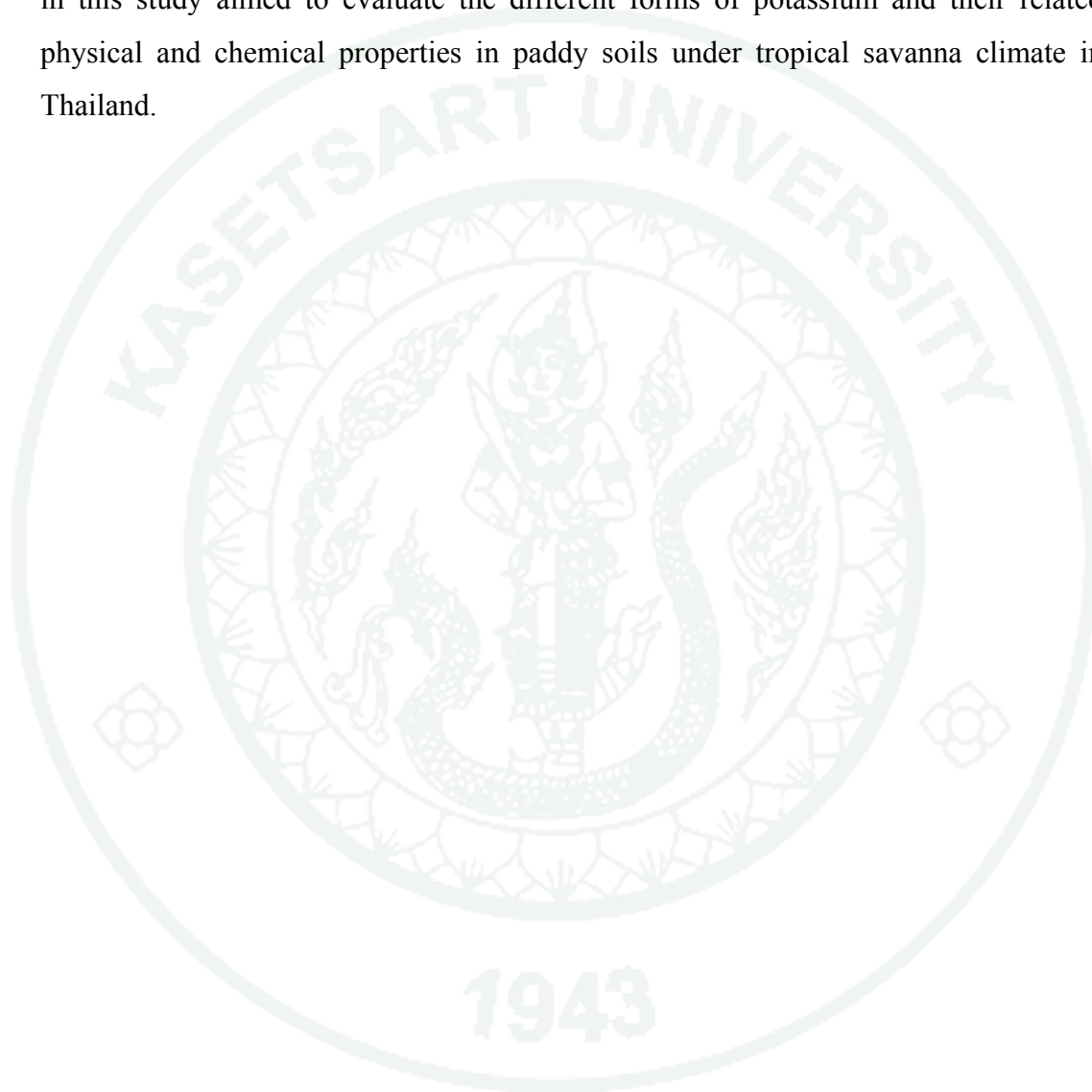
Rice (*Oryza sativa* L) is vital to more than half of the world's population who live in the Tropics and Subtropics (Fageria *et al.*, 2003). Food supplement is the major responsibility according to the increasing population. Enhancement of rice production

and sustainability are important features of grain production to benefit the world's people who depend on rice for their livelihood and as their staple food (Cassman *et al.*, 1995; Von Uexkull, 1995; Fagiea *et al.*, 1997). As the world population is still increasing and will be about 8.3 billion by 2025, and expansion of arable land is hardly realistic in densely populated Asia, crop intensification is the main vehicle for increasing food output (Cassman *et al.*, 2003). To provide enough food for the still growing population in Asia, large quantities of fertilizers, mainly nitrogen (N) and phosphorous (P) fertilizers, have been used in agriculture. In contrast, potassium (K), an essential element for crops, has not been paid much attention (Dobermann *et al.*, 1998). As a result, agricultural practice involves nil K application or low rate of K fertilization. Intensification of crop production, in combination with unbalanced fertilization has already resulted in depletion of potassium (K) in soils over large areas in India (Hasan, 2002; Singh *et al.*, 2002), Indonesia (Wihardjaka *et al.*, 1999) and other countries in Southeast Asia (Ladha *et al.*, 2003; Hoa *et al.*, 2006).

Potassium in soils mainly resides in K-bearing mineral. Total potassium reserves in soils are generally large although the distribution of K forms differs from soil to soil as a function of the dominant soil minerals (Mclean and Watson, 1985). The K-supplying power of a soil depends not only on content and kind of K-bearing minerals in the soil but also on the rate at which structural and fixed K becomes available to plants (Song and Huang, 1988). The different forms of potassium are interrelated and maintain equilibrium in the soil system (Shanwal and Dahiya, 2006). There are physical, chemical, biological, and climatic factors affecting K form and equilibrium of K in soil, which could be related to clay mineralogy (Sharpley, 1989; Barre *et al.*, 2008), texture (Pal *et al.*, 2001), moisture (Olk *et al.*, 1995), cation exchange capacity (CEC) (Sharpley, 1990; Sardi and Csitari, 1998), pH (Uribe and Cox, 1988), and concentration of other ions (Zawartka *et al.*, 1999) of the soil.

To understand the behavior of K in soil, many Thai scientists have already carried out researches on the content of potassium forms and availability (Darunsontaya *et al.*, 2012; Phetchawee *et al.*, 1985), potassium dynamic (Suwanarit,

1995), potassium fixation (Chittamart *et al.*, 2010), and the kinetics of potassium release (Nilawonk *et al.*, 2008; Darunsontaya *et al.*, 2010). Limited information is available, however, on the status and the distribution of various forms of potassium and their affiliation with physical and chemical properties of paddy soils. Researches in this study aimed to evaluate the different forms of potassium and their related physical and chemical properties in paddy soils under tropical savanna climate in Thailand.



OBJECTIVES

This study carried out on potassium chemistry in paddy rice growing soils under tropical savanna climate with the following objectives:

1. To study the potassium behavior of paddy rice growing soils under tropical savanna climate.
2. To study the relationship of potassium availability with other properties of paddy rice growing soils under tropical savanna climate.

Hypothesis

Due to the various development stages of paddy soils, knowledge on different forms of potassium and their related soil properties should enhance the understanding for the effective management of potassium fertility in these soils.

LITERATURE REVIEW

1. Soil Potassium Chemistry

Potassium is the seventh most common element in the earth's crust and is essential for plant growth (Sparks and Huang, 1985). Its availability to plants is varied and related in many ways to the crystal chemistry and structure of soil minerals (Rich, 1968). Potassium along with N and P are the three essential known after Von Liebig's published work in 1840 (Sparks, 2000).

Total K contents in soil range between 3000 and 100,000 kg ha⁻¹ in the upper 0.2 m of the soil profile. Of this total K content, 98% is bound in mineral form whereas 2% is in soil solution and exchangeable phases (Bertsch and Thomas, 1985; Sparks, 2000).

Igneous rocks of the earth's crust have higher K content than do the sedimentary rocks (Malavolta, 1985). Of the igneous rocks, it varies from 46 to 54 g K kg⁻¹ in granites and syenites to 7 g K kg⁻¹ in basalts and 2.0 g K kg⁻¹ in peridotites. Among the sedimentary rocks, clayey shales contain 30 g K kg⁻¹ whereas limestones have an average of only 6 g K kg⁻¹ (Malavolta, 1985; Sparks 2000).

Potassium among mineral cations required by plants, is the largest cation in nonhydrated size ($r = 0.133$ nm), and the number of oxygen atoms surrounding it in mineral structure is high (8-12), which suggests that the strength of each K-O bond is relatively weak (Sparks and Huang, 1985).

Potassium has a polarizability equal to 0.088 nm³, which is higher than Ca²⁺, Li⁺, Mg²⁺, and Na⁺ but lower than that of Ba²⁺, Cs⁺, NH₄⁺, and Rb⁺ ions (Rich, 1968; Sparks and Haung, 1985). Ions having higher polarizability are preferred in ion exchange reactions (Sparks, 2000). Potassium has a hydration energy of 142.5 kJ g⁻¹ ion⁻¹, which indicates little ability to cause soil swelling (Sparks, 2000; Rich, 1968).

2. Forms of Soil Potassium

Soil K can be divided into solution K, exchangeable K, fixed or non-exchangeable K and structural or mineral K (Sparks and Huang, 1985; Huang, 2000). The bulk portion of total soil K is in the mineral fraction, and exchangeable and non-exchangeable K is regarded as a small portion of the total K (Sparks and Huang, 1985). There are equilibrium and kinetic reactions between the four forms of soil K that affect the level of soil solution K at any particular time, and thus, the amount of readily available K for plant (Sharpley and Smith, 1988; Sparks, 2000; Brady and Weil, 2008) (Figure 1).

Equilibrium reactions existing between solution, exchangeable, non-exchangeable, and mineral phases of K profoundly influence K chemistry (Sparks and Carski, 1985).

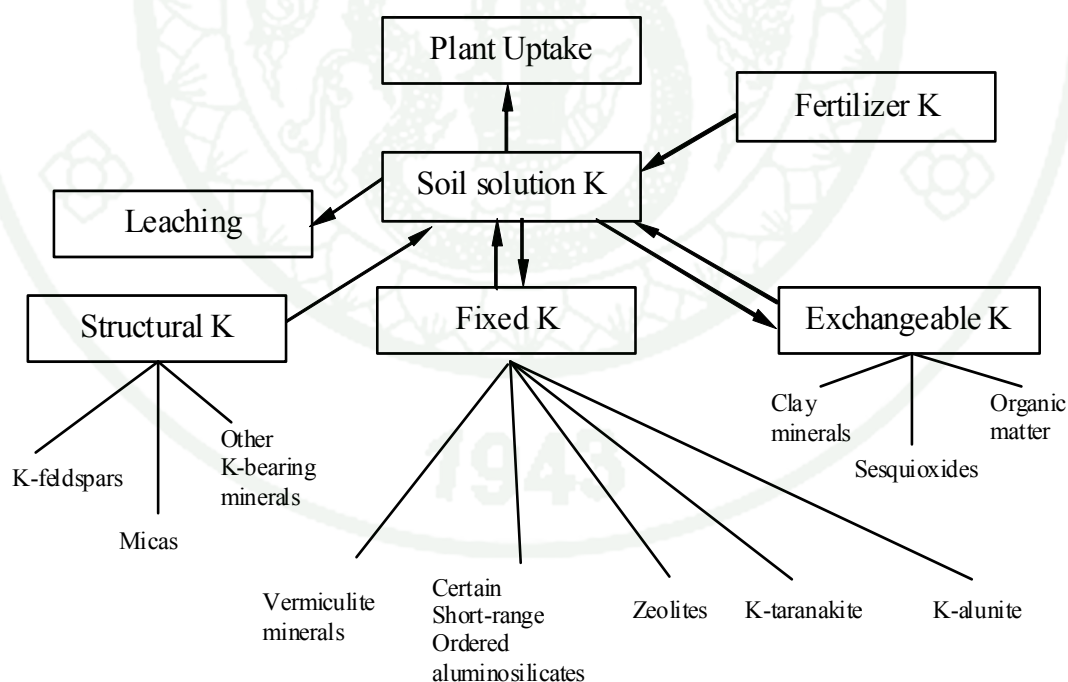


Figure 1 Interrelationship of various forms of soil K (modified from Sparks and Huang, 1985).

2.1 Solution potassium

Soil solution K is the form of K that is directly taken up by plants and microorganism and also is the form most subjected to leaching in soils (Sparks, 1980; Huang, 2005). The amount of soil solution K is generally too low to meet the requirement of K by a crop during a growing season (Sparks, 2000).

The level of solution K are affected by the equilibrium and kinetic reactions that occur between the form of soil K, the soil moisture content, and the concentration of bivalent cations in solution and on the exchanger phase (Sparks and Huang, 1985). Potassium concentration in soil solution also depends on the degree of replenishment of K in solution from non-exchangeable sites (Kirkman, *et al.*, 1994). Factors that decrease the K concentration of soil solution influence the release of K from the non-exchangeable K reserve (Hay *et al.*, 1976).

2.2 Exchangeable potassium

Exchangeable K is the fraction of the soil K that is electrostatically bound as an outer sphere complex to the surfaces of clay minerals, sesquioxides, and organic matter (Martin and Sparks, 1985). It exchanges readily with other cations and is readily available to plant (Selim *et al.*, 1976; Sparks, 2000). For optimum K nutrition of a crop, the replenishment of a K-depleted soil solution is affected by the release of exchangeable K from soils (Huang, 2005).

The exchangeable K is held by different bond strengths at the non-specific adsorption sites via planer or edge positions of clay minerals, and the negative charges created by carboxylic and phenolic groups of humus colloids compared to pH-dependent negative charges on clays (Kirkman *et al.*, 1994). The number of exchange sites derived from isomorphism is constant, but the negative charge on humic and amorphous clay colloids increases with increasing pH due to the dissociation of H⁺ from weak acid groups (Gast, 1977). Both kinetic and

thermodynamic factors affect the amount of K^+ held by clay minerals at exchange sites (Parfitt, 1992).

Other factors that affect the K^+ concentration on exchange sites are affinity of exchange sites for K^+ in relation to the nature of the soil surface and concentration of K^+ compared to the concentration of other cations especially bivalent cations, on exchange sites of clay minerals (Barber, 1985).

2.3 Non-exchangeable or fixed potassium

Non-exchangeable or fixed K differs from mineral K in which it is not bonded within the crystal structures of soil mineral particles (Sparks, 2000) Non-exchangeable K is held between adjacent tetrahedral layers of dioctahedral and trioctahedral micas, vermiculite and intergrade clay minerals such as chloritized vermiculite (Rich, 1972; Sparks and Huang, 1985; Sparks, 1987). Potassium becomes fixed because the binding forces between K and the mineral surfaces are greater than the hydration forces between individual K^+ ions (Sparks, 1987). This results in a partial collapse of the crystal structures, and the K^+ ions are physically trapped to varying degrees, making K release a slow, diffusion controlled process (Sparks, 2000).

Non-exchangeable K is not readily accessible for exchange with other cations in the soil solution and, therefore, is slowly available to plants (Sparks, 2000). However non-exchangeable K from reserves makes an important contribution to plant K^+ supply (Mengel and Busch, 1982; Mengel and Uhlenbecker, 1993).

Non-exchangeable K can be found in wedge zones of weathered micas and vermiculites (Rich, 1964). Release of non-exchangeable K to the exchangeable K form occurs when levels of exchangeable and soil solution K are decreased by crop removal and/or leaching and perhaps by large increases in microbial activity (Sparks, 1980; Spraks, 2000; Martin and Sparks, 1985).

According to Goulding (1987), there are several adsorption sites for K^+ on clay minerals (Figure.2). Adsorption site for K^+ on planar surfaces (p-site) has low K^+ selectivity, those on wedge (w-site) and edge positions (e-site) have medium K^+ selectivity, and sites at the interlayer (i-site) and crack positions (c-site) have high K^+ selectivity.

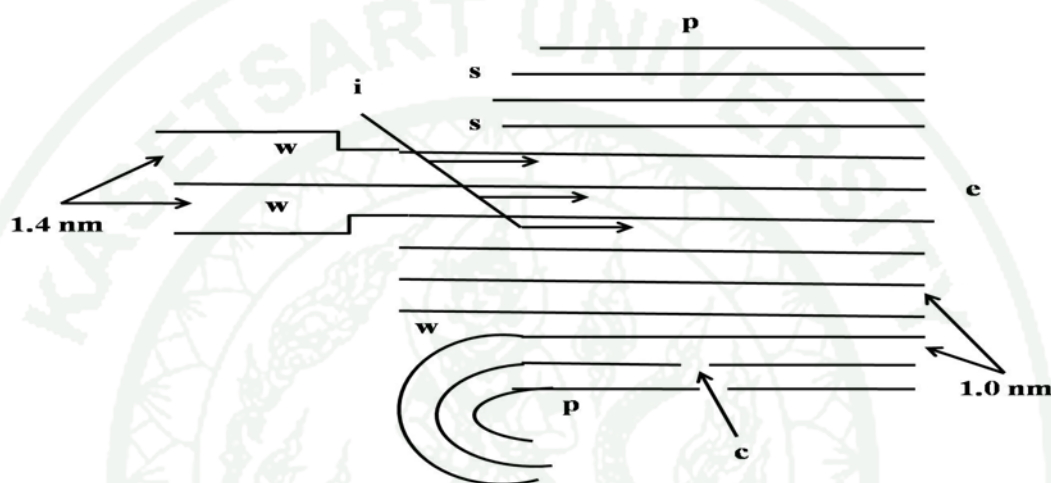


Figure 2 Model of 2:1 layer silicate with planar (p), edge (e), interlayer (i), wedge (w), crack (c), and step (s) potassium exchange sites.

Sources: Goulding (1987)

2.4 Structural or mineral potassium

Mineral K or structural K or Lattice K is normally considered to be of little significance for the K supply to plants during a single growing season (Barber, 1985; Askegaard *et al.*, 2004). The vast majority of the total soil K is the form of structural K mainly as K-bearing primary minerals such as feldspars (orthoclase and microcline) and micas (biotite and muscovite) (Sparks and Huang, 1985).

Structural K is generally assumed to be only slowly available to plants (Sparks, 2000). However, the dynamics of K release from these primary materials are

related to their crystal structure and atomic bonding (Sadusky *et al.*, 1987; Sparks, 1987).

The availability of structural K depends on the dynamics of K release from K-bearing micas and feldspars (Song and Huang, 1988; Zhou and Huang, 1995), the degree of weathering of these minerals (Parker *et al.*, 1989; Sparks and Huang, 1985) and the level of K in the soluble, exchangeable and non-exchangeable potassium forms (Huang, 2005). Complex interactions of soil mineralogical and textural factors, and biological processes, determine how readily structural K in soil minerals may become available for crop uptake (Hinsinger and Jaillard, 1993; Hinsinger *et al.*, 1993; Wang *et al.*, 2000).

3. Potassium Transformation

The dynamics of K in the soil-plant-water system, which is sometimes referred to as the cycle of potassium, has been adapted by Malavolta (1985) and Suwanarit (1995) is shown in Figure (3).

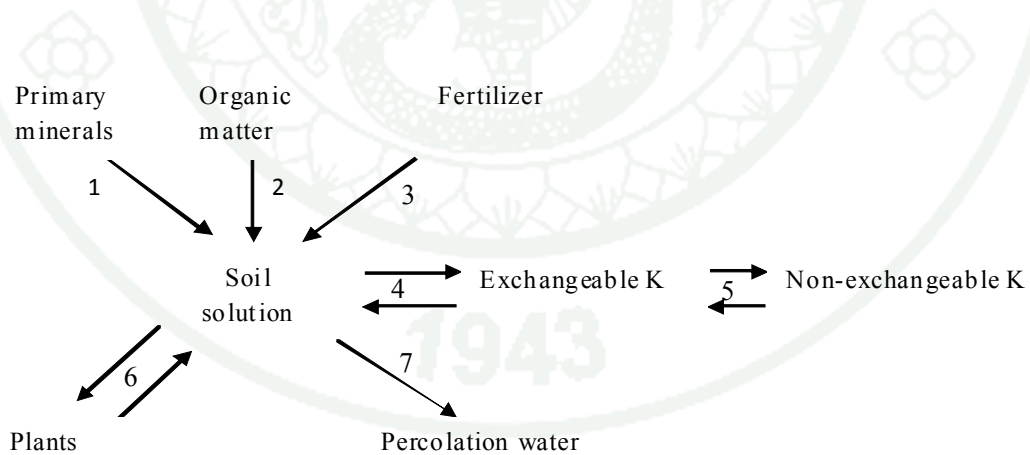


Figure 3 Schematic presentation of biochemical K transformation.

Sources: Malavolta (1985)

3.1 Type of potassium-bearing minerals

Potassium contained in the rocks as primary minerals represents the source for all other forms and sources of the element, including the minerals of secondary origin (Malavolta, 1985). A classification of the K-bearing minerals is given in Table (1).

Table 1 Classification of K bearing minerals.

Mineral	Chemical composition*	K content (g kg ⁻¹)
<u>Primary</u>		
Feldspars	KAlSi ₃ O ₈ (general)	
Orthoclase	(K, Na) AlSi ₃ O ₈	
Sanidine	KAlSi ₂ O ₆	
Microcline	(Na, K) AlSiO ₄	= 110
Leucite		
Micas		
Muscovite	KAl ₂ (AlSi ₃)O ₁₀ (OH) ₂	= 80
Biotite	K(Mg, Fe ²⁺) ₃ (AlSi ₃)O ₁₀ (OH) ₂	= 70
<u>Secondary</u>		
Illite**		
Diocahedral	(K _{0.58} X _{0.17})(Al _{1.55} Fe ⁺³ _{0.20} Mg _{0.25} Al _{0.50} Si _{0.50})O ₁₀ (OH) ₂ .nH ₂ O	
Triocahedral	(K _{0.45} X _{0.21})(Mg _{2.61} Fe ⁺³ _{0.10} Al _{0.29} Al _{1.05} Si _{2.95})O ₁₀ (OH) ₂ .nH ₂ O	
Allophane	SiO ₂ .Al ₂ O ₃ .2H ₂ O 2SiO ₂ .Al ₂ O ₃ .3H ₂ O	1.0-1.3

* X = cations held at edge sites; n = number of water molecules.

** Diocahedral, from muscovite; triocahedral, from biotite.

Sources: Rich (1972); Sticher (1972); Schroeder (1978); Malavolta (1985).

3.2 Weathering of K-bearing minerals

The principal K-bearing minerals in soils are feldspars and micas (Rich, 1968). Micas are more important than feldspars in supplying K to plants (Rich, 1972). Plant uptake of K is however related to the weathering of feldspars and micas in soil environments (Fanning, *et al.*, 1989; Gourley, 1999). The native K status of soils depends on their parent material and on the subsequent stage of weathering of that material (Bertsch and Thomas, 1985; Churchman, 2000; Huang and Wang, 2005).

3.2.1 Feldspars

Three types of hydrolysis of feldspars have been distinguished as shown in Figure 4: (1) total hydrolysis leading to the precipitation of $\text{Al}(\text{OH})_3$, solubilization of silica and liberation of K^+ ; (2) partial hydrolysis producing layer silicate clay as kaolinite, soluble silica and K^+ ; and partial hydrolysis producing layer silicate clay of monmorillonite type, soluble silica and K^+ (Huang, 1989; Suwanarit, 1995).

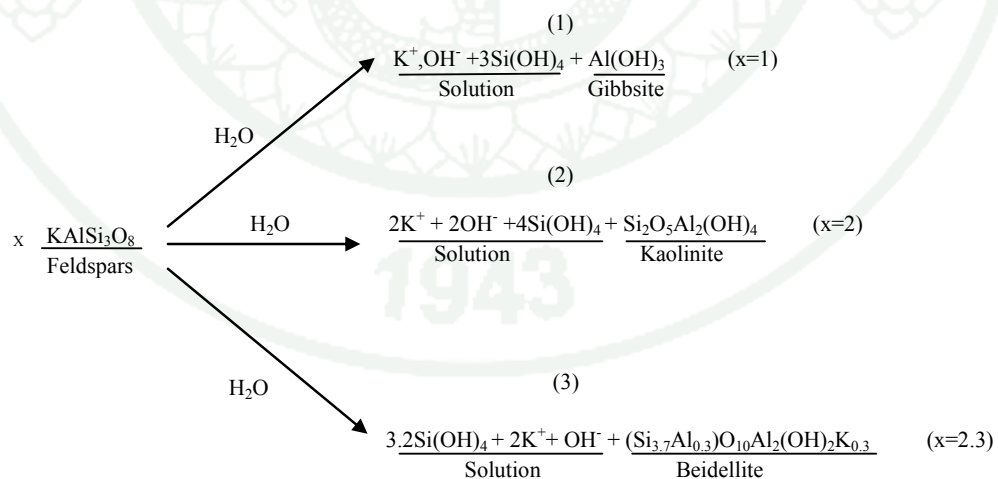


Figure 4 Hydrolysis of feldspars (modified from Suwanarit, 1995)

It is usually accepted that the sequence found during the weathering of feldspars can be shown in Figure 5.

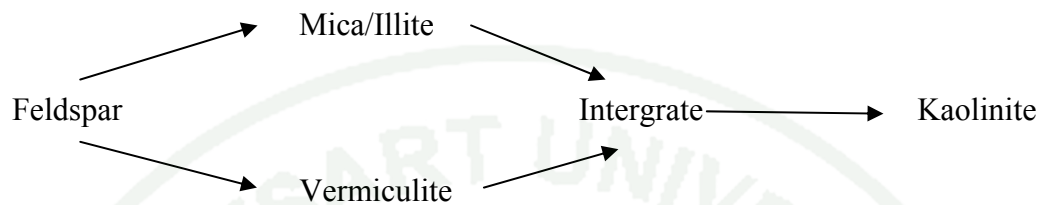


Figure 5 Weathering sequence of feldspars.

Source: Suwanarit (1995)

In the regions of high rainfall and high temperature and good drainage, the sequence can be short-circuited so that feldspars yield kaolinite directly, accompanied by dissolved silica and K^+ (Suwanarit, 1995). Malavolta (1985) pointed out that in the old, highly weathered soils of the Tropic and Subtropics, feldspars have already been broken down. This evidence suggests that release of K from feldspars in highly leached and strongly weathered soils would not be a significant source of K to plants growing on such soils (Suwanarit, 1995).

3.2.2 Micas

The transformation of micas into clay minerals, with a consequently gradual decrease in K content due to its liberation from the lattice is presented in Figure (6). Within the environment that exists in soil formation in the tropical regions, two different sequences have been postulated:

- (1) micas → vermiculite → kaolinite → gibbsite, and
- (2) mica → chloritized vermiculite → gibbsite → kaolinite (Malavolta, 1985; Karathanasis, 2006).

The weathering of the mica end member includes the transition through soil micaceous minerals, illite or hydrous mica, which can be described more simply as K-depleted mica ((Bertsch and Thomas, 1985). Further K depletion results in other clay mineral end members, the vermiculites and the smectites; however the interstratified or mixed layer transitional minerals are often intermediates during these weathering stages (Sawhney, 1977).

Varying contents of potassium are found in the mineral soils depending upon the kind of K-bearing minerals, their degree of weathering and the intensity of soil forming process (Kirkman, *et al.*, 1994). Most K in tropical and subtropical regions has been leached out of the soil profile because of strong weathering condition (Shanwal and Dahiya, 2006).

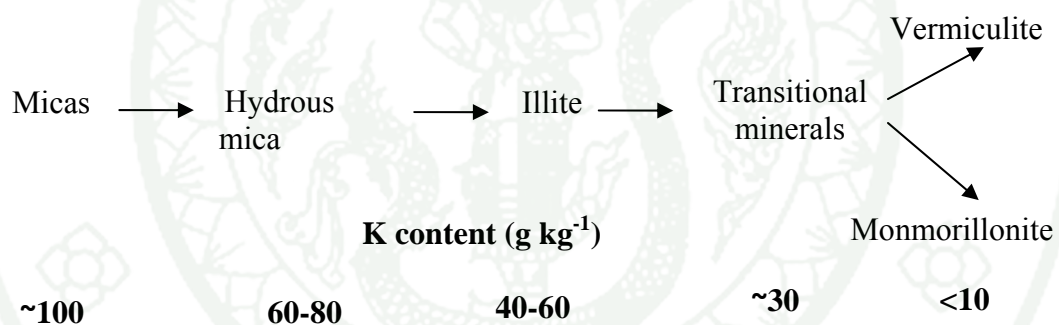


Figure 6 Transformation of mica into clay and changes in K content.

Source: Malavolta (1985).

4. Potassium Dynamics

The dynamic equilibrium between solution, exchangeable, non-exchangeable and mineral forms of K strongly influences K chemistry (Shanwal and Dahiya, 2006). The rate and direction of these reactions determine the release, fixation, plant uptake

and leaching of applied and native K (Sparks and Carski, 1985; Sparks, 2000; Huang, 2005).

The forms of soil K in the order of their availability to plants are solution > exchangeable > non-exchangeable > mineral (Sparks, 2000). The concentration of soil solution K is very low at any one time, thus the replenishment of the solution from other K-bearing phases is of great importance in determining a soil's K fertility status (Bertsh and Thomas, 1985).

The rate kinetics between the various forms of soil K determine the magnitude of leaching, release, and fixation in soil (Hinsinger, 2006). The kinetic reactions between exchangeable and non-exchangeable phases of K are slow (Sparks, 1987). Potassium release from minerals was found extremely slow as compared with reactions between soluble and exchangeable forms (Rich, 1972). The kinetics of K exchange in soils depend on the type of clay minerals present (Sparks, 1980).

In tropical soils, K dynamic depends on type and quality of clay, soil texture, pH, cation exchange capacity(CEC), and the ratio of $(Ca^{+2})+(Mg^{+2})/K$. These factors regulate the exchangeable/solution K ratio and K availability (Rosolem *et al.*, 2010).

5. Factors Affecting Potassium Availability

There are (a) solution-exchangeable K dynamics, (b) potassium fixation, (c) potassium release and (d) leaching of potassium in soils (Sparks, 2000).

5.1 Solution-exchangeable K dynamics

The rate and direction of reactions between solution and exchangeable forms of K determine whether applied K will be leached into lower horizons, taken up by plants, converted into unavailable forms or released into available forms (Sparks, 2000). The reaction rate between soil solution and exchangeable phases of K is

strongly dependent on the type of clay minerals present (Jardine and Sparks, 1984; Sparks, 2000). Vermiculite, smectite, kaolinite, and hydrous mica vary drastically in their ionic preferences, ion binding affinities, and types of ion exchange reactions (Sparks, 2000). Such fundamental differences in these clay minerals account for the varying kinetic of K exchange (Huang, 2005).

Kinetics of K exchange on kaolinite and smectite are usually quite rapid (Malcolm and Kennedy, 1969). In the case of kaolin clays, the tetrahedral layers of adjacent clay layers are held tightly by H bonds, thus, only planar external surface and edge sites are available for ionic exchange (Malcolm and Kennedy, 1969; Jardine and Sparks, 1984; Huang, 2005). With smectite, the inner peripheral space is not held together by H bonds, but instead is able to swell with adequate hydration, and thus allows for rapid passage of ions into the interlayer space (Sharpley and Buol, 1987; Huang, 2005). The kinetics of K exchange on vermiculite and micaceous minerals tend to be extremely slow. Both are 2:1 phyllosilicates with peripheral spaces that impede many ion exchange reactions (Sharpley, 1989; Sparks, 2000).

The amount and type of layer silicates in the clay fraction have a strong influence on storage capacity and binding force of exchangeable potassium. Both govern the equilibrium concentration of potassium in the external soil solution, its buffering by the adsorption and desorption equilibrium and thus the potassium supply to root (Mutscher, 1985). Soils containing vermiculite, smectite or illite have more K than do the soils containing kaolinite clays (Sharpley and Buol, 1987). Intensively cropped smectitic soils may be low in K and require K fertilization for optimum crop production (Havlin *et al.*, 2005).

5.2. Potassium fixation

The phenomenon of K fixation or retention significantly affects K availability (Rich, 1968; Seal *et al.*, 2006). The degree of K fixation in clays and soils depends on the type of clay mineral and its charge density, the degree of interlayering,

the moisture content, the concentration of K^+ ions as well as the concentration of competing cations and the pH of the ambient solution bathing the clay or soil (Rich, 1968; Sparks, 2000; Huang, 2005; Shanwal and Dahiya, 2006).

The major clay minerals responsible for K fixation are smectite, vermiculite, and weathered micas (Rich, 1968). In acid soils, the principal clay mineral responsible for K fixation is dioctahedral vermiculite (Sparks, 2000). Weathered micas fix K under moist as well as dry conditions, whereas some smectites fix K only under dry condition (Rich, 1968 and Sparks, 2000). The degree of K fixation is strongly influenced by the charge density on the layer silicate (Huang, 2005). Those with high charge density fix more K than those with low charge density (Sparks, 2000). Soil smectites have higher charge density and a greater probability of having wedge positions near micas-like zones where the selectivity for K is high (Rich, 1968; Huang, 2005).

Wetting and drying can significantly affect K fixation (Miklos and Cichel, 1993; Sardi and Csitari, 1998). The degree of K fixation or release on wetting or drying is dependent on the type of colloid present and the level of K^+ in the soil solution (Zeng and Brown, 2000). Potassium fixation by 2:1 clay minerals may be strongly influenced by the kind of adsorbed cations or anions within the system (Sucha and Siranova, 1991; Sparks, 2000). Montmorillonite clays are altered their swelling properties and fixed large amount of K after dried (Huang, 2005).

Martin *et al.* (1964) showed that at pH values up to 2.5 there is no fixation; between pH 2.5 and 5.5, the amount of K fixation increase very rapidly. Above pH 5.5, fixation increased more slowly (Thomas and Hipp, 1968; Sparks, 2000). At pH value > 5.5 , Al^{3+} cations precipitate as hydroxyl polycations, which increase in the number of OH groups as pH increases until they have a form like gibbsite (Hsu, 1989). At the pH 8, Al^{3+} does not neutralize the charge on the clay and can't prevent K fixation. Below pH 5.5, Al^{3+} and $Al(OH)_x$ species dominate. Below pH 3.5, H_3O^+ predominates (Sparks, 2000).

The increase in K fixation between pH 5.5 and pH 7.0 can be ascribed to the decreased number of $\text{Al}(\text{OH})_x$ species which decrease K fixation (Rich and Black, 1964; Murdock and Rich, 1972). At low pH, the lack of K fixation is probably due to large numbers of H_3O^+ and their ability to replace K (Thomas and Hipp, 1968; Huang, 2005).

5.3 Potassium release

The release of potassium from micas proceeds by two processes: (1) the transformation of K-bearing micas to expansible 2:1 layer silicates by exchanging the K with hydrated cations, and (2) the dissolution of the micas followed by the formation of weathering products (Sparks and Huang, 1985). The relative importance of these two mechanisms depends on the stability of micas and the nature of soil environments (Sodusky *et al.*, 1987; Troeh and Thompson, 2005; Hinsinger, 2006).

The activity of K^+ ions in soil solution around micas particles greatly influences the release of K from micas by cation exchange (Sparks, 2000). When the K level is less than the critical value, K is replaced from the interlayer by other cations from the solution (Henderson *et al.*, 1976). On the contrary, when the K is greater than the critical value, the micas expansible 2:1 mineral takes K from the solution (Scott and Smith, 1967). The critical K level is highly mineral dependent, being much higher for the trioctahedral minerals (Sparks, 2000).

The release of K on drying a soil is related to the clay fraction (Rich, 1968; Luo and Jackson, 1985; Jajali, 2007). When a soil is dried, the degree of rotation of weathered soil minerals, such as micas, may be changed. Thus, the K-O bond may be modified (Sparks, 2000). Dehydration of interlayer cations may permit a redistribution of interlayer cations, because Ca could now compete with K for wedge sites (Sparks, 2000). The presence of the hydroxyl Al interlayers may block or retard the interlayer diffusion of K ions and may change the b dimension of micas, the

degree of tetrahedral rotation, and the length and strength of K-O bond (Rich, 1968; Sparks, 2000; Huang, 2005).

Other factors that can affect K release from soils are leaching, redox potential (Eh), and temperature (Sparks, 2000). Leaching promotes the K release from K-bearing minerals by carrying away the reaction products. Therefore, leaching accelerates the transformation of minerals, e.g. micas, to expansible 2:1 layer silicates and other weathering product if the chemistry of leaching water favors the reaction (Song and Huang, 1988; Sparks, 2000).

Redox potential of soils could influence K release from micas since it has been pointed out that the tenacity with which K is held by biotite is greater after oxidation of its structural Fe (Sparks, 2000). The extent of the K release from biotite should be less in soil environments that oxidize Fe than in soil environments that reduce it (Huang, 2005).

Major elements in K-bearing feldspars do not exist in more than one valence state, thus prevailing Eh of a soil may not be of direct concern to chemical weathering of the feldspars (Sparks, 2000). However, the weatherability of feldspars can be affected by complexing organic acids that are vulnerable to oxidation. Therefore, the stability of feldspars may be indirectly related to the prevailing Eh of a soil (Sparks, 2000; Huang, 2005).

Complex interactions of soil mineralogical and textural factors, and biological processes, determine how readily structural K in soil minerals, or fixed K, may become available for crop uptake (Wang *et al.*, 2000; Simonsson *et al.*, 2007).

5.4 Leaching of potassium in soils

Soil solution K is either leached or sorbed by plant or soils. A number of factors influence the movement of K in soils including the CEC, soil pH, liming,

method and rate of potassium application, and absorption by plants (Munson and Nelson, 1963; Sparks, 1980).

The ability of a soil to retain applied K is highly dependent on the CEC of the soil. Thus, the amounts of clay and soil organic matter (SOM) in the soil strongly influence the degree of leaching (Alfaro *et al.*, 2004). Soil with higher CEC has a greater ability to retain added K, whereas leaching of K is often a problem on sandy soils (Olk and Cassman, 1995; Huang, 2005).

Retention of K can often be enhanced in sandy soils after application of lime; the CEC is increased as soil pH is increased (Sparks, 1980). Potassium was replaced by Ca on the exchange complex at higher levels of limestone application (Sparks, 2000). Less leaching of K occurred at pH 6.0 to 6.5 due to enhanced substitution of K for Ca than for Al, which was more abundant at low pH (Munson and Nelson, 1963).

Crops reduce K leaching by assimilating K into their tissue as well as by reducing water percolation through soil. Rainfall duration and intensity affects K movement in soil (Sparks, 1980). Downward water movement occurs in soil during a rain and upward movement occurs when water is lost at the surface through evapotranspiration (Sparks *et al.*, 1980). Upward movement of K salts may accompany this upward movement of water (Sparks, 2000; Huang, 2005).

6. Assessing Potassium Extractability and Availability

6.1 Chemical extractant for soil K forms

Methods to determine total K in soils use acids or a high temperature fusion to decompose the soil. The most widely employed digestion techniques for total elements in soil have used combination of HF and either H₂SO₄ or HClO₄ (Helmke and Sparks, 1996).

Exchangeable K is that K which is typically extracted with a neutral normal salt, usually 1.0 M NH_4OAc minus the water soluble K. In soils that are not saline, levels of water soluble K are minimal and can be ignored. However, in saline soils, the levels of water soluble K should be determined from a saturated extract or some similar extract and subtracted from the amount of K determined using 1 M NH_4OAc (Knudsen *et al.*, 1982).

There are number of chemical methods that can be employed to extract non-exchangeable K. These include boiling HNO_3 , H_2SO_4 , hot HCl, electro-ultrafiltration, Na tetraphenylboron with EDTA, and ion exchange resins such as H and Ca saturated resin. The most commonly used methods for extraction of non-exchangeable K is the boiling HNO_3 technique (Wanasuria *et al.*, 1981; Martin and Sparks, 1985; Helmke and Sparks, 1996).

One can quantitatively analyze for mineral K (K feldspars and micas) by using a selective dissolution method employing $\text{Na}_2\text{S}_2\text{O}_7$ fusion (Helmke and Sparks, 1996). A semiquantitative approach for measuring mineral K is to subtract the quantity of nonexchangeable K, using the boiling HNO_3 procedure, from the quantity of total K, using the HF digestion method (Parker *et al.*, 1989).

