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THESIS

THE MINERALOGY OF UPLAND AGRICULTURAL SOILS UNDER TROPICAL MONSOONAL ENVIRONMENT IN THAILAND

TIMTONG DARUNSONTAYA

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy (Soil Science) Graduate School, Kasetsart University 2011

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Twenty one soils profiles on various parent materials under a tropical monsoonal climate in Thailand were analyzed for chemical and mineralogical properties of the clay-sized minerals. These Oxisols and Ultisols have kaolinite as the dominant clay mineral and various amounts of accessory minerals with higher amounts of sesquioxide minerals in Oxisols. The crystal size of kaolinite and iron oxides is smaller for basaltic soils relative to soils on granite and sedimentary rocks. Halloysite tubes occur in some soil clays particularly for basaltic soils and these soils also contain gibbsite. Oxisols derived from basalt have relatively higher contents of Fe, Ti, Mg, Mn, Ba, Be, Bi, Ce, Co, Cr, Cu, Ga, La, Nd, Ni, Sc, Sr and Zn. Statistical analysis indicates a lithosequence where soil parent material is the main factor influencing the mineralogical and chemical properties of the clay fraction of these soils.

Clay samples from surface and subsurface horizons of these upland soils were characterized for chemical composition, mineralogy and K release to 0.3M sodium tetraphenylboron (NaTPB) solution for periods up to 168 hours. Analytical TEM and XRD show that most clays contain small amounts of illite. Potassium release kinetics for all samples are adequately described by the parabolic diffusion (r=0.91-0.99), power function (r=0.87-0.99) and Elovich equations (r=0.86-0.99). The intercept constants of the equations are strongly positively related to the ratio of illite to kaolinite and total K and Mg contents of the clays. These relationships indicate that minor amounts of illite in these clays strongly affect the kinetics of K release. The slope constants of the parabolic and Elovich equations are also positively related to these clay properties. Some kaolinite particles contain K which may be present in residual micaceous layers interleaved in kaolinite crystals. XRD patterns from samples extracted with NaTPB show a decrease in illite peak intensity with a concomitant increase in vermiculite peak intensity due to K removal from illite by NaTPB.

Critical assessment of the forms of K in soils and of the ability of soils to release K for plant uptake was also studied. The relationships between different pools of K were investigated as a function of silt and clay mineralogy. Most soils contain no K-minerals in the silt fraction. For some soils, both conventional and synchrotron XRD were unable to detect illite. Analytical TEM including EFTEM of individual clay crystals show that clay in the apparently illite-free samples contain very small amounts of illite. A glasshouse K-depletion experiment was conducted to assess the K supply capacity and changes in chemical forms of K and K- bearing minerals using exhaustive K depletion by Guinea grass (*Panicum maximum*). Potassium deficiency symptoms and mortality of plants occurred on light textured soils, whereas plants survived for six harvests for Oxisols with clay texture, relatively high CEC and higher exchangeable K. There is a strong linear relationship of unit slope between exchangeable soil K and cumulative K uptake by plants indicating that exchangeable K is a major form of K available to plants. Thus K-bearing minerals contributed little K to plants over the time scale of the experiment and XRD patterns of whole soil samples, silt and clay from soils after cropping mostly showed no change from those for the initial soil. An exception was for a single surface soil clay where a minor amount of smectite was formed from illite by K release to plants.

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Timtong Darunsontaya

March 2011

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THE MINERALOGY OF UPLAND AGRICULTURAL SOILS UNDER TROPICAL MONSOONAL ENVIRONMENT IN THAILAND

INTRODUCTION

The tropical monsoon may be defined as a seasonal wind blowing in almost opposite directions in summer and winter. However, what is important in this type of climate is not so much the wind regime but the rainfall potential and distribution associated with the monsoon. The monsoon climate of Thailand prevails in the Peninsula and Southeast Coast of the country (Köppen, 1931; Yoothong *et al*., 1997). Agricultural soils, especially upland soils under this climate heavily depend on the precipitation derived from the monsoon. High rainfall in this zone induces a high leaching condition. The soils in this region are classified as having a udic soil moisture regime (Moncharoen *et al*., 1987; Soil Survey Division Staff, 1999). The land uses are mostly para rubber, tropical orchards and natural vegetation which is characteristically tropical rain forest (Tawornpruek *et al*., 2006). To assess inherent soil fertility for appropriate soil management, it is important to understand the mineralogy of these soils, particularly their clay fractions because the clay is the most active fraction and its properties strongly influence soil behavior and management (Schwertmann and Herbillon, 1992).