6.2 Soil test for potassium

Soil test extractants for K were developed to easily and rapidly measure K in soils and to estimate K availability (Sparks, 2000). Based on the amounts of extractable K, recommendations that are based on field test calibrations can then be made on the amount of K that is needed to maximize plant yield (Huang *et al.*, 2005).

Soil tests for K usually estimate the quantity of solution and exchangeable K, and since acids are usually employed as extractants, some non-exchangeable K and mineral K are also extracted (Helmke and Sparks, 1996; Sparks, 2000).

6.3 Q/I analysis

The intensity of K in a soil at equilibrium with its soil solution could best be defined by the ratio $a_K/(a_{Ca} + a_{Mg})^{1/2}$ of the solution. This equilibrium activity ratio for K or AR^k has often been used as a measure of K availability to plants (Sparks, 2000; Saleque *et al.*, 2008).

Beckett (1964) suggested that exchangeable K is held by two distinct mechanisms. The majority is held by general force fields comparable with those that hold exchangeable Na^+ or Ca^{2+} . A small proportion is held at sites offering a specific binding force for K but not for Ca^{2+} and Mg^{2+} . The electrochemical potential of exchangeable K in the diffuse double layer dictates the chemical potential of K in the soil solution (Bohn *et al.*, 2001; Haung, 2005). The K activity is also affected by the difference in electrical potential across the diffuse double layer that surrounds the exchange complex (Beckett, 1964; Sparks 2000; Haung, 2005).

The relationship of the amount of exchangeable K to AR^k must be specified to accurately describe the K status of a soil (Beckett, 1964). Different soils showing the same value of AR^k may not possess the same capacity for maintaining AR^k while K is removed by plant roots (Le Roux and Sumner, 1968). Soils can have the same AR^k but contain different amounts of labile K (Sparks and Liebhardt, 1981). Therefore, one must include not only the current potential of K in the labile pool but also the way in which the potential depends on quantity of labile K present (Huang, 2005). These findings brought about the Q/I curves where the ratio of $a_K/(a_{Ca}+a_{Mg})^{1/2}$ is related to the change in exchangeable K to obtain the effect of quantity (exchangeable K) on intensity (Sparks, 2000; Huang, 2005). The Q/I concept has been widely disseminated in the soil literature in studying soil K status (Singh, *et al.*, 1978; Evangelou *et al.*, 1994; Sparks, 2000; Ranjha *et al.*, 2001).

7. Potassium Availability in Paddy Soils

Paddy soils provide the staple diet for nearly half the world's population. Worldwide, the total harvested rice area covers approximately 150 million hectares, and approximately 90% of this rice area is situated in Asia, with a similar share in rice production (Witt and Haefele, 2005). Rice is grown in wide variety of soils with varying moisture regimes ranging from moisture deficiency to flooding excesses that vary from a 30 to 600 cm water depth (De Datta, 1981). Rice is grown under a wider variety of climate, soil and hydrological conditions than any other crop; therefore a paddy soil can be any type of soil (Kyuma, 2004) except Gelisols.

The physical, physiochemical, and biochemical changes that accompany this wide range of soil conditions are unique and important in determining a soil's suitability for rice production (De Datta and Mikkelsen, 1985).

The extensive research of Ponnamperna (1972, 1976), Patrick and Mikkelsen (1971), and De Datta (1981) are summarized in the following important chemical and electrochemical changes occurring in flooding soils:

1. Depletion of molecular oxygen.
2. Chemical reduction of the soil or a decrease in redox potential.
3. Increase in pH of acid soils and decrease in pH of calcareous and sodic soils.
4. Increase in specific conductance.
5. Reduction of Fe^{3+} to Fe^{2+} and Mn^{4+} to Mn^{2+} .
6. Reduction of NO_3^- and NO_2^- to N_2 and N_2O .
7. Reduction of SO_4^{2-} to S^{2-} .
8. Increase in supply and availability of N.
9. Increase in availability of P, Si, and Mo.
10. Decrease in concentration of water soluble Zn and Cu.
11. Generation of CO_2 , CH_4 and toxic reduction products such as organic acids

(-COOH) and H₂S.

Flooding, increases K⁺ concentration in the soil solution; under reduction conditions, Fe²⁺ and NH⁴⁺ are released by various processes and displace K⁺ from exchange sites, thus increasing the concentration of K⁺ in solution and, therefore, its availability to rice (Patrick and Mikkelsen, 1971).

Available K is kept at relatively high levels in flooded soils because large amounts of soluble Fe²⁺ and Mn²⁺ ions brought into solution displace cations from the clay complex, and exchangeable K⁺ is then released into the soil solution (De Datta and Mikkelsen, 1985).

Potassium has received much less attention in rice research than nitrogen, despite the fact that total K uptake can be greater than N uptake (Dobermann *et al.*, 1996). For rice yields in the range of 9-10 t ha⁻¹, total K uptake may be as high as 250-300 kg ha⁻¹, compared with 160-220 kg ha⁻¹ of N (Yoshida, 1981; De Datta and Mikkelsen, 1985; Dobermann *et al.*, 1996, Dobermann *et al.*, 1998, Dawe *et al.*, 2000).

Most soils of the alluvial floodplains in Asia were generally regarded as high in extractable K, and it was thought that additional K supply from irrigation water would make K a rare limiting factor in irrigated rice systems (De Datta and Mikkelsen, 1985, Kawaguchi and Kyuma, 1975). However, the seasonal and annual crop demand for K has increased markedly and K balances have shifted towards the negative side (Von Uexkuell, 1995; Dobermann *et al.*, 1996).

Yield response of rice to K fertilization becomes more evident after years of intensive cropping, particularly when both N and P are applied or when the K-supplying capacity of the soil is low (Dobermann *et al.*, 1998; Dobermann *et al.*, 2003; Hoa *et al.*, 2006). Consequently, soil K deficiency in paddy fields is becoming

one of the key limiting factors for sustainable agricultural production (Chen *et al.*, 1992; Dobermann and White, 1999; Cakmak, 2002; Sheldrick *et al.* 2003)

Prasad and Prasad (1992) reported that critical levels of 1M ammonium acetate-extractable potassium have vary from 0.17-0.21 cmol K kg⁻¹ for paddy rice soils in India. Soils have been grouped into three categories of low, medium and high on the basis of 1M ammonium acetate extractable potassium values; soils analyzing < 55 mg K kg⁻¹ soil are rated as low with respect to available potassium and soils analyzing >110 mg K kg⁻¹ soils are rated as high in available potassium (Singh *et al.*, 2004).

Dobermann and Fairhurst, (2000) reported that critical values of NH₄OAc-extractable K in lowland rice soil with general applicability are as follows:

- 1) Exchangeable K < 0.15 cmol_ckg⁻¹, low K status, respond to K fertilizer certain,
- 2) Exchangeable K 0.15 – 0.45 cmol_ckg⁻¹, medium K status, respond to K fertilizer probable, and
- 3) Exchangeable K > 0.45 cmol_ckg⁻¹, high K status, respond to K fertilizer only at very high yield levels (> 8 t ha⁻¹).

Greenland (1985) reported that potassium is unlikely to be used economically for rice-based cropping systems unless those soils where it is needed are adequately defined, and the requirements of the cropping system determined.

8. Function and Deficiency of Potassium in Plant

The functions of K in growth and yield formation are biophysical and biochemical characters. Potassium is an essential cation in any process which is activated by proton pumps (photosynthesis, phloem loading) and K is needed for the activation of many enzymes (Liebhardt, 1968; Mengel *et al.*, 2004).

Potassium has essential functions in osmoregulation, enzyme activation (Suelter, 1985), regulation of cellular pH, cellular cation-anion balance, regulation of transpiration by stomata, and the production of photosynthesis (Huber, 1985; Jackson and Volk, 1968; Marschner, 1995). On the whole rice plant, potassium increases the number of spikeletes per panicle, percentage of filled grains and 1000 grain weight (Bahmaniar *et al.*, 2007). Potassium improves the rice plants tolerance of adverse climatic condition, lodging, insect pest and disease because K is very mobile within the plant and is translocated to young leaves from old senescing leaves (Dobermann and Fairhurst, 2000; Williams and Smith, 2001).

An important role of K in plant growth is its influence on water use efficiency (Mengel *et al.*, 2004). The process of opening and closing of stomata is regulated by K concentration in cell which surrounds the stomata (Leonard, 1985). A shortage of K causes the stomata to open only partially and to be slower in closing. This increases the stress from drought and K helps to control ionic balance and also overcome the disease incidence (Huber and Army, 1985; Mengel *et al.*, 2004; Bahmanair *et al.*, 2007). These functions explain why K is such a universal nutrient for the production of high yields (Dobermann and Fairhurst, 2000).

Potassium deficiency in rice is more common under the following crop management practices:

- 1) Excessive use of N or N plus P fertilizer with insufficient K application.
- 2) In direct sown rice during early growth stages, when the plant population is large and root system is shallow.
- 3) Cultivars differ in susceptibility to K deficiency and response to K fertilizer (Dobermann and Fairhurst, 2000).

Soils particularly prone to K deficiency include 1) soils inherently low in K and 2) soils on which K uptake is inhibited (Dobermann and Fairhurst, 2000). Coarse-textured soils with low CEC and small K reserves and highly weathered acid soil with

low CEC and low K reserves, e.g., acid upland soils (Ultisols or Oxisols) and degraded lowland soils are soils inherently low in K (Doberman *et al.*, 1998). Lowland clay soils with high K fixation due to the presence of large amounts of 2:1 layer clay minerals (illitic clay soils, vermiculitic clay soils), soils with a large K content but very wide (Ca + Mg):K ratio (e.g: some calcareous soils) and result in stronger K adsorption to cation exchange sites and reduce the concentration of K in the soil solution are soils on which K uptake is inhibited (Dobermann and Fairhurst, 2000).

Potassium deficiency is frequently occurred on poor drained soils, partly because toxic substances produced in highly reductive soils, retard potassium uptake and partly because less soil K is released under poorly drained conditions (Yoshida, 1981).

Increasing rice yields through high yielding cultivars and more intense cropping depletes available K faster than it can be replenished naturally (Neue, 1989). Potassium response is becoming increasingly apparent in flooded rice soils in South and Southeast Asia (De Datta and Gomez, 1982).

9. Potassium Availability of Paddy Soils in Thailand

The total area of Thailand is approximately 513120 km² lying between 5° 40' and 20° 30' N latitudes and 97° 70' and 105° 45' E longitudes. Thailand is divided into 6 physiographic regions: Central Plain, Southeast Coast, Northeast Plateau, Central Highlands, North and West Continental Highlands and Peninsula Thailand. There are three main seasons: rainy from May to October, cool and dry from November to February, and hot and humid from March to May, but the Peninsula and Southeast Coast have no pronounced dry season. Temperature is even throughout the country (26-28°C) except in the North and at high altitude. Most of the continental Thailand is under tropical savanna ("Koppen-Aw"), the northern mountain and higher altitudes under humid subtropical (Cw); the eastern most part of the Southeast Coast, western

mountains and Peninsular Thailand where rainfall is very heavy has tropical monsoon climate (Am) (Phetchawee *et al.*, 1985).

The combination of the climatic and physiographic conditions has made Thailand, one of the most important rice- growing countries in the world. Today, rice is not only the staple food of the Thai people but also one of the high-ranking export commodities of the country (Attanandana *et al.*, 1996). In Thailand, total land area of 25 percent is lowlands where rice, the staple food crop, has been dominantly grown (Changprai, 1987). The total area for rice cultivation is estimated to be approximately 10 million hectares of which 9 million hectares are in lowlands (Kupkanchanakul *et al.*, 2001; Prakongkep *et al.*, 2007).

The Central plain borders are hilly in the east and west, with the gulf of Thailand in the south, and Nakhon Sawan Province in the north. The large plain of the central region consists of unconsolidated Quaternary sediments. The broad delta of the Chao Phraya river system is located in the south (at about 1-3m above sea level), and is known as the Bangkok Plain (Yoothong *et al.*, 1997). Marine sediments are found in the southern part of the Bangkok plain, while in the middle of the plain brackish water sediments dominate. In the east, limestone and volcanic rocks (andesite, basalt and rhyolite) occur (Takaya, 1971; Rua and Nutalaya, 1980; Takaya and Thiramongkol, 1982). The clay mineral assemblage in the marine sediments of the tidal swamp areas in the south is smectite-kaolinite-illite in composition. Soils of the flood plain are composed of kaolinite, smectite and illite. Vermiculite, chlorite, interstratified clay minerals, goethite and quartz are also present in minor quantities in some soil series. Soils in the western part of the Central Plain which derive from marls and volcanic rocks are mainly composed of smectite clays (Yoothong *et al.*, 1986). Kheoruenromne and Suddhiprakarn (1984) studied the genetic factors for Alfisols in the Mae Klong Basin (Western Thailand), and concluded that the type of parent material and the topographic variation of landforms in the past are the main factors causing genetic differences among the soils.

The north-east region known as Khorat Plateau borders are the Phetchabun and Dong Phaya Yen Ranges in the west, the Mekong river in the north and east, and the Phanom Dongrak scarps in the south. The central northeast region consists of two basins which are mutually separated by the NW-SE trending Phu Phan Range: the Sakon Nakhon Basin in the north, and the larger Khorat Basin in the south (Yoothong *et al.*, 1997). Kaolinite is the most important clay mineral in the red and yellow Ultisols and Oxisols of the north-east plateau (Suddhiprakarn *et al.*, 1985). Vermiculite, smectite and illite are only in minor amounts. Soils with kaolinite and illite are found in areas along the Mekong river, with minor smectite, vermiculite and chlorite. The alluvium of the Khorat basin is dominated by a kaolinite-smectite-illite assemblage (Yoothong *et al.*, 1997).

Mineralogical and characteristics are of dominant importance in affecting the extent of soil K reserves (Motomura *et al.*, 1985). Mica is dominant in alluvial soils around Bangkok; kaolinite in soils of Phitsanulok, Saraburi, Nakhon Nayok, Chacherngsao and Kamphaeng Phet derived from sandstone and shale. Smectite dominates in limestone soils of Lop Buri. In the northeast, kaolinite is dominant in sandstone-derived soils (Nakhon Ratchasima, Khon Kaen, Ubon Ratchathani) and mica in alluvium derived soils (Nong Khai, Nakhon Phanom). Northern soils are dominated by mica or kaolinite depending on parent material. Kaolinite is abundant in southern soils (Ogawa *et al.*, 1980; Motomura *et al.*, 1985).

Chemical composition of paddy soils from the northern region was characterized by a high content of either kaolinitic minerals or mica clay minerals. Predominance of kaolinitic minerals was found in Chiang Mai and Chiang Rai basins. Soils with predominance of mica clay minerals are common in the Nan and Phrae basins (Motomura *et al.*, 1997). Northeast Thailand is one of the representative rainfed rice culture areas in Asia, where rice productivity is limited not only by unstable rainfall but also by poor soils (Nakamura and Matoh, 1996; Wade *et al.*, 1999; Mochizuki *et al.*, 2005).

Alluvial soils are generally high in K but sandy soils have low K. Total K is high in Central Plain lowland soils with available K ranging from 74-327 mg kg⁻¹. It is low in the northeast with available K ranging from 15-77 mg kg⁻¹ (Phetchawee *et al.*, 1985). Alluvial soils with high clay content are high in available K. Low Humic Gley, Hydromorphic Gray Podzolic soils and Hydromorphic Regosols derived from sandstone in the northeast are low in total and available K (Phetchawee *et al.*, 1985). Chittamart *et al.* (2009) reported that the lowland Vertisols in Central Plain have low weathered mineral reserve especially K.

Most of the paddy rice soils of Thailand are Paleaquults and Tropaquepts. Paleaquults are the major rice soils in the northeast. Their fertility level is obviously much lower than the rice soils in the Central Plain, where Tropaquepts are dominant. It should be noted that Paleaquults are low in organic matter, available P and available K (Attanandana and Kunaporn, 1995).

Supapoj *et al.*, (1998) reported that northeast Thailand is notorious for its low rice yields and poor soil quality, and exchangeable K and available P are very limiting.

10. Genesis and Properties of Inceptisols, Vertisols, Alfisols and Ultisols

10.1 Inceptisols

As noted in Soil Taxonomy (Soil Survey Staff, 1999; 2010), the definition of Inceptisols is complicated, this results from the variety of drainage classes, temperature and moisture regimes, and different pathways of genesis involved in this order. Typically, these soils will have an ochric or umbric epipedon over a cambic horizon. Inceptisols appear two major situations: (1) soils that are developing on geologically young sediments or landscapes; and (2) soils developing in areas where environmental conditions inhibit soil-forming processes (Foss *et al.*, 1983).

Inceptisols may also have fragipans or duripans and they may have a mollic epipedon (Soil Survey Staff, 2010).

10.2 Vertisols

According to Soil Taxonomy (Soil Survey Staff, 2010), Vertisols are mineral soils that have all of the followings:

1. A layer 25 cm or more thick, within 100 cm of the mineral soil surface, that has either slickensides or wedge-shaped peds that have their long axes tilted 10 to 60 degrees from the horizontal; and
2. A weighted average of 30 percent or more clay in the fine-earth fraction either between the mineral soil surface and a depth of 18 cm or in an Ap horizon, whichever is thicker, and 30 percent or more clay in the fine-earth fraction of all horizons between a depth of 16 cm and either a depth of 50 cm or a densic, lithic, or paralithic contact, a duripan, or a petrocalcic horizon if shallower; and
3. Cracks that open and close periodically.

10.3 Alfisols

According to Soil Taxonomy (Soil Survey Staff, 1999; Athrens and Arnold, 2000), Alfisols form in semiarid to humid areas and have a clay enriched and nutrient enriched subsoil (argillic horizon).

Alfisols are defined as soils that have an argillic horizon and with base saturation of more than 35 percent (Soil Survey Staff, 2006). Alfisols have the potential to be very productive if conserved, but can also degrade rapidly if eroded. The diagnostic features are the ochric epipedon and the argillic horizon (Soil Survey Staff, 1999; Hallmark and Franzmeier, 2000).

10.4 Ultisols

Ultisols are soils that have an argillic or kandic horizon as a subsurface horizon enriched with illuvial clay, with low base saturation (Soil Survey Staff, 1999; West and Beinroth, 2000). They have lower pH and organic matter than do Alfisols and often are redder in colour. With soil amendments they are productive (Boul *et al.*, 2003; Brady and Weil, 2008). These soils form either in a wetter climate or in more strongly weathered parent material than do Alfisols. Leaching has removed most of the exchangeable cations from the soil profile. As a result, the soils are strongly to extremely acid throughout. Ultisols have less than 35 percent base saturation in the lower part of the argillic horizon (Soil Survey Staff, 1999, 2006; Brady and Weil, 2008).

MATERIALS AND METHODS

Sampling Sites

The soil map (1:100,000 scale) (Soil Survey Division, 1986), topographic map (1:50,000 scale) and geological map (1:500,000, 1:250,000, 1:50,000 scales) (Geological Survey Division, 1985) were used as base maps to select the study area. The study was carried out on thirteen representative lowland paddy soils under a tropical savanna climate in Thailand (Figure 7). These soils are widely distributed in the Central Plain and Northeast Plateau. The sampling sites are located in Lop Buri, Saraburi, Maha Sarakham, Roi Et, Udon Thani, Nakhon Phanom and Phetchaburi provinces. The soil consisted of five Vertisols (Ustic Endoaquert) namely Ban Mi1 (Bm1), Ban Mi2 (Bm2), Chong Khae (Ck), Lop Buri (Lb) and Watanna (Wa); three Alfisols namely Ubon (Ub) Aeric Haplaqualf, Tha Tum (Tt) Typic Endoaqualf, Doem Bang (Db) Aeric Endoaqualf; four Ultisols namely Roi Et (Re) Aeric Pleaquult, Phen (Pn) Kandic Plithaquult, Renu (Rn) Typic Plithaquult, Nakhon Phanom (Nn) Typic Endoaquult and one Inceptisol namely Samut Prakan (Sm) Aeric Endoaquert.

Field Analysis and Sample Preparation

Pedon analysis and soil profile description were recorded. Soil samples were collected by genetic horizons down to 200 cm depth according to standard methodology (Kheoruenromne, 2009, Soil Survey Division Staff, 1993). Soil color was determined on moist soils by reference to Munsell soil color charts (Munsell Color, 2000). Bulk samples were air-dried, crushed and then passed through a 2-mm sieve for routine, laboratory analysis.

Laboratory Analyses

A summary of methods for physical and chemical analysis used in the study is shown in Table 2. The details of each method are in Appendix Table A.

Table 2 Laboratory methods.

Analysis	Method	Reference
<i>Physical analysis</i>		
1. Particle size analysis	Pipette method	Gee and Bauder (1986)
<i>Chemical analysis</i>		
1. Soil pH	1:1 soil: solution in H ₂ O, 1 M KCl measured by pH meter	National Soil Survey Center (1996)
2. Organic carbon	Wet digestion and titration by Walkey-Black method	Nelson and Sommers (1996)
3. Total N	Kjeldahl method	National Soil Survey Center (1996)
4. Available P	Bray II	Bray and Kurtz (1945)
5. Extractable bases (Ca ²⁺ , Mg ²⁺ , Na ⁺ , K ⁺)	1 M NH ₄ OAc at pH 7.0 extraction and measured by AAS	Thomas (1987a)
6. Extractable acidity	Barium chloride-triethanolamine solution at pH 8.2	Thomas (1987b)
7. Cation exchange capacity		
-CEC by NH ₄ OAc	Saturating the exchange site and displacing by 1M NH ₄ OAc at pH 7.0	Chapman (1965)
-CEC by summation of Cations	Sum of extractable bases plus extractable acidity	National Soil Survey Center (1996)
8. Base saturation percentage	By sum of bases extracted by NH ₄ OAc at pH 7.0, divided by the CEC by sum of cations and multiplied by 100	National Soil Survey Center (1996)

Table 2 (Continued)

Analysis	Method	Reference
9. NH ₄ OAc – exchangeable potassium	1 M NH ₄ OAc at pH 7.0 extraction and measured by AAS	Knudsen and Peterson (1982)
10. HNO ₃ -extractable Potassium	Boiling with HNO ₃ and measured by AAS	Knudsen and Peterson (1982)
11. Total potassium	Pressed powder samples and measured by X-ray fluorescence spectrometer (XRF)	Jones (1987)

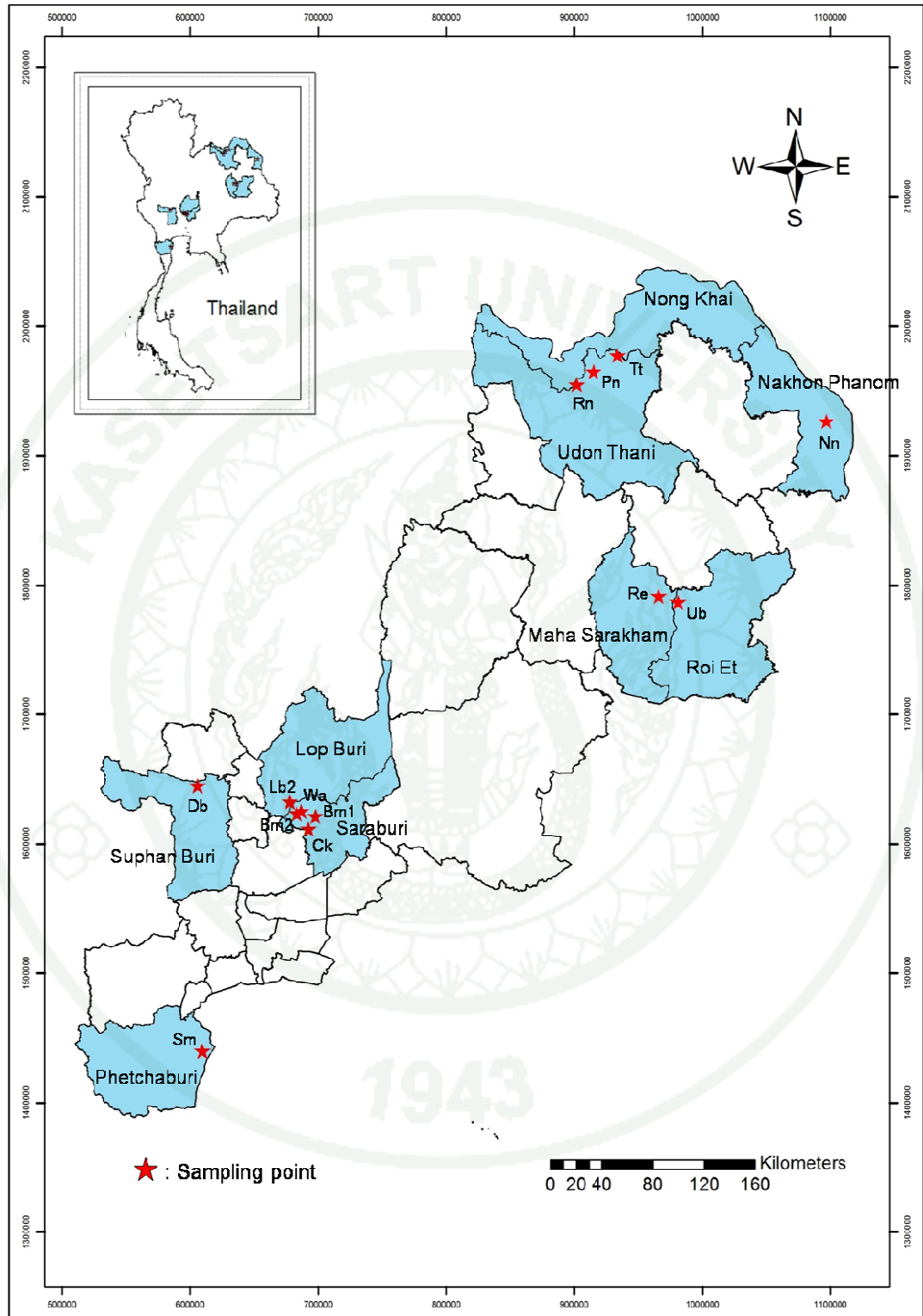


Figure 7 Soil sampling sites in Thailand for the study of paddy soils.

RESULTS AND DISCUSSION

1. Soil Characteristics

1.1 Field morphological properties

The typical appearance of paddy soils profiles is shown in Figure 8 and 9. Environmental setting and use of paddy soils in Thailand are given in Table 3. These soils are on flat to undulating (1 to 2% slope) sites and most of them developed at low positions in the local landscape with elevations ranging from 5 to 102 m MSL. Local alluvium derived from limestone is the most common parent material of Bm1, Bm2, Ck, Lb and Wa (Vertisols), and wash and local alluvium derived from weathered sedimentary rocks is the parent material of Re, Pn, Rn, and Nn (Ultisols). Alluvium over marine deposits is the parent material of Sm (Inceptisols). Wash (sandy) is the parent material of Ub (Alfisols). Mixed marine and local alluvium derived from metasedimentary rocks is the parent material of Db (Alfisols) and recent alluvium on residuum derived from fine grained clastic sedimentary rocks is the parent material of Tt (Alfisols).

All soils have developed on lower positions in the landscape. They are generally very deep and A-Bt profile development is common. The color of soils ranges from brown to black (2.5YR-10YR, Apg/B) (Munsell Color, 2000) (Table 4). Faint to distinct mottles are common in paddy soils that have developed under aquic conditions. Most of the soils have a clayey texture, except, Ub that soil has sand texture. Some deeper horizons are slightly to very gravelly which reflects the accumulation of calcium carbonate, and iron-manganese oxide nodules. Strong angular blocky and sub-angular blocky structures are common within both surface and subsurface soil horizons, with cracks, pressure faces and slickensides. Field pH of most soils ranges from strongly acid to slightly alkaline (Appendix Table B).

Table 3 Classification and environmental setting of paddy soils in Thailand investigated in this research.

Soil series	Classification	Land form	Parent material	Surrounding landform	Slope (%)	Elevation (m MSL)	Coordination	Location
Ban Mi 1 (Bm1)	Ustic Endoaquert	Lower footslope	Wash and Local alluvium derived from weathered limestone	Undulating	2	26	47P 0697976E 1621108N	Phra Phutthabat, Saraburi Province
Ban Mi 2 (Bm2)	Ustic Endoaquert	Depression in local alluvial plain (Basin)	Local alluvium partially derived from limestone	Flat	2	5	47P 0683633E 1623175N	Nong Don, Saraburi Province
Chong Khae (Ck)	Ustic Endoaquert	Semi-recent terrace	Mixed alluvium and Local alluvial derived from limestone	Slightly undulating	2	9	47P 0692725E 1611533N	Sao Hai, Saraburi Province
Lop Buri (Lb)	Ustic Endoaquert	Toeslope	Local alluvium derived from limestone	Nearly flat	1	7	47P 0678145E 1632258N	Muang, Lop Buri Province
Wattana (Wa)	Ustic Endoaquert	Local alluvial plain	Local alluvium derived from limestone	Flat	1	9	47P 0687175E 1625088N	Phra Phutthabat, Saraburi Province
Ubon (Ub)	Aeric Haplaqualf	Lower erosional terraces	Wash (sandy)	Undulating	3	150	47Q0339405E 1782074N	Mueang, Maha Sarakham Province
Tha Tum (Tt)	Typic Endoaqualf	Lower part of low terraces	Recent alluvium on residuum derived from fine grained clastic sedimentary rocks	Gently undulating	1	177	48P 0298096E 1973631N	Srang Khom, Udon Thani Province
Doem Bang (Db)	Aeric Endoaqualf	Toeslope extended from extensive footslope	Mixed marine and Local alluvium derived from metasedimentary rocks	Slightly undulating	2	19	47P 0606037E 1644777N	Doem Bang Nang, Suphan Buri Province
Roi Et (Re)	Aeric Paleaquult	Lower erosional terraces	Wash and local alluvium derived from weathered sedimentary rocks	Gently undulating	1	134	47Q0324498E 1787184N	Mueang, Roi Et Province
Phen (Pn)	Kandic Plithaquult	Upper part of low erosional terraces	Wash over residuum derived from fine grained clastic sedimentary rocks	Slightly undulating	1	173	48P 0265243E 1952043N	Phen, Udon Thani Province

Table 3 (Continued)

Soil series	Classification	Land form	Parent material	Surrounding landform	Slope (%)	Elevation (m MSL)	Coordination	Location
Renu (Rn)	Typic Plinthaquult	Strath terrace	Wash over residuum derived from fine grained weathered clastic sedimentary rocks	Flat	0	151	48P 0461766E 1990195N	Renu, Nakhon Phanom Province
Nakhon Phanom (Nn)	Typic Endoaquult	Lower part of low erosional terraces	Wash over residuum derived from fine grained clastic sedimentary rocks	Gently undulating	1	191	48P 0458629E 1917550N	Mueang, Nakhon Phanom Province
Samut Prakan (Sm)	Aeric Endoaquert	Floodplain	Alluvium over marine deposits	Level to nearly level	1	2	47P 0609735E 1439836N	Mueang, Phechaburi Province

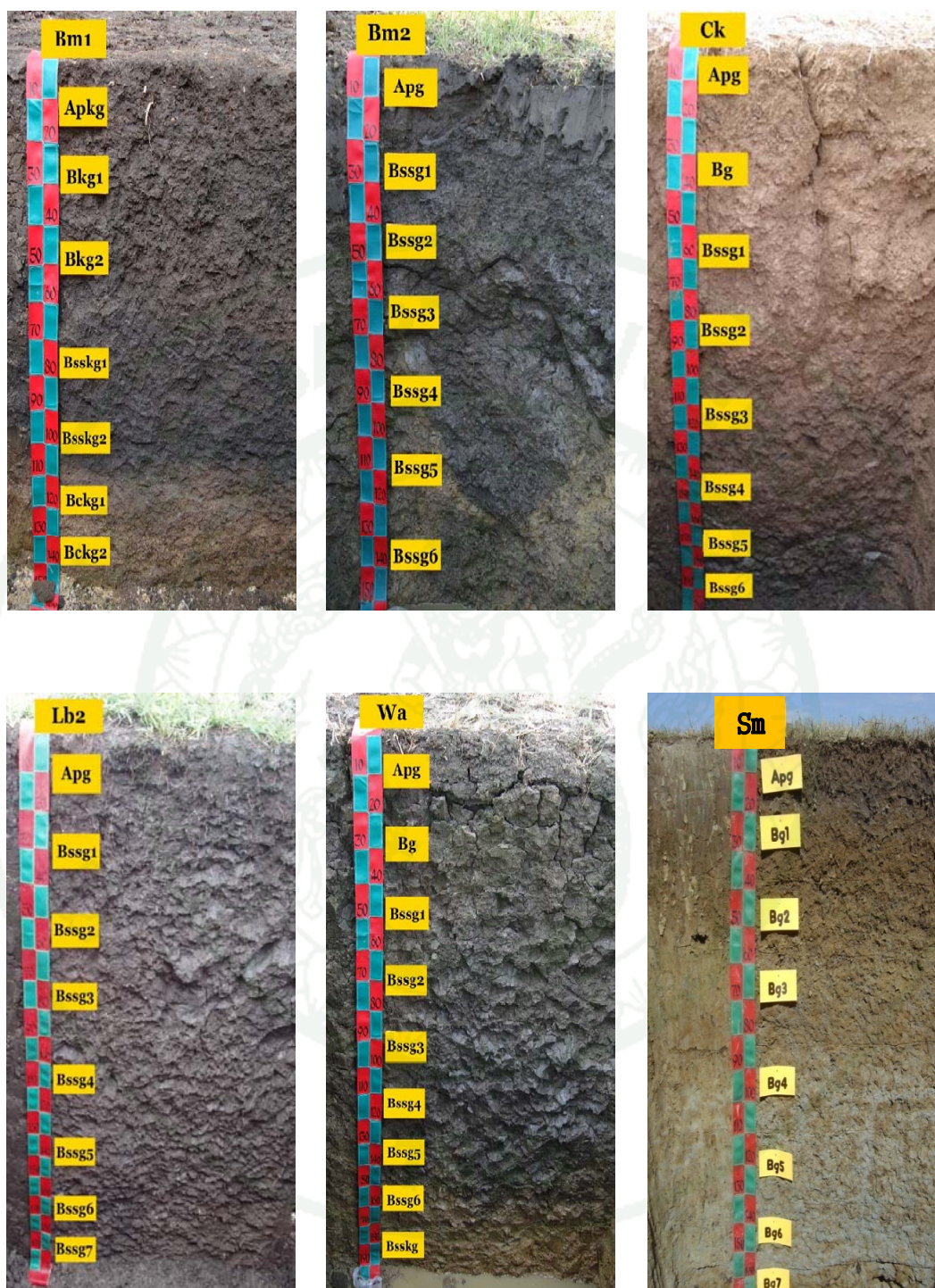


Figure 8 Representative paddy soil profiles of Vertisols (Bm1, Bm2, Ck, Lb, Wa) and Inceptisols (Sm) in this study.

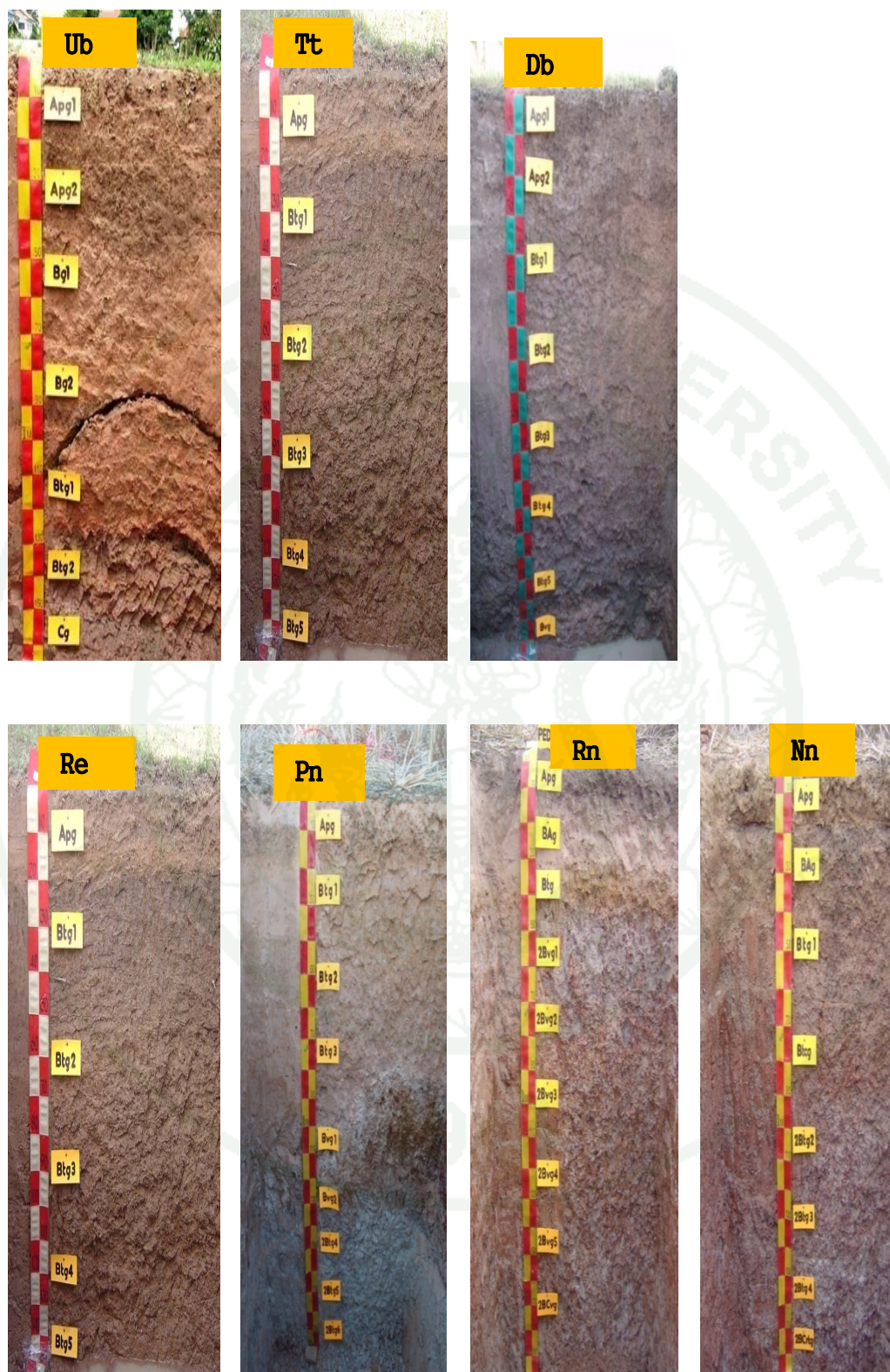


Figure 9 Representative paddy soil profiles of Alfisols (Ub, Tt, Db) and Ultisols (Re, Pn, Rn, Nn) in this study.

Table 4 Field morphology of paddy soils.

Horizon	Depth (cm)	Color of matrix Color of mottle	Texture ^{1/}	Structure ^{2/}	Other features
Ban Mi 1 (Bm1) <i>Ustic Endoaquert, fine, smectitic, isohyperthermic</i>					
Apkg	0-20	<u>10YR 3/2</u> 7.5YR 3/6	C	3-Semi- ABK	Rock fragment, cracks, pressure faces
Bkg1	20-40	<u>10YR 3/2</u> <u>10YR 4/6</u>	C	3-Semi- ABK	Cracks, pressure faces, dead roots
Bkg2	40- 55/63	<u>10YR 3/2</u> 5YR4/4, 10YR4/6	C	3-ABK	Cracks, dead roots, pressure faces
Bsskg1	63-84	<u>10YR 2/2</u> 5YR 4/6	C	2-ABK	Slickensides, Rock fragment, dead roots
Bsskg2	84-106	<u>10YR2/2</u> 5YR4/6	C	3-ABK	Cracks, root frangment, slickensides
Bckg1	106- 123	<u>Mixed 10YR5/3,</u> <u>10YR5/1</u> 10YR4/6, 10YR2/1 (Fe-Mn nodule), 2.5R 3/6	SCG	2-Semi- ABK	Cracks, pressure faces, Fe-Mn nodules
Bckg2	123- 145+	<u>10YR 7/2</u> 10YR 5/8, 2.5YR 3/6, 10YR 2/1	GC	2-Semi- ABK	Fe-Mn nodules, Black clay spot, pressure faces
Ban Mi 2 (Bm2) <i>Ustic Endoaquert, fine, mixed, isohyperthermic</i>					
Apg	0-18	<u>Mixed 10YR 4/1,</u> <u>10YR 3/2</u> 10YR 4/6	C	3-SBK	Pressure faces, cracks, dead roots,
Bssg1	18-35	<u>2.5 Y4/1</u> 2.5y 4/4	C	3-SBK	Slickensides, cracks, dead roots
Bssg2	35-55	<u>Mixed 10YR 4/1,</u> <u>10YR 3/2</u> 2.5Y 4/4, 7.5YR 5/8	C	3-SBK	Slickensides, cracks, dead roots
Bssg3	55-74	<u>2.5Y 4/2</u> 2.5Y 4/4, 7.5YR 5/8	C	3-SBK	Slickensides, cracks, fine roots, rock frangment
Bssg4	74-98	<u>2.5Y 4/2</u> 2.5Y 5/4, 7.5YR 5/4	C	3-SBK	Slickensides, cracks, clay ball, rock frangment
Bssg5	98-130	<u>Mixed 2.5Y 6/3</u> <u>10YR 4/1</u> 2.5Y 6/8	C	3-Semi- ABK	Slickensides, cracks, rock fragment, clay ball
Bssg6	130- 160+	<u>Mixed 10YR 6/2,</u> <u>10YR 5/1</u> 2.5Y 6/8 (40%)	C	3-Semi- ABK	Slickensides, cracks, clay ball, rock frangment

Table 4 (Continued)

Horizon	Depth (cm)	Color of matrix Color of mottle	Texture ^{1/}	Structure ^{2/}	Other features
Chong Khae (Ck) <i>Ustic Endoaquert, very fine, smectitic, isohyperthermic</i>					
Apg	0-27	<u>10YR 5/3</u> 2.5YR 4/6, 5YR4/4, 5YR 5/6	C	3-ABK	Cracks, pressure faces, dead roots
Bg	27-50	<u>10YR 5/3</u> 5YR 4/4, 5YR 5/6	C	3-Semi-ABK	Cracks, pressure faces, dead roots
Bssg1	50-75	<u>10YR 6/3</u> 5YR 7/6 , 5YR 4/6	C	3-Semi-ABK	Cracks, pressure faces, slickensides, fine roots
Bssg2	75-105	<u>10YR 6/3</u> 5YR 5/4 (70%)	C	3-Semi-ABK	Cracks, soft Fe-Mn nodules, slickensides
Bssg3	105-135	<u>Mixed 7.5YR 5/3,</u> <u>7.5YR 5/2</u> 5YR 5/6	C	3-ABK	Cracks, pressure faces, slickensides, fine/dead roots
Bssg4	135-160	<u>Mixed 7.5YR 5/3,</u> <u>7.5YR 4/2</u> 7.5YR 5/6	C	3-ABK	Slickensides, cracks, dead roots
Bssg5	160-180	<u>Mixed 7.5YR 5/3,</u> <u>7.5YR 5/4</u> 7.5YR 4/4	C	3-ABK	Slickensides, cracks, dead roots
Bssg6	180-200+	<u>Mixed 7.5YR 5/3,</u> <u>7.5YR 4/2</u> 7.5YR 4/4	C	3-Semi-ABK	Slickensides, cracks, dead roots
Lop Buri (Lb) <i>Ustic Endoaquert, very fine, smectitic, isohyperthermic</i>					
Apg	0-20	10YR 2/1	C	3-Semi-ABK	Dead roots, rock fragment, cracks
Bssg1	20-40	<u>10YR 3/1</u> 10YR3/4, 10YR 4/4	C	3-ABK	Cracks, rock fragment, slickensides
Bssg2	40-65	<u>10YR 2/1</u> 10YR3/4, 10YR 5/6	C	3-ABK	Cracks, rock fragment, slickensides, fine roots
Bssg3	65-90	<u>10YR 3/1</u> 10YR3/4, 10YR 5/5	C	3-ABK	Fine/dead roots, lime fragment
Bssg4	90-120	<u>10YR 3/1</u> 10YR3/4, 10YR 5/6	C	3-ABK	Slickensides, cracks, dead roots
Bssg5	120-150	<u>10YR 3/1</u> 10YR3/4, 10YR 5/5	C	3-ABK	Cracks, rock, lime frangment, dead roots
Bssg6	150-175	<u>10YR 4/1</u> 10YR3/4, 10YR 5/6	C	3-ABK	Cracks, rock, lime frangment, fine/dead roots
Bssg7	175-200+	<u>10YR 4/1</u> 10YR5/6, 10YR 5/8	C	3-ABK	Cracks, lime frangment, slickensides

Table 4 (Continued)

Horizon	Depth (cm)	Color of matrix Color of mottle	Texture ^{1/}	Structure ^{2/}	Other features
Watanna (Wa) <i>Ustic Endoaquert, fine, mixed, isohyperthermic</i>					
Apg	0-12/20	<u>10YR 3/1</u> 7.5YR 5/6	C	3-ABK	Cracks, pressure faces, dead roots
Bg	20-40	<u>Mixed 2.5Y 4/3,</u> <u>10YR 3/1</u> 7.5 YR 5/6	C	3-ABK	Cracks, pressure faces, dead roots
Bssg1	40-59	<u>Mixed 2.5Y 4/3,</u> <u>10YR 3/1</u> 7.5 YR 5/6	SiC	3-ABK	Cracks, slickensides, pressure faces
Bssg2	59-80	<u>Mixed 2.5Y 3/3,</u> <u>10YR 3/1</u> 10YR 6/6, 7.5 YR 5/6	C	3-ABK	Cracks, pressure faces, slickensides
Bssg3	80-105	<u>Mixed 2.5Y 3/2,</u> <u>10YR 3/1</u> 7.5 YR 5/6, 10YR 6/6	C	3-ABK	Cracks, pressure faces, slickensides, rock fragment
Bssg4	105-124	<u>Mixed 2.5Y 3/2,</u> <u>10YR 3/1</u> 7.5 YR 5/6	C	3-ABK	Cracks, pressure faces, slickensides, rock fragment
Bssg5	124-145	<u>Mixed 10YR 4/2,</u> <u>2.5Y 4/2, 2.5Y 4/3</u> 2.5Y 5/4, 7.5YR 5/6	C	3-ABK	Cracks, pressure faces, slickensides, rock fragment
Bssg6	145-170	<u>Mixed 2.5Y 5/6,</u> <u>10YR 3/1</u> <u>2.5Y 6/2</u> 10YR 6/6, 7.5YR 5/6	C	3-ABK	Cracks, pressure faces, slickensides, lime nodules
Bsskg	170-190+	<u>Mixed 2.5Y 5/4,</u> <u>2.5Y 5/6, 2.5Y 6/3</u> 10YR 5/8, 10YR 6/6	C	2-ABK	Pressure faces, Mn-oxide, slickensides
Ubon (Ub) <i>Aeric Haplaqualf, sandy, siliceous, subactive, isohyperthermic</i>					
Apg1	0-18	<u>7.5YR 4/2</u> 7.5YR 5/8	S	2-SBK	Variegated sands, fine dead roots
Apg2	18-40	<u>7.5YR 4/2, 5YR 6/4</u> 7.5YR 5/8	S	2-SBK	Variegated sands, charcoal fragment, fine dead roots
Bg1	40-68	<u>5YR 6/4</u> 7.5YR 5/8	S	2-SBK	Variegated sands, fine dead roots, charcoal fragment
Bg2	68-96	<u>7.5YR 6/4</u> 7.5YR 5/8	S	2-SBK	Variegated sands, fine dead roots, charcoal fragment
Btg1	96-125	<u>5YR 6/6</u> 7.5YR 5/8	S	1-SBK	Variegated sands, fine dead roots

Table 4 (Continued)

Horizon	Depth (cm)	Color of matrix Color of mottle	Texture ^{1/}	Structure ^{2/}	Other features
Btg2	125-148	<u>7.5YR 6/3</u> 7.5YR 5/8	S	1-SBK	Variegated sands, fine dead roots
Cg	148-170	<u>10YR 5/2, 10YR 6/4</u> 2.5Y 5/6	SL	2-SBK	Variegated sands
Tha Tum (Tt) <i>Typic Endoaqualf, fine, mixed, subactive, isohyperthermic</i>					
Apg1	0-12	<u>10YR 4/2</u> 10YR 5/8	L	2-SBK	Fine roots, root mottle, fine variegated sands
Apg2	12-30	<u>Mixed</u> <u>10YR5/1,10YR 4/2,</u> 7.5YR 4/6,10YR 5/6	L	2-SBK	Fine dead roots, charcoal fragment
ABg	30-50	<u>Mixed 10YR 4/1,</u> <u>10YR 7/3, 7.5YR 5/6,</u> 7.5YR 4/4	CL	2-SBK	Fine dead roots, fine variegated sands
Btg1	50-72	<u>Mixed 10YR 4/1,</u> <u>10YR 7/3, 7.5YR</u> 4/4,10YR 5/6	CL	2-SBK	Fine dead roots, fine variegated sands
Btg2	72-99	<u>10YR 6/2,</u> 7.5YR 5/8, 10YR 6/8	CL	2-SBK	Fine dead roots, fine variegated sands
2Btg3	99-124	<u>Mixed 10YR 6/2,</u> <u>10YR 7/2, 10YR 6/8,</u> 10YR 5/6	C	2-SBK	Fine dead roots, white sand spot
2Btg4	124-148	<u>Mixed 10YR 5/1,</u> <u>10YR 7/3, 10YR 6/8,</u> 10YR 5/8	C	2-SBK	Fine dead roots, white sand spot
2Btg5	148-174	<u>Mixed 10YR 6/1,</u> <u>10YR 7/1, 10YR 6/8,</u> 5YR 5/6, 10YR 2/1	C	2-SBK	Fine dead roots, white sand spot, black spot of Mn
2Btg6	174-200	<u>Mixed 10YR 6/1,</u> <u>10YR 7/1, 7.5YR 7/4</u> 5YR 5/6, 10YR 6/8	C	2-SBK	Clay coating, fine variegated sands
Doem Bang (Db) <i>Aeric Endoaqualf, coarse-loamy, mixed, semiactive, isohyperthermic</i>					
Apg1	0-10	<u>Mixed 5YR 4/1,</u> <u>5YR 6/4</u> 10YR 5/8	SL	2-SBK	Variegated sands, fine/dead roots
Apg2	10-25/32	<u>Mixed 5YR 4/1,</u> <u>5YR 6/4</u> 7.5YR 5/8	SL	2-SBK	Variegated sands, fine dead roots
Btg1	32-55	<u>Mixed 7.5YR 5/2,</u> <u>5YR 6/4</u> 7.5YR 5/6	SL	2-SBK	Clay coating, variegated sands, fine/dead roots
Btg2	55-80	<u>Mixed 7.5YR 5/2,</u> <u>5YR 6/3</u> 7.5 YR 5/8,7.5YR5/6	SL	2-SBK	Clay coating, variegated sands, fine dead roots

Table 4 (Continued)

Horizon	Depth (cm)	Color of matrix Color of mottle	Texture ^{1/}	Structure ^{2/}	Other features
Btg3	80-105	<u>Mixed 7.5YR 4/1,</u> <u>5YR 6/3</u> 7.5 YR 4/6, 7.5YR5/8	SL	2-SBK	Clay coating, variegated sands, iron oxide accumulation, fine dead roots
Btg4	105-132	<u>Mixed 7.5YR 5/1,</u> <u>5YR 6/3</u> 7.5 YR 4/6, 7.5YR5/8	SCL	2-SBK	Clay coating, variegated sands, fine/dead roots
Btg5	132-165	<u>Mixed 5YR</u> <u>7/3,7.5YR 5/1,</u> 7.5 YR 4/6, 7.5YR5/8, 5YR 5/2	SL	2-SBK	Clay coating, variegated sands, iron oxide accumulation, fine dead roots
Bvg	165-180	<u>Mixed 10YR</u> <u>6/1,7.5YR 7/3</u> 10 YR 5/8, 10YR 4/6, 10YR 5/6, 10YR 2/1, Fe-Mn nodule	SL	3-SBK	Clay coating, segregation iron oxide and clay
Roi Et (Re) <i>Aeric Paleaquult, coarse-loamy, siliceous, semiactive, isohyperthermic</i>					
Ap _g	0-16/20	<u>7.5YR 5/2</u> 5YR 5/8	SL	2-SBK	Variegated sands, cracks, fine dead roots
Btg1	20-50	<u>5YR 4/2</u> 5YR 4/6	SL	2-SBK	Clay coating, variegated sands, fine dead roots
Btg2	50-78	<u>7.5YR 5/3</u> 5YR 4/6	SL	2-SBK	Clay coating, variegated sands, fine dead roots
Btg3	78-108	<u>7.5YR 5/3</u> 5YR 5/8, 5YR 4/6	SL	2-SBK	Clay coating, variegated sands, fine dead roots
Btg4	108-135	<u>7.5YR 6/3</u> 7.5YR 5/8	SL	2-SBK	Clay coating, variegated sands, fine dead roots
Btg5	135-150	<u>7.5YR 6/4</u> 7.5YR 5/8	SL	2-SBK	Clay coating, variegated sands, iron oxide concretion
Phen (Pn) <i>Kandic Plithaquult, fine, mixed, superactive, isohyperthermic</i>					
Ap _g 1	0-19	<u>10YR 6/2</u> 7.5YR 5/8	SCL	2-SBK	Fine dead roots, fine variegated sands
Btg1	19-40	<u>10YR 7/3</u> 10YR 6/8	SCL	2-SBK	Fine dead roots, fine variegated sands
Btg2	40-61	<u>10YR 7/3</u> 5YR 5/8, 7.5YR 6/8	SCL	2-SBK	Dead roots, fine variegated sands

Table 4 (Continued)

Horizon	Depth (cm)	Color of matrix Color of mottle	Texture ^{1/}	Structure ^{2/}	Other features
Btg3	61-78/110	<u>7.5YR 7/2</u> , 7.5YR 5/8, 5YR 5/6	SC	2-SBK	Clay coating, dead roots
Bvg1	110-130	<u>2.5YR 8/2</u> , 2.5YR 4/4, 10YR 6/8	C	2-SBK	Clay coating, dead roots
Bvg2	130-146	<u>2.5YR 8/2</u> , 10YR 7/8, 7.5YR 6/8, 2.5YR 5/8	C	2-SBK	Clay coating, dead roots, variegated sands, cracks
2Btg4	146-159	<u>2.5YR 8/2</u> , 2.5YR 5/6	C	3-SBK	Pressure faces, cracks, variegated sands
2Btg5	159-183	<u>2.5YR 8/2</u> , 10YR 6/8	C	3-SBK	Pressure faces, cracks, variegated sands
2Btg6	183-200	<u>2.5YR 8/2</u> , 2.5YR 4/6, 10YR 5/8	C	3-SBK	Pressure faces, cracks, variegated sands
Renu (Rn) <i>Typic Plinthaquult, fine, kaolinitic, isohyperthermic</i>					
Apg	0-13	<u>10YR 3/2, 10YR 6/3</u> , 7.5YR 5/6, 10YR 5/8	SL	2-SBK	Fine dead roots, fine variegated sands
BAG	13-31	<u>7.5YR 8/3</u> , 7.5YR 5/8, 10YR 7/8	SL	2-SBK	Fine dead roots, fine variegated sands
Btg	31-43	<u>7.5Y 8/3</u> , 7.5Y 5/8, 10YR 6/8, 5YR 5/8	SCL	2-SBK	Clay coating, fine roots, Fe-nodules, variegated sands
2Bvg1	43-65	<u>2.5Y 6/1, 2.5Y 8/1</u> , 10R 4/8, 10R 3/6, 10YR 5/8, 2.5Y 6/8	CL	2-SBK	Clay coating, fine roots, Mn-nodules, cracks
2Bvg2	65-83	<u>2.5Y 6/1, 2.5Y 8/1</u> , 10R 4/8, 10YR 5/8, 10R 6/3,	SC	2-SBK	Clay coating, Fe-nodules, cracks
2Bvg3	83-107	<u>2.5Y 7/2, 2.5Y 8/1</u> , <u>2.5Y 6/1</u> , 10R 5/8, 10YR 5/8	SC	2-SBK	Clay coating, Fe-nodules, cracks
2Btg4	107-132	<u>2.5Y 8/1, 2.5Y 7/1</u> , 10YR 6/8, 10R 5/8	SC	2-SBK	Clay coating, Fe-nodules
2Bvg5	132-160	<u>2.5Y 8/1, 2.5Y 7/1</u> , 10YR 5/8, 10R 5/8	SC	2-SBK	Clay coating, Fe-nodules, cracks
2BCrg	160-195	<u>2.5Y 8/1, 10R 8/4</u> , 10YR 6/8, 2.5Y 6/8	C	2-SBK	Clay coating, cracks

Table 4 (Continued)

Horizon	Depth (cm)	Color of matrix Color of mottle	Texture ^{1/}	Structure ^{2/}	Other features
Nakhon Phanom (Nn) <i>Typic Endoaquult, fine, illitic, isohyperthermic</i>					
Apg	0-18	<u>10YR 5/3</u> 10YR 5/8	SiCL	2-SBK	Fine dead roots, cracks
BAG	18-39	<u>10YR 6/3, 10YR 7/2</u> 7.5YR 5/4, 5YR 5/6, 10YR 5/8	C	2-SBK	Fine dead roots, clay ball, iron oxide nodules
Btg1	39-63	<u>Mixed 10YR 6/3, 10YR 7/2</u> 7.5YR 5/4, 2.5YR 5/6, 10YR 4/8	C	2-SBK	Fine roots, iron oxide nodules
Btcg	63-94	<u>Mixed 10YR 7/2, 10YR 7/1</u> 10YR 4/8, 7.5Y 6/8	C	2-SBK	Fine roots, iron oxide nodules, rock fragments
2Btg2	94-115	<u>2.5Y 7/2</u> 10 YR 4/8, 10YR 4/4, 10YR 5/8	C	2-SBK	Clay coating, iron oxide nodules
2Btg3	115-146	<u>2.5Y 7/1</u> 10 R 4/8, 10R 4/4, 10YR 5/8	CL	2-SBK	Clay coating
2Btg4	146-170	<u>2.5Y 7/1</u> 10 R 4/8, 10YR 4/8, 10YR 7/8	C	2-SBK	Clay coating
2BCrtg	170-200	<u>2.5Y 7/1</u> 2.5YR 4/6, 10YR 7/8	C	2-SBK	Clay coating, rock fragments
Samut Prakan (Sm) <i>Aeric Endoaquept, fine loam, mixed, semiactive, isohyperthermic</i>					
Apg	0-15	<u>10YR 4/1</u> 7.5YR 4/6, 7.5YR 4/6, 7.5YR 5/6, 7.5YR 3/1, Fe-Mn nodule	SCL	2-SBK	Variegated sands, fine dead roots
Bg1	15-38	<u>Mixed 2.5Y 5/2, 2.5Y 6/1</u> 5YR 4/4, 7.5YR 5/8, 10YR 3/1, Fe-Mn nodule	C	2-SBK	Clay coating, variegated sands, pressure faces, fine dead roots, mica flakes
Bg2	38-55	<u>Mixed 2.5Y 5/1, 2.5Y 5/2</u> 10Y 6/8, 5YR 5/6, 2.5YR 6/4, 10YR 3/1, Fe-Mn nodule	CL	2-SBK	Clay coating, variegated sands, pressure faces, fine dead roots, mica flakes, Mn spot
Bg3	55-82	<u>2.5Y 5/1</u> 10YR 6/6, 7.5YR 5/8, 5YR 4/4, 10YR 3/1	SCL	2-SBK	Clay coating, variegated sands, fine dead roots, mica flakes, Mn spot

Table 4 (Continued)

Horizon	Depth (cm)	Color of matrix Color of mottle	Texture ^{1/}	Structure ^{2/}	Other features
Bg4	82-110	<u>5Y 6/1</u> 10YR 6/8, 7.5YR 6/6, 2.5Y 5/3, 10YR 3/1	SCL	2-SBK	Clay coating, variegated sands, fine dead roots, mica flakes
Bg5	110- 130	<u>5Y 6/1</u> 10YR 6/6, 7.5YR 6/4, 2.5Y 6/3, 10YR 3/1	SL	2-SBK	Clay coating, variegated sands, dead roots, mica flakes, Fe-Mn spot
Bg6	130- 158	<u>5Y 6/1, 10YR 6/6,</u> 7.5YR 6/8, 7.5YR 4/6, 2.5Y 6/6, 10YR 3/1, Fe-Mn nodule	CL	2-SBK	Clay coating, variegated sands, pressure faces, mica flakes, fine dead roots
Bg7	158- 170+	<u>5Y 6/1</u> 5YR 4/4, 5YR 4/6, 10YR 5/6, 10YR 5/4, 10YR 3/1, Fe-Mn nodule	SL	1-SBK	Variegated sands, mica flakes, Fe-Mn spot

Notes: ^{1/} C= clay, CL = clayey loam, GC= gravelly clay, GSC = gravelly sandy clay, SGC = slightly gravelly clay, SiCL = silty clay loam, SC = sandy clay, SCL = sandy clay loam, SL = sandy loam, S = sandy. ^{2/} 1 = weak, 2 = moderate, 3 = strong, ABK = angular blocky, SBK = subangular blocky.

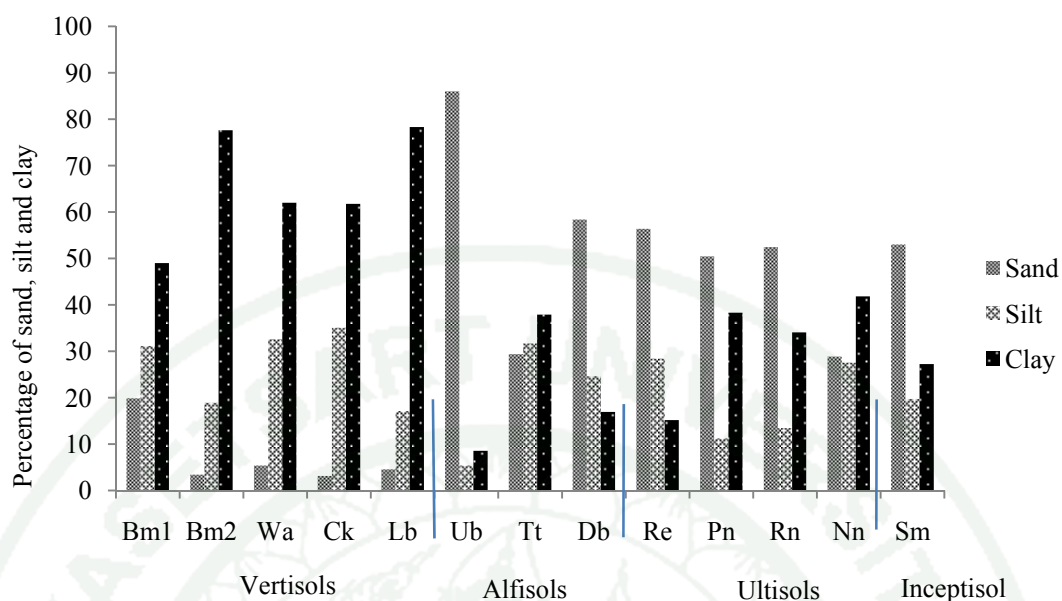


Figure 10 Particle size distribution of investigated paddy soils.

1.2 Physical properties

Physical properties of these paddy soils are summarized in the Appendix Table A. Statistical summary of physical and chemical properties is shown in Table 5.

Textural classes of these soils vary from sandy to clayey. Clay content of these soils ranges from 67 g kg^{-1} to 878 g kg^{-1} . Soil texture includes clay texture (Bm1, Bm2, Ck, Lb, Wa), loam (Tt), sandy clay loam (Pn, Sm), sandy loam (Rn, Db), silty clay loam (Nn), sandy loam (Re), and sand (Ub) (Figure 10). Textural class was determined by plotting the relative proportion of sand, silt and clay particles of the fine earth fraction ($<2 \text{ mm}$) of the soil as textural triangle classes in Figure 11 (Soil Survey Staff, 1999, 2010). Bulk density of all paddy soils are shown in Appendix Table-A. Bulk density of these soils ranges from moderately low to very high (1.38 to 2.01 Mg m^{-3}) ($n=103$) and the distribution of BD values is quite constant in paddy soils (Figure 12d).

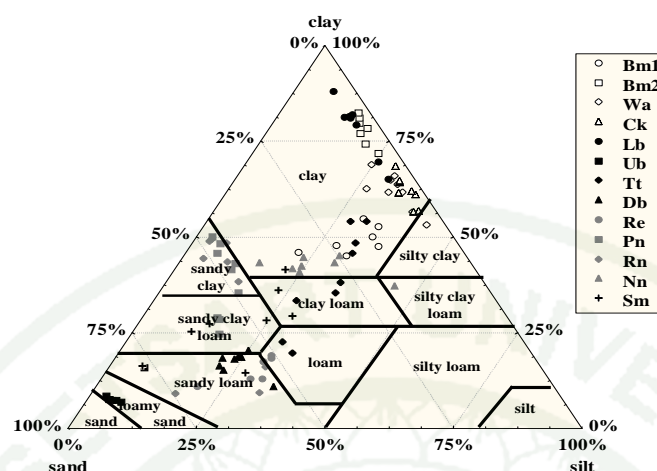


Figure 11 Textural classes of the <2 mm fraction of investigated paddy soils.

1.3 Chemical properties

Chemical properties of the paddy soils are given in the Appendix Table B. The pH values of paddy soils range from 3.9 to 8.4 with a mean value of 6.16 for pH in water and 2 to 7 with mean value of 4.84 for pH in KCl (Table 5). Most of soils are very strongly to slightly acidic. But Bm2, Lb, Wa and Tt are slightly alkaline (Figure 13a,b).

Organic matter (OM) content is very low to high in most topsoil horizons ranging from 48.2 g kg⁻¹ to 0.20 g kg⁻¹ with a mean value of 6.03 g kg⁻¹. The OM content in most of topsoils are high and decreasing with depth in paddy soils (Figure 9c). Topsoil of Bm2 profile has high content of OM and Lb, Wa and Bm1 have moderately high contents of OM.

Total N content is generally low in most soils ranging from 0.04 g kg⁻¹ to 1.98 g kg⁻¹ with a mean value of 0.50 g kg⁻¹. Figure 13d shows that total N content in the soil profiles generally decreases with depth.

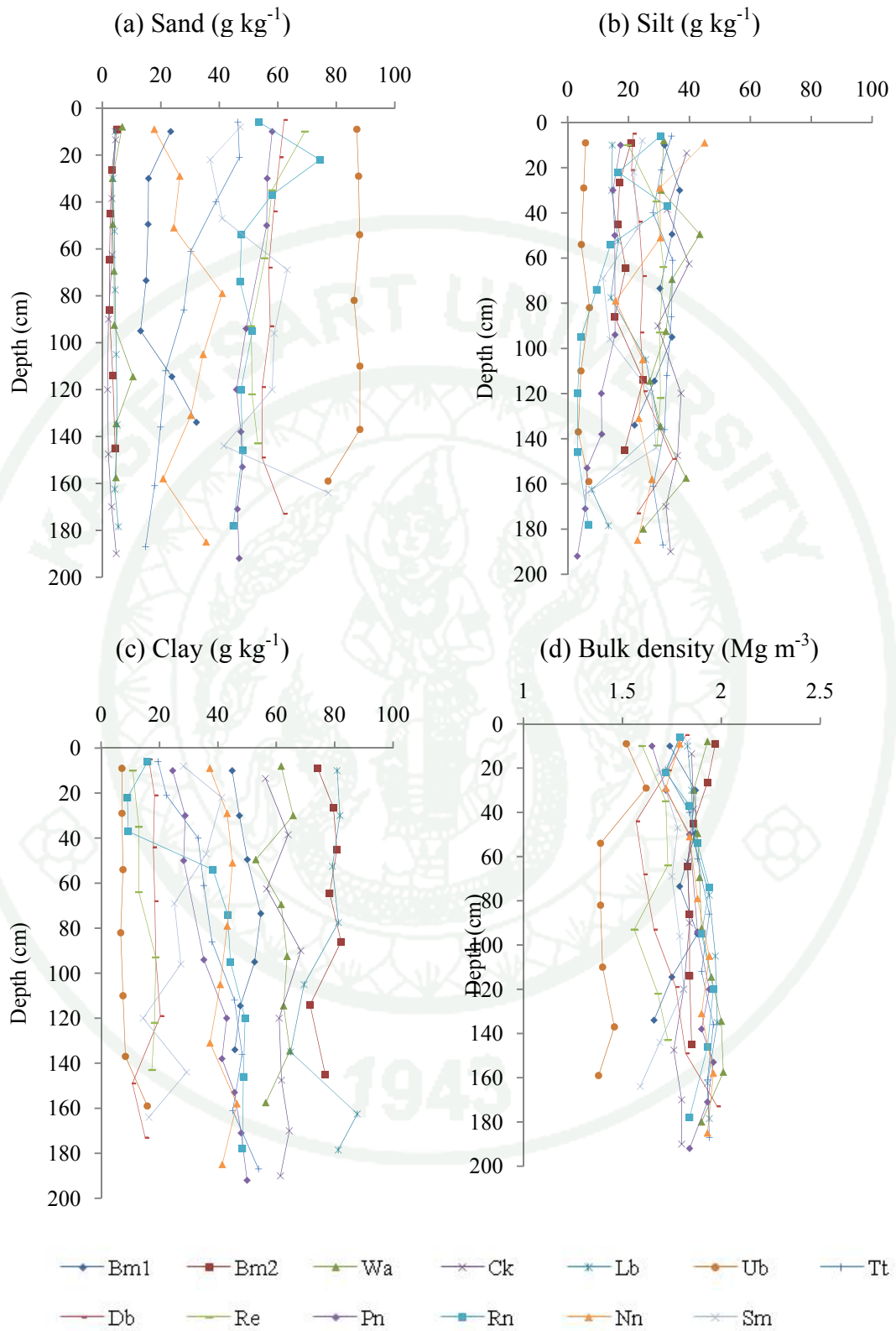


Figure 12 Depth functions of sand, silt, clay and bulk density of paddy soils.

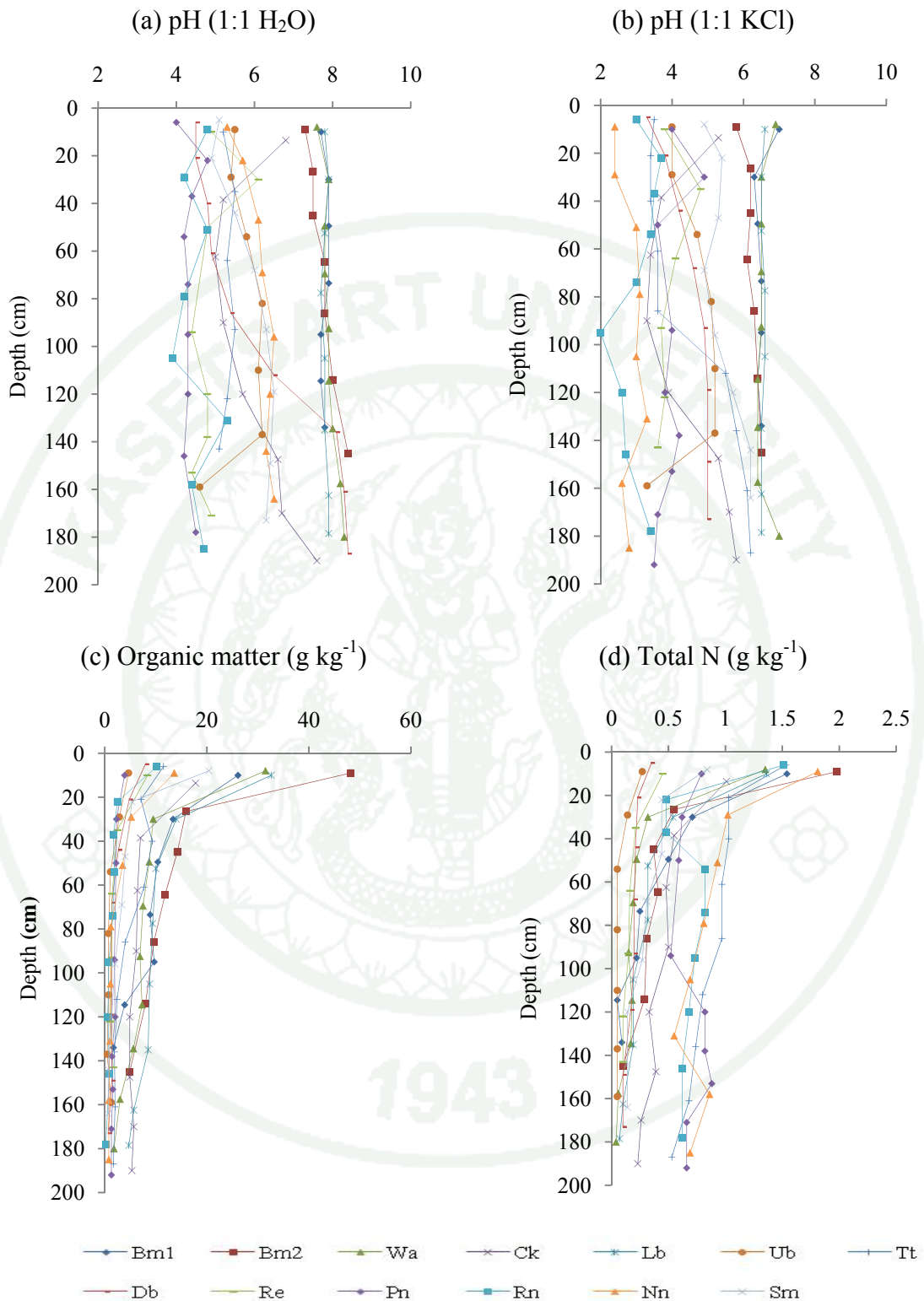


Figure 13 Depth function of pH (1:1 H₂O), pH (1:1 KCl), organic matter and total nitrogen of paddy soils.

Table 5 Statistical summary of some physicochemical properties of paddy soils.

Soil property (n = 103)	Mean	Median	Min	Max	Stdev
<i>Physical properties</i>					
Sand (g kg ⁻¹)	342	427	18	881	262
Silt (g kg ⁻¹)	228	274	32	450	107
Clay (g kg ⁻¹)	427	300	67	878	226
Bulk density (Mg m ⁻³)	1.81	1.86	1.38	2.01	0.14
<i>Chemical properties</i>					
pH (1:1 H ₂ O)	6.2	7.1	3.9	8.4	1.4
pH (1:1 KCl)	4.9	6.6	2.0	7	1.4
Organic matter (g kg ⁻¹)	6.03	13.19	0.20	48.2	7.36
Total nitrogen (g kg ⁻¹)	0.50	0.84	0.04	1.98	0.41
Cation exchangeable capacity (cmol kg ⁻¹)	22.91	18.76	0.45	80.41	23.96
Available P (mg kg ⁻¹)	3.90	5.38	0.01	198.05	19.63
Exchangeable Ca (cmol kg ⁻¹)	18.28	19.22	0.19	67.01	23.32
Exchangeable Mg (cmol kg ⁻¹)	1.64	1.88	0.01	6.47	1.93
Exchangeable Na (cmol kg ⁻¹)	1.29	0.35	0.02	10.82	1.98
Base saturation (%)	58.54	72.66	7.22	89.12	20.45
Extractable Acidity (cmol kg ⁻¹)	9.02	8.45	0.49	26.95	9.06

Available phosphorus ranges from very low to very high (0.01 mg kg⁻¹ to 198.05 mg kg⁻¹) with a mean value of 3.90 mg kg⁻¹ and it is generally high in topsoils and low in subsoils (Figure 14a). Extraordinary high available phosphorus content in the Ap_{kg} horizon of Bm1 is probably due to the intensive application of P fertilizer.

The soils generally have very low to very high cation exchange capacity (CEC) ranging from 0.45 cmol kg⁻¹ to 80.41 cmol kg⁻¹. Figure 14b shows that Ub, Re, Tt, Re and Nn have very low to moderately low CEC, paddy soil of Sm has medium, Ck, Bm1, Wa, Bm 2 and Db have high to very high CEC. The CEC of these soils are quite constant with depth for each profile as the same as sum bases (Figure 14c).

These soils have low to high base saturation ranging from 7.22% to 89.12% (Figure 15a). Calcium is the dominant exchangeable cation (0.19-67.01 cmol kg⁻¹) (Figure 15b) with lesser amounts of Mg (Figure 15c) and Na (Figure 15d).

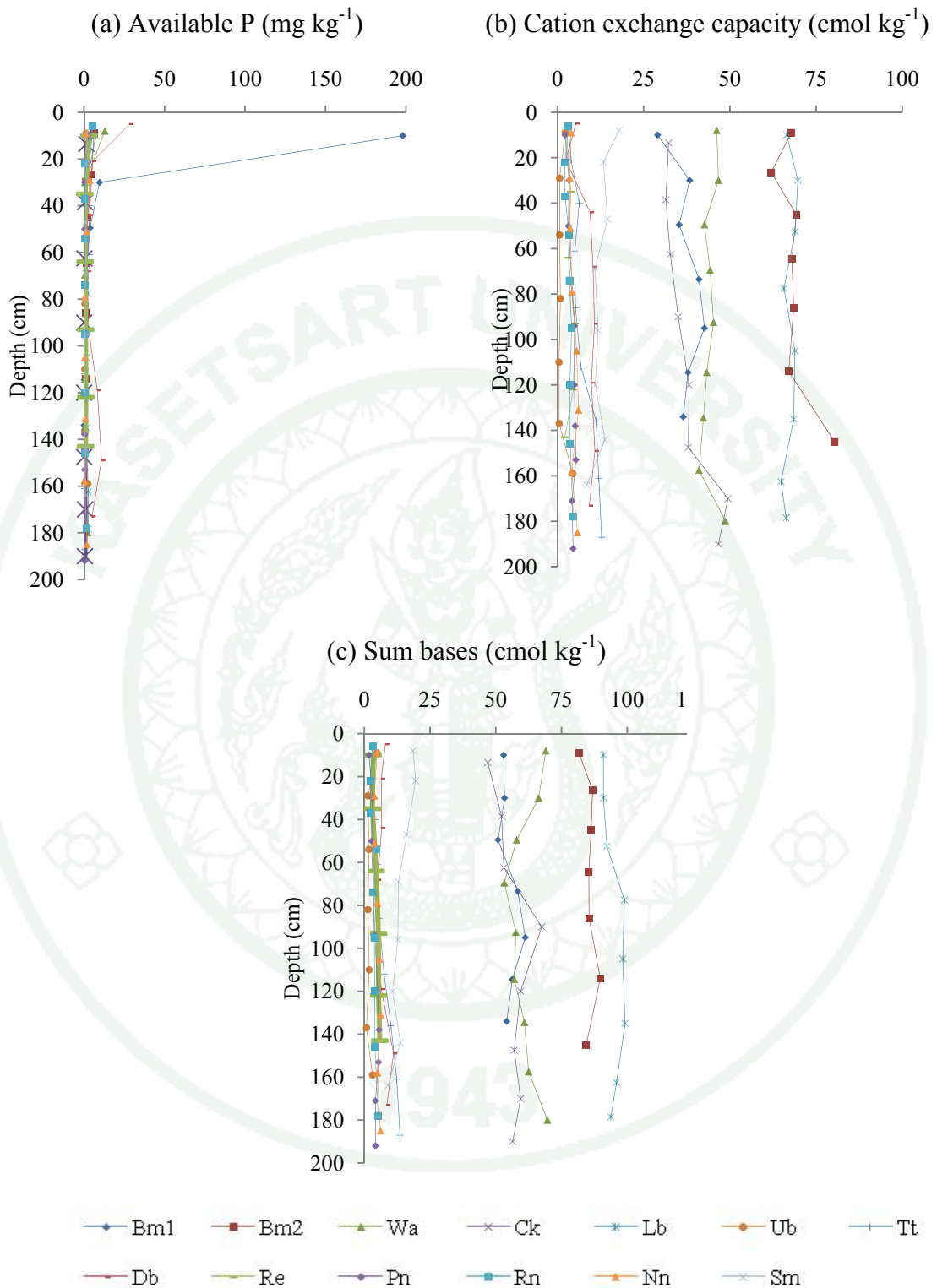


Figure 14 Depth functions of available P, cation exchangeable capacity and sum bases of paddy soils.