Most of upland soils in the humid Tropics are Ultisols and Oxisols (Sanchez, 1976). They are highly weathered or highly developed soils that have various physical and chemical properties. Clay in these upland soils under a tropical monsoonal environment consists of silicate clay minerals and accessory minerals. The clay mineral part is dominated by kaolins whereas the accessory mineral part is dominated by sesquioxides (e.g. gibbsite, hematite and goethite). Amounts of minerals depend on parent material and degree of weathering (Kanket *et al*., 2005; Watanabe *et al*., 2006). The kaolin group has several members including kaolinite, halloysite, dickite and nacrite of which kaolinite is most abundant in tropical soils. The mineralogical properties of kaolin such as crystallinity and crystal size are related to cation exchange capacity (CEC) and specific surface area (SSA) and so affect these

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soil properties (Hughes and Brown, 1979; Hart *et al*., 2003). Sesquioxides present in the clay fraction depend on soil parent material and pedogenetic environment. Normally, goethite is favored over hematite under moist conditions as such exist in this region and gibbsite commonly occurs in the highly weathered soils in this high rainfall zone with high leaching conditions (Tawornpruek, *et al*. 2006; Osher and Buol, 1998). Hydroxy-Al interlayered vermiculite (HIV) and quartz are also generally found in the clay fraction of soils under this climate regime. However, the interactions between kaolin and sesquioxides in soils in the Tropics are generally poorly understood and there is a need for more knowledge on these relationships for tropical soils.

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OBJECTIVES

This study was carried out on upland agricultural soils under a tropical monsoonal environment in Thailand on various parent materials:

1. To determine morphological, physical, chemical and mineralogical properties of these soils.

2. To study relationship between silicate clays, sesquioxides and their activities in clay fraction of these soils.

Hypothesis

The mineralogical properties of upland agricultural soils under tropical monsoonal environment in Thailand are diverse due to differences in the composition of soil parent material and variations in pedogenesis.

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LITERATURE REVIEW

Climate of Thailand

Thailand has three main seasons: a rainy, a cool and dry and a hot and dry season. The eastern part of the Southeast Coast and most parts of Peninsular Thailand experience the tropical monsoon. The northern mountainous region is characterized by a humid subtropical climate. Most of the continental area of the country is characterized by a tropical savanna climate (Köppen, 1931). Mean annual temperature varies between 24-26°C in the north, between 28-30°C in the central region and between 26-28°C in the rest of the country. The average annual rainfall ranges between 1,000 and 4,000 mm (Meteorological Department, 2002). In the southern and southeast regions, however, rainfall is generally the highest compared to the rest of the country. As a consequence, these regions do not have a pronounced dry season.

1. Tropical Monsoonal Climate (Am)

The importance of monsoon in this study is the rainfall potential and distribution associated with the monsoon. Agriculture in the regions which have monsoon climate heavily depends on the monsoonal precipitation. This type of climate most commonly found in southern Asia, West Africa, India, Burma, and the eastern Amazon valley (Ritter, 2006). The monsoonal climate is essentially characterized by a long season of fairly evenly distributed rainfall, which supports rainforest vegetation, and a short dry season. Annual precipitation is more than 1500 mm and precipitation in the driest month is less than 60 mm (Köppen, 1931).

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2. Soil Climatic Regimes of Thailand

Moncharoen *et al*. (1987) distinguished five soil moisture regimes: aquic, peraquic, udic, ustic and perudic. The different regimes occur in the following regions;

1. Aquic, in low-lying paddy lands throughout the country;
2. Peraquic, in tidal flats and swamp areas, especially along the Gulf of Thailand;
3. Udic, in the peninsular region, with an annual rainfall higher than 2,000 mm, and with more than 160 days of rain, as well as in the northern region where hills, between 1,000 and 1,600 m in altitude, are covered with an evergreen vegetation;
4. Perudic, in areas above 1,600 m MSL and
5. Ustic, in the remaining areas of the country

Physiography and Geology of Tropical Monsoonal Regions in Thailand

Details on the geology of Thailand are contained in the geological map published by the Geological Survey Division (Department of Mineral Resources, 1987). The monsoon climate of Thailand prevails in the Peninsula and the Southeast Coast of the country.