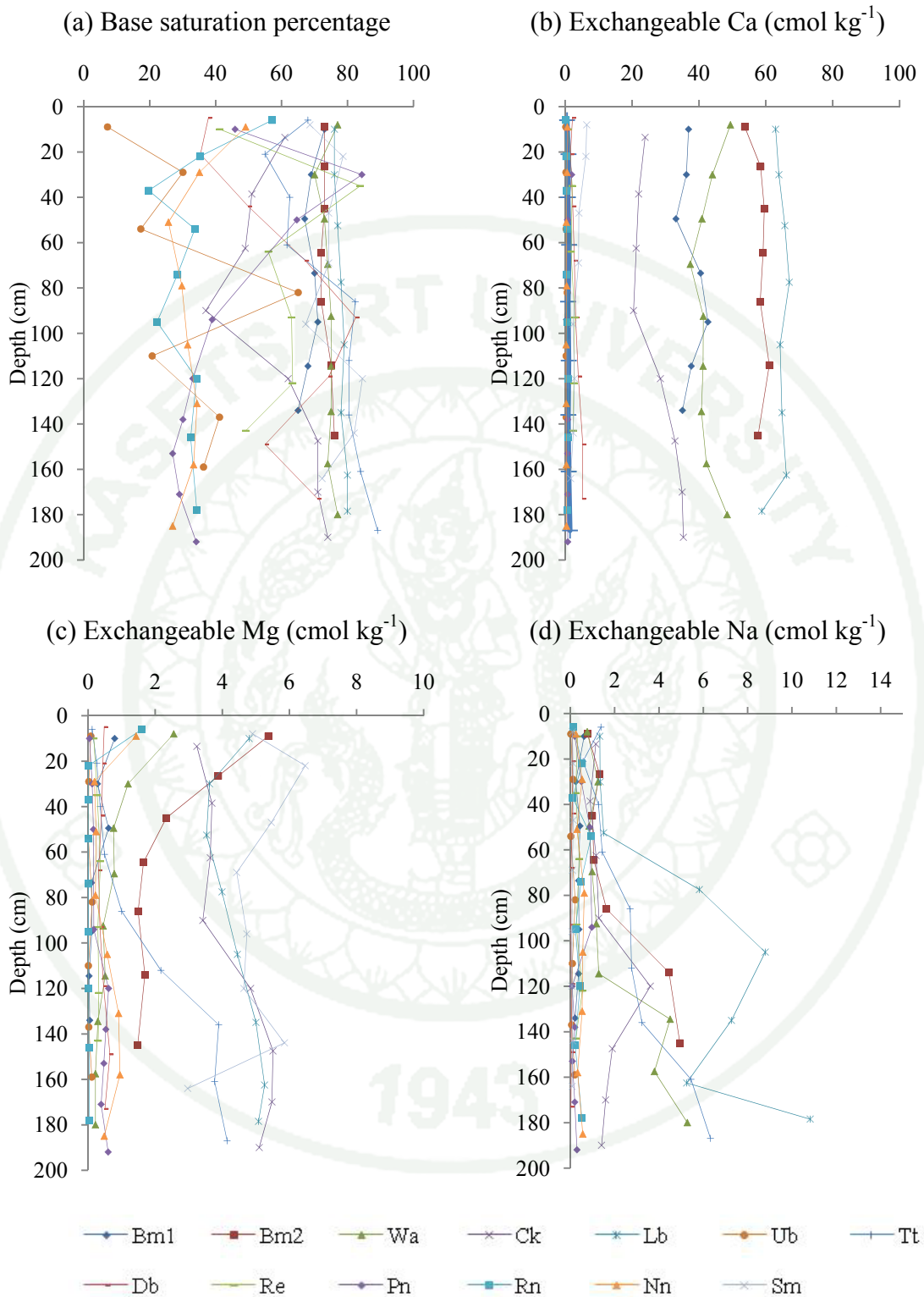


Figure 15 Depth variation of base saturation percentage (PBS), exchangeable Ca, exchangeable Mg and exchangeable Na for paddy soils.

High base saturation percentage is due to the low leaching rate since most of these soils have developed on a low topographical landscape. Dissolved cations from limestone and mafic rocks accumulated in these low positions and induced the neoformation of smectite which contributes high cation retention (Borchardt, 1989; Wilson, 1999). In addition, the presence of Ca in soil solution reflects the precipitation of CaCO₃ in these soil profiles under the relatively dry climatic condition (Srivastava *et al.*, 2002).

1.4 Classification of paddy soils in this study

The paddy soils investigated in this research have developed under tropical savanna climate. These soils conform to the criteria for Vertisols, Alfisols, Ultisols and Inceptisols according to USDA Soil Taxonomy (Soil Survey Staff, 1999; 2006; 2010) (Table 6).

Table 6 Classification of the investigated paddy soils.

Soil series	Classification
Ban Mi 1 (Bm1)	Ustic Endoaquert, fine, smectitic, isohyperthermic
Ban Mi 2 (Bm2)	Ustic Endoaquert, fine, mixed, superactive, isohyperthermic
Chong Khae (Ck)	Ustic Endoaquert, very fine, smectitic, isohyperthermic
Lop Buri (Lb)	Ustic Endoaquert, very fine, smectitic, isohyperthermic
Wattana (Wa)	Ustic Endoaquert, fine, mixed, superactive, isohyperthermic
Ubon (Ub)	Aeric Haplaqualf, sandy, siliceous, subactive, isohyperthermic
Tha Tum (Tt)	Typic Endoaqualf, fine, mixed, subactive, isohyperthermic
Doem Bang (Db)	Aeric Endoaqualf, coarse-loamy, mixed, semiactive, isohyperthermic
Roi Et (Re)	Aeric Paleaquult, coarse-loamy, siliceous, semiactive, isohyperthermic
Phen (Pn)	Kandic Plithaquult, fine, mixed, superactive, isohyperthermic
Renu (Rn)	Typic Plinthaquult, fine, kaolinitic, isohyperthermic
Nakhon Phanom (Nn)	Typic Endoaquult, fine, illitic, isohyperthermic
Samut Prakan (Sm)	Aeric Endoaquert, fine loam, mixed, semiactive, isohyperthermic

1.5 Mineralogical properties

The clay mineralogy is consisting smectite, kaolinite and interstratified kaolinite-smectite in different soil orders (Table 7). Smectite is dominant in Bm1, Ck and Lb. Kaolinite is dominant in Ub, Db, Re and Rn. An interstratified kaolinite-smectite occurs in Wa and Bm2 soils. A small amount (5-20%) of illite presents in Ck and Ub profiles.

Moderate amount of kaolinite (20-40%) and small amount of illite (<20%) occurs in Tt profile. In Pn and Nn profiles, there is a moderate amount (20-40%) of kaolinite and illite. However, Sm consists of 20-40% kaolinite, <20% smectite and illite. A large amount (40-60%) of smectite and kaolinite exists in Re. A trace amount of quartz is present in almost all clay samples except in Ub and Re.

Table 7 Semi-quantitative mineralogical composition of clay and silt of paddy soils estimated by XRD.

Horizon	Depth (cm)	Clay fraction					Silt fraction		
		Sm	Kao	Inters	Ill	Qtz	Qtz	Fel	M
Ban Mi 1 (Bm1) <i>Ustic-Endoaquert, fine, smectitic, isohyperthermic</i>									
Apg	0-20	xxxx	tr	-	-	tr	xxxx	-	-
Bkg2	40- 55/66	xxxx	tr	-	-	tr	xxxx	-	-
Bsskg2	84-106	xxxx	tr	-	-	tr	xxxx	-	-
Bckg1	106-123	xxxx	x	-	-	tr	xxxx	-	-
Ban Mi 2 (Bm2) <i>Ustic-Endoaquert, fine, mixed, isohyperthermic</i>									
Apg	0-18	-	tr	xxxx	-	tr	xxxx	-	-
Bssg2	35-55	-	tr	xxxx	-	tr	xxxx	-	-
Bssg4	74-98	-	tr	xxxx	-	tr	xxxx	-	-
Bssg6	130- 160+	-	tr	xxxx	-	tr	xxxx	-	-
Chong Khae (Ck) <i>Ustic-Endoaquert, very fine, smectitic, isohyperthermic</i>									
Apg	0-27	xxx	xx	-	x	tr	xxxx	-	-
Bg	27-50	xx	xx	-	x	tr	xxxx	-	-
Bssg2	75-105	xxxx	x	-	x	tr	xxxx	-	-
Bssg4	135-160	xxxx	x	-	x	tr	xxxx	x	x
Bssg6	180- 200+	xxxx	x	-	x	tr	xxxx	-	-

Table 7 (Continued)

Horizon	Depth (cm)	Clay fraction					Silt fraction		
		Sm	Kao	Inters	Ill	Qtz	Qtz	Fel	M
Lop Buri (Lb) <i>Ustic-Endoaquert, very fine, smectitic, isohyperthermic</i>									
Apg	0-20	xxxx	tr	-	-	tr	xxxx	-	-
Bssg1	20-40	xxxx	tr	-	-	tr	xxxx	-	-
Bssg3	65-90	xxxx	tr	-	-	tr	xxxx	-	-
Bssg5	120-150	xxxx	tr	-	-	tr	xxxx	-	-
Bssg7	175- 200+	xxxx	tr	-	-	tr	xxxx	-	-
Wattana (Wa) <i>Ustic-Endoaquert, fine, mixed, isohyperthermic</i>									
Apg	0-12/20	-	tr	xxxx	-	tr	xxxx	-	-
Bg	20-40	-	tr	xxxx	-	tr	xxxx	-	-
Bssg2	59-80	-	tr	xxxx	-	tr	xxxx	-	-
Bssg4	105-124	-	tr	xxxx	-	tr	xxxx	-	-
Bsskg	170- 190+	-	tr	xxxx	-	tr	xxxx	-	-
Ubong (Ub) <i>Aeric Haplaqualf, sandy, siliceous, subactive, isohyperthermic</i>									
Apg1	0-18	x	xxxx	tr	tr	-	xxxx	tr	-
Apg2	18-14	x	xxxx	tr	x	-	xxxx	tr	-
Bg1	40-68	x	xxxx	tr	x	-	xxxx	tr	-
Tha Tum (Tt) <i>Typic Endoaqualf, fine, mixed, subactive, isohyperthermic</i>									
Apg1	0-12	tr	xx	-	x	tr	xxxx	tr	-
ABg	30-50	tr	xx	tr	x	tr	xxxx	tr	-
Btg1	50-72	tr	xx	tr	x	tr	xxxx	tr	-
2Btg3	99-124	-	xx	-	xx	tr	xxxx	tr	-
2Btg5	148-174	-	xx	-	xxx	tr	xxxx	tr	-
Doem Bang (Db) <i>Aeric Endoaqualf, coarse-loamy, mixed, semiactive, isohyperthermic</i>									
Apg1	0-10	tr	xxxx	-	-	tr	xxxx	-	-
Btg1	32-55	tr	xxxx	-	tr	tr	xxxx	-	-
Btg3	80-105	x	xxx	-	tr	tr	xxxx	-	-
Bvg	165- 180+	x	xxx	-	tr	-	xxxx	-	-
Roi Et (Re) <i>Aeric Paleaquult, , coarse-loamy, siliceous, semiactive, isohyperthermic</i>									
Apg	0-16/20	xxx	xxx	-	tr	-	xxxx	tr	-
Btg1	20-50	xxx	xxx	-	tr	-	xxxx	tr	-
Btg2	50-78	xxx	xxx	-	tr	-	xxxx	tr	-
Phen (Pn) <i>Kandic Plithaquult, fine, mixed, superactive, isohyperthermic</i>									
Apg	0-19	-	xx	-	xx	tr	xxxx	-	-
Btg1	19-40	tr	xx	-	xx	tr	xxxx	-	-
Btg3	62- 78/110	tr	xxx	-	x	tr	xxxx	-	-
Bvg2	130-146	tr	x	-	xx	tr	xxxx	-	-
2Btg5	159-183	tr	x	-	xx	tr	xxxx	-	-

Table 7 (Continued)

Horizon	Depth (cm)	Clay fraction					Silt fraction		
		Sm	Kao	Inters	Ill	Qtz	Qtz	Fel	M
Phen (Pn) <i>Kandic Plithaquult, fine, mixed, superactive, isohyperthermic</i>									
Apg	0-19	-	xx	-	xx	tr	xxxx	-	-
Btg1	19-40	tr	xx	-	xx	tr	xxxx	-	-
Btg3	62- 78/110	tr	xxx	-	x	tr	xxxx	-	-
Bvg2	130-146	tr	x	-	xx	tr	xxxx	-	-
2Btg5	159-183	tr	x	-	xx	tr	xxxx	-	-
Renu (Rn) <i>Typic Plinthaquult, fine, kaolinitic, isohyperthermic</i>									
Apg	0-13	tr	x	tr	tr	x	xxxx	-	-
Btg	31-43	tr	xxx	-	tr	x	xxxx	-	-
2Bvg3	83-107	-	xxxx	-	x	-	xxxx	tr	-
2Bvg5	132-160	tr	xxxx	-	x	-	xxxx	tr	-
2BCvg	160- 195+	tr	xxxx	-	x	-	xxxx	tr	-
Nakhon Phanom (Nn) <i>Typic Endoaquult, fine, illitic, isohyperthermic</i>									
Apg	0-20	tr	xx	-	xx	tr	xxxx	tr	tr
ABg	20-40	tr	xx	-	xx	tr	xxxx	tr	tr
Btg3	85-114	x	xx	-	xx	-	xxxx	tr	tr
Btg4	114-138	x	xx	-	xx	-	xxxx	tr	tr
Samut Prakan (Sm) <i>Aeric Endoaquapt, fine loam, mixed, semiactive, isohyperthermic</i>									
Apg	0-15	x	xx	-	x	tr	xxxx	tr	-
Bg1	15-38	x	xx	-	xx	-	xxxx	tr	-
Bg3	55-82	x	xx	-	x	-	xxxx	tr	-

xxxx = dominant (>60%), xxx = large (40-60%), xx = moderate (20-40%), x = small (5 -20%), tr = trace (<5%), - = non-detectable, Sm=smectite, Kao=kaolinite, Inters = Interstratified kaolinite-smectite, Ill = illite, Qtz = quartz, Fel = feldspar, M = mica.

2. Potassium Status in Paddy Soils

The different forms of K, namely soluble K, exchangeable K, non-exchangeable K, reserved K and total K, estimated in the horizons of profile samples of the thirteen soil series are present in Table (8).

Table 8 Contents of soluble K, exchangeable K, non-exchangeable K, reserve K and total K in paddy soils.

Horizon	Depth (cm)	Soluble K and exchangeable K (----- mg kg ⁻¹ -----)	Non- exchangeable K	Reserved K	Total K
Ban Mi 1 (Bm1) <i>Ustic Endoaquert, fine, smectitic, isohyperthermic</i>					
Apkg	0-20	130.53	73.79	295.50	500
Bkg1	20-40	27.38	38.43	254.19	320
Bkg2	40-55/63	25.95	35.57	228.48	290
Bsskg1	63-84	24.10	123.15	87.75	230
Bsskg2	84-106	19.67	174.26	6.07	200
Ban Mi 2 (Bm2) <i>Ustic Endoaquert, fine, mixed, isohyperthermic</i>					
Apg	0-18	55.83	220.04	34.13	310
Bssg1	18-35	28.87	6.42	124.71	160
Bssg2	35-55	22.78	18.17	89.05	130
Bssg3	55-74	21.69	24.01	84.28	130
Bssg4	74-98	19.74	31.03	99.23	150
Chong Khae (Ck) <i>Ustic Endoaquert, very fine, smectitic, isohyperthermic</i>					
Apg	0-27	93.19	569.58	897.23	1560
Bg	27-50	57.81	644.48	997.71	1700
Bssg1	50-75	47.25	728.14	894.61	1670
Bssg2	75-105	58.82	744.32	776.86	1580
Lop Buri (Lb) <i>Ustic Endoaquert, very fine, smectitic, isohyperthermic</i>					
Apg	0-20	70.31	33.04	266.65	370
Bssg1	20-40	36.64	22.73	210.63	270
Bssg2	40-65	32.09	18.19	169.71	220
Bssg3	65-90	36.06	13.64	180.30	230
Bssg4	90-120	32.34	21.61	176.05	230
Wattana (Wa) <i>Ustic Endoaquert, fine, mixed, isohyperthermic</i>					
Apg	0-12/20	89.19	197.26	33.55	320
Bg	20-40	28.51	30.93	90.56	150
Bssg1	40-59	24.25	41.19	64.56	130
Bssg2	59-80	22.79	65.92	31.29	120
Bssg3	80-105	19.32	54.64	66.04	140
Ubon (Ub) <i>Aeric Haplaqualf, sandy, siliceous, subactive, isohyperthermic</i>					
Apg1	0-18	22.51	30.84	859.65	913
Apg2	18-40	20.01	32.96	860.03	913
Bg1	40-68	4.65	25.09	590.26	620
Bg2	68-96	7.05	55.52	767.43	830
Btg1	96-125	1.87	32.84	858.65	620

Table 8 (Continued)

Horizon	Depth (cm)	Soluble K and exchangeable K (----- mg kg ⁻¹ -----)	Non- exchangeable K	Reserved K	Total K
Tha Tum (Tt) <i>Typic Endoaqualf, fine, mixed, subactive, isohyperthermic</i>					
Apg1	0-12	16.36	60.8	3325.84	3403
Apg2	12-30	14.57	101.79	383.64	5000
ABg	30-50	18.40	143.52	6146.08	6308
Btg1	50-72	23.20	171.46	6113.34	6308
Btg2	72-99	28.23	201.14	7738.635	7968
Doem Bang (Db) <i>Aeric Endoaqualf, coarse-loamy, mixed, semiactive, isohyperthermic</i>					
Apg1	0-10	43.2	5.71	1113.09	1162
Apg2	10-25/32	29.4	15.65	950.95	1198
Btg1	32-55	33.8	13.91	948.29	996
Roi Et (Re) <i>Aeric Paleaqualf, coarse-loamy, siliceous, semiactive, isohyperthermic</i>					
Apg	0-16/20	8.65	25.74	463.61	498
Btg1	20-50	5.03	31.79	793.17	830
Btg2	50-78	5.51	25.44	799.04	830
Btg3	78-108	7.12	43.79	1277.08	1328
Phen (Pn) <i>Kandic Plithaqualf, fine, mixed, superactive, isohyperthermic</i>					
Apg1	0-19	8.95	127.67	2934.39	3071
Btg1	19-40	40.67	88.08	3855.25	3984
Btg2	40-61	39.38	188.03	6412.59	6640
Btg3	62-78/110	21.72	201.88	5752.4	5976
Renu (Rn) <i>Typic Plinthaqualf, fine, kaolinitic, isohyperthermic</i>					
Apg	0-13	8.65	25.74	1044.61	1079
BAG	13-31	5.03	31.79	461.17	498
Btg	31-43	5.51	25.44	1297.05	1328
2Bvg1	43-65	17.12	43.79	779.08	830
Nakhon Phanom (Nn) <i>Typic Endoaqualf, fine, illitic, isohyperthermic</i>					
Apg	0-18	41.67	267.70	437.62	747
BAG	18-39	33.88	494.76	13249.33	13778
Btg1	39-63	53.69	465.01	14504.3	15023
Btcg	63-94	79.66	518.13	23140.21	23738
Samut Prakan (Sm) <i>Aeric Endoaqualf, fine loam, mixed, semiactive, isohyperthermic</i>					
Apg	0-15	34.90	447.35	19271.75	19754
Bg1	15-38	47.40	606.56	22171.04	22825
Bg2	38-55	52.60	629.53	22142.87	22825
Bg3	55-82	36.80	547.49	21493.71	22078
Bg4	82-110	29.10	497.58	20638.32	21165

2.1 Soluble K plus exchangeable K

Soluble K plus exchangeable K represents readily available K (Sparks, 2000). The mean value of soluble K plus exchangeable K is illustrated in Figure 16. Soluble K plus exchangeable K shows an overall range of 1.87-130.53 mg kg⁻¹, with average value of 31.83 mg kg⁻¹. Soluble K plus exchangeable K, determined as that replaced by NH₄⁺ from NH₄OAc, is held by negative charges of organic matter and clay particles and readily available to plant (Sharpley and Boul, 1987). This investigation found that Ub, Tt, Re, Pn and Rn have very low content of soluble K plus exchangeable K whereas Bm1, Bm2, Lb, Wa, Db, Nn and Sm have low content of soluble K plus exchangeable K. The Ck soil has medium content of soluble K plus exchangeable K.

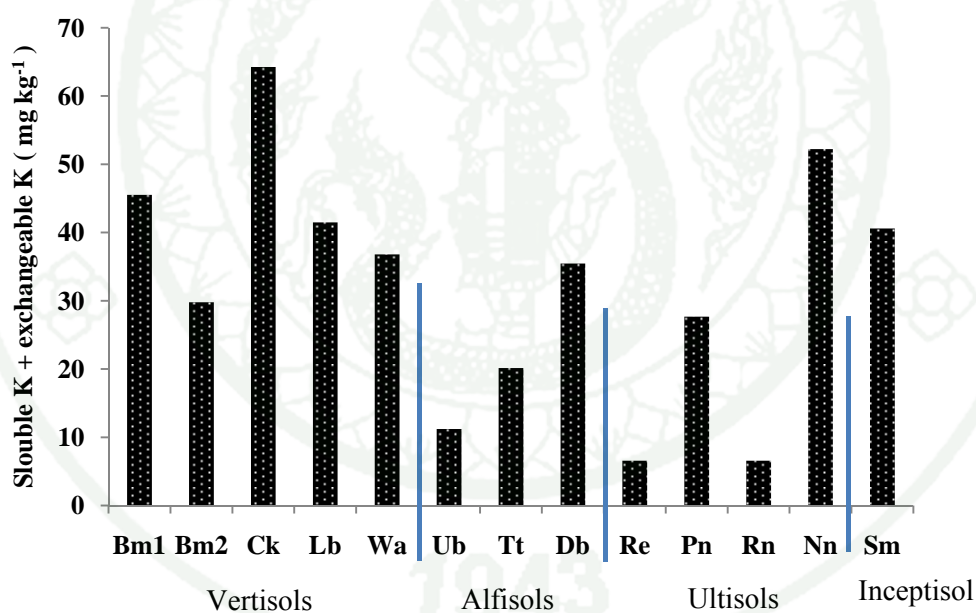


Figure 16 Mean values of soluble K plus exchangeable K content of the paddy soils.

For K fertility status, topsoil of Re, Pn, Rn (Ultisols) have “very low” content of available K while Bm2 (Vertisol), Ub, Tt, Db (Alfisols), Nn (Ultisol) and Sm (Inceptisol) have “low” content of available K. However, Wa and Ck (Vertisols) have “high” and Bm1 (Vertisol) has “very high” content of available K.

Chittamart, *et al.*, (2010) reported that most of lowland Vertisols in Thailand have smectite clay mineral predominantly. Vertisols contain the highest potential K higher than do Inceptisol, Ultisols and Alfisols because Vertisols generally contain smectite clay mineral as result of weathering process of mica that contains high K (Nursyamsi *et al.*, 2008). Figure 17 shows that topsoil of Bm1, Bm2, Wa, Ck, Lb (Vertisols) have more soluble K plus exchangeable K content than do other soils, whereas soluble K plus exchangeable K value of Bm1 (Vertisol) is greatest of all soil profiles in this study.

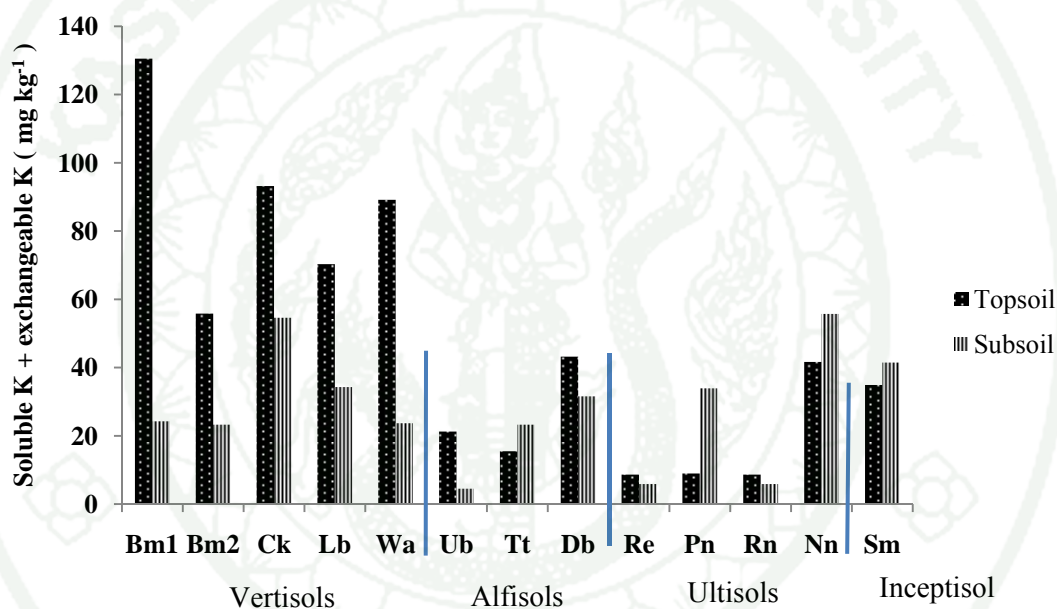


Figure 17 Mean values of soluble K plus exchangeable K content of topsoil and subsoil of the paddy soils.

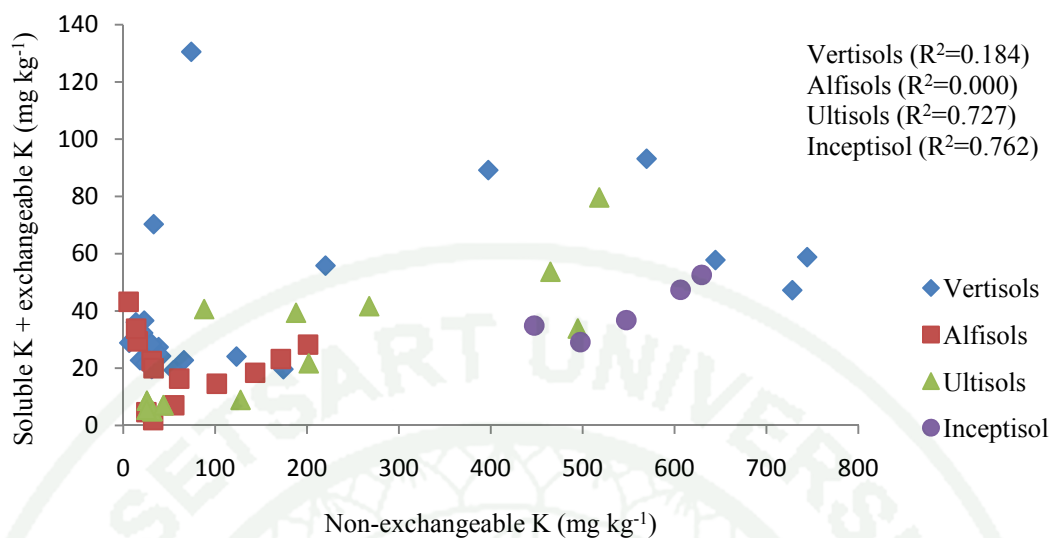


Figure 18 Relationship between soluble K plus exchangeable K and non-exchangeable K of paddy soils.

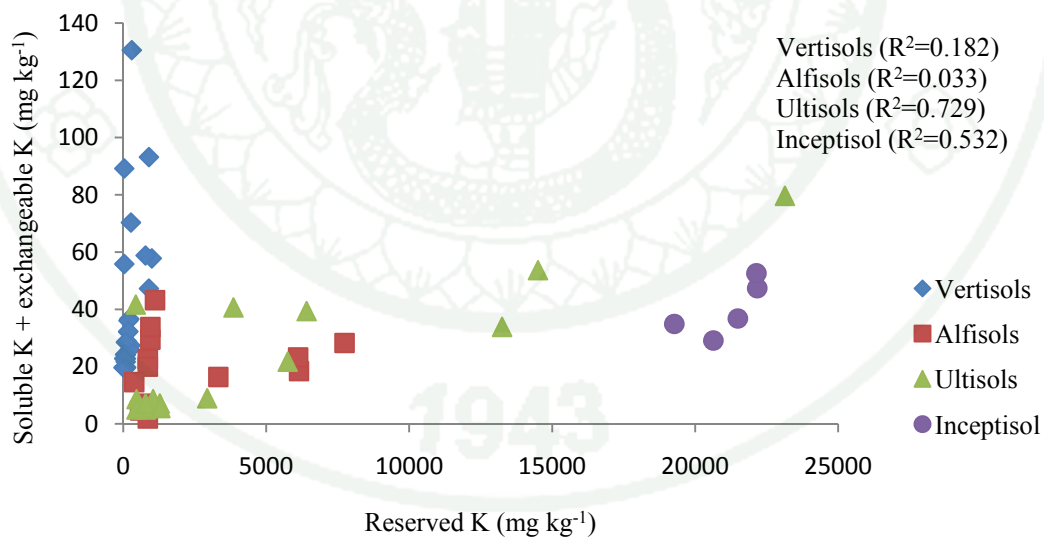


Figure 19 Relationship between soluble K plus exchangeable K and reserved K of the paddy soils.

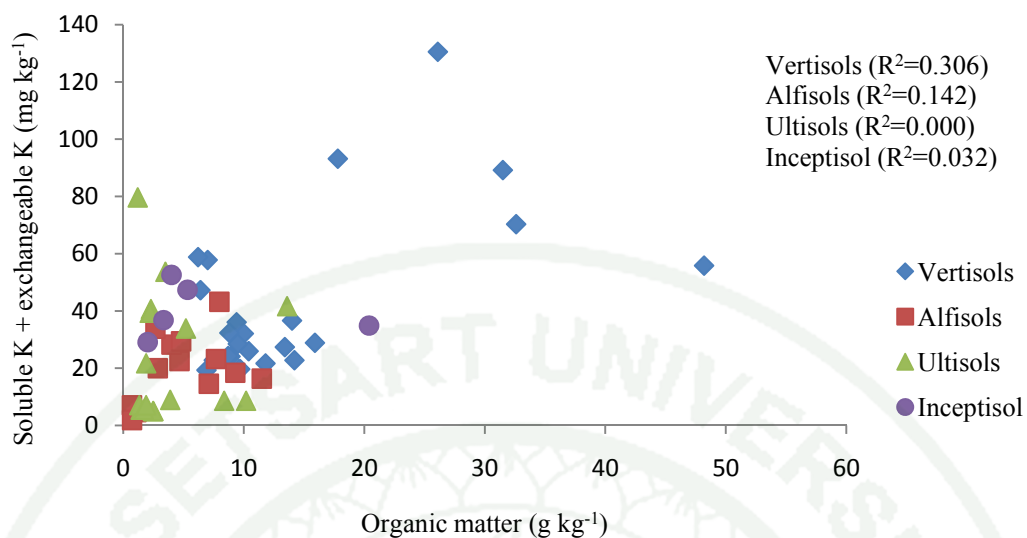


Figure 20 Relationship between soluble K plus exchangeable K content and organic matter content of the paddy soils.

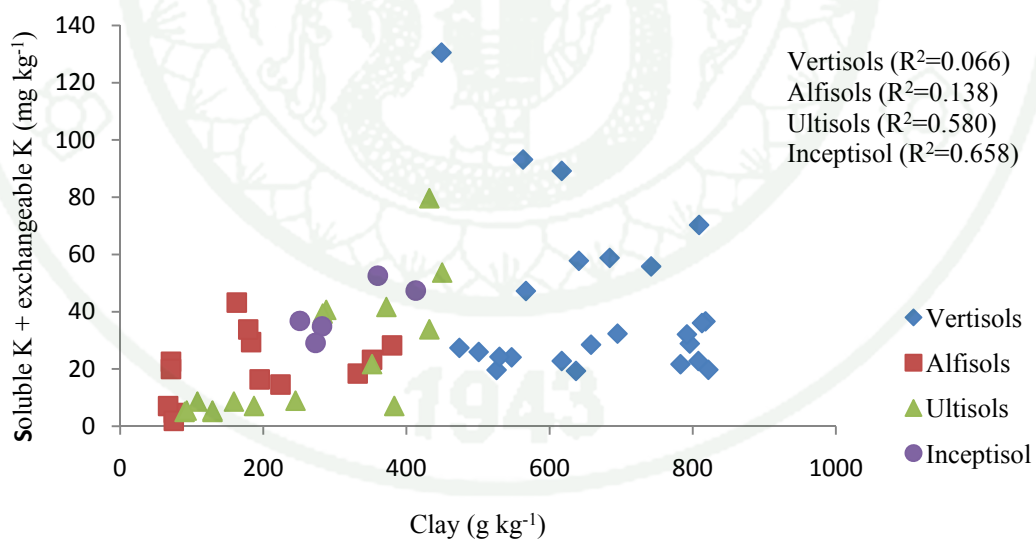


Figure 21 Relationship between soluble K plus exchangeable K content and clay content of the paddy soils.

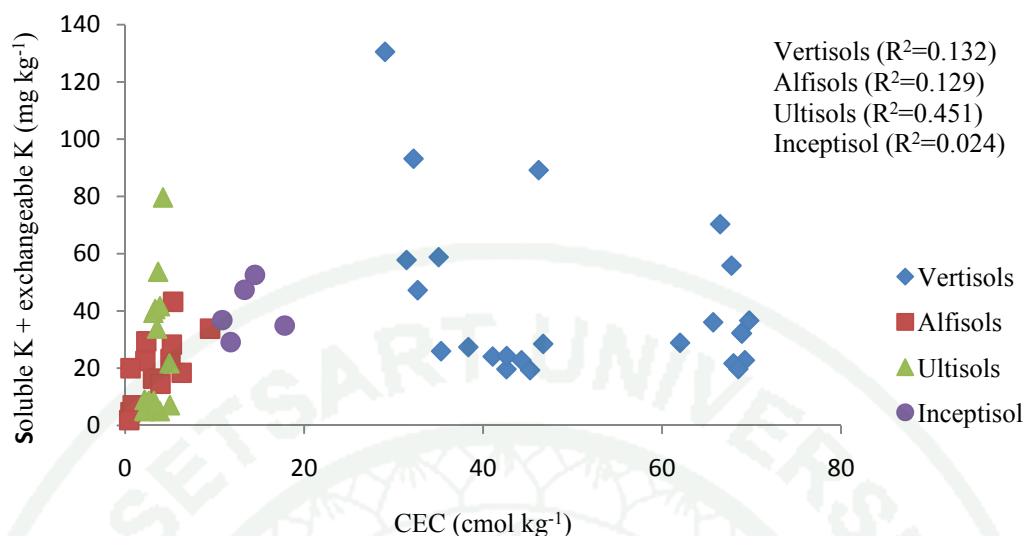


Figure 22 Relationship between soluble K plus exchangeable K content and cation exchange capacity (CEC) of the paddy soils.

Figure 18 shows that soluble K plus exchangeable K is positively significant correlated with non-exchangeable K in Ultisols ($R^2=0.727$) and Inceptisol ($R^2=0.762$). Soluble K plus exchangeable K is also positively significant correlated with reserved K in Ultisols ($R^2=0.729$) and Inceptisol ($R^2=0.532$) (Figure 19). Figure 20 shows that soluble K plus exchangeable K is positively correlated with organic matter in Vertisols ($R^2=0.306$). Soluble K plus exchangeable K is also positively significant correlated with clay content in Ultisols ($R^2=0.580$) and Inceptisol ($R^2=0.658$) (Figure 21). Soluble K plus exchangeable K is also related with cation exchange capacity in Ultisols ($R^2=0.451$) (Figure 22).

2.2 Non-exchangeable K

Non-exchangeable K content measured by soluble K plus exchangeable K subtracted from HNO_3 -extractable K. This K form ranges from 5.71-744.32 mg kg^{-1} soil with an average of 179.53 mg kg^{-1} in the paddy soils under tropical savanna climate in Thailand. The data show that non-exchangeable K content in the soil profiles generally decreases with depth, with more or less accumulation in the Bt

horizon. This K form, is fixed in the interlayer spaces of 2:1 type clay minerals (Malavolta, 1985). It is the reserve of K in the soil potentially plant-available, since it is the “pool” in direct dynamic equilibrium with the exchangeable K form (Hinsinger, 2006).

Based on profile average, Ck (Ustic Endoaquert), Nn (Typic Endoaquult) and Sm (Aeric Endoaquert) registered a high content of non-exchangeable K of $671.63 \text{ mg kg}^{-1}$, $436.42 \text{ mg kg}^{-1}$ and $545.70 \text{ mg kg}^{-1}$ respectively. Figure 23 shows that the content of non-exchangeable K is low in Db (Aeric Endoaqualf), Ub (Aeric Haplaqualf), Lb (Ustic Endoaquert), and Rn (Typic Plinthaquult) with 11.76 mg kg^{-1} , 35.38 mg kg^{-1} , 21.84 mg kg^{-1} and 31.69 mg kg^{-1} respectively. Figure 24 demonstrates that most of the subsoils tend to contain more non-exchangeable K than do the topsoils except for Bm2 (Ustic Endoaquert) and Wa (Ustic Endoaquert).

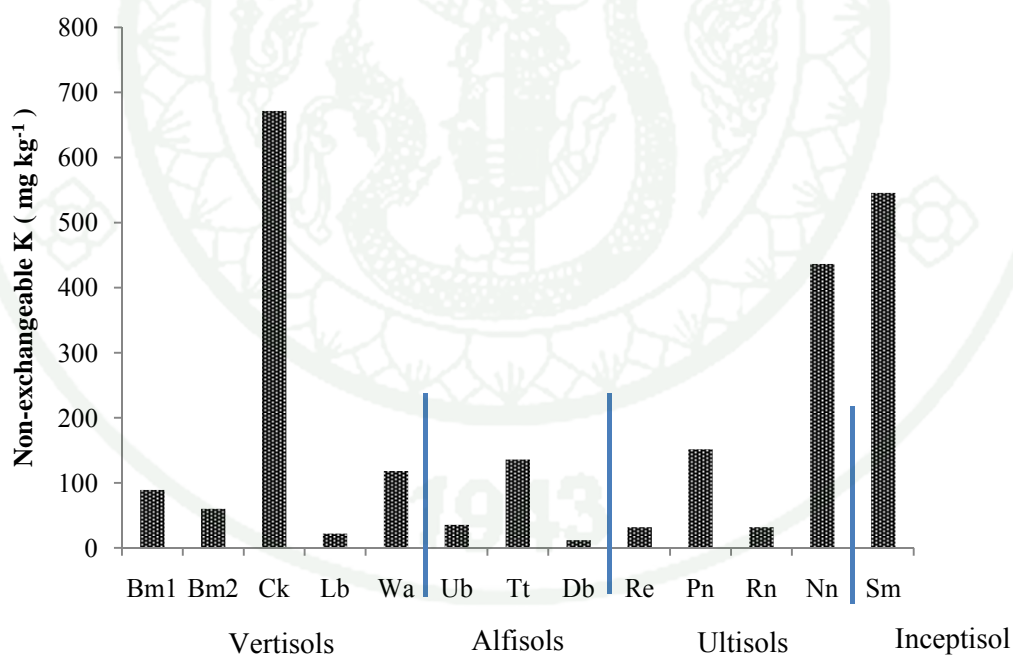


Figure 23 Mean values of non-exchangeable K of the paddy soils.

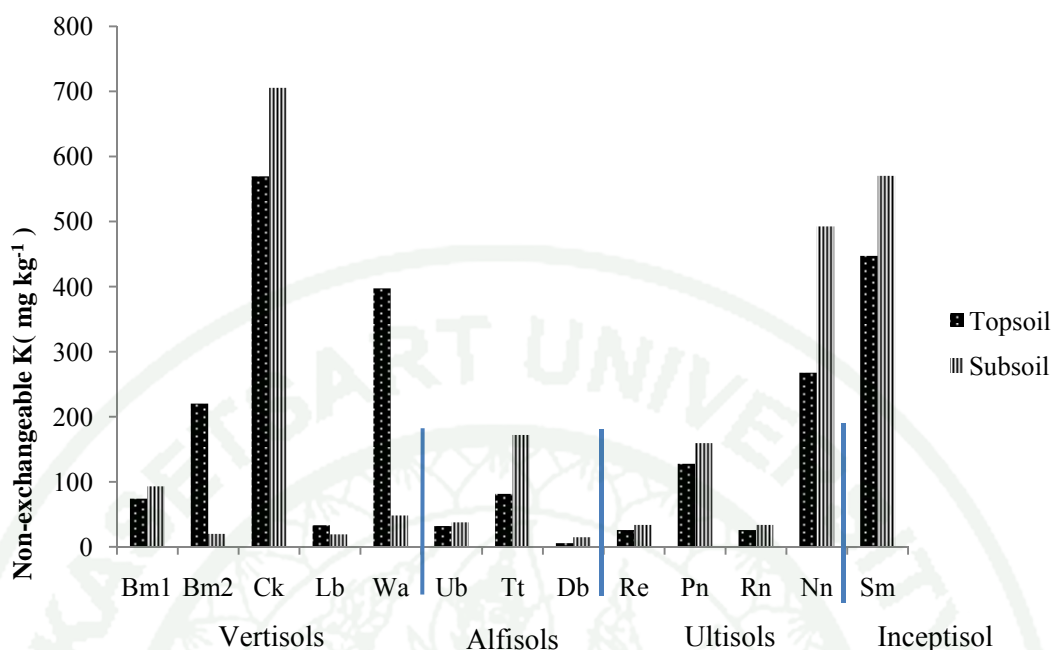


Figure 24 Mean values of non-exchangeable K of topsoil and subsoil of the paddy soils.

2.3 Reserved K

The reserved K content is calculated by soluble K, exchangeable K and non-exchangeable K subtracted from total K. The reserved K content vary from 6.07 to 23140.21 mg kg⁻¹ with a mean of 3788.51 mg kg⁻¹ in the paddy soils of Thailand under tropical savanna climate. In the topsoils and subsoils, it ranges from 33.55 to 19271.75 mg kg⁻¹, 63.11 to 21611.49 mg kg⁻¹ with means of 2875.65 mg kg⁻¹ and 4287.75 mg kg⁻¹, respectively. On the basis of profile average, high content of the reserved K are in Sm (Inceptisol) (21143.54 mg kg⁻¹) and Nn (Ultisol) (12832.87 mg kg⁻¹). Low contents of reserved K in Wa, Bm2, Bm1 and Lb (Vertisols) are 66.04 mg kg⁻¹, 86.28 mg kg⁻¹, 174.40 mg kg⁻¹ and 176.05 mg kg⁻¹ respectively (Figure 25). In this study, the reserved K contents are higher in subsoils than in topsoils (Figure 26). The reserved K measures readily available K, slowly available K and the capacity of supply K under continuous intensive cropping and, thus represents primarily a capacity factor (Sharpley and Smith, 1988).

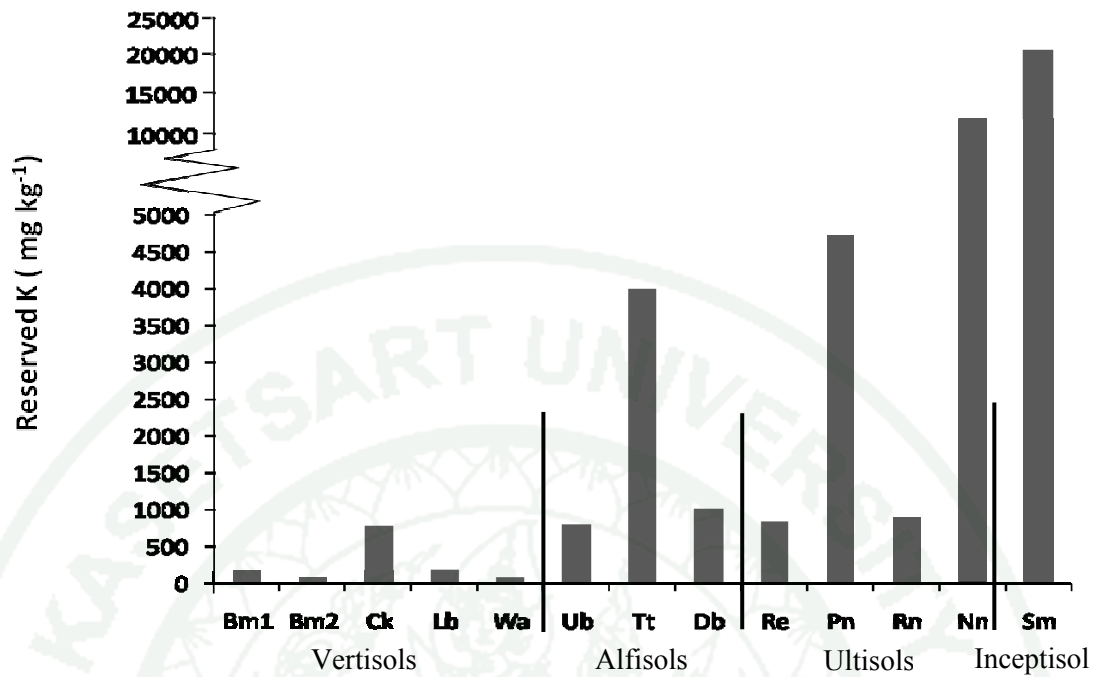


Figure 25 Mean values of reserved K of paddy soils.

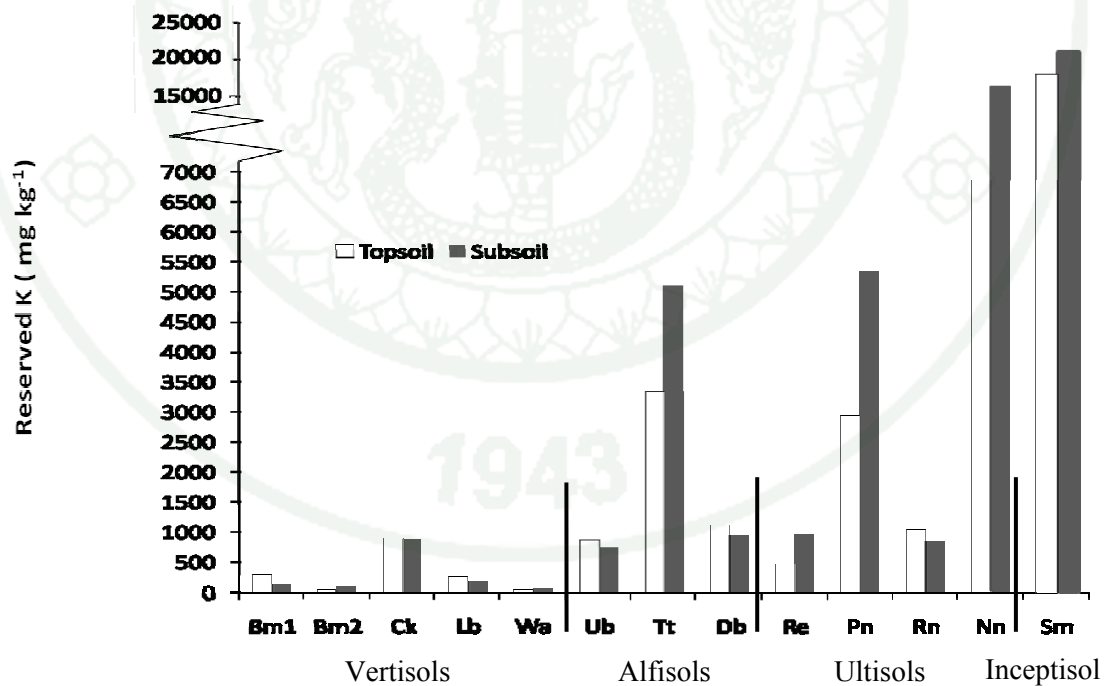


Figure 26 Mean values of reserved K of topsoil and subsoil of paddy soils.

2.4 Total K

The total K content of the soils ranges from 120 to 23738 mg kg⁻¹ with a mean value of 3926.47 mg kg⁻¹ in these paddy soils under tropical savanna climate. In the topsoils and subsoils, it ranges from 310 to 19754 mg kg⁻¹, 135 to 22223 mg kg⁻¹ with mean values of 2430 and 4478.42 mg kg⁻¹, respectively. Sha'ato *et al* (2000) reported that total K content in soil reflects the degree of weathering and nature of its parent materials. Soils containing K-bearing minerals like K-feldspars and micas, and which are subjected to mild weathering conditions tend to have high total K contents, whereas soils formed in sandy sediments and subjected to more severe weathering environments contain low levels of total potassium. Figure 27 shows that Sm (Inceptisol) has higher total K than do other soils. This may be due to the fact that Sm is derived from marine deposits. On an individual profile basis, Sm (Inceptisol) that soils derived from alluvium over marine deposits has the highest amount of total K with a profile average of 21729.4mg kg⁻¹ soil, while the lowest content of total K is in Wa (172 mg kg⁻¹) and Bm2 (Vertisols)(176 mg kg⁻¹) that developed on local alluvial partially derived from limestone. Total K content of the subsoils is higher than that of topsoils (Figure 28).

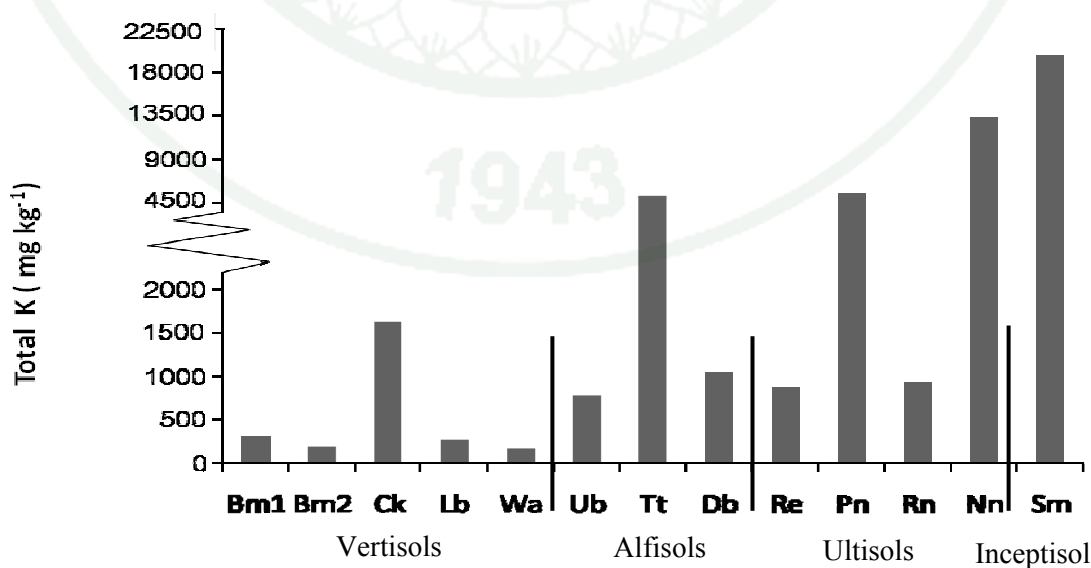


Figure 27 Mean values of total K of paddy soils.

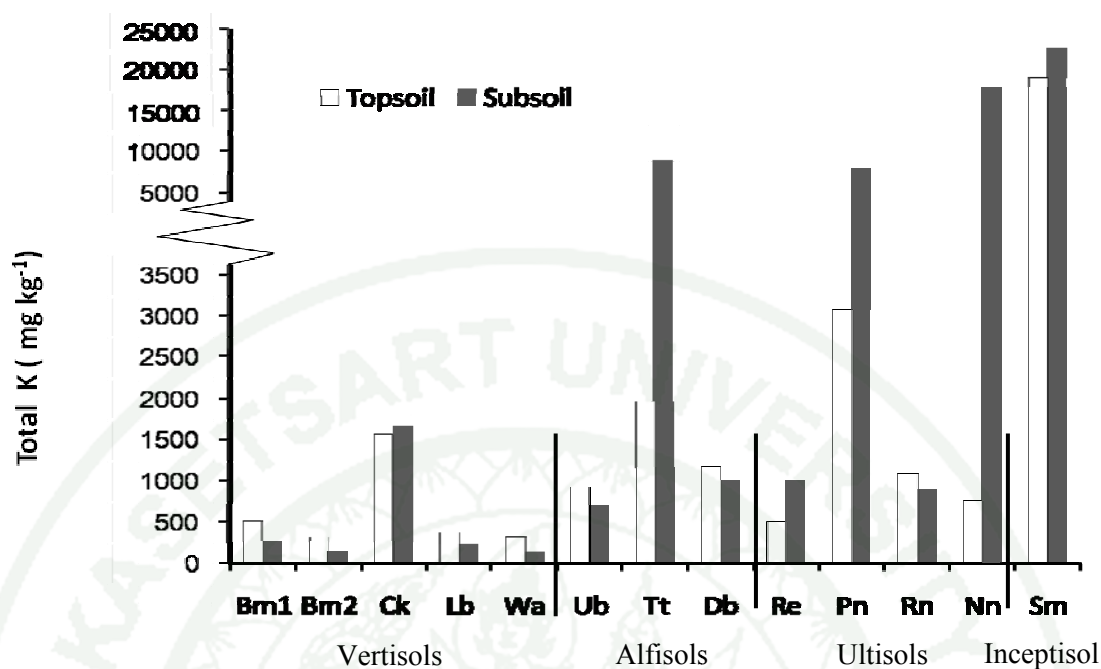


Figure 28 Mean values of total K of topsoil and subsoil of paddy soils.

2.5 Forms and content of K in different paddy soils

The content of different forms of K (Soluble K plus exchangeable K, non-exchangeable K and reserved K) in different soil orders is shown in Table 9. The highest content of total K is in Inceptisol, followed by Ultisols, Alfisols and Vertisols. Among these forms of K, the reserved K is the major portion of total K in paddy soils in this study. Comparing soluble K and exchangeable K, the highest percentage is in Vertisols (9.23%), followed by Alfisols, Ultisols and Inceptisol (0.83%, 0.47% and 0.19%) respectively. The non-exchangeable K also follows the same pattern.

Table 9 Forms and content of K in different soil paddy soils

Forms of K	K content							
	Vertisols		Alfisols		Ultisols		Inceptisol	
	mg kg ⁻¹	(%)	mg kg ⁻¹	(%)	mg kg ⁻¹	(%)	mg kg ⁻¹	(%)
Soluble K & Exchangeable K	1025.11	9.23	263.25	0.83	372.24	0.47	200.8	0.19
Non-exchangeable K	4130.71	37.18	890.85	2.83	2604.81	3.25	2728.5	2.51
Reserved K	5954.18	53.59	30382.9	96.34	77202	96.28	105728	97.3
Total K	11110		31537		80178		108647	

2.6 Correlations between the potassium forms and physical and chemical properties of paddy soils

Table 10 shows the simple correlation coefficients for the relationship between some soil properties and the various K forms in the soils. Clay content is positively and significantly correlated with soluble K plus exchangeable K ($r=0.404^{**}$), non-exchangeable K ($r=0.421^{***}$), and reserved K ($r=0.443^{***}$). Organic matter content of the soil is significantly correlated with soluble K plus exchangeable K ($r=0.476^{***}$).

In this study, cation exchange capacity is correlated with soluble K plus exchangeable K ($r=0.321^*$). The sand content of the soil is negatively correlated with soluble K plus exchangeable K and non-exchangeable K.

Table 10 Correlation coefficients of different forms of potassium with physical and chemical properties of paddy soils under tropical savanna climate.

Soil properties	Soluble K and exchangeable K	Non-exchangeable K	Reserved K	Total K
Soluble K and exchangeable K		0.502***	0.207	0.222
Non-exchangeable K	0.502***		0.635***	0.654***
Reserved K	0.207	0.635***		0.996***
Total K	0.222	0.654***	0.996***	
Sand	-0.425**	-0.183	0.190	0.178
Silt	0.204	0.312*	0.320*	-0.120
Clay	0.404**	0.119	0.164	-0.154
OM	0.475***	0.097	-0.038	0.033
CEC	0.320*	-0.071	-0.350*	0.343*

*** Very highly significant at $P \leq 0.001$

** Highly significant at $0.01 > P > 0.001$

* Significant at $0.05 > P \geq 0.01$

2.6 Correlations among forms of potassium

Correlation coefficients calculated reveal that the total K is not related with the soluble K plus exchangeable K ($r=0.222$) but significantly related with non-exchangeable K ($r=0.654***$) and reserved K ($0.996***$). The reserved K is significantly correlated with total K ($r=0.996***$) and non-exchangeable K ($r=0.635***$). The significant correlations obtained between soluble K plus exchangeable K and non-exchangeable K ($r=0.502***$) show the existence of equilibrium between these forms of K. The overall study on the correlation between forms of K also reveals a reversible equilibrium among them.

CONCLUSIONS

The paddy soils have developed from alluvium and residuum derived from limestone, weathered sedimentary rocks, metasedimentary rocks, clastic sedimentary rocks and marine deposits under tropical savanna climate. They have sandy to clayey texture, strong to slightly acidic condition to slightly alkaline condition, very low to very high cation exchange capacity and low to high base saturation.

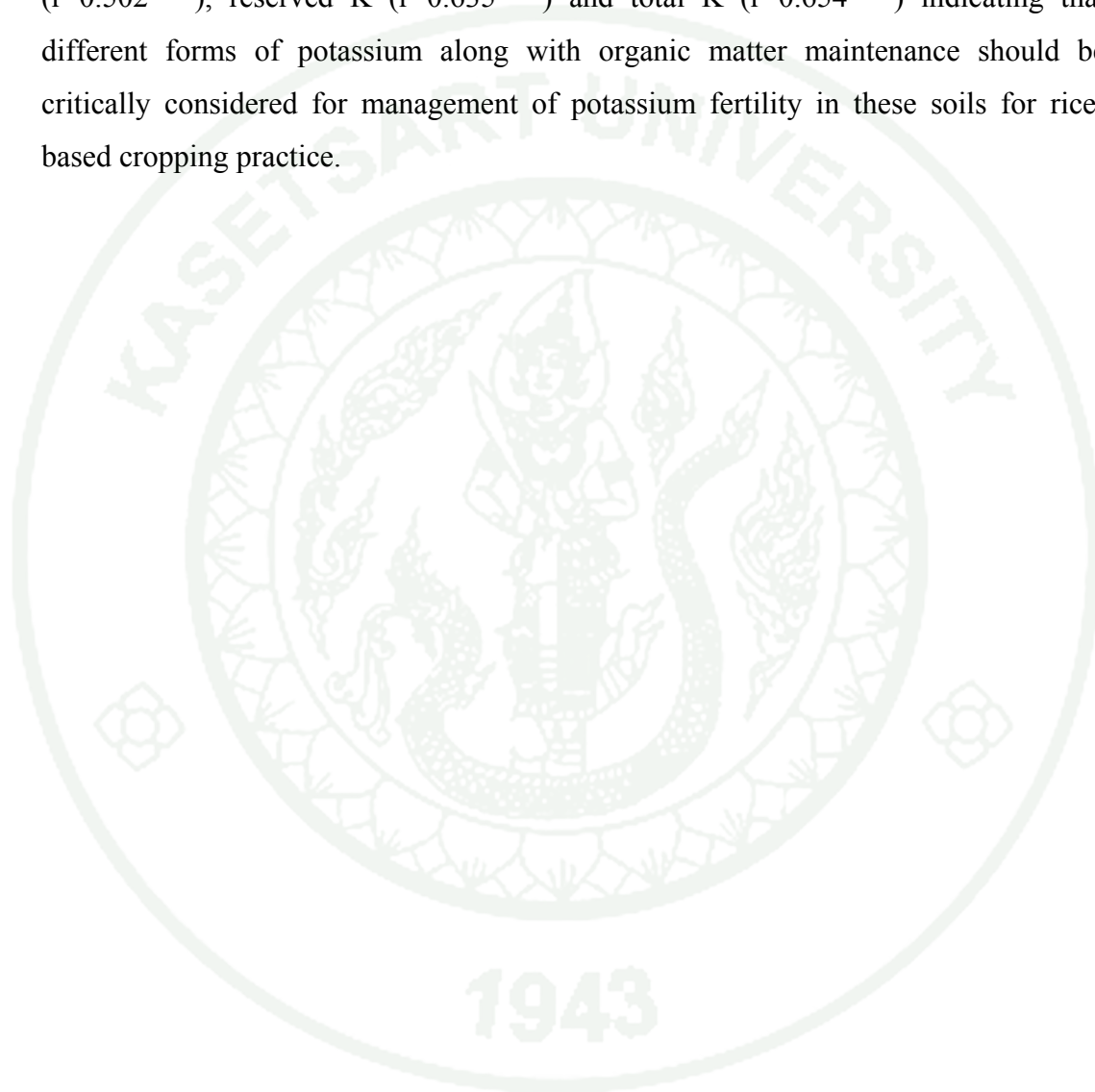
Soluble K plus exchangeable K content is “very low” in Ub, Tt, Re, Pn and Rn, “low” in Bm1, Bm2, Lb, Wa, Db, Nn, Sm and “medium” in Ck soils (average profile basis). In the topsoil (Ap horizon), the content of soluble K plus exchangeable K of Re, Pn, Rn (Ultisols) are “very low” while that of Bm2 (Vertisol), Ub, Tt, Db (Alfisols), Nn (Ultisol) and Sm (Inceptisol) are “low” that of Lb, Wa and Ck (Vertisols) are “medium to high” and that of Bm1 (Vertisol) is “very high”. Soil soluble K plus exchangeable K contents from high to low are in order of Vertisols > Inceptisol > Alfisols > Ultisols.

Non-exchangeable K content is “high” in Ck (Vertisol), Nn (Ultisol) and Sm (Inceptisol) but “low” in Db and Ub (Alfisols), Lb (Vertisol) and Rn (Ultisol) (average profile basis). In this study, most of the subsoils tend to have more non-exchangeable K than do the topsoils except for Bm2 and Wa. On the basis of profile average, high content of reserved K is found in Sm and Nn. Low content of reserved K is found in Wa and Bm2. The content of reserved K in subsoil is higher than that in topsoil.

Total K content of Sm (Inceptisol) is higher than that of other soils. This may be due to the fact that Sm soil is derived from marine deposits. The lowest content of total K is found in Wa and Bm2 developed on local alluvium partially derived from limestone.

The clay content and organic matter are positively and significantly correlated with the soluble K plus exchangeable K in these soils, more than with any other soil

properties. Soluble K plus exchangeable K is significantly correlated with non-exchangeable K. Total K is not correlated with soluble K plus exchangeable K but significantly correlated with non-exchangeable K and reserved K. The non-exchangeable K is significantly correlated with soluble K plus exchangeable K ($r=0.502^{***}$), reserved K ($r=0.635^{***}$) and total K ($r=0.654^{***}$) indicating that different forms of potassium along with organic matter maintenance should be critically considered for management of potassium fertility in these soils for rice-based cropping practice.



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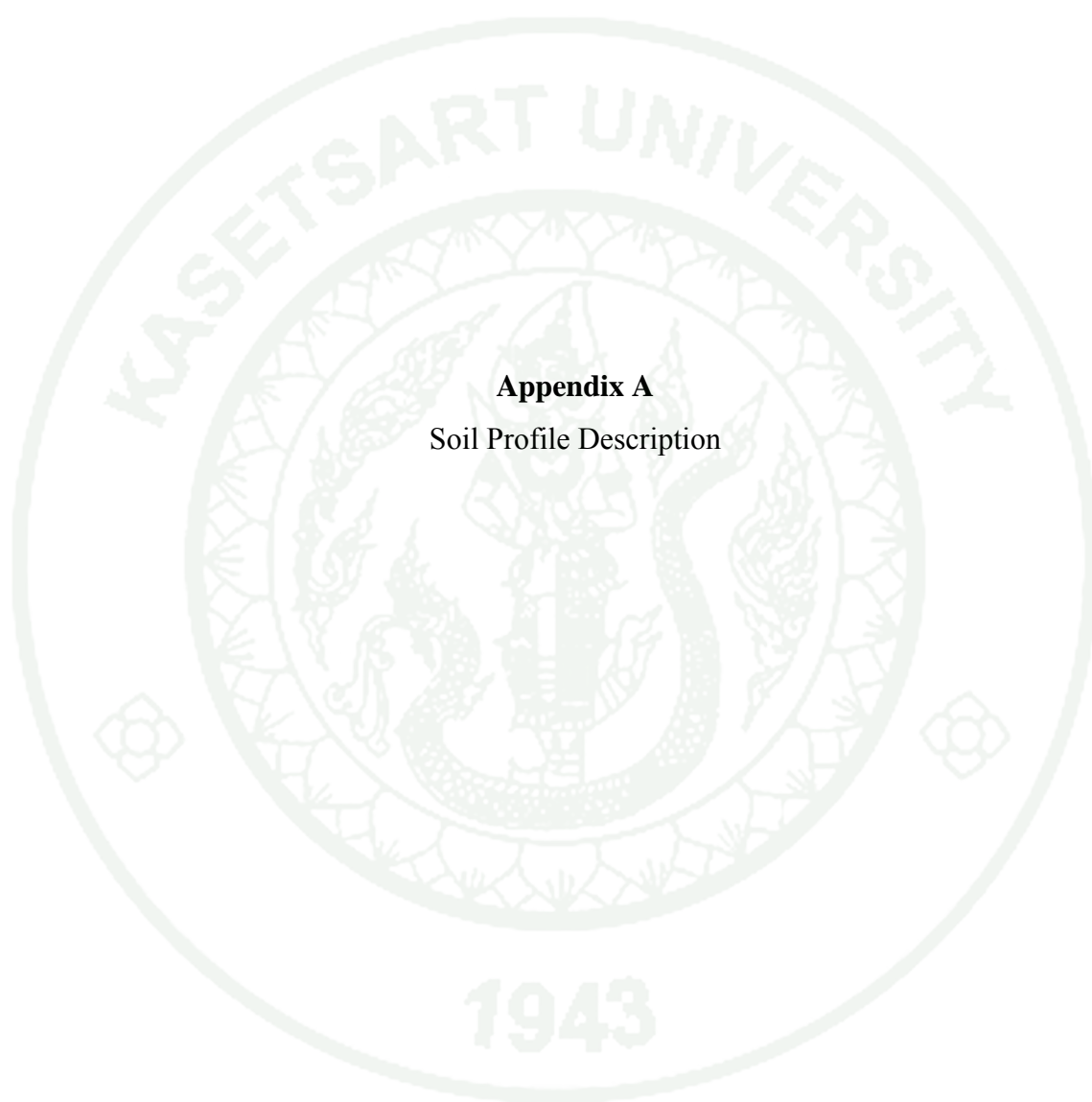
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APPENDICES



Appendix A
Soil Profile Description

Soil Profile Description

Ban Mi (Bm)

I Information on the site

Profile symbol	: Bm1
Soil name	: Ban Mi
Classification	: Ustic Endoaquert, fine, smectitic, isohyperthermic
Date of examination	: 8 April 2007
Described by	: Irb Kheoruenromne, Somchai Anusontpornperm, Supicha Thanachit, Natthapol Chittamart, Worachart Wisawapipat, and Noppadon Prayunsuk
Location	: Ban Nong Kong, Amphoe Pra Puthabath, Saraburi
Province.	
Elevation	: Approximately 26 m(MSL)
Map sheet number	: 5138 II Coordination: 47P 0697976 ^E , 1621108 ^N
Landform	
1. Physiographic position	: Lower footslope
2. Surrounding land form	: Gently undulating
3. Slope on which profile site	: 2% Aspect: 270 Azimuth
Land use	: Paddy rice, left idle
Annual rainfall	: Approximately 1,100 mm
Mean temperature	: Approximately 26 °C
Climate	: Tropical savanna

II General information on the soil

Parent material :	: Wash and local alluvium derived from weathered limestone
Drainage	: Poorly drained
Permeability	: Slow
Runoff	: Slow
Flooding depth	: 20-30 cm
Depth of groundwater	: 150 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Apkg	0-20	Very dark grayish brown (10YR 3/2), few fine distinct strong brown (7.5YR 4/6) mottles; clay; strong medium and coarse semi-angular blocky structure; very hard (dry), firm (moist), very sticky and very plastic; common faint pressure faces and small oyster shell; few very fine and fine vesicular and fine simple tubular pores; common very fine and fine roots; few small rock fragments, few vertical cracks and few trace of dead roots; moderately alkaline (field pH 8.0); gradual and smooth boundary to Bkg1.
Bkg1	20-40	Very dark grayish brown (10YR 3/2); few fine distinct dark yellowish brown (10YR 4/6) mottles; clay; strong medium and coarse semi-angular blocky structure; very hard (dry), firm (moist), very sticky and very plastic; common distinct pressure faces and few fine slickensides; few very fine and fine vesicular and fine simple tubular pores; common very fine and fine roots; common cracks, few fine rock fragments and few trace of dead roots; moderately alkaline (field pH 8.0); gradual and smooth boundary to Bkg2.

Bkg2	40-55/63	Very dark grayish brown (10YR 3/2), common fine prominent reddish brown (5YR 4/4) and few fine faint dark yellowish brown (10YR 4/6) mottles; clay; strong medium and coarse angular blocky; very hard (dry), firm (moist), very sticky and very plastic; common distinct pressure faces; few very fine and fine vesicular and few fine simple tubular pores; few very fine and fine roots; common cracks and few trace of dead roots; moderately alkaline (field pH 8.0); clear and wavy boundary to Bsskg1.
Bsskg1	63-84	Very dark brown (10YR 2/2), few fine prominent yellowish red (5YR 4/6) mottles; clay; moderate fine and medium angular blocky; hard (dry), firm (moist), very sticky and very plastic; many distinct pressure faces and slickensides; few very fine and common fine vesicular and common fine tubular pores; few very fine and fine roots; very few fine rock fragments; moderately alkaline (field pH 8.0); gradual and smooth boundary to Bsskg2.
Bsskg2	84-106	Very dark brown (10YR 2/2), few fine prominent yellowish red (5YR 4/6) mottles; clay; strong medium and coarse angular blocky structure; very hard (dry), firm (moist), very sticky and very plastic; many distinct pressure faces and slickensides; few very fine and fine vesicular and fine simple tubular pores; very few very fine and fine roots; common cracks and small rock fragments; moderately alkaline (field pH 8.0); clear and smooth boundary to Bckg1.
Bckg1	106-123	Mixed brown (10YR 5/3) 60%, gray (10YR 5/1) 30%, common fine and medium faint dark yellowish brown (10YR 4/6) and few fine prominent dark red (2.5YR 3/6) mottles and common fine distinct black (10YR 2/1) of iron and manganese concretion; slightly gravelly clay; moderate fine and medium semi-angular blocky structure; hard (dry), firm (moist), moderately sticky and moderately plastic; common faint pressure faces and iron and manganese small nodules; few very, fine, and medium vesicular and few fine simple tubular pores; very few very fine and fine roots; common fine cracks and few trace of dead roots; moderately alkaline (field pH 8.0); clear and smooth boundary to Bckg2.
Bckg2	123-145+	Mixed brown (10YR 5/3) 14%, dark grayish brown (10YR 4/2) 10%, light gray (10YR 7/2) 5%; many medium distinct yellow (10YR 5/8) and few fine prominent dark red (2.5YR 3/6) mottles and common fine and medium distinct black (10YR 2/1) of iron and manganese concretion; gravelly clay; moderate fine and medium semi-angular blocky structure; hard (dry), firm (moist), moderately sticky and moderately plastic; common faint pressure faces and iron and manganese small nodules; few very, fine, and medium vesicular and few fine simple tubular pores; practically no roots; few very fine cracks and common block clay spots; moderately alkaline (field pH 8.0).

Ban Mi (Bm)**I Information on the site**

Profile symbol	: Bm2
Soil name	: Ban Mi variant
Classification	: Ustic Endoaquert, very fine, mixed (interstratified), isohyperthermic
Date of examination	: 10 April 2007
Described by	: Irb Kheoruenromne, Somchai Anusontpornperm, Supicha Thanachit, Natthapol Chittamart, Worachart Wisawapipat, and Noppadon Prayunsuk
Location	: Ban Klom Bun, Tumbon Nong Don, Amphoe Nong Don Saraburi Province.
Elevation	: Approximately 5 m(MSL)
Map sheet number	: 5138III Coordination: 47P 0683633 ^E , 1623175 ^N
Landform	
1. Physiographic position	: Depression in local alluvial plain
2. Surrounding land form	: Flat
3. Slope on which profile site	: 2% Aspect: 270 Azimuth
Land use	: Paddy rice, left idle
	: Agricultural; bamboo, banana, coconut
Annual rainfall	: Approximately 950 mm
Mean temperature	: Approximately 27 °C
Climate	: Tropical savanna

II General information on the soil

Parent material	: Local alluvial partially derived from limestone
Drainage	: Poorly drained
Permeability	: Slow
Runoff	: Slow
Flooding depth	: ~40+cm
Depth of groundwater	: 160 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Apg	0-18	Mixed dark gray (10YR 4/1) 78%, very dark grayish brown (10YR 3/2) 20%, few fine distinct dark yellowish brown (10YR 4/6) mottles; clay; strong medium and coarse subangular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; common faint pressure faces; common very fine and fine vesicular and few fine simple tubular pores; many very fine and fine roots; common cracks of various sizes and common trace of dead roots; moderately alkaline (field pH 8.0); clear and smooth boundary to Bssg1.
Bssg1	18-35	Dark gray (2.5Y 4/1) 98%, few fine distinct olive brown (2.5Y 4/4) mottles; clay; strong medium and coarse subangular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; many prominent pressure faces and slickensides; few very fine and fine vesicular and few fine simple tubular pores; few very fine and fine roots; common cracks of various sizes, common trace of dead roots and very few fine rock fragments; moderately alkaline (field pH 8.0); clear and smooth boundary to Bssg2. A broad wedge shaped tongue extends from the upper boundary of Bssg2 to Bssg5.
Bssg2	35-55	Mixed dark gray (10YR 4/1) 60%, dark gray (2.5Y 4/1) 37%;

		few fine distinct olive brown (2.5Y 4/4) and few fine distinct strong brown (7.5YR 5/8) mottles; clay; strong medium and coarse subangular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; common distinct pressure faces and prominent slickensides; few very fine and fine vesicular and few fine simple tubular pores; very few very fine and fine roots; common cracks, few traces of dead roots and very few fine rock fragments; moderately alkaline (field pH 8.0); clear and smooth boundary to Bssg3.
Bssg3	55-74	Dark grayish brown (2.5Y 4/2), few fine distinct olive brown (2.5Y 4/4) and few fine prominent strong brown (7.5YR 5/8) mottles; clay; strong medium and coarse subangular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; common distinct pressure faces and prominent slickensides; few very fine and fine vesicular and few fine simple tubular pores; very few very fine and fine roots; common cracks and very few fine rock fragments; moderately alkaline (field pH 8.0); clear and smooth boundary to Bssg4.
Bssg4	74-98	Dark grayish brown (2.5Y 4/2), common fine distinct strong brown (2.5Y 5/4) and common fine distinct yellowish brown (10YR 5/4) mottles; clay; strong coarse angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; common distinct pressure faces and prominent slickensides; very few very fine and few fine vesicular and very few very fine simple tubular pores; practically no roots; common cracks, very few fine rock fragments and few small clay balls; moderately alkaline (field pH 8.0); clear and smooth boundary to Bssg5.
Bssg5	98-130	Mixed light yellowish brown (2.5Y 6/3) 70%, dark gray (10YR 4/1) 20%, common fine distinct olive yellow (2.5Y 6/8) mottles; clay; strong medium and coarse semi-angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; common distinct pressure faces and prominent slickensides; very few very fine and few fine vesicular and very few very fine simple tubular pores; practically no roots; common cracks, very few fine rock fragments and few small clay balls; moderately alkaline (field pH 8.0); clear and smooth boundary to Bssg6.
Bssg6	130-160+	Mixed light brownish gray (10YR 6/2) 50%, gray (10YR 5/1) 10%, common fine distinct olive yellow (2.5Y 6/8) mottles; clay; strong medium and coarse semi-angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; common distinct pressure faces and prominent slickensides; very few very fine and few fine vesicular and very few very fine simple tubular pores; practically no roots; common cracks, very few fine rock fragments and few small clay balls; moderately alkaline (field pH 8.0). Some bands of oxidizing zones exist in Bssg5 to Bssg6.

Chong Khae (Ck)**I Information on the site**

Profile symbol	: Ck
Soil name	: Chong Khae
Classification	: Ustic Endoaquert, very fine, smectitic, isohyperthermic
Date of examination	: 11 April 2007
Described by	: Irb Kheoruenromne, Somchai Anusontpornperm, Supicha Thanachit, Natthapol Chittamart, Worachart Wisawapipat, and Noppadon Prayunsuk
Location	: Ban Roeng Rang, 3048 Rd. Amphoe Sao Hai, Saraburi Province
Elevation	: Approximately 9 m(MSL)
Map sheet number	: 5138II Coordination: 47P 0692725 ^E , 1611533 ^N
Landform	
1. Physiographic position	: Semi-recent terrace
2. Surrounding land form	: Slightly undulating
3. Slope on which profile site	: 2% Aspect: 220 Azimuth
Land use	: Paddy rice, settlement and agricultural; neem, tamarind, mango, kapok
Annual rainfall	: Approximately 1,000 mm
Mean temperature	: Approximately 27 °C
Climate	: Tropical savanna

II General information on the soil

Parent material	: Mixed alluvium and Local alluvial derived from limestone
Drainage	: Poorly drained
Permeability	: Slow
Runoff	: Slow
Flooding depth	: ~30 cm
Depth of groundwater	: >200 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Apg	0-27	Mixed Brown (10YR 5/3) 85%, very dark grayish brown (2.5YR 4/6) 10%, few fine distinct yellowish red (5YR 5/6) and few fine faint reddish brown(5YR 4/4) mottles; clay; strong medium and coarse angular blocky parting to small clay blocks; very hard (dry), very firm (moist), very sticky and very plastic; common fine cracks, common faint pressure faces and traces of dead roots; few very fine and fine vesicular and few fine simple tubular pores; many very fine and fine roots; common vertical cracks downs to 100 cm; surface initiated cracks, moderately alkaline (field pH 8.0); clear and smooth boundary to Bg.
Bg	27-50	Brown (10YR 5/3), many fine distinct yellowish red (5YR 5/6) and few fine faint reddish brown (5YR 4/4) mottles; clay; strong medium and coarse semi-angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; common distinct pressure faces and common fine cracks; few very fine and fine vesicular and very few fine simple tubular pores; few very fine and fine roots; common vertical cracks and few traces of dead roots; strongly acid (field pH 5.5); clear and smooth boundary to Bssg1.
Bssg1	50-75	Pale brown (10YR 6/3), many fine and medium distinct

yellowish red (5YR 5/6) and common fine and medium distinct strong brown (7.5YR 4/6) mottles; clay; strong medium and coarse semi-angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; few faint clay coats on ped faces; common distinct pressure faces and few distinct slickensides; very few very fine and few fine vesicular and few fine simple tubular pores; very few very fine and fine roots; common vertical cracks, fine cracks and few traces of dead roots; moderately acid (field pH 6.0); clear and smooth boundary to Bssg2.

Bssg2	75-105	Pale brown (10YR 6/3), many fine and medium distinct reddish brown (5YR 5/4) mottles; clay; strong medium and coarse semi-angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; few faint clay coats on pore walls and ped faces; common fine cracks, distinct pressure faces and common slickensides; few very fine and fine vesicular and few fine simple tubular pores; very few very fine and fine roots; common vertical cracks and few soft accumulation of iron-manganese oxides; moderately acid (field pH 6.0); clear and smooth boundary to Bssg3.
Bssg3	105-135	Mixed Brown (7.5YR 5/3) 85%, grayish brown (10YR 5/2) 10%, few fine distinct yellowish red (5YR 5/6) mottles; clay; strong medium and coarse angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; very few faint clay coats on ped faces; common distinct pressure faces, fine cracks and slickensides; few very fine and fine vesicular and very few fine simple tubular pores; very few very fine and fine roots; few vertical cracks and few traces of dead roots; moderately acid (field pH 6.0); clear and smooth boundary to Bssg4.
Bssg4	135-160	Mixed brown (7.5YR 5/3) 75%, brown (7.5YR 4/2) 20%, common fine distinct yellowish red (5YR 5/6) mottles; clay; strong medium and coarse angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; very few faint clay coats on ped faces and pore walls; common distinct pressure faces and slickensides; few very fine and fine vesicular and very few fine simple tubular pores; practically no roots; very few vertical cracks and few traces of dead roots; slightly acid (field pH 6.5); clear and smooth boundary to Bssg5.
Bssg5	160-180+	Mixed brown (7.5YR 5/3) 80%, yellowish brown (10YR 5/4) 10%, common fine distinct brown (7.5YR 4/4) mottles; clay; strong medium and coarse angular blocky structure; hard (dry), firm (moist), very sticky and very plastic; very few faint clay coats mainly on ped faces; common distinct pressure faces and slickensides and fine cracks; few very fine and fine vesicular and very few fine simple tubular pores; practically no roots; few traces of dead roots; neutral (field pH 7.0); clear and smooth boundary to Bssg6.
Bssg6	180-200+	Mixed dark gray (7.5YR 4/1) 60%, dark grayish brown (10YR 4/2) 20%, common fine and medium distinct faint brown (7.5YR 4/4) mottles; clay; strong medium and coarse semi-

angular blocky structure; hard (dry), firm (moist), very sticky and very plastic; very few faint clay coats on ped faces and pore walls; common faint pressure faces, common slickensides and few fine cracks; common very fine and few fine vesicular and very few fine simple tubular pores; practically no roots; few fine rounded rock fragments; moderately alkaline (field pH 8.0).



Lop Buri (Lb)

I Information on the site

Profile symbol	: Lb
Soil name	: Lop Buri
Classification	: Ustic Endoaquert, very fine, smectitic, isohyperthermic
Date of examination	: 5 May 2007
Described by	: Irb Kheoruenromne, Somchai Anusontpornperm, Supicha Thanachit, Natthapol Chittamart, Worachart Wisawapipat, and Noppadon Prayunsuk
Location	: Ban Pa Wai, Amphoe Muang, Lop Buri Province.
Elevation	: Approximately 7 m(MSL)
Map sheet number	: 5138IV Coordination: 47P 068145 ^E , 1632258 ^N
Landform	
1. Physiographic position	: Toeslope
2. Surrounding land form	: Nearly flat
3. Slope on which profile site	: 1% Aspect: 240 Azimuth
Land use	: Paddy rice, left idle, settlement agricultural; local weeds
Annual rainfall	: Approximately 1,100 mm
Mean temperature	: Approximately 28 °C
Climate	: Tropical savanna

II General information on the soil

Parent material	: Local alluvial derived from limestone
Drainage	: Poorly drained
Permeability	: Slow
Runoff	: Slow
Flooding depth	: ~30 cm
Depth of groundwater	: >200cm cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Apg	0-20	Black (10YR 2/1); clay; strong medium and coarse semi-angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; few fine faint pressure faces and few fine slickensides; few very fine and common fine vesicular pores; many very fine and fine and few medium roots; common traces of dead roots, few fine roots and common fine rock fragments and common fine cracks; strongly alkaline (field pH 8.5); clear and smooth boundary to Bssg1.
Bssg1	20-40	Very dark gray (10YR 3/1); clay; strong medium and coarse angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; common distinct pressure faces and slickensides; few very fine and fine vesicular and few fine simple tubular pores; common very fine and fine roots; common traces of dead roots, common fine cracks and few fine rock fragments; strongly alkaline (field pH 8.5); gradual and smooth boundary to Bssg2.
Bssg2	40-65	Very dark gray (10YR 3/1), common medium faint dark yellowish brown (10YR 3/4) and few fine faint yellowish brown (10YR 5/6) mottles; clay; strong medium and coarse angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; many distinct pressure faces and

slickensides; very few very fine and fine vesicular pores; few very fine and fine roots; few traces of dead roots, few fine lime fragments and common cracks; moderately alkaline (field pH 8.0); gradual and smooth boundary to Bssg3.

Bssg3	65-90	Very dark gray (10YR 3/1), common medium faint dark yellowish brown (10YR 3/4) and few fine faint yellowish brown (10YR 5/6) mottles; clay; strong coarse angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; many distinct pressure faces and slickensides; few very fine and fine vesicular and few fine simple tubular pores; few very fine and fine roots; few traces of dead roots and common fine cracks; strongly alkaline (field pH 8.5); gradual and smooth boundary to Bssg4.
Bssg4	90-120	Very dark gray (10YR 3/1), common medium faint dark yellowish brown (10YR 3/4) and few fine faint yellowish brown (10YR 5/6) mottles; clay; strong medium and coarse angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; many distinct pressure faces and slickensides; few very fine and fine vesicular and few fine simple tubular pores; very few very fine and fine roots; common cracks and few rock and lime fragments; strongly alkaline (field pH 8.5); clear and smooth boundary to Bssg5.
Bssg5	120-150	Very dark gray (10YR 3/1), common medium faint dark yellowish brown (10YR 3/4) and few fine faint yellowish brown (10YR 5/6) mottles; clay; strong medium and coarse angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; many distinct pressure faces and slickensides; very few very fine and few fine vesicular and tubular pores; very few very fine and fine roots; common cracks and traces of dead roots and few rock and lime fragments; moderately alkaline (field pH 8.0); gradual and smooth boundary to Bssg6.
Bssg6	150-175	Dark gray (10YR 4/1), common medium faint dark yellowish brown (10YR 3/4) and few fine faint yellowish brown (10YR 5/6) mottles; clay; strong medium and coarse angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; common distinct pressure faces and slickensides; few very fine and very few fine vesicular pores and common very fine tubular pores; very few very fine and fine roots; common cracks and traces of dead roots and few rock and large lime fragments; moderately alkaline (field pH 8.0); clear and smooth boundary to Bssg7.
Bssg7	175-200+	Dark gray (10YR 4/1), many medium distinct yellowish brown (10YR 5/6) and few fine distinct yellowish brown (10YR 5/8) mottles; clay; strong medium and coarse angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; common distinct pressure faces and slickensides; few very fine and fine vesicular and few fine tubular pores; practically no roots; common cracks and traces of dead roots and few rock and large lime fragments; strongly alkaline (field pH 8.5).

Wattana (Wa)**I Information on the site**

Profile symbol	: Wa
Soil name	: Wattana
Classification	: Ustic Endoaquert, very fine, mixed (interstratified), isohyperthermic
Date of examination	: 10 April 2007
Described by	: Irb Kheoruenromne, Somchai Anusontpornperm, Supicha Thanachit, Natthapol Chittamart, Worachart Wisawapipat, and Noppadon Prayunsuk
Location	: Ban Dong Tan Sium, ~100 m Nong Don Rd (3020), Amphoe Pra Puthabath, Saraburi Province.
Elevation	: Approximately 9 m(MSL)
Map sheet number	: 5138III Coordination: 47P 0687175 ^E , 1625088 ^N
Landform	
1. Physiographic position	: Local alluvial plain (basin) (depression in local alluvial plain)
2. Surrounding land form	: Flat
3. Slope on which profile site	: 1% Aspect: 320 Azimuth
Land use	: Paddy rice, left idle
Annual rainfall	: Approximately 1,100 mm
Mean temperature	: Approximately 26 °C
Climate	: Tropical savanna

II General information on the soil

Parent material	: Local alluvial derived from Limestone
Drainage	: Poorly drained
Permeability	: Slow
Runoff	: Slow
Flooding depth	: ~40 cm
Depth of groundwater	: 190 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Apg	0-12/20	Very dark gray (10YR 3/1), few fine distinct strong brown (7.5YR 5/6) mottles; clay; strong medium and coarse angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; common faint pressure faces; few very fine and fine vesicular pores; common very fine and fine roots; many cracks of various sizes and common trace of dead roots; moderately alkaline (field pH 8.0); clear and wavy boundary to Bg.
Bg	20-40	Mixed olive brown (2.5Y 4/3) 88%, very dark gray (10YR 3/1) 10%; few fine prominent strong brown (7.5YR 5/6) mottles; clay; strong coarse angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; many distinct pressure faces and small slickensides; very few very fine and fine vesicular and few fine simple tubular pores; few very fine and fine roots; many cracks of various sizes and few trace of dead roots; moderately alkaline (field pH 8.0); clear and wavy boundary to Bssg1.
Bssg1	40-59	Mixed olive brown (2.5Y 4/3) 88%, very dark gray (10YR 3/1)

10%; few fine prominent strong brown (7.5YR 5/6) mottles; clay; strong coarse angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; many distinct pressure faces and slickensides; few very fine and very few fine vesicular and very few fine simple tubular pores; practically no roots; common cracks of various sizes; moderately alkaline (field pH 8.0); gradual and smooth boundary to Bssg2.

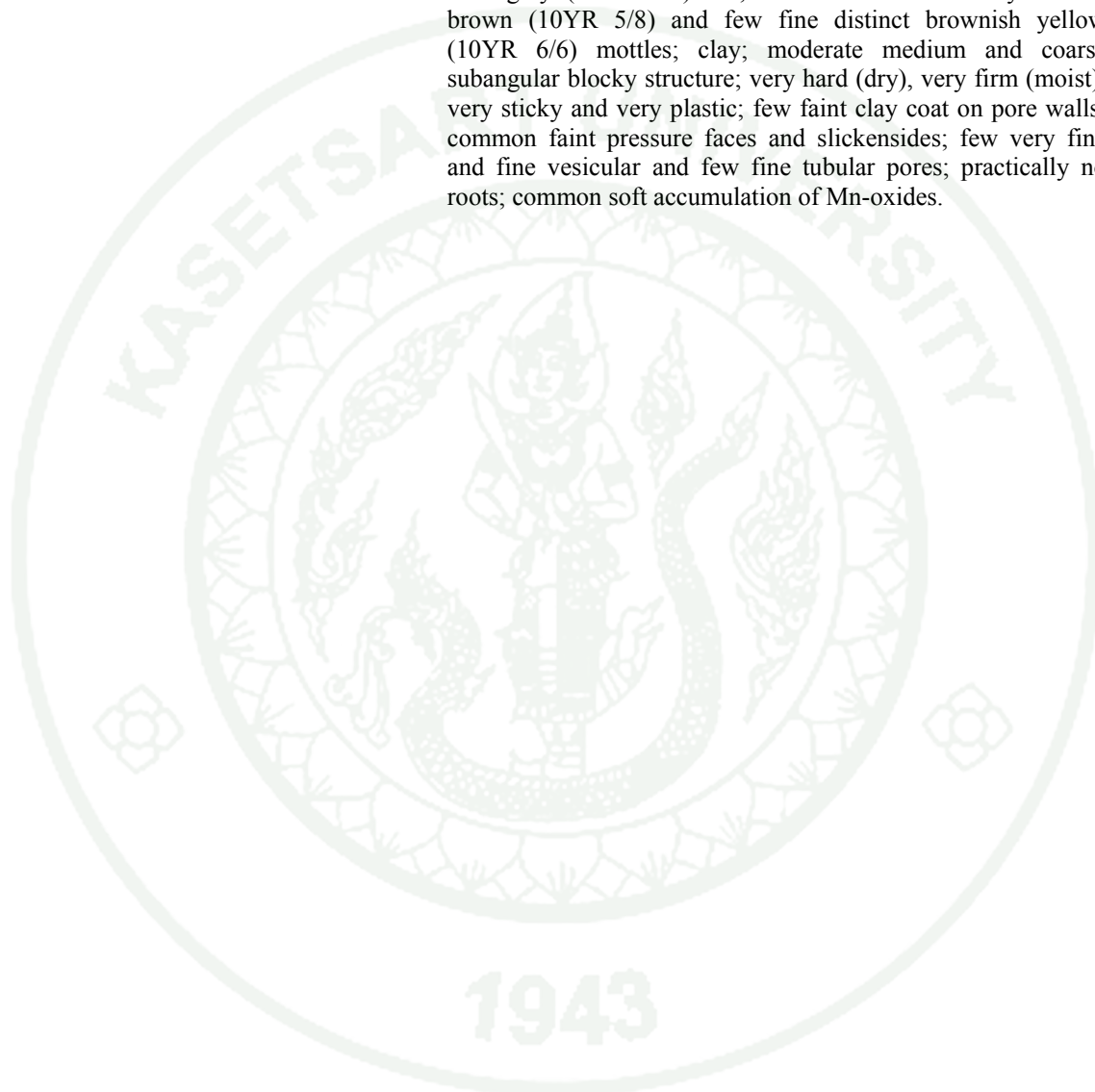
Bssg2	59-80	Mixed dark olive brown (2.5Y 3/3) 90% and very dark gray (10YR 3/1) 5%, common fine prominent brownish yellow (10YR 6/6) and few fine prominent strong brown (7.5YR 5/6) mottles; clay; strong coarse angular blocky; very hard (dry), very firm (moist), very sticky and very plastic; many distinct pressure faces and slickensides, very few fine rock fragments; few very fine and very few fine vesicular and very few fine simple tubular pores; practically no roots; common cracks of various sizes; moderately alkaline (field pH 8.0); clear and smooth boundary to Bssg3.
Bssg3	80-105	Mixed very dark grayish brown (2.5Y 3/2) 90% and very dark gray (10YR 3/1) 5%, common fine prominent strong brown (7.5YR 5/6) and few fine prominent brownish yellow (10YR 6/6) mottles; clay; strong coarse angular blocky; very hard (dry), very firm (moist), very sticky and very plastic; many distinct pressure faces and slickensides, very few fine rock fragments; few very fine and very few fine vesicular and very few fine simple tubular pores; practically no roots; common cracks of various sizes; moderately alkaline (field pH 8.0); clear and smooth boundary to Bssg4.
Bssg4	105-124	Mixed very dark grayish brown (2.5Y 3/2) 93% and very dark gray (10YR 3/1) 5%, few fine prominent strong brown (7.5YR 5/6) mottles; clay; strong coarse angular blocky; very hard (dry), very firm (moist), very sticky and very plastic; many distinct pressure faces and slickensides, very few fine rock fragments; few very fine and very few fine vesicular and very few fine simple tubular pores; practically no roots; common cracks of various sizes; moderately alkaline (field pH 8.0); clear and smooth boundary to Bssg5.
Bssg5	124-145	Mixed dark grayish brown (10YR 4/2) 48%, dark grayish brown (2.5Y 4/2) 30%, olive brown (2.5Y 4/3) 10%; common fine distinct light olive brown (2.5Y 5/4), few fine distinct strong brown (7.5YR 5/6) mottles; clay; strong coarse angular blocky; very hard (dry), very firm (moist), very sticky and very plastic; many distinct pressure faces and slickensides, very few fine rock fragments; few very fine and very few fine vesicular and very few fine simple tubular pores; practically no roots; common cracks of various sizes; moderately alkaline (field pH 8.0); clear and smooth boundary to Bssg6.
Bssg6	145-170	Mixed light olive brown (2.5Y 5/6) 73%, very dark gray (10YR 3/1) 20%, light brownish gray (2.5Y 6/2) 5%, few fine distinct brownish yellow (10YR 6/6) and few fine prominent (7.5 YR 5/6) mottles; clay; strong medium and coarse angular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; many distinct pressure faces and slickensides,

few lime nodules; few very fine and very few fine vesicular and very few fine simple tubular pores; practically no roots; common cracks of various sizes; moderately alkaline (field pH 8.0); clear and smooth boundary to Bsskg.

Bsskg

170-190+

Mixed light olive brown (2.5Y 5/4) 40%, light olive brown (2.5Y 5/6) 38%, light yellowish brown (2.5Y 6/3) 5%, very dark gray (10YR 3/1) 5%, common fine distinct yellowish brown (10YR 5/8) and few fine distinct brownish yellow (10YR 6/6) mottles; clay; moderate medium and coarse subangular blocky structure; very hard (dry), very firm (moist), very sticky and very plastic; few faint clay coat on pore walls; common faint pressure faces and slickensides; few very fine and fine vesicular and few fine tubular pores; practically no roots; common soft accumulation of Mn-oxides.



Ubón (Ub)

I Information on the site

Profile symbol	: Ub
Soil name	: Ubón series
Classification	: Aeric Haplaqualf, sandy, siliceous, subactive, isohyperthermic
Date of examination	: July 17, 2009
Described by	: Irb Kheouruenromne, Wittaya Jindaluang, Wipawan Taimuang, Kamolwan Laopoonkit, Worachart Wisawapipat, Khwunta Khawmee, Daojarut Ketrot and Boontarik Chimchart
Location	: Approximately 100 m South-West of road No.23 at km 23.2 from Maha Sarakham. Ban Pim Pisan, Tambon Si Keaw, Amphoe Mueang, Roi Et Province
Elevation	: Approximately 150 m (MSL)
Map sheet number	: 4745 IV Coordination: 47Q 0339405E UTM: 1782074N
Landform	
1. Physiographic position	: Lower erosional terrace
2. Surrounding landform	: Undulating
3. Slope on which profile site	: 3% (aspect: 88 Azim.)
Land use	: Left idle under grasses at time of sampling, Paddy
Annual rainfall	: Approximately 1,300 mm
Mean temperature	: Approximately 26 °C
Climate	: Tropical savanna
Others	: Agricultural and settlement

II General information on the soil

Parent material	: Wash (sandy)
Drainage	: Poorly drained
Permeability	: Moderate
Runoff	: Slow
Depth of ground water	: Deeper than 1.70 m at time of sampling
Flooding depth	: Approximately 30 cm
Duration	: 1-2 months
Frequency	: Once a year or less

III Profile description

Horizon	Depth (cm)	Description
Apg1	0-18	(7.5YR 4/2) and (7.5YR 5/8) mottles; loam; moderate weak fine and medium subangular blocky structure; soft dry, very friable moist, none sticky and none plastic; few fine variegated sands; few very fine and fine vesicular pores; many very fine, fine and few medium roots; few traces of dead roots; very strongly acid (field pH 5.0); clear and smooth boundary to Apg2.
Apg2	18-40	(7.5YR 4/2) (5YR 6/4) and (7.5YR 5/8) mottles; loam; moderate weak fine and medium subangular blocky structure; soft dry, friable moist, none sticky and none plastic; few fine variegated sands and few fine charcoal fragments; few very fine and few medium vesicular pores; common very fine and fine roots; few traces of dead roots and few pale sand particles; very strongly acid (field pH 4.5); clear and wavy boundary to Bg1.
Bg1	40-68	(5YR 6/4) and (7.5YR 5/8) mottles; loamy sand; moderate weak fine and medium subangular blocky structure; soft dry,

		friable moist, none sticky and none plastic; very few very fine variegated sands; few very fine and fine vesicular pores; few very fine and common fine roots; few traces of dead roots and few traces of charcoal fragments; very strongly acid (field pH 5.0); clear and smooth boundary to Bg2.
Bg2	68-96	(7.5YR 6/4) and (7.5YR 5/8) mottles; loamy sand; moderate weak fine and medium subangular blocky structure; soft dry, slightly firm moist, none sticky and none plastic; few fine variegated sands; very few very fine and few fine vesicular pores; few very fine and common fine roots; few traces of dead roots and few fine charcoal fragments; strongly acid (field pH 5.5); clear and smooth boundary to Btg1.
Btg1	96-125	(5YR 6/6) and (7.5YR 5/8) mottles; sandy loam; moderate weak fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and none plastic; few faint clay bridges among sand grains; few fine variegated sands; few very fine, fine and medium vesicular pores; very few very fine roots; few traces of dead roots; strongly acid (field pH 5.5); clear and smooth boundary to Btg2.
Btg2	125-148	(7.5YR 6/3) and (7.5YR 5/8) mottles; sandy loam; moderate weak fine and medium subangular blocky structure and semi-massive structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; few faint clay bridges among sand grains; common very fine variegated sands; very few very fine and fine vesicular pores; very few fine roots; few traces of dead roots and few pale sand particles; moderately acid (field pH 6.0); abrupt and smooth boundary to Cg.
Cg	148-170+	(10YR 5/2) 80%, (10YR 6/4) 20% and (2.5Y 5/6) mottles; sandy loam; moderate fine and medium semi-angular blocky structure; slightly hard dry, firm moist, slightly sticky and moderately plastic; few faint bridges among sand grains; very few very fine variegated sands; very few very fine and common fine vesicular pores; practically no roots; slightly acid (field pH 6.5).

Tha Tum (Tt)

I Information on the site

Profile symbol	: Tt
Soil name	: Tha Tum series
Classification	: Typic Endoaqualf, fine, mixed, subactive, isohyperthermic
Date of examination	: 9 January 2006
Described by	: Irb Kheoruenromne, Somchai Anusontpornperm, Supicha Thanachit, and Chuthamard Kaewmano
Location	: Approximately 1.5 km North of Srang Khom-Ban Pak Suay Road at Km 3 Ban Pone Khong, Tambon Srang Khom, Amphoe Srang Khom, Changwat Udon Thani
Elevation	: Approximately 177 m(MSL)
Map sheet number	: 5544IV Coordination: 48 0298096 ^E , 19 73631 ^N
Landform	
1. Physiographic position	: Lower part of low terraces
2. Surrounding land form	: Gently undulating
3. Slope on which profile site	: 1% Aspect: Northwest
Land use	: Paddy rice, agricultural, eucalyptus species and remnants of moist mixed deciduous forest
Annual rainfall	: Approximately 1,500 mm
Mean temperature	: Approximately 26 °C
Climate	: Tropical savanna

II General information on the soil

Parent material	: Recent alluvium on residuum derived from fine grained clastic sedimentary rocks
Drainage	: Poorly drained
Permeability	: Slow
Runoff	: Slow
FloodingDepth	: ~20 cm
Duration	: 2-3 months
Frequency	: 1 time/year
Depth of groundwater	: 190 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Apg1	0-12	Dark grayish brown (10YR 4/2) common fine distinct yellowish brown (10YR 5/8) root mottles; loam; moderate fine and medium subangular blockly structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; common very fine, fine and few medium vesicular pores; common very fine, fine and medium roots; many root mottles; few fine variegated sands, few; extremely acid (field pH 4.5); clear, smooth boundary to Apg2.
Apg2	12-30	Mixed gray (10YR 5/1) 60% and dark grayish brown (10YR 4/2) 40% common fine prominent strong brown (7.5YR 4/2) common fine distinct yellowish brown (10R 5/6) root mottles; sandy clay loam; moderate medium and coarse subangular blockly structure; hard dry, slightly firm moist, slightly sticky and slightly plastic; few faint clay coat on pore walls; few very fine, common fine and few medium vesicular pores, few fine simple tabular pore; common very fine and fine roots; common traces of dead roots; few fine variegated sands; extremely acid

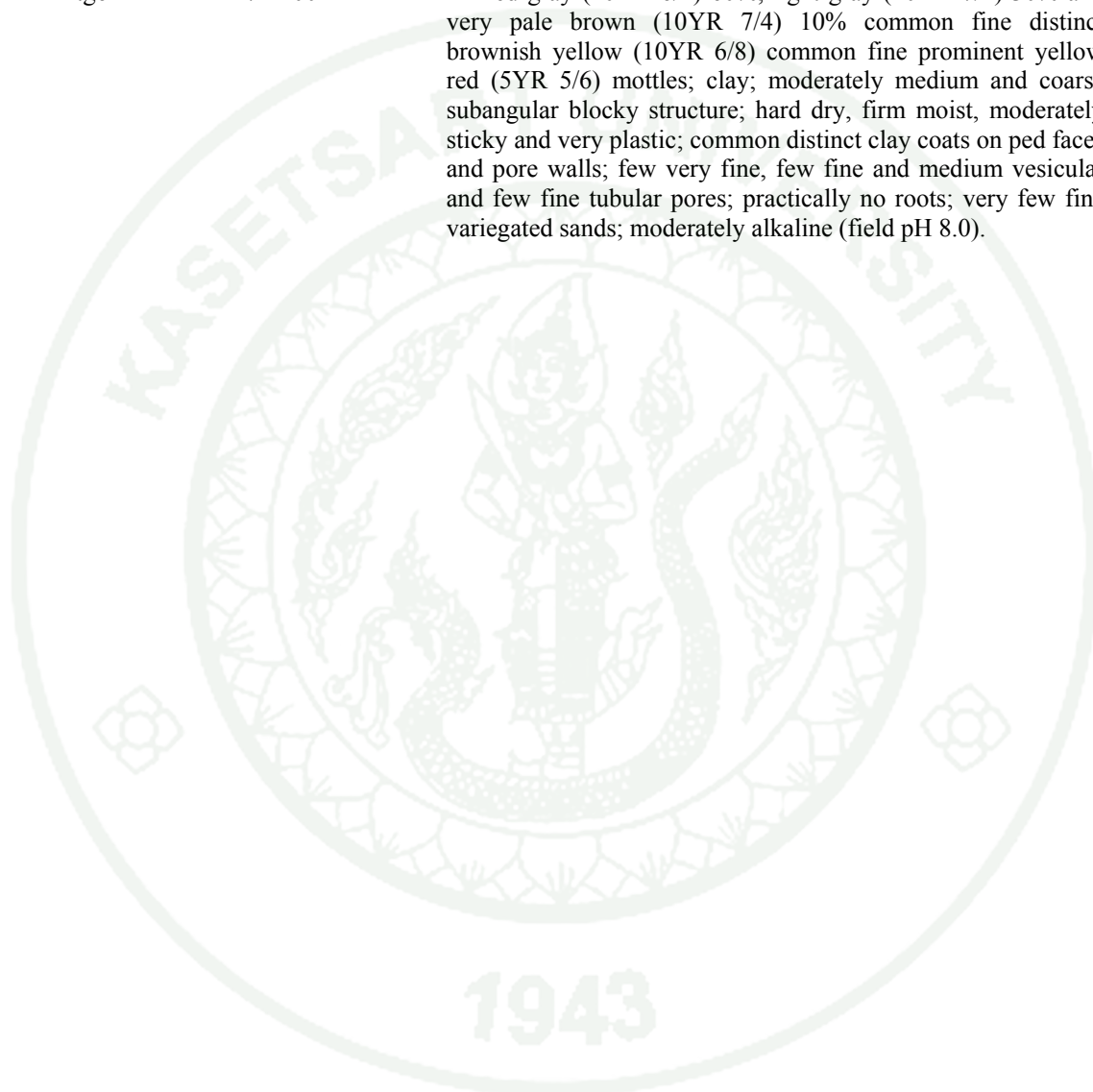
ABg	30-50	(field pH 4.5); clear, smooth boundary to ABg. Mixed dark gray (10YR 4/1) 90% and very pale brown (10YR 7/3) 10% common fine distinct yellowish brown (10YR 5/6) common fine prominent dark brown (7.5YR 4/4) mottles; clay loam; moderate medium and coarse subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; very few faint clay coat on pore walls; few very fine and fine vesicular and few fine simple tabular pores; few very fine and fine roots; many traces of dead roots; some large charcoal fragments; extremely acid(field pH 4.5); clear, smooth boundary to Btg1.
Btg1	50-72	Mixed dark gray (10YR 4/1) 80% and very pale brown (10YR 7/3) 20% common fine prominent dark brown (7.5YR 4/4) few fine faint yellowish brown (10YR 5/6) mottles; clay loam; moderate medium and coarse semi-angular blocky structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; common faint clay bridges among sand grains and common faint clay coat pore walls; common very fine, few fine and few medium vesicular and few fine simple tabular pores; few very fine and fine roots; common traces of dead roots; very few fine variegated sands; very strongly acid (field pH 5.0); clear, smooth boundary to Btg2.
Btg2	72-99	Light brownish gray (10YR 6/2) common fine prominent strong brown (7.5YR 5/8) common fine faint brownish yellow (10YR 6/8) mottles; clay loam; moderately medium and coarse semi-angular blocky structure; hard dry, firm moist, slightly sticky and moderately plastic; common faint clay bridges among sand grains and clay coat on pore walls; few very fine, few fine and medium vesicular and few fine simple tabular pores; very few very fine and fine roots; few traces of dead roots and very few fine variegated sands; slightly acid (field pH 6.5); clear, smooth boundary to 2Btg3.
2Btg3	99-124	Mixed lightly brownish gray (10YR 6/2) 85% and light gray (10YR 7/2) 15% common fine and medium distinct brownish yellow (10YR 6/8) common fine and medium distinct yellowish brown (10YR 5/6) mottles; clay; moderately medium and coarse subangular blocky structure; hard dry, firm moist, moderately sticky and very plastic; few faint clay bridges among sand grains and clay coats on pore walls; very few very fine and common fine vesicular pores; very few very fine and fine roots; few traces of dead roots; common white fine sand spots; moderately alkaline (field pH 8.0); clear, smooth boundary to 2Btg4.
2Btg4	124-148	Mixed gray (10YR 5/1) 80% and very pale brown (10YR 7/3) 20% common fine and medium distinct brownish yellow (10YR 6/8) common fine distinct yellowish brown (10YR 5/8) mottles; clay; moderately medium and coarse semi-angular blocky structure; hard dry, firm moist, moderately sticky and very plastic; common distinct clay coat on ped faces and pore walls; few very fine and fine vesicular and few fine simple tabular pores; very few very fine and fine roots; few traces of dead roots; common white fine sand spots; moderately alkaline (field pH 8.0); clear, smooth boundary to 2Btg5.
2Btg5	148-174	Mixed gray (10YR 6/1) 50% and light gray (10YR 7/1) 50% common fine distinct brownish yellow (10YR 6/8) common fine prominent yellowish red (5YR 5/6) few fine distinct black (10YR 2/1) mottles; clay; moderately medium and coarse semi-

angular blocky structure; hard dry, firm moist, moderately sticky and very plastic; common distinct clay coat on ped faces and pore walls; few very fine and fine vesicular and few fine simple tubular pores; practically no roots; few fine cracks and slickensides; common white fine sand spots and few black spots of manganese; moderately alkaline (field pH 8.0); clear, smooth boundary to 2Btg6.

2Btg6

174-200+

Mixed gray (10YR 6/1) 60%, light gray (10YR 7/1) 30% and very pale brown (10YR 7/4) 10% common fine distinct brownish yellow (10YR 6/8) common fine prominent yellow red (5YR 5/6) mottles; clay; moderately medium and coarse subangular blocky structure; hard dry, firm moist, moderately sticky and very plastic; common distinct clay coats on ped faces and pore walls; few very fine, few fine and medium vesicular and few fine tubular pores; practically no roots; very few fine variegated sands; moderately alkaline (field pH 8.0).



Doem Bang (Db)**I Information on the site**

Profile symbol	: Db
Soil name	: Doem Bang
Classification	: Aeric Endoaqualf, coarse loamy, mixed, semiactive, isohyperthermic
Date of examination	: 24 January 2008
Described by	: Irb Kheoruenromne, Worachart Wisawapipat, Natthapol Chittamart, and Chuthamard Kaewmano, Timtong Darunsontaya, Wipawan Insomboon and Noppadon Prayunsuk
Location	: Ban Thakham, Tambon Huana, Amphoe Doem Bang nang buat, Changwat SuphanBuri
Elevation	: Approximately 19 m(MSL)
Map sheet number	: 5138IV Coordination: 47P 0606037 ^E , 1644777 ^N
Landform	
1. Physiographic position	: Toeslope extended from extensive footslope
2. Surrounding land form	: Slightly undulating
3. Slope on which profile site	: 2% Aspect: 260 Azimuth
Land use	: Paddy rice, left idle
Annual rainfall	: Approximately 1,000 mm
Mean temperature	: Approximately 27 °C
Climate	: Tropical savanna

II General information on the soil

Parent material	: Mixed marine and local alluvium derived from metasedimentary rocks
Drainage	: Poorly drained
Permeability	: Moderate
Runoff	: Slow
Depth of groundwater	: 180 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Apg1	0-10	Mixed dark gray (5YR4/1) 60% and light reddish brown (5YR6/4) 38% and few fine yellowish brown (10YR5/8) <2% mottles; sandy clay loam; moderate fine and medium subangular blocky structure; hard dry, slightly firm moist, slightly sticky and slightly plastic; few variegated sands; few very fine, fine and common fine vesicular and few fine tubular pores; many very fine and fine roots; common traces of dead roots; neutral (field pH 6.5); clear, smooth boundary to Apg2.
Apg2	10-25/32	Mixed dark gray (5YR4/1) 47% and light reddish brown (5YR6/3) 20% and few fine yellowish brown (7.5YR5/8) 3% mottles; fine sandy clay loam; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; few variegated sands; few very fine, fine and common fine vesicular and few fine tubular pores; many very fine and fine roots; common traces of dead roots; neutral (field pH 5.5); clear, wavy boundary to Btg1.
Btg1	32-55	Mixed brown (7.5YR5/2) 47% and light brown (5YR6/4) 40% and common fine strong brown (7.5YR5/6) 5% mottles; fine sandy clay loam; moderate fine and medium subangular blocky

		structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; few faint clay coat on pore wall and common faint clay bridges among sand grain; few variegated sands; few very fine, fine and few medium vesicular and few fine tubular pores; many very fine and fine roots; common traces of dead roots; neutral (field pH 6.5); clear, smooth boundary to Btg2.
Btg2	55-80	Mixed brown (7.5YR5/2) 75% and light brown (5YR6/3) 15% and common fine strong brown (7.5YR5/8) 5% and common fine strong brown (7.5YR5/6) 5% mottles; fine sandy clay loam; moderate fine and medium coarse semi-angular blocky structure; hard dry, slightly firm moist, slightly sticky and slightly plastic; few faint clay coat on pore wall and common faint clay bridges among sand grain; common variegated sands; few very fine, fine and common medium vesicular and common tubular pores; many very fine and fine roots; common traces of dead roots; neutral (field pH 6.5); clear, smooth boundary to Btg3.
Btg3	80-105	Mixed dark gray (7.5YR4/1) 30% and light brown (5YR6/3) 45% and common fine and medium strong brown (7.5YR4/6) 10% and common fine strong brown (7.5YR5/8) 5% mottles; fine sandy clay loam; moderate fine and medium coarse semi-angular blocky structure; hard dry, slightly firm moist, moderately sticky and moderately plastic; few faint clay coat on pore wall and common faint clay bridges among sand grain; common variegated sands and few reddish yellow iron oxides accumulations; few very fine, fine and medium vesicular and few fine tubular pores; common very fine and fine roots; few traces of dead roots; neutral (field pH 6.5); clear, smooth boundary to Btg4.
Btg4	105-132	Mixed gray (7.5YR5/1) 48% and light brown (7.5YR6/3) 40% and common fine and medium strong brown (7.5YR4/6) 10% and common fine black (7.5YR5/8) 2% mottles; fine sandy clay; moderate and medium coarse semi-angular blocky structure; hard dry, slightly firm moist, moderately sticky and moderately plastic; few faint clay coat on pore wall and common faint clay bridges among sand grain; few very fine, fine and medium vesicular and few fine tubular pores; common very fine and fine roots; few traces of dead roots; neutral (field pH 6.5); clear, smooth boundary to Btg5.
Btg5	132-165	Mixed pink (5YR7/3) 48% and gray (7.5YR5/1) 65% and common fine and medium yellowish brown (7.5YR4/6) 7 % and common fine and medium dark reddish brown (7.5YR5/8) 7% and few fine reddish gray (5YR5/2) <2% mottles; fine sandy clay loam; moderate and medium coarse subangular blocky structure; hard dry, slightly firm moist, very sticky and very plastic; few faint clay coat on pore wall and common faint clay bridges among sand grain; common variegated common soft accumulations of iron oxides; few very fine, fine and medium vesicular and few fine tubular pores; few very fine and fine roots; few traces of dead roots and half ripe; moderately fluid; neutral (field pH 7.0); abrupt, smooth boundary to Bvg.
Bvg	165-180+	Mixed gray (10YR6/1) 45% and pink (7.5YR7/3) 30% and common fine and medium yellowish brown (10YR5/8) 5 % and common fine and medium dark yellowish brown (10YR5/6) and black (5YR2/1) 10% of iron-manganese oxides nodules mottles; very gravelly sandy clay; strong fine and medium

subangular blocky structure; very hard dry, slightly firm moist, moderate sticky and moderate plastic; common clay coat on pore wall and common faint clay bridges among sand grain; common segregations of iron oxides and clay; few very fine; fine and medium vesicular and few tubular pores; few very fine and fine roots; neutral (field pH7.0)



Roi Et (Re)**I Information on the site**

Profile symbol	: Re
Soil name	: Roi Et series
Classification	: Aeric Paleaquult, coarse-loamy, siliceous, semiactive, isohyperthermic
Date of examination	: July 19, 2009
Described by	: Irb Kheouruenromne, Wittaya Jindaluang, Wipawan Taimuang, Kamolwan Laopoonkit, Worachart Wisawapipat, Khwunta Khawmee, Daojarut Ketrot and Boontarik Chimchart
Location	: Approximately 100 m South of road No.23 from Maha Sarakham to Roi Et at km 7.1. Ban Siang Hien, Tambon Si Keaw, Amphoe Mueang, Maha Sarakham Province
Elevation	: Approximately 134 m (MSL)
Map sheet number	: 4745 IV Coordination: 47Q 0324498E UTM: 1787184N
Landform	
1. Physiographic position	: Lower erosional terrace
2. Surrounding landform	: Gently undulating
3. Slope on which profile site	: 1% (aspect: 132 Azim.)
Land use	: Paddy field, left idle at time sampling, neem, banana, Eucalyptus
Annual rainfall	: Approximately 1,300 mm
Mean temperature	: Approximately 26 °C
Climate	: Tropical savanna
Others	: Agricultural and settlement

II General information on the soil

Parent material	: Wash and local alluvium derived from weathered sedimentary rocks
Drainage	: Poorly drained
Permeability	: Moderate
Runoff	: Slow
Depth of ground water	: Deeper than 1.50 m at time of sampling
Flooding depth	: Approximately 30 cm
Duration	: 2-3 months
Frequency	: Once a year

III Profile description

Horizon	Depth (cm)	Description
Apg	0-16/20	(7.5YR 5/2) and (5YR 5/8) mottles; sandy loam; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; few faint clay bridges among sand grains; many very fine variegated sands and few fine cracks; very few very fine and common fine vesicular pores; many very fine, fine and few medium roots; few traces of dead roots; very strongly acid (field pH 5.0); clear and smooth boundary to Btg1.
Btg1	20-50	(5YR 4/2) and (5YR 4/6) mottles; sandy loam; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; common faint clay bridges and few faint clay coats on ped faces and pore walls; few fine variegated sands; very few very fine and common fine vesicular pores; common very fine, fine and very

Btg2	50-78	<p>fine medium roots; few traces of dead roots; strongly acid (field pH 5.5); clear and smooth boundary to Btg2. 7.5YR 5/3) and (5YR 4/6) mottles; sandy loam; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; common faint clay bridges among sand grains and few faint clay coats on ped faces and pore walls; common fine variegated sands; very few very fine and common fine vesicular pores; few very fine and fine roots; few traces of dead roots; very strongly acid (field pH 5.0); clear and smooth boundary to Btg3.</p>
Btg3	78-108	<p>(7.5YR 5/3) and (5YR 5/8) (5YR 4/6) mottles; sandy clay loam; moderate fine and medium subangular blocky structure; hard dry, firm moist, slightly sticky and moderately plastic; common faint clay bridges among sand grains and few faint clay coats on ped faces and pore walls; common fine variegated sands; very few very fine and common fine vesicular pores and few fine tubular pores; few very fine and common fine roots; very few traces of dead roots; strongly acid (field pH 5.5); clear and smooth boundary to Btg4.</p>
Btg4	108-135	<p>(7.5YR 6/3) and (7.5YR 5/8) mottles; sandy clay; moderate weak fine and medium subangular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; common faint clay bridges among sand grains and common faint clay coats on ped faces and pore walls; few fine variegated sands; few very fine and common fine vesicular pores and few fine tubular pores; very few very fine and fine roots; strongly acid (field pH 5.5); clear and smooth boundary to Btg5.</p>
Btg5	135-150+	<p>(7.5YR 6/4) and (7.5YR 5/8) mottles; sandy clay; moderate fine and medium subangular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; common faint clay bridges among sand grains and common faint clay coats on ped faces and pore walls; few fine variegated sands and common weak iron oxide concretions; very few very fine and fine vesicular pores and few fine tubular pores; practically no roots; very few fine iron and manganese oxide nodules; moderately acid (field pH 6.0)</p>

Phen (Pn)**I Information on the site**

Profile symbol	: Pn
Soil name	: Phen series
Classification	: Kandic Plinthaquilt, fine, mixed, subactive, isohyperthermic
Date of examination	: 9 January 2006
Described by	: Irb Kheoruenromne, Pean Singjanusong, Somchai Anusontpornperm, Supicha, Thanachit, and Chuthamard Kaewmano
Location	: Approximately 50 m East of Udon Thani-Nong Khai Road at Km 27 between Ban Nikhom and Ban Na Di Ya, Tambon Chiang Wang, Phen, Changwat Udon Thani
Elevation	: Approximately 173 m (MSL)
Map sheet number	: 5544II
Landform	: Coordination: 48 0265243 ^E , 19 52043 ^N
1. Physiographic position	: Upper part of low erosional terraces
2. Surrounding land form	: Slightly undulating
3. Slope on which profile site	: 1% Aspect: Northeast
Land use	: Paddy rice, settlement, agricultural and remnants of deciduous forest
Annual rainfall	: Approximately 1,400 mm
Mean temperature	: Approximately 26 °C
Climate	: Tropical savanna

II General information on the soil

Parent material	: Wash over residuum derived from fine grained clastic sedimentary rocks
Drainage	: Poorly drained
Permeability	: Moderate
Runoff	: Slow
FloodingDepth	: ~30 cm
Duration	: 2-3 months
Frequency	: 1 time/year
Depth of groundwater	: 200 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Apg	0-19	Light brownish gray (10YR 6/2) common fine and medium prominent strong brown (7.5YR 5/8) mottles; fine sandy clay loam; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; few very fine and fine, common medium vesicular pores; many very fine and common fine roots; common traces of dead roots; few fine variegated sands; strongly acid (field pH 5.5); clear, smooth boundary to Btg1.
Btg1	19-40	Very pale brown (10YR 7/3) common fine distinct brownish yellow (10YR 6/8) mottles; fine sandy clay loam; moderate fine and medium semi-angular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and moderate plastic; few faint clay bridges among sand grains and few faint clay coats on pore walls; few very fine, fine and medium vesicular pores; few very fine and fine roots; common traces of dead roots; few fine variegated sands; slightly acid (field pH 6.5); clear, smooth boundary to Btg2.

Btg2	40-61	Very pale brown (10Y 7/3) common fine and medium prominent yellowish red (5YR 5/8), few fine distinct reddish yellow (7.5YR 6/8) mottles; fine sandy clay loam; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; few faint clay coats on pore walls and few faint clay bridge among sand grains; common very fine, few fine and medium vesicular pores; very few very fine and fine roots; few fine variegated sands; few traces of dead roots; extremely acid (field pH 4.5); clear, smooth boundary to Btg3.
Btg3	61-78/110	Pinkish gray (7.5YR 7/2); common fine distinct strong brown (7.5Y 5/8), few fine prominent yellowish red (5YR 5/6) mottles; fine sandy clay loam; moderate fine and medium semi-angular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and very plastic; few faint clay coats pore walls and few faint clay bridge among sand grains; few very fine, common fine and few medium vesicular pores; very few traces of dead roots; few fine variegated sands and some black spots of manganese; extremely acid (field pH 4.5); abrupt, wavy boundary to Bvg1.
Bvg1	110-130	White (2.5Y 8/2); common fine distinct olive brown (2.5Y 4/4), common fine prominent brownish yellow (10YR 6/8) mottles; lateritic gravels; mainly compacted pisolithic; very hard dry, very firm moist, moderately sticky and very plastic; common distinct clay coats on pore walls; common large vesicular pores; very few very fine and fine roots; practically no roots; few traces of dead roots; extremely acid (field pH 4.5); clear, smooth boundary to Bvg2.
Bvg2	130-146	White (2.5Y 8/2); common fine prominent yellow (10YR 7/8), common fine prominent reddish yellow (7.5YR 6/8) and few fine prominent red (2.5YR 5/8) mottles; very gravelly clay; strong medium and coarse semi-angular blocky structure; very hard dry, very firm moist, moderately sticky and very plastic; common distinct clay coats on nodules surfaces and pore walls; few very fine, fine and medium vesicular pores; practically no roots; few variegated sands and few fine cracks; extremely acid (field pH 4.5); gradual, smooth boundary to 2Btg4.
2Btg4	146-159	White (2.5Y 8/2); few fine distinct light olive brown (2.5Y 5/6) mottles; very gravelly sandy clay; strong coarse semi-angular blocky structure; very hard dry, very firm moist, very sticky and very plastic; common distinct clay coats on pore walls and ped faces; few very fine, fine and medium vesicular pores; practically no roots; common distinct pressure faces of various sized, few fine cracks and few fine variegated sands; extremely acid (field pH 4.5); clear, smooth boundary to 2Btg5.
2Btg5	159-183	White (2.5Y 8/2); few fine prominent brownish yellow (10YR 6/8) mottles; very gravelly sandy clay; strong coarse semi-angular blocky structure and semi-massive; very hard dry, very firm moist, very sticky and very plastic; common distinct clay coats on pore walls and ped faces; few very fine, fine and medium vesicular pores; practically no roots; common distinct of pressure faces, few fine cracks and few fine variegated sands; extremely acid (field pH 4.5), clear, smooth boundary to 2Btg6.
2Btg6	183-200+	White (2.5Y 8/2); common fine prominent red (2.5YR 4/6), few fine prominent yellowish brown (10YR 5/8) mottles; very gravelly sandy clay; strong coarse semi-angular blocky

structure and semi-massive; very hard dry, very firm moist, very sticky and very plastic; common distinct clay coats on pore walls and ped faces; few very fine, fine and medium vesicular pores; practically no roots; common distinct of pressure faces, few fine cracks and few fine variegated sands; extremely acid (field pH 4.5)



Renu (Rn)**I Information on the site**

Profile symbol	: Rn
Soil name	: Renu series
Classification	: Typic Plinthaquult, fine, kaolinitic, isohyperthermic
Date of examination	: 13 February 2006
Described by	: Irb Kheoruenromne, Pean Singjanusong, Somchai Anusontpornperm, Supicha, Thanachit, and Chuthamard Kaewmano, Worachart Wisawapipat, Natthapol Chittamart
Location	: Ban Sri Bunruang, Tambol Sri Bunruang, Amphoe Renu Nakhon, Nakhon Phanom Province
Elevation	: Approximately 151 m (MSL)
Map sheet number	: 5438 II Coordination: 48 0461766 ^E , 19 90195 ^N
Landform	
1. Physiographic position	: Strath terrace
2. Surrounding land form	: Flat
3. Slope on which profile site	: 0% Aspect:
Land use	: Paddy rice, agricultural and settlement
Annual rainfall	: Approximately 2,260 mm
Mean temperature	: Approximately 26 °C
Climate	: Tropical savanna

II General information on the soil

Parent material	: Wash over residuum derived from fine grained weathered clastic sedimentary rocks
Drainage	: Poorly drained
Permeability	: Moderate
Runoff	: Slow
Flooding Depth	: ~30 cm
Duration	: 2-3 months
Frequency	: 1 time/year
Depth of groundwater	: 200 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Apg	0-13	Mixed very dark grayish brown (10YR 3/2) 80% and pale brown (10YR 6/3) 20%, common fine prominent strong brown (7.5YR 5/6) and few fine distinct yellowish brown (10YR 5/8) mottles; sandy loam; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; common very fine and fine vesicular pores; many very fine and fine roots, traces of dead roots; common fine cracks, few variegated sands and sand patches; strongly acid (field pH 5.5); clear, smooth boundary to BA _g .
BAG	13-31	Pink (7.5YR 8/3) few fine prominent strong brown (7.5YR 5/8) and few fine prominent yellow (10YR 7/8) mottles; loamy sand; moderate fine and medium semi-angular blocky structure; slightly hard dry, friable moist, non sticky and non plastic; few plastic; few patches with common faint clay bridge among sand grains; common very fine and fine vesicular pores; common very fine and fine roots, traces of dead roots; common variegated sands; strongly acid (field pH 5.5); clear, smooth boundary to B _{tg} .
Btg	31-43	Pink (7.5Y 8/3), common fine and medium prominent strong

		<p>brown (7.5Y 5/8) and brownish yellow (10YR 6/8) and few fine prominent yellowish red (5YR 5/8) mottles; slightly gravelly sandy loam; moderate fine and medium semi-angular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; very few faint clay coats on pore walls and common faint clay bridge among sand grain; common very fine and fine, few medium vesicular pores; very few very fine and fine roots; few fine iron oxide nodules; common variegated sands; strongly acid (field pH 5.5); abrupt, smooth boundary to 2Bvg1.</p>
2Bvg1	43-65	<p>Mixed gray (2.5Y 6/1) 70% and white (2.5Y 8/1) 30%, common fine and medium prominent red (10R 4/8), common medium and coarse prominent dark red (10R 3/6) and yellowish brown (10YR 5/8) and common fine and medium distinct olive yellow (2.5Y 6/8) mottles; sandy clay; strong medium and coarse angular blocky structure; very hard dry, very firm moist, moderately sticky and moderately plastic; common prominent clay coats on ped faces and pore walls; few very fine, fine and very few medium vesicular and common fine simple tabular pores; very few very fine and fine roots; few very fine dark spots of manganese nodules, few fine cracks and plinthite fabric partially; strongly acid (field pH 5.5); clear, smooth boundary to 2Bvg2.</p>
2Bvg2	65-83	<p>Mixed gray (2.5Y 6/1) 70% and white (2.5Y 8/1) 30%, common medium and coarse prominent red (10R 4/8) and yellowish brown (10YR 5/8) and few medium prominent pale red (10R 6/3) mottles; slightly gravelly sandy clay; strong medium and coarse semi-angular blocky structure; very hard dry, very firm moist, moderately sticky and moderately plastic; many prominent clay coats on pore walls and ped faces and around iron oxide separation surface; very few very fine and fine, few medium vesicular and common fine simple tubular pores; practically no roots; few fine iron oxide nodules, few fine cracks in plinthite fabric; strongly acid (field pH 5.5); clear, smooth boundary to 2Bvg3.</p>
2Bvg3	83-107	<p>Mixed light gray (2.5Y 7/2) 35%, white (2.5Y 8/1) 35% and gray (2.5Y 6/1) 30%, common medium and coarse prominent yellowish brown (10YR 5/8), common fine and medium prominent red (10R 5/8) and brownish yellow (10YR 6/8) mottles; gravelly sandy clay; strong medium and coarse semi-angular blocky structure; very hard dry, very firm moist, moderately sticky and moderately plastic; many prominent clay coats on pore walls and ped faces and around iron oxide separation surface; very few very fine, fine and medium vesicular and few fine simple tabular pores; practically no roots; common fine iron oxide nodules, common fine cracks in plinthite fabric; strongly acid (field pH 5.5); gradual, smooth boundary to 2Bvg4.</p>
2Bvg4	107-132	<p>Mixed white (2.5Y 8/1) 60% and light gray (2.5Y 7/1) 40%, common fine and medium prominent brownish yellow (10YR 6/8) and red (10R 5/8) mottles; slightly gravelly sandy clay; strong fine and medium semi-angular blocky structure; very hard dry, very firm moist, moderately sticky and moderately plastic; many prominent clay coats on pore walls and ped faces and around iron oxide separation surface; very few very fine, fine and medium vesicular and few fine simple tabular pores; practically no roots; common iron oxide nodules and soft</p>

2Bvg5	132-160	<p>accumulation of iron oxide; strongly acid (field pH 5.5); clear, smooth boundary to 2Bvg5.</p> <p>Mixed white (2.5Y 8/1) 80% and light gray (2.5Y 7/1) 20%, common fine and medium prominent yellowish brown (10YR 5/8) and red (10R 5/8) mottles; sandy clay; strong medium and coarse semi-angular blocky structure; very hard dry, very firm moist, moderately sticky and moderately plastic; many prominent clay coats on pore walls and ped faces and around iron oxide separation surface; few very fine and fine vesicular and few fine simple tabular pores; practically no roots; few fine iron oxide nodules, common fine cracks in plinthite fabric; strongly acid (field pH 5.5), clear, smooth boundary to 2BCrg.</p>
2BCrg	160-195+	<p>White (2.5Y 8/1), common medium and coarse prominent red (10R 4/8), common medium prominent brownish yellow (10YR 6/8) and common fine distinct olive yellow (2.5Y 6/8) mottles; clay; strong medium and coarse semi-angular blocky structure; very hard dry, very firm moist, slightly sticky and moderately plastic; many prominent clay coats on ped faces and pore walls; few very fine and fine vesicular and few fine simple tabular pores; practically no roots; common fine cracks; strongly acid (field pH 5.5).</p>

Nakhon Phanom (Nn)**I Information on the site**

Profile symbol	: Nn
Soil name	: Nakhon Phanom series
Classification	: Typic Plinthaquilt, fine, illitic, isohyperthermic
Date of examination	: 12 February 2006
Described by	: Irb Kheoruenromne, Pean Singjanusong, Somchai Anusontpornperm, Supicha, Thanachit, and Chuthamard Kaewmano, Worachart Wisawapipat, Natthapol Chittamart
Location	: Ban Namon, Tambol Ban Pueng, Amphoe Maung, Nakhon Phanom Province
Elevation	: Approximately 191 m (MSL)
Map sheet number	: 5438 II Coordination: 48 0458629 ^E , 19 17550 ^N
Landform	
1. Physiographic position	: Lower part of erosional terrace
2. Surrounding land form	: Gently undulating
3. Slope on which profile site	: 1% Aspect: North-West
Land use	: Irrigated paddy rice, agricultural and settlement
Annual rainfall	: Approximately 2,260 mm
Mean temperature	: Approximately 26 °C
Climate	: Tropical savanna

II General information on the soil

Parent material	: Wash over residuum derived from fine grained clastic sedimentary rocks
Drainage	: Poorly drained
Permeability	: Slow
Runoff	: Slow
Flooding	: ~40 cm
Duration	: 2-3 months
Frequency	: 1 time/year
Depth of groundwater	: 190 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Apg	0-18	Brown (10YR 5/3) common fine distinct yellowish brown (10YR 5/8) mottles; clay loam; moderate fine and medium semi-angular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; few very fine and fine vesicular pores; many very fine and fine, few medium roots, traces of dead roots, few fine cracks; strongly acid (field pH 5.5); abrupt, smooth boundary to BA _g .
BAG	18-39	Mixed pale brown (10YR 6/3) 90% and light gray (10YR 7/2) 10%, common fine and medium prominent brown (7.5YR 5/4), common fine prominent yellowish red (5YR 5/6) and common fine distinct yellowish brown (10YR 5/8) mottles; slightly gravelly clay; moderate fine and medium semi-angular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; few faint clay coats on tubular pore walls; few very fine, fine and medium vesicular pores; few fine and medium roots, traces of dead roots; few clay balls, very few fine iron oxide nodules; strong acid (field pH 5.5); clear, smooth boundary to Btg ₁ .
Btg ₁	39-63	Mixed pale brown (10YR 6/3) 90% and light gray (10YR 7/2)

		10%, common fine prominent red (2.5YR 5/8) and red (10R 4/8) and common fine distinct brown (7.5YR 5/4) mottles; clay; moderate fine and medium subangular blocky structure; hard dry, slightly firm moist, moderately sticky and very plastic; common faint clay coats on ped faces and pore walls; few very fine and fine, very few medium vesicular and few fine simple tubular pores; very few very fine and fine roots; very few iron oxide nodules; strongly acid (field pH 5.5); abrupt, smooth boundary to Bt _{cg} .
Bt _{cg}	63-94	Mixed light gray (10YR 7/2) 90% and light gray (10YR 7/1) 10%, common fine prominent red (10R 4/8) and common fine distinct reddish yellow (7.5Y 6/8) mottles; very gravelly sandy clay; moderate fine and medium subangular blocky structure; hard dry, firm moist, slightly sticky and moderate plastic; common faint clay coats on ped faces and pore walls and on some nodules surfaces; few very fine and fine vesicular and few fine simple tubular pores; very few very fine and fine roots; common fine of iron oxide nodules and concretion; few fine weathered red rock fragments; very strongly acid (field pH 4.5); clear, smooth boundary to 2Bt _{g2} .
2Bt _{g2}	94-115	Light gray (2.5Y 7/2), common fine prominent red (10R 4/8) and olive brown (10R 4/4) and few fine prominent yellowish brown (10YR 5/8) mottles; slightly gravelly clay; moderate fine and medium subangular blocky structure; hard dry, firm moist, moderately sticky and very plastic; common distinct clay coats on ped faces and pore walls; few very fine, fine and medium vesicular pores; practically no roots; few fine iron oxide nodules; very strongly acid (field pH 4.5); gradual, smooth boundary to 2Bt _{g3} .
2Bt _{g3}	115-146	Light gray (2.5Y 7/1) common fine and medium prominent red (10R 4/8) and few fine prominent yellowish brown (10YR 5/8) mottles; clay; moderate medium and coarse subangular blocky structure; very hard dry, very firm moist, moderately sticky and moderately plastic; common distinct clay coats on ped faces and pore walls; few very fine, fine and medium vesicular pores; practically no roots; very strongly acid (field pH 4.5); clear, smooth boundary to 2Bt _{g4} .
2Bt _{g4}	146-170	Light gray (2.5Y 7/1) common fine and medium prominent red (10R 4/8), few fine prominent brownish yellow (10YR 6/8) and few fine prominent yellow (10YR 7/8) mottles; clay; moderate medium and coarse semi-angular blocky structure; very hard dry, very firm moist, moderately sticky and moderately plastic; common prominent clay coats on ped faces and pore walls; ; few very fine, fine and medium vesicular pores; practically no roots; very strongly acid (field pH 4.5); clear, smooth boundary to 2BCrt _g .
2BCrt _g	170-200+	Light gray (2.5Y 7/1) common fine prominent dark red (2.5YR 4/6) and few fine prominent yellow (10YR 7/8) mottles; very gravelly clay; moderate fine and medium subangular blocky structure mixed with rock structure; very hard dry, very firm moist, moderately sticky and moderately plastic; few distinct clay coats on ped faces and rock fragment surfaces; very few very fine and fine vesicular pores; practically no roots; many rock fragment of various size; very strongly acid (field pH 4.5).

Samut Prakan (Sm)

I Information on the site

Profile symbol	: Sm
Soil name	: Samut Prakan series
Classification	: Aeric Endoaquept, fine-silty, mixed, superactive, isohyperthermic
Date of examination	: 1 February 2008
Described by	: Irb Kheoruenromne, Chuthamard Kaewmano, Worachart Wisawapipat, Natthapol Chittamart, Tingtong Darunsontaya, Wipawan Insomboon and Noppadon Prayunsuk
Location	: Ban Nhong Khanhan, Tambol Nhong Khanhan, Amphoe Maung, Changwat Phetchaburi.
Elevation	: Approximately 2 m (MSL)
Map sheet number	: 4935 II Coordination: 47 06009735 ^E , 1439836 ^N
Landform	
1. Physiographic position	: Floodplain
2. Surrounding land form	: Level to nearly level
3. Slope on which profile site	: 1% Aspect: 60 Azimuth
Land use	: Pangola grass field
Annual rainfall	: Approximately 1000 mm
Mean temperature	: Approximately 27°C
Climate	: Tropical savanna
Others	: Paddy rice, coconut, sugar palm, banana, mainly agricultural

II General information on the soil

Parent material	: Alluvium over marine deposits
Drainage	: Poorly drained
Permeability	: Slow
Runoff	: Slow
Depth of groundwater	: 170 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Apg	0-15	Dark gray (10YR4/1) and common fine strong brown (7.5YR4/6) 5%, common fine strong brown (7.5YR5/6) 5%, few fine very dark gray (7.5YR3/1) of iron-manganese oxides nodules mottles; sandy clay loam; strong fine and medium subangular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; very few variegated sands; few very fine, fine and medium vesicular and few tubular pores; many very few and fine roots; common traces of dead roots; neutral (field pH6.0); clear, smooth boundary to Bg1.
Bg1	15-38	Mixed weak red (2.5Y5/2) and reddish gray (2.5Y6/1) 10% and common fine reddish brown (5YR4/4) 10%, common fine strong brown (7.5YR5/8) 5%, common fine very dark gray (10YR3/1) 5% of iron-manganese oxides nodules mottles; clay loam; medium fine and medium subangular blocky structure; hard dry, firm moist, very sticky and very plastic; very few variegated sands and few faint pressure faces; few very fine, fine and medium vesicular and few tubular pores; common very fine and fine roots; common traces of dead roots and few micas flakes; neutral (field pH7.0); clear, smooth boundary to Bg2.
Bg2	38-55	Mixed reddish gray (2.5Y5/1) 10% and weak red (2.5Y5/2)

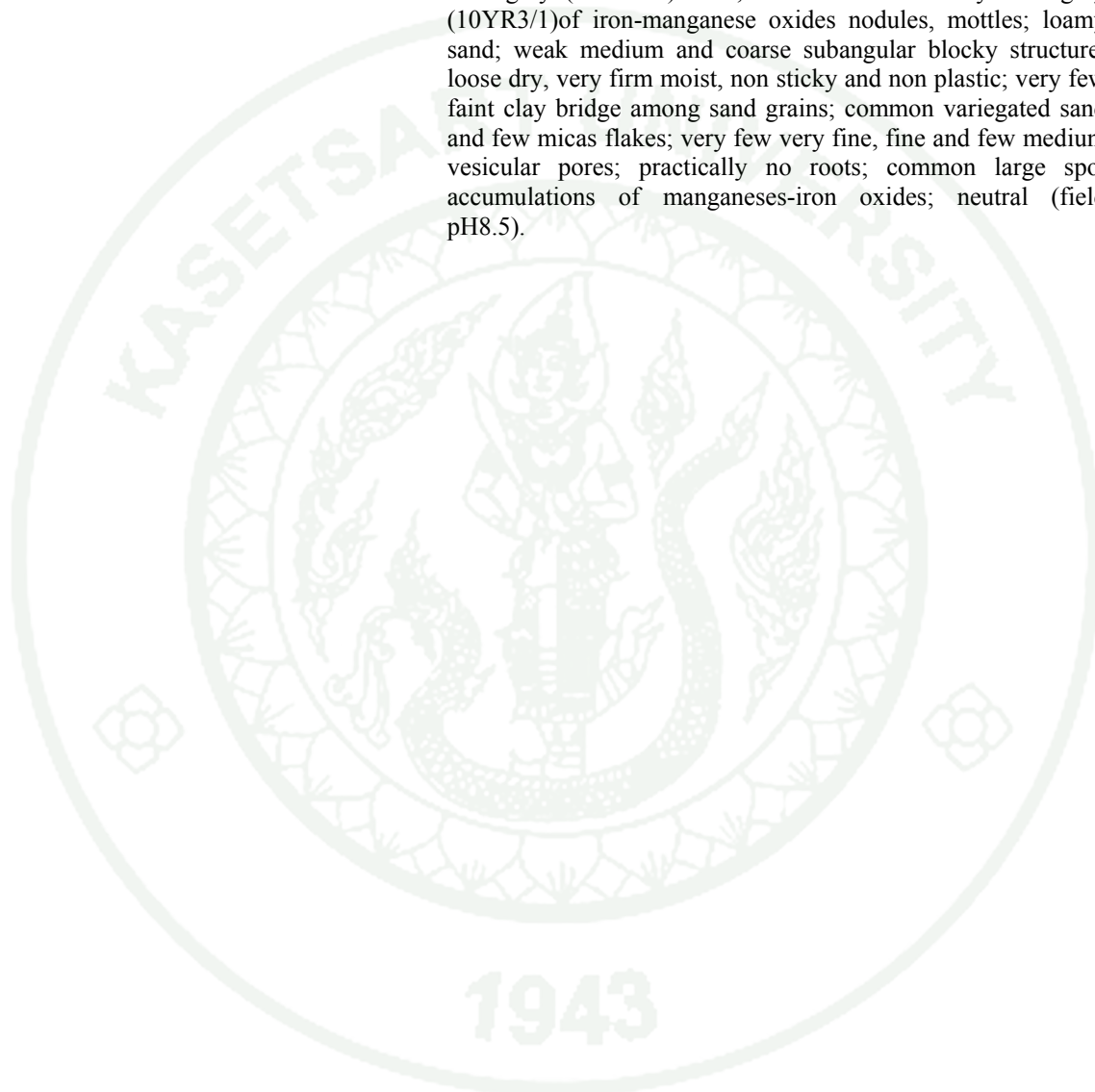
		and common fine reddish brown yellowish red (10YR6/8) 5%, common fine and medium dark gray (5YR5/6) 5%, common fine medium very dark gray (2.5YR6/4) 7%, common fine and medium dark gray (10YR3/1) of iron-manganese oxides nodules mottles; sandy clay; medium fine and medium subangular blocky structure; hard dry, firm moist, very sticky and moderate sticky and moderate plastic; few faint clay coat on ped faces and pore walls and clay bridge among sand grains; few variegated sands and few faint pressure faces; few very fine, fine and medium vesicular and few tubular pores; few very fine and fine roots; common traces of dead roots and few micas flakes and spot accumulations of manganese oxide ; neutral (field pH7.0); clear, smooth boundary to Bg3.
Bg3	55-82	Reddish gray (2.5Y5/1) and common medium and coarse brownish yellow (10YR6/6) 20% and common fine strong brown (7.5YR5/8) 10%, few fine reddish brown (5YR4/4) 2%, and common fine very dark gray (10YR3/1) 5%, mottles; sandy clay; medium fine and medium subangular blocky structure; hard dry, firm moist, very sticky and moderate sticky and moderate plastic; few faint clay coat among sand grains and few faint clay coat on ped faces and pore walls; few variegated sands and fine micas flakes; very fine, fine and medium vesicular and few tubular pores; few traces of dead roots and spot accumulations of manganese oxide ; neutral (field pH7.0); clear, smooth boundary to Bg4.
Bg4	82-110	Gray (5Y6/1) and common medium and coarse brownish yellow (10YR6/8) 15% and common fine reddish yellow (7.5YR6/6) 10%, common fine reddish brown (2.5Y5/3) 7%, and common fine very dark gray (10YR3/1) 2%, mottles; sandy clay loam; medium fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, very sticky and slightly sticky and slightly plastic; few faint clay coat among sand grains and few faint clay coat on ped faces and pore walls; few variegated sands and fine micas flakes; very fine, fine and medium vesicular and few tubular pores; few traces of dead roots; neutral (field pH7.0); clear, smooth boundary to Bg5.
Bg5	110-130	Gray (5Y6/1) and common medium light reddish brown (2.5Y6/3) 10%, common medium and medium brownish yellow (10YR6/6) 10%, common fine medium dark gray (10YR3/1) 7% of iron-manganese oxides nodules, common fine light brown (7.5Y6/4) 10%, mottles; sandy loam; medium fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, very sticky and slightly sticky and slightly plastic; few faint clay coat among sand grains and few faint clay coat on ped faces and pore walls; few variegated sands and fine micas flakes; very fine, fine and medium vesicular and few tubular pores; few very fine and fine roots; few traces of dead roots and spot accumulations of iron oxides, iron-manganese oxides and manganese oxides; neutral (field pH8.0); clear, smooth boundary to Bg6.
Bg6	130-158	Gray (5Y6/1) and few fine light red (2.5Y6/6) 2%, common medium and medium reddish yellow (7.5YR6/8) 10%, common fine medium strong brown (7.5YR4/6) 10%, common fine medium very dark (10YR3/1) of iron-manganese oxides nodules, mottles; sandy loam; medium fine and medium subangular blocky structure; hard dry, firm moist, moderate sticky and moderate plastic; few faint clay coat on pore walls;

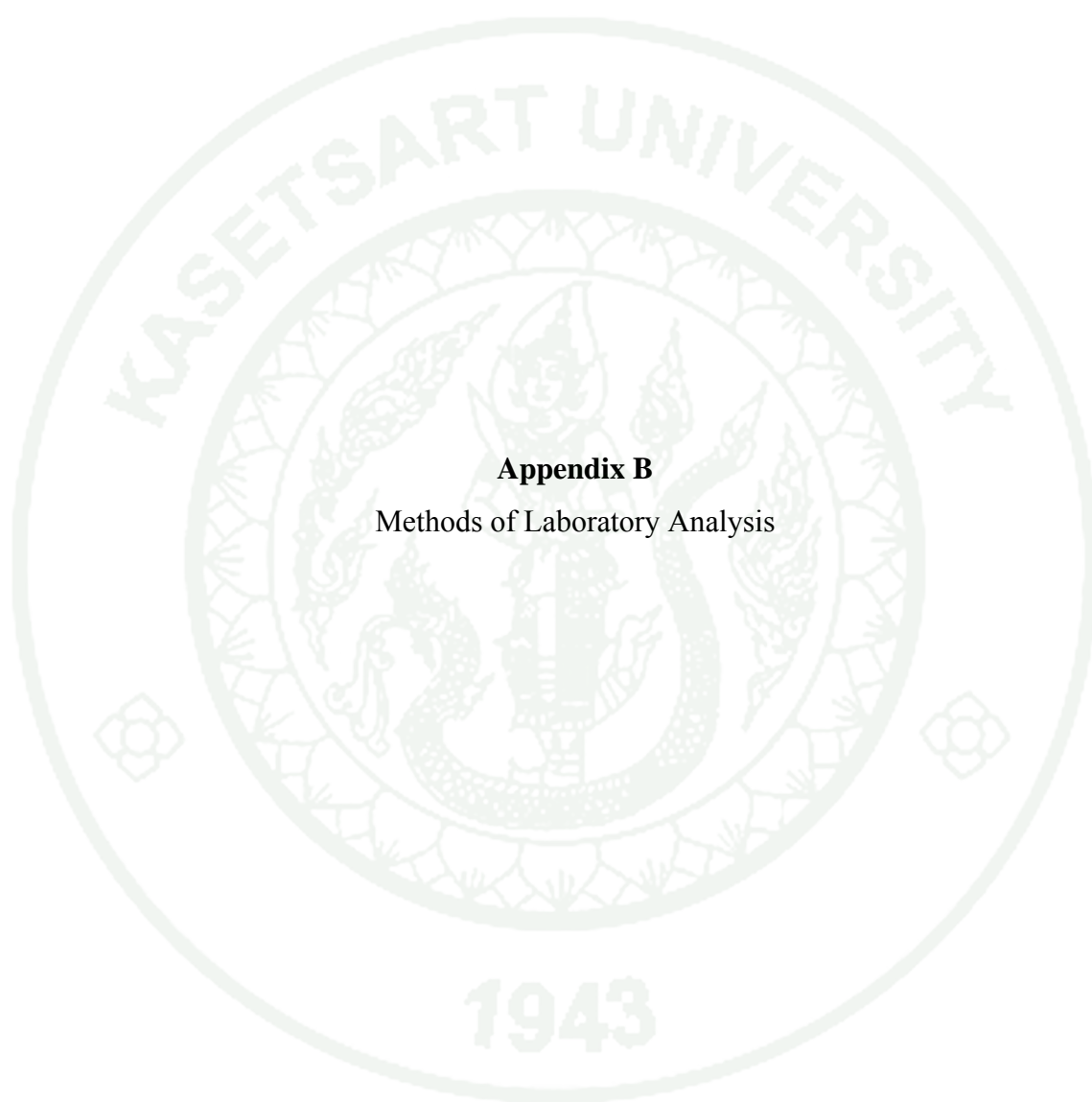
Bg7

158-170+

few variegated sands and fine micas flakes and few faint pressure faces; very fine, fine and medium vesicular and few tubular pores; few very fine and fine roots; few traces of dead roots; neutral (field pH8.0); clear, smooth boundary to Bg7.

Gray (5Y6/1) and common medium reddish brown (5YR4/4) 7%, common medium yellowish red (5YR4/6) 7%, common medium yellow red (10YR5/6) 12%, common medium very dark gray (10YR5/4) 12%, common medium very dark gray (10YR3/1) of iron-manganese oxides nodules, mottles; loamy sand; weak medium and coarse subangular blocky structure; loose dry, very firm moist, non sticky and non plastic; very few faint clay bridge among sand grains; common variegated sand and few micas flakes; very few very fine, fine and few medium vesicular pores; practically no roots; common large spot accumulations of manganese-iron oxides; neutral (field pH8.5).





Appendix B
Methods of Laboratory Analysis

Physical Analysis

1. Particle Size Analysis

Particle size analysis was carried out to evaluate soil texture. Ten grams of air dried soil sample was pretreated with 5% hydrogen peroxide to remove organic matter. For dispersion of soil, the suspension was placed in a milk shake container and 10 mL of 5% sodium hexametaphosphate, a dispersing agent, was added. The volume of the contents was made up to about 200 mL with deionized water.

The contents were stirred for 15 minutes on the milk shake mixer. The contents were then sieved through a 300-mesh (0.047 mm) sieve into a one litre cylinder and volume was made up to about 200 mL with deionized water. The sand grains that remained in the sieve were dried at 105° C for overnight and were weighed. The suspension in the cylinder was stirred well with an agitator in an up-down motion for 30 s. The pipette method was used as a direct sampling procedure. Twenty-five millilitres of suspension was pipetted out from a depth of 10 cm for clay at appropriate times based on Stokes' law (i.e. at 28° C for <0.002 mm sized fraction sampling time at 10 cm depth is 6.5 h). Suspensions were dried at 105° C and weighed (Gee and Bauder, 1986). The amount of sand, silt and clay were calculated. The percentage of clay (<2 µm), silt (0.002 to 0.05 mm) and sand (0.05 to < 2 mm) were plotted on ternary plots and soils were classified using soil textural triangle classes (Soil Survey Staff, 1999).

The clay fraction for mineralogical analysis was separated using the above procedure to obtain 10 g of clay fraction. The clay suspension was transferred from the measuring cylinder to a plastic container, by repeated suspension and decantation until little clay was left in suspension. The clay suspension was next flocculated by adding excess solid NaCl and the supernatant was then decanted. The flocculated clay was transferred to a centrifuged tube to wash and remove excess salt. The procedure was repeated several times until the conductivity of suspension was equal to that of

the deionized water. The washed clay fraction was dried in an oven at 60° C for further analysis.

Chemical Analysis

1. Soil reaction (pH)

Soil pH was determined in water and 1N KCl at a solid to solution ratio of 1:1 and water for a saturation paste. The contents were stirred with a glass rod for 30 minutes before measuring the pH by a standardized pH meter (National Soil Survey Centre, 1996).

2. Organic matter (OM)

The organic matter content of soil was indirectly estimated through multiplication of the organic carbon concentration by 1.724. The organic carbon was determined according to the Walkey and Black wet oxidation procedure. This involved wet combustion of organic carbon with a mixture of potassium dichromate and sulfuric acid. After reaction the residual dichromate was titrated against ferrous sulphate (Nelson and Sommer, 1996). A weight of 0.5 g of soil (<0.5 mm) was placed in a 250 mL Erlenmeyer flask. Five mL of 1 N $K_2Cr_2O_7$ was added and the flask was swirled gently to disperse the soil into suspension. Then 10 mL of concentrated H_2SO_4 was added to the flask, swirled gently until the soil and reagents were mixed. The solution takes on greenish cast and then changes to dark green. The flask was allowed to stand with occasional swirling for 30 minutes. Then 30 mL of deionized water was added to the flask, swirled gently then 3-4 drops of o-phenanthroline indicator were added and the solution was titrated with 1 N $FeSO_4$ until the color changed to a red end point.

3. Total N

A ground soil weighing 1.0 g was placed in micro kjeldahl flask and digestion mixture solution 5mL was added. Swirl vigorously and digest, rotating the flask frequently until fumes are emitted. Continue digestion for at least 1 hour after mixture becomes white. Cool to room temperature and added 15 mL water. Shake until the contents of the flask are thoroughly mixed. The contents were next filtered using No. 5 Whatman filter paper. The 10 mL of aliquot was placed in distillation flask and 5 mL of 10 N NaOH was added. Distill for 7 minutes, add 5 mL H₃BO₃ acid indicator for containing NH₃. Titrate the absorbed ammonia with 0.01N H₂SO₄ until color changed from green to end point of pink color.

4. Available Phosphorus

A soil sample weighing 3 g was placed in the 250 mL flask and Bray II extracting solution 30 mL, shaken for 40 seconds. The contents were filtered with No. 42 Whatman filter paper. Aliquot 1-10 mL was pipette in volumetric flask 25 mL and adjusted by distilled water. After 10 minutes, solution was transferred to tubes for determining by spectrophotometer at wavelength 882 mili-micron. A standard curve for 0, 0.2, 0.4, 0.6, 0.8 and 1.0 mg P kg⁻¹ was prepared (Bray and Kurtz, 1945).

5. Extractable Bases

The bases (Ca²⁺, Mg²⁺, Na⁺ and K⁺) that are extracted by NH₄OAc extraction are generally exchangeable bases located on the cation exchange sites of the soil (Chapman, 1965). A soil sample weighing 10 g was placed in an Erlenmeyer flask and approximately 50 mL 1 N NH₄OAc, at pH 7.0, was added, swirled and allowed to stand overnight. The contents were next filtered using a Buchner funnel with No. 42 Whatman filter paper and a 250 mL suction flask. The volume of the extract was made up to 100 mL Ca, Mg, K and Na contents in the leachate were determined by atomic absorption spectrophotometry.

6. Extractable Acidity

Extractable acidity is the acidity released from the soil by barium chloride-triethanolamine solution buffer ($\text{BaCl}_2\text{-TEA}$) at pH 8.2 (Thomas, 1987). It includes all acidity generated by replacement of the hydrogen and aluminum ions from permanent and pH-dependent exchange sites. A soil sample weighing 5 g was placed in an Erlenmeyer flask and 15 ml of buffer solution at 8.2 (0.5N $\text{BaCl}_2\cdot\text{H}_2\text{O}$ and 0.2 N Triethanolamine) were added. The contents were stirred and allowed to equilibrate for 30 min before filtering using the Buchner funnel procedure. The contents were given 3 additional washing with 20 mL buffer solution and 5 washing with 20 mL of the replacing solution (0.5 N $\text{BaCl}_2\cdot\text{H}_2\text{O}$ and 0.4 mL of buffer solution in 1 L). The volume of the extracts was made up to 100 mL and 5 drops of mixed indicator (Bromocresol green and methyl red in 95% ethyl alcohol) were added. The extract was titrated with 0.2 N HCl. The acid was added drop by drop until the colour change from green to an end point of purplish red colour. The amount of HCl consumed was used to calculate the extractable acidity expressed as $\text{cmol H}^+ \text{ kg}^{-1}$.

7. Cation Exchange Capacity (CEC)

The CEC is defined as the sum total of the exchangeable cations that a soil can adsorb. It is dependent upon the negative charges of soil component. Two main methods of CEC determination were used (Thomas, 1987; National Soil Survey Centre, 1996).

CEC by NH_4OAc at pH 7.0 was determined by saturating the exchange sites with an index cation (NH_4^+), washing the soil free of entrained index cation, displacing the index cation (NH_4^+) adsorbed by soil and measuring the index cation. A soil sample weighing 10g was placed in an Erlenmeyer flask, to which 50 mL of 1 N NH_4OAc , pH 7.0 were added. The flask was stirred occasionally and allowed to stand overnight. The contents were filtered by the Buchner funnel procedure. The soil was next given 6 washing with 25 mL of 1 N NH_4OAc and 5 washings with 25 mL of 95% ethyl alcohol. The aliquots from these washings were discarded. The index

cation was next displaced by giving 6 washing with 25 mL of 10% acidified NaCl, and filtrates were collected in filtering flasks. The filtrates were transferred to kjeldahl flask to which 25 mL of 50% NaOH were added. A fifty mL of 4% boric acid was placed into a 100 mL flask and 5 drops of bromocresol green methyl red indicator were added. The kjeldahl flask was connected to the distillation unit and the boric solution flask with condenser, and was then distilled for 30 min. The solution was titrated with 0.01 N H₂SO₄ until color changed from green to the pink end point. The volume of H₂SO₄ recorded and used to calculate the CEC as cmol kg⁻¹.

The cation exchange capacity (CEC) at pH 8.2 was calculated by summing the NH₄OAc extractable bases plus the BaCl₂-TEA extractable acidity (at pH 8.2) (National Soil Survey Center, 1996).

8. Base saturation

Base saturation percentage by NH₄OAc at pH 7.0 is equal to the sum of bases extracted by NH₄OAc, divided by the CEC by NH₄OAc, and multiplied by 100. Base saturation percentage by sum of cations is equal to the sum of bases extracted by NH₄OAc, divided by the the CEC by sum of cations, and multiplied by 100 (National Soil Survey Center, 1996).

9. NH₄OAc-extractable K (soluble K + exchangeable K)

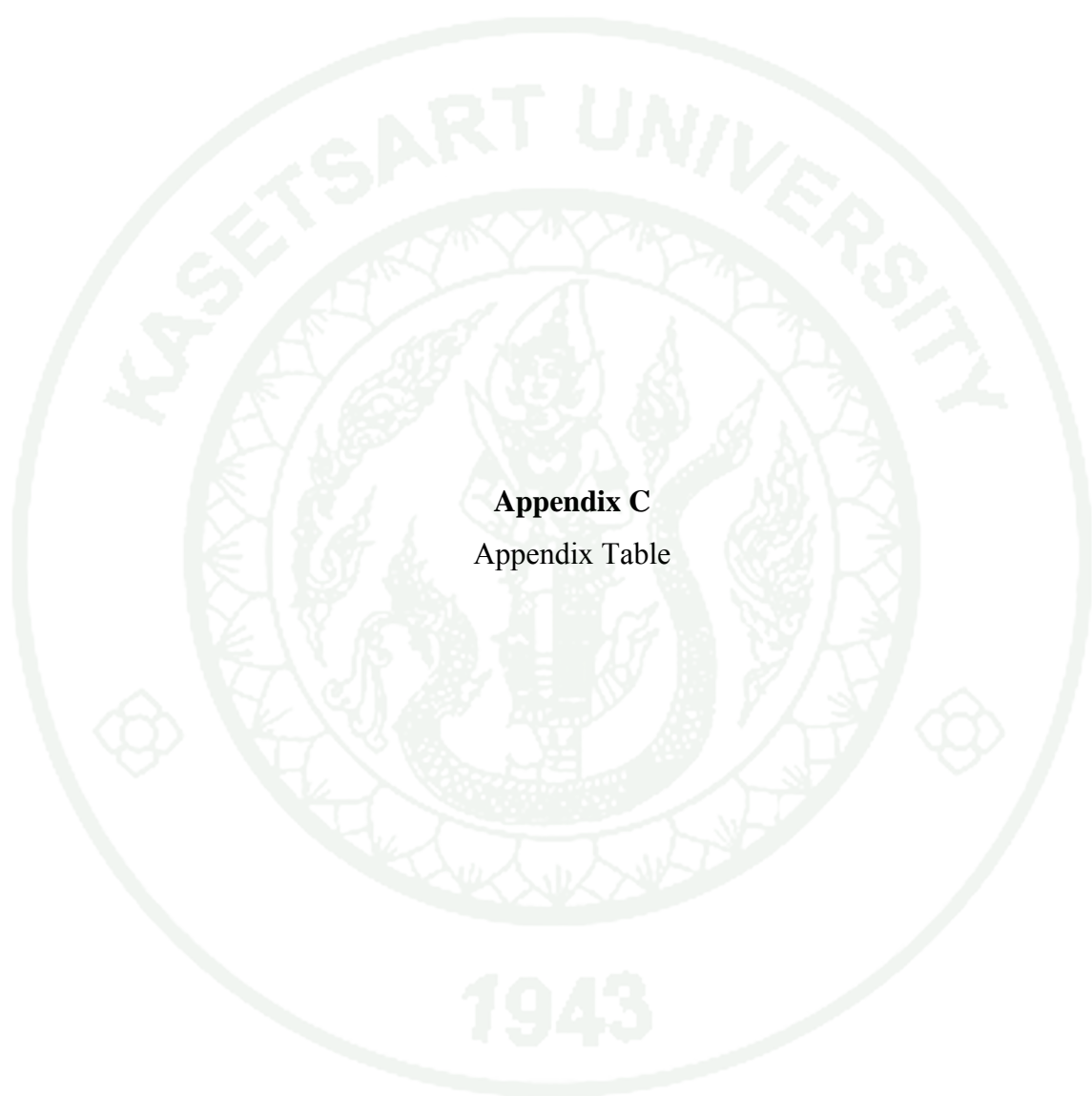
A soil sample weighing 10 g was placed in an erlenmeyer flask and approximately 50 mL 1 M NH₄OAc, at pH 7.0 was added, swirled and allowed to stand overnight. The contents were next filtered using a buchner funnel with No. 42 Whatman filter paper and a 250 mL, suction flask. The volume of the extract was made up to 100 mL. K contents in the leachate were determined by atomic absorption spectrophotometry.

10. HNO₃-extractable K (soluble K + exchangeable K + non-exchangeable K)

Two and a half grams of air-dried soil was put into 125 mL Erlenmeyer flask. 25 mL of 1M HNO₃ was added, and the flask was placed on a temperature-adjusted hoptate. When boiling started (after 5 min), temperature was reduced, and the suspension boiled gently for 10 min. The suspension was then filtered and the soil on the filter washed with four 15 mL portions of 0.1M HNO₃. The filtrate was collected in a 100-mL volumetric flask. The solution was cooled, diluted and mixed thoroughly. K was determined by atomic absorption spectrophotometer.

11. Total K

Total K in soil samples were determined by X-ray fluorescence spectrometry (XRF) on pressed powder samples using a Philips PW1480 XRF spectrometer (Jones, 1987). Pelleted samples were produced with a boric back and edge designed to fit into Philips sample holders (Pw 1480). A teaspoon of boric acid (fine powder of B.P. grade) was poured into the sample holder to encase the sample.



Appendix C
Appendix Table

Appendix Table C1 Physical properties of paddy soils.

Depth (cm)	Horizon	Particle size distribution (g kg ⁻¹) (USDA grading)			Textural class	Bulk density (Mg m ⁻³)
		Sand	silt	clay		
Ban Mi 1 (Bm1) <i>Ustic Endoaquert, fine, smectitic, isohyperthermic</i>						
10	Apkg	234	318	449	C	1.74
30	Bkg1	158	368	474	C	1.87
49.5	Bkg2	157	343	501	C	1.87
73.5	Bsskg1	150	303	547	C	1.79
95	Bsskg2	131	343	526	C	1.88
114.5	BCkg1	238	285	477	C	1.75
134	Bckg2	322	220	458	C	1.66
Ban Mi 2 (Bm2) <i>Ustic Endoaquert, fine, mixed, superactive, isohyperthermic</i>						
9	Apg	50	208	742	C	1.97
26.5	Bssg1	33	171	796	C	1.93
45	Bssg2	28	164	808	C	1.86
64.5	Bssg3	25	191	783	C	1.83
86	Bssg4	24	155	822	C	1.84
114	Bssg5	36	248	716	C	1.84
145	Bssg6	44	187	768	C	1.85
Chong Khae (Ck) <i>Ustic Endoaquert, very fine, smectitic, isohyperthermic</i>						
13.5	Apg	46	391	563	C	1.85
38.5	Bg	33	327	641	C	1.86
62.5	Bssg1	34	399	567	C	1.83
90	Bssg2	21	296	684	C	1.84
120	Bssg3	18	373	610	C	1.81
147.5	Bssg4	21	361	618	C	1.76
170	Bssg5	32	323	645	C	1.80
190	Bssg6	48	338	614	C	1.80
Lop Buri (Lb) <i>Ustic Endoaquert, very fine, smectitic, isohyperthermic</i>						
10	Apg	44	147	809	C	1.83
30	Bssg1	37	145	818	C	1.85
52.5	Bssg2	42	166	792	C	1.86
77.5	Bssg3	44	142	813	C	1.94
105	Bssg4	48	257	695	C	1.97
135	Bssg5	51	300	649	C	1.98
162.5	Bssg6	43	79	878	C	1.93
178.5	Bssg7	55	134	812	C	1.94
Wattana (Wa) <i>Ustic Endoaquert, fine, mixed, superactive, isohyperthermic</i>						
8	Apg	68	316	617	C	1.93
30	Bg	35	307	658	C	1.86
49.5	Bssg1	36	434	530	SiC	1.88
69.5	Bssg2	40	343	617	C	1.89
92.5	Bssg3	41	323	637	C	1.90
114.5	Bssg4	105	270	625	C	1.95
134.5	Bssg5	48	305	647	C	2.00
157.5	Bssg6	47	389	564	C	2.01
180	Bsskg	64	248	688	C	1.90

Appendix Table C1 (Continued)

Depth (cm)	Horizon	Particle size distribution (g kg ⁻¹) (USDA grading)			Textural class	Bulk density (Mg m ⁻³)
		Sand	silt	clay		
Ubon (Ub) <i>Aeric Haplaqualf, sandy, siliceous, subactive, isohyperthermic</i>						
0-18	Apg1	870	59	71	S	1.52
18-40	Apg2	876	53	71	S	1.62
40-68	Bg1	880	45	75	S	1.39
68-96	Bg2	861	72	67	S	1.39
96-125	Btg1	881	44	75	S	1.40
125-148	Btg2	881	35	83	S	1.46
148-170+	Cg	772	70	158	SL	1.38
Tha Tum (Tt) <i>Typic Endoaqualf, fine, mixed, subactive, isohyperthermic</i>						
0-12	Apg1	464	341	195	L	1.79
12-30	Apg2	469	307	224	L	1.72
30-50	ABg	388	280	332	CL	1.84
50-72	Btg1	303	345	352	CL	1.88
72-99	Btg2	279	341	380	CL	1.94
99-124	2Btg3	217	326	457	C	1.90
124-148	2Btg4	199	318	483	C	1.96
148-174	2Btg5	179	281	451	C	1.93
174- 200+	2Btg6	148	313	539	C	1.94
Doem Bang (Db) <i>Aeric Endoaqualf, coarse-loamy, mixed, semiactive, isohyperthermic.</i>						
0-10	Apg1	622	215	163	SL	1.82
10-25/32	Apg2	607	210	183	SL	1.73
32-55	Btg1	586	235	179	SL	1.57
55-80	Btg2	569	247	184	SL	1.61
80-105	Btg3	574	239	187	SL	1.66
105-132	Btg4	547	250	203	SCL	1.77
132-165	Btg5	546	346	107	SL	1.82
165-180	Bvg	620	229	151	SL	1.98
Roi Et (Re) <i>Aeric Paleaquult, coarse-loamy, siliceous, semiactive, isohyperthermic</i>						
0-16/20	Apg	693	199	108	SL	1.60
20-50	Btg1	580	291	129	SL	1.72
50-78	Btg2	556	315	129	SL	1.73
78-108	Btg3	510	302	187	SL	1.56
108-135	Btg4	512	305	183	SL	1.68
135-150+	Btg5	532	294	174	SL	1.73
Phen (Pn) <i>Kandic Plithaquult, fine, mixed, subactive, isohyperthermic.</i>						
0-19	Apg1	581	174	245	SCL	1.65
19-40	Btg1	564	149	288	SCL	1.72
40-61	Btg2	562	155	283	SCL	1.84
62-78/110	Btg3	492	156	352	SC	1.88
110-130	Bvg1	459	111	430	C	1.94
130-146	Bvg2	474	112	414	C	1.90
146-159	2Btg4	479	64	457	C	1.96
159-183	2Btg5	462	58	480	C	1.93
183-200+	2Btg6	468	32	500	C	1.84

Appendix Table C1 (Continued)

Depth (cm)	Horizon	Particle size distribution (g kg ⁻¹) (USDA grading)			Textural class	Bulk density (Mg m ⁻³)
		Sand	silt	clay		
Renu (Rn) <i>Typic Plinthaquult, fine, kaolinitic, isohyperthermic</i>						
0-13	Apg	536	305	159	SL	1.79
13-31	BAg	744	166	90	SL	1.72
31-43	Btg	580	327	93	SCL	1.84
43-65	2Bvg1	476	141	383	CL	1.88
65-83	2Bvg2	471	95	434	SC	1.94
83-107	2Bvg3	513	44	443	SC	1.90
107-132	2Btg4	474	33	493	SC	1.96
132-160	2Bvg5	480	33	487	SC	1.93
160-195+	2BCrg	448	68	484	C	1.84
Nakhon Phanom (Nn) <i>Typic Endoaquult, fine, illitic, isohyperthermic</i>						
0-18	Apg	178	450	372	SiCL	1.79
18-39	BAg	265	303	432	C	1.72
39-63	Btg1	245	305	450	C	1.84
63-94	Btcg	410	158	432	C	1.88
94-115	2Btg2	345	247	408	C	1.94
115-146	2Btg3	303	234	373	CL	1.90
146-170	2Btg4	208	277	465	C	1.96
170-200+	2BCrtg	355	230	415	C	1.93
Samut Prakan (Sm) <i>Aeric Endoaquept, fine loamy, mixed, semiactive, isohyperthermic</i>						
0-15	Apg	472	246	282	SCL	1.83
15-38	Bg1	369	218	413	C	1.69
38-55	Bg2	410	230	360	CL	1.78
55-82	Bg3	633	116	251	SCL	1.75
82-110	Bg4	588	139	273	SCL	1.79
110-130	Bg5	581	275	144	SL	1.81
130-158	Bg6	416	291	293	CL	1.69
158-170+	Bg7	773	64	163	SL	1.59

SL= sandy loam, L= loam, SCL= sandy clay loam, CL= clay loam, SC= sandy clay, SiC= silty clay, C= clay, S= sandy

Appendix Table C2 Chemical properties of paddy soils.

Horizon	Depth (cm)	pH (1:1)		OM (g kg ⁻¹)	Total N (g kg ⁻¹)	Avail. P (mg kg ⁻¹)	Avail. K (mg kg ⁻¹)	EA (mg kg ⁻¹)	Extractable Bases (cmol kg ⁻¹)				Sum bases (cmol kg ⁻¹)	CEC (cmol kg ⁻¹)		BS %
		H ₂ O	KCl						Ca	Mg	Na	K		By sum (cmol kg ⁻¹)	NH ₄ Oc pH 7 (cmol kg ⁻¹)	
Ban Mi 1 (Bm1) <i>Ustic Endoaquert, fine, smectitic, isohyperthermic</i>																
Apkg	0-20	7.7	7.0	26.1	1.54	198.05	130.53	14.41	36.87	0.79	0.62	0.33	38.61	53.02	29.05	73
Bkg1	20-40	7.9	6.3	13.4	0.71	9.57	27.38	16.56	36.23	0.28	0.24	0.07	36.82	53.39	38.36	69
Bkg2	40- 55/63	7.9	6.4	10.4	0.50	3.62	25.95	16.64	33.13	0.61	0.43	0.06	34.24	50.88	35.31	67
Bsskg1	63-84	7.9	6.5	8.9	0.25	0.71	24.10	17.38	40.49	0.10	0.37	0.06	41.03	58.41	41.08	70
Bsskg2	84-106	7.7	6.5	9.7	0.22	0.68	19.67	18.03	42.68	0.11	0.39	0.05	43.23	61.26	42.62	71
BCkg1	106- 123	7.7	6.4	3.9	0.05	0.16	16.41	18.18	37.68	0.03	0.37	0.04	38.12	56.30	37.89	68
Bckg2	123- 145+	7.8	6.5	1.7	0.09	0.01	14.67	18.86	35.05	0.05	0.21	0.04	35.34	54.20	36.48	65
Ban Mi 2 (Bm2) <i>Ustic Endoaquert, fine, mixed, superactive, isohyperthermic</i>																
Apg	0-18	7.3	5.8	48.2	1.98	6.17	55.83	21.67	53.71	5.37	0.78	0.14	60.01	81.68	67.77	73
Bssg1	18-35	7.5	6.2	15.9	0.55	4.60	28.87	23.13	58.43	3.88	1.31	0.07	63.70	86.83	62.02	73
Bssg2	35-55	7.5	6.2	14.2	0.37	2.11	22.78	23.40	59.52	2.33	0.99	0.06	62.91	86.31	69.26	73
Bssg3	55-74	7.8	6.1	11.8	0.41	1.59	21.69	23.50	59.15	1.65	1.06	0.05	61.91	85.42	67.99	72
Bssg4	74-98	7.8	6.3	9.6	0.31	0.99	19.74	24.01	58.33	1.49	1.63	0.05	61.50	85.51	68.53	72
Bssg5	98-130	8.0	6.4	8.0	0.29	1.08	18.71	22.56	61.04	1.69	4.45	0.05	67.23	89.79	67.09	75
Bssg6	130- 160+	8.4	6.5	4.9	0.10	0.40	18.47	20.29	57.68	1.48	4.94	0.05	64.14	84.43	80.41	76

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Appendix Table C2 (Continued)

Horizon	Depth (cm)	pH (1:1)		OM	Total N	Avail. P	Avail. K	EA	Extractable Bases				Sum bases	CEC		BS
		H ₂ O	KCl						Ca	Mg	Na	K		By sum	NH ₄ OA c pH. 7	
					(g kg ⁻¹)	(mg kg ⁻¹)	(cmol kg ⁻¹)				(cmol kg ⁻¹)	%				
Chong Khae (Ck) <i>Ustic Endoaquert, very fine, smectitic, isohyperthermic</i>																
Apg	0-27	6.8	5.3	17.8	1.01	1.32	93.19	18.48	23.87	3.24	1.15	0.24	28.49	46.97	32.24	61
Bg	27-50	5.2	3.7	7.0	0.55	0.49	57.81	25.50	21.99	3.69	0.89	0.15	26.71	52.22	31.46	51
Bssg1	50-75	5.0	3.4	6.4	0.48	0.16	47.25	26.95	21.23	3.64	1.16	0.12	26.15	53.10	32.70	49
Bssg2	75-105	5.2	3.3	6.2	0.50	0.01	58.82	24.19	20.44	3.42	1.29	0.15	25.30	67.49	35.04	37
Bssg3	105-135	5.7	3.9	4.9	0.33	0.02	63.02	22.67	28.47	4.84	3.61	0.16	37.07	59.47	38.18	62
Bssg4	135-160	6.6	5.3	4.9	0.39	0.01	73.18	16.57	32.84	5.51	1.89	0.19	40.43	57.00	37.97	71
Bssg5	160-180	6.7	5.6	5.7	0.26	0.56	58.36	17.35	34.93	5.48	1.59	0.15	42.15	59.50	49.45	71
Bssg6	180- 200+	7.6	5.8	5.3	0.23	0.45	56.30	14.46	35.34	5.10	1.41	0.14	42.00	56.46	46.68	74
Lop Buri (Lb) <i>Ustic Endoaquert, very fine, smectitic, isohyperthermic</i>																
Apg	0-20	7.8	6.6	32.6	1.36	7.31	70.31	21.68	62.94	4.80	1.33	0.18	69.24	90.92	66.50	76
Bssg1	20-40	7.9	6.5	14.0	0.54	1.69	36.64	22.01	63.89	3.62	1.34	0.09	68.95	90.96	69.75	76
Bssg2	40-65	7.8	6.5	10.0	0.32	1.77	32.09	21.53	65.69	3.53	1.50	0.08	70.79	92.32	68.93	77
Bssg3	65-90	7.7	6.6	9.4	0.32	2.33	36.06	22.05	67.01	3.99	5.82	0.09	76.91	98.96	65.72	78
Bssg4	90-120	7.8	6.6	8.8	0.19	1.46	32.34	20.73	64.25	4.45	8.79	0.08	77.57	98.31	68.87	79
Bssg5	120-150	7.8	6.5	8.5	0.19	1.66	33.40	22.06	64.78	5.00	7.27	0.08	77.13	99.19	68.52	78
Bssg6	150-175	7.9	6.5	5.7	0.10	2.50	31.89	19.20	66.15	5.26	5.25	0.08	76.74	95.94	64.84	80
Bssg7	175- 200+	7.9	6.5	4.7	0.07	2.69	25.61	19.06	58.77	5.08	10.82	0.06	74.73	93.80	66.33	80

Appendix Table C2 (Continued)

Horizon	Depth (cm)	pH (1:1)		OM (g kg ⁻¹)	Total N (g kg ⁻¹)	Avail. P (mg kg ⁻¹)	Avail. K (mg kg ⁻¹)	EA (mg kg ⁻¹)	Extractable Bases (cmol kg ⁻¹)				Sum bases (cmol kg ⁻¹)	CEC (cmol kg ⁻¹)		BS %
		H ₂ O	KCl						Ca	Mg	Na	K		By sum	NH ₄ OA c pH. 7	
Wattana (Wa) <i>Ustic Endoaquert, fine, mixed, superactive, isohyperthermic</i>																
Apg	0-12/20	7.6	6.9	31.5	1.35	12.89	89.19	16.15	49.38	2.55	0.76	0.23	52.92	69.08	46.22	77
Bg	20-40	7.9	6.5	9.5	0.32	0.47	28.51	19.81	44.03	1.19	1.25	0.07	46.54	66.35	46.73	70
Bssg1	40-59	7.8	6.5	8.7	0.22	0.47	24.25	15.43	40.90	0.76	0.85	0.06	52.56	57.99	42.65	73
Bssg2	59-80	7.8	6.5	7.5	0.19	0.44	22.79	14.02	37.42	0.78	0.98	0.06	39.25	53.27	44.30	74
Bssg3	80-105	7.9	6.5	6.9	0.15	0.10	19.32	14.68	41.28	0.45	1.17	0.05	42.94	57.63	45.26	75
Bssg4	105-124	7.9	6.4	7.3	0.18	0.09	19.32	14.01	41.23	0.51	1.28	0.05	43.07	57.08	43.29	75
Bssg5	124-145	8	6.4	5.6	0.17	0.47	18.94	15.37	40.73	0.29	4.50	0.05	45.58	60.95	42.35	75
Bssg6	145-170	8.2	6.4	3.0	0.06	0.32	22.01	16.25	42.24	0.22	3.79	0.05	46.30	62.55	41.07	74
Bsskg	170- 190+	8.3	7.0	1.8	0.04	2.26	25.92	15.70	48.41	0.22	5.28	0.06	53.98	69.68	48.76	77
Ubon (Ub) <i>Aeric Haplaqualf, sandy, siliceous, subactive, isohyperthermic</i>																
Apg1	0-18	5.5	4.0	4.67	0.27	1.19	22.51	1.50	0.19	0.08	0.02	0.06	0.35	4.85	2.25	7
Apg2	18-40	5.4	4.0	2.87	0.14	0.84	20.01	1.00	0.23	0.02	0.12	0.05	0.43	1.43	0.60	30
Bg1	40-68	5.8	4.7	1.10	0.05	0.55	4.65	1.48	0.26	0.01	0.02	0.01	0.31	1.79	0.60	17
Bg2	68-96	6.2	5.1	0.72	0.05	0.56	7.05	0.50	0.58	0.12	0.22	0.02	0.93	1.43	0.85	65
Btg1	96-125	6.1	5.2	0.73	0.05	0.47	1.87	1.49	0.28	0.01	0.09	0.00	0.39	1.88	0.45	20
Btg2	125-148	6.2	5.2	0.48	0.05	0.47	4.41	0.50	0.25	0.02	0.06	0.01	0.35	0.85	0.50	41
Cg	148-170	4.6	3.3	1.28	0.05	2.29	19.47	2.00	0.78	0.11	0.20	0.05	1.14	3.14	4.40	36

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Appendix Table C2 (Continued)

Horizon	Depth (cm)	pH (1:1)		OM (g kg ⁻¹)	Total N (g kg ⁻¹)	Avail .P (mg kg ⁻¹)	Avail. K (mg kg ⁻¹)	EA (mg kg ⁻¹)	Extractable Bases (cmol kg ⁻¹)				Sum bases	CEC (cmol kg ⁻¹)		BS %
		H ₂ O	KCl						Ca	Mg	Na	K		By sum	NH ₄ OA c pH. 7	
Tha Tum (Tt) Typic Endoaqualf, fine, mixed, subactive, isohyperthermic																
Apg1	0-12	4.5	3.5	11.5	1.53	5.49	16.36	0.98	0.54	0.12	1.38	0.04	2.08	3.06	3.11	68
Apg2	12-30	4.5	3.4	7.1	1.03	3.42	14.57	1.50	0.96	0.26	0.57	0.04	1.83	3.33	3.94	55
ABg	30-50	4.8	3.4	9.3	1.03	3.42	18.40	1.50	0.82	0.36	1.27	0.05	2.50	4.00	6.31	63
Btg1	50-72	4.9	3.6	7.7	0.97	3.53	23.20	1.96	1.16	0.49	1.44	0.06	3.15	5.11	5.06	62
Btg2	72-99	5.4	3.6	4.0	0.97	0.80	28.23	0.99	0.85	1.00	2.70	0.07	4.62	5.61	5.22	82
2Btg3	99-124	6.5	5.5	2.4	0.80	0.35	40.02	1.48	1.05	2.17	2.76	0.10	6.08	7.56	6.83	80
2Btg4	124-148	8.1	5.8	1.9	0.74	0.334	52.41	1.99	0.91	3.89	3.23	0.13	8.16	10.15	11.21	80
2Btg5	148-174	9.0	6.1	2.0	0.68	0.35	52.72	1.99	1.04	3.77	5.44	0.13	10.38	12.37	11.98	83
2Btg6	174-200	8.7	6.2	1.7	0.53	0.35	67.50	1.48	1.43	4.14	6.32	0.17	12.12	13.60	12.83	89
Doem Bang (Db) Aeris Endoaqualf, coarse-loamy, mixed, semiactive, isohyperthermic																
Apg1	0-10	5.1	3.3	7.98	0.35	28.3	43.21	5.01	2.15	0.48	0.11	0.30	3.04	8.05	5.36	38
Apg2	10-25/32	4.9	3.8	4.80	0.23	5.3	29.40	4.18	1.54	0.44	0.08	0.24	2.29	6.46	2.36	35
Btg1	32-55	5.5	4.2	2.67	0.21	3.3	33.82	3.34	2.25	0.40	0.09	0.59	3.32	6.66	9.49	50
Btg2	55-80	6.0	4.6	1.36	0.20	1.8	10.11	1.67	2.72	0.31	0.03	0.37	3.42	5.09	10.30	67
Btg3	80-105	6.3	4.9	1.34	0.20	2.8	11.83	0.83	3.11	0.35	0.03	0.43	3.92	4.75	10.74	82
Btg4	105-132	6.5	5.0	1.35	0.17	8.2	18.23	1.67	3.91	0.46	0.05	0.42	4.84	6.51	9.83	74
Btg5	132-165	6.4	5.0	1.37	0.10	10.8	15.94	5.01	5.23	0.65	0.04	0.22	6.13	11.14	10.84	55
Bvg	165-180	6.3	5.0	0.67	0.10	4.9	11.05	2.50	5.14	0.50	0.03	0.45	6.12	8.62	9.23	70

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Appendix Table C2 (Continued)

Horizon	Depth (cm)	pH (1:1)		OM (g kg ⁻¹)	Total N (g kg ⁻¹)	Avail .P (mg kg ⁻¹)	Avail. K (mg kg ⁻¹)	EA (mg kg ⁻¹)	Extractable Bases (cmol kg ⁻¹)				Sum bases (cmol kg ⁻¹)	CEC (cmol kg ⁻¹)		BS %	
		H ₂ O	KCl						Ca	Mg	Na	K		By sum (cmol kg ⁻¹)	NH ₄ OA c pH. 7 (cmol kg ⁻¹)		
Roi Et (Re) <i>Aeric Paleoaquult, , coarse-loamy, siliceous, semiactive, isohyperthermic</i>																	
Apg	0-16/20	5.2	3.8	8.38	0.45	2.99	8.65	2.00	0.90	0.17	0.32	0.02	1.41	3.41	2.63	41	
Btg1	20-50	5.5	4.8	2.47	0.21	0.41	5.03	0.50	2.08	0.27	0.24	0.01	2.60	3.10	3.87	84	
Btg2	50-78	5.3	4.1	1.45	0.16	0.61	5.51	2.00	1.75	0.37	0.41	0.01	2.54	4.54	3.12	56	
Btg3	78-108	5.5	3.7	1.33	0.15	0.93	7.12	2.00	2.83	0.29	0.27	0.02	3.41	5.41	5.00	63	
Btg4	108-135	5.3	3.8	1.11	0.12	1.07	9.60	2.00	2.58	0.32	0.54	0.02	3.46	5.46	4.62	63	
Btg5	135-150	5.1	3.6	1.68	0.11	0.91	8.36	3.00	2.32	0.30	0.25	0.02	2.89	5.89	2.13	49	
Bckg2	123-145+	7.8	6.5	1.7	0.09	0.01	14.67	18.86	35.0	0.05	0.21	0.04	35.34	54.2	36.48	65	
Phen (Pn) <i>Kandic Plithaquult, fine, mixed, subactive, isohyperthermic.</i>																	
Apg1	0-19	4.9	4.0	3.9	0.79	2.49	8.95	0.99	0.58	0.04	0.20	0.02	0.84	1.83	2.17	46	
Btg1	19-40	6.1	4.9	2.3	0.62	0.34	40.67	0.49	1.92	0.12	0.50	0.10	2.64	3.13	3.35	84	
Btg2	40-61	4.8	3.6	2.2	0.59	0.34	39.38	0.99	0.67	0.16	0.88	0.10	1.81	2.80	3.15	65	
Btg3	62-78/110	4.4	4.0	1.9	0.52	0.34	21.72	2.46	0.38	0.17	0.97	0.05	1.57	4.03	4.95	39	
Bvg1	110-130	4.8	3.8	2.0	0.82	0.34	77.63	3.44	0.82	0.61	0.08	0.19	1.70	5.14	4.88	33	
Bvg2	130-146	4.8	4.2	1.4	0.82	0.35	79.32	3.93	0.76	0.53	0.20	0.20	1.69	5.62	5.13	30	
2Btg4	146-159	4.4	4.0	1.6	0.88	0.34	70.66	3.96	0.72	0.47	0.09	0.18	1.46	5.42	5.32	27	
2Btg5	159-183	4.9	3.6	1.3	0.66	0.34	47.02	3.50	0.72	0.39	0.20	0.12	1.73	4.23	4.24	29	
2Btg6	183-200	4.9	3.5	1.3	0.66	0.35	55.42	3.48	0.76	0.60	0.30	0.14	1.80	4.28	4.55	34	

Appendix Table C2 (Continued)

Horizon	Depth (cm)	pH (1:1)		OM (g kg ⁻¹)	Total N (g kg ⁻¹)	Avail. P (mg kg ⁻¹)	Avail. K (mg kg ⁻¹)	EA (g kg ⁻¹)	Extractable Bases (cmol kg ⁻¹)				Sum bases	CEC		BS %
		H ₂ O	KCl						Ca	Mg	Na	K		By sum (cmol kg ⁻¹)	NH ₄ OA c pH. 7 (cmol kg ⁻¹)	
Renu (Rn) <i>Typic Plinthaquult, fine, kaolinitic, isohyperthermic</i>																
Apg	0-13	4.0	3.0	10.2	1.51	5.13	7.71	1.47	0.21	1.60	0.13	0.02	1.96	3.43	3.21	57
BAg	13-31	4.8	3.7	2.5	0.48	0.34	6.20	1.49	0.25	0.01	0.53	0.02	0.81	2.30	2.15	35
Btg	31-43	4.4	3.5	1.7	0.48	0.34	5.94	1.96	0.35	0.01	0.11	0.01	0.48	2.44	2.18	20
2Bvg1	43-65	4.2	3.4	1.9	0.82	0.70	19.60	2.97	0.51	0.01	0.94	0.05	1.51	4.48	3.35	34
2Bvg2	65-83	4.3	3.0	1.6	0.82	0.35	15.33	2.49	0.46	0.01	0.48	0.04	0.99	3.48	3.47	28
2Bvg3	83-107	4.3	2.0	0.8	0.73	0.70	14.50	2.97	0.57	0.01	0.23	0.04	0.85	3.82	4.12	22
2Btg4	107-132	4.3	2.6	0.6	0.68	0.70	22.30	2.45	0.83	0.01	0.43	0.06	1.33	3.98	3.58	34
2Bvg5	132-160	4.2	2.7	0.9	0.62	0.34	27.21	2.44	0.85	0.03	0.22	0.07	1.17	4.09	3.66	32
2BCrg	160-195	4.5	3.4	0.2	0.62	1.35	33.64	2.46	0.70	0.04	0.52	0.08	1.34	5.28	4.53	34
Nakhon Phanom (Nn) <i>Typic Endoaquult, fine, illitic, isohyperthermic</i>																
Apg	0-18	4.8	2.4	13.6	1.81	1.38	41.67	2.48	0.61	1.43	0.25	0.10	2.39	4.87	3.89	49
BAg	18-39	4.2	2.4	5.2	1.02	3.45	33.88	2.46	0.53	0.19	0.53	0.08	1.33	3.79	3.57	35
Btg1	39-63	4.8	3.0	3.5	0.93	1.40	53.69	2.98	0.36	0.24	0.30	0.13	1.03	4.01	3.68	26
Btcg	63-94	4.2	3.1	1.2	0.81	0.34	79.66	3.45	0.41	0.22	0.63	0.20	1.46	4.91	4.23	30
2Btg2	94-115	3.9	3.0	1.1	0.69	0.35	85.51	3.50	0.27	0.57	0.56	0.21	2.25	5.75	5.56	32
2Btg3	115-146	5.3	3.3	1.0	0.55	0.70	141.6	3.99	0.30	0.91	0.53	0.35	2.09	6.28	6.11	34
							5									
2Btg4	146-170	4.4	2.6	0.8	0.86	0.35	64.29	2.97	0.33	0.95	0.33	0.16	1.77	4.98	4.12	33
2BCrtg	170-200	4.7	2.8	0.8	0.69	1.72	86.34	4.50	0.40	0.48	0.56	0.22	1.66	6.16	5.79	27

Appendix Table C2 (Continued)

Horizon	Depth (cm)	pH (1:1)		OM	Total N	Avail. P	Avail. K	EA	Extractable Bases				Sum bases	CEC		BS
		H ₂ O	KCl						Ca	Mg	Na	K		By sum	NH ₄ OA c pH. 7	
				(g kg ⁻¹)	(mg kg ⁻¹)			(cmol kg ⁻¹)				(cmol kg ⁻¹)		%		
Samut Prakan (Sm) <i>Aeric Endoaquept, fine loamy, mixed, semiactive, isohyperthermic</i>																
Apg	0-15	5.3	4.9	20.3	0.84	2.3	34.9	5.84	6.42	4.90	0.09	1.35	12.75	18.60	17.83	69
Bg1	15-38	5.7	5.4	5.33	0.44	1.3	47.4	4.18	6.19	6.47	0.12	2.57	15.34	19.52	13.34	79
Bg2	38-55	6.1	5.3	4.01	0.44	0.8	52.6	4.18	4.08	5.46	0.13	2.37	12.04	16.22	14.50	74
Bg3	55-82	6.2	4.9	3.34	0.31	0.9	36.8	3.34	3.97	4.43	0.09	1.17	9.67	13.01	10.85	74
Bg4	82-110	6.5	5.2	2.02	0.27	0.5	29.1	4.18	2.34	4.73	0.07	1.45	8.59	12.77	11.79	67
Bg5	110-130	6.4	5.7	1.36	0.14	0.4	26.	1.67	2.79	4.64	0.07	1.60	9.10	10.77	10.99	84
Bg6	130-158	6.3	6.2	0.67	0.14	0.8	44.7	2.50	2.43	5.85	0.11	3.04	11.43	13.74	13.80	82
Bg7	158-170	6.5	6.2	0.68	0.14	1.2	29.6	2.50	1.58	2.97	0.08	1.92	6.55	9.05	8.47	72

Appendix Table C3 Soil pH (soil:water=1:1)

Rating	Range
Ultra acid	<3.5
Extremely acid	3.5-4.4
Very strongly acid	4.5-5.0
Strongly acid	5.1-5.5
Moderately acid	5.6-6.0
Slightly acid	6.1-6.5
Neutral	6.6-7.3
Slightly alkaline	7.4-7.8
Moderately alkaline	7.9-8.4
Strongly alkaline	8.5-9.0
Very strongly alkaline	>9.0

Appendix Table C4 Organic matter content (%organic carbon x 1.724)

Rating	Range (g kg ⁻¹)
Very low	<5
Low	5-10
Moderately low	10-15
Medium	15-25
Moderately high	25-35
High	35-45
Very high	>45

Appendix Table C5 Total nitrogen

Rating	Range (g kg ⁻¹)
Very low	<0.25
Low	0.50-0.75
Medium	0.75-1.25
High	1.25-1.75
Very high	>2.25

Appendix Table C6 Available phosphorus (Bray II)

Rating	Range (mg kg ⁻¹)
Very low	<3
Low	3-6
Moderate low	6-10
Medium	10-15
Moderately high	15-25
High	25-45
Very high	>45

Appendix Table C7 Available potassium

Rating	Range (mg kg ⁻¹)
Very low	<30
Low	30-60
Medium	60-90
High	90-120
Very high	>120

Appendix Table C8 Cation exchange capacity

Rating	Range (cmol kg ⁻¹)
Very low	<3
Low	3-5
Moderately low	5-10
Medium	10-15
Moderately high	15-20
High	20-30
Very high	>30

Appendix Table C9 Base saturation percentage (BSP)

Rating	Range (%)
Low	<35
Medium	35-75
High	>75

Appendix Table C10 Extractable acidity (EA)

Rating	Range (cmol kg ⁻¹)
Very low	<1.0
Low	1.0-2.0
Medium	2.0-5.0
Moderately high	5.0-10.0
High	10.0-20.0
Very high	>20.0

Appendix Table C11 Bulk density (BD)

Rating	Range (Mgm-1)
Low	<1.2
Moderately low	1.2-1.4
Medium	1.4-1.6
Moderately high	1.6-1.8
High	1.8-2.0
Very high	>2.0

Source: Kanchanasert (1986)

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