The Southeast Coast is subdivided into 7 provinces. Its borders are the hills to the north, the Gulf of Thailand to the south and west, and the Banthat Range to the east (Thai-Cambodia border). In the areas dominated by terrace formations, numerous separate hills and ranges with a NW-SE strike occur. Along the coast, small interconnected marine and brackish water alluvial plains are common. Granites of several ages also occur. Various Carboniferous rocks are overlain by Permian sediments. The volcanic plateau of this region dates from the Tertiary period and consists of corundum-bearing basalt (Yoothong *et al*., 1997).

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The Southern region or Peninsular Thailand is subdivided into 14 provinces. Its borders are the Chumphon-Prachuap Kiri Khan Province to the north, the Pacific Ocean to the east, the Andaman sea to the west and Malaysia to the south. This region is characterized by a number of hilly and mountainous ranges. The most important rocks date from late Triassic/middle Tertiary (granite) (Charusiri *et al*., 1993), and from Ordovician/Carboniferous-Permian/Permian (limestone). These rocks have been locally metamorphosed into slate, schist and gneiss. The coastal terraces and plains on the west coast are narrow, but they are much wider on the east coast.

Classification of Upland Soils Under Monsoon Climate

Soil-forming processes proceed at faster rates in rainy climates than in other climates because of the almost constant downward water movement, the large amounts of biomass added to the soil, and the constantly high temperatures (Buol *et al*., 2003). The predominant soils of the consequent udic soil moisture regime are Oxisols, Ultisols, and Alfisols (Sanchez, 1976; Soil Survey Staff, 1999). In Thailand, most upland soils in this region are classified as Ultisols and some of them are Oxisols.

Ultisols which cover more than 50 percent of the acid upland soil area in tropical Asia, have an argillic or kandic horizon in which clay has accumulated. In other words, clay content normally increases in subsoils. Clay minerals are predominately kaolinitic and are generally less weathered than those found in Oxisols. Base saturation is less than 35 percent, especially below the A horizon (Sanchez, 1976; Soil Survey Staff, 1999).

Oxisols cover vast areas in South America and Africa, they are less common in Asia. Their clay mineralogy is dominated by kaolinite and oxides of iron and aluminum. Oxisols are poor in nutrients, especially calcium, magnesium, and phosphorus. Phosphorus fixation is generally more severe in Oxisols than in Ultisols. The cation exchange capacity is less than 16 centimoles per kilogram of clay, of which less than 10 centimoles may be due to permanent charge.

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General Characteristics of Upland Soil with Moist Climate

Soils in udic soil moisture regime of Thailand occupy uplands in Peninsular Thailand and Southeast Coast where the climate is tropical monsoonal. Their land uses are mostly para rubber, tropical orchards and their natural vegetation is tropical rain forest. These soils have an increase of clay content in subsoils. Most of the tropical upland soils have colors ranging from yellow, brown to red which reflects the presence of iron oxide minerals and is indicative of an oxidizing condition. A report on the color of Malaysian upland soils indentified a dark brown color (10YR 4/3 – 7.5YR 4/3) for soils developed from basalt while the soil from serpentine was dark redish brown (2.5YR4/6) to weak red (2.5YR 3/3) and the soil from andesite was red (2.5YR 4/6) (Anda *et al.*, 2008).

The upland soils under a tropical monsoon climate are highly weathered and highly developed. They are, in general infertile and the organic matter can be easily degraded or lost due to the high temperature and heavy rainfall. They have low cation exchange capacity and are strongly acid to extremely acid. Some soils in Peninsular Thailand that derived from granite have low CEC (<6 cmol kg^{-1}) and they also have low pH (pH 4.2-5.3), low base saturation, high exchangeable aluminum and rather low weatherable mineral content (Vijarnsorn and Fehrenbacher, 1973). Upland Oxisols generally have excellent physical properties even with high clay content. They are stable, having rapid water infiltration and good internal drainage however they may dry quickly and be drought prone.

Clay Mineralogy of Upland Soils Under Tropical Monsoonal Environment

Soil formation processes are complex and largely dependent on the parent material, climate and site conditions. Primary mineral transformations in well-drained soils in tropical areas have been extensively studied (Fisher and Ryan, 2006; Cho and Komarneni, 2007). Clay mineralogical compositions of these upland soils under a tropical monsoonal environment are normally dominated by kaolin group minerals, sesquioxides, quartz together with minor amount of hydroxy-Al interlayered

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vermiculite (HIV). The end-product of physico-chemical weathering processes is generally kaolinite with a various amount of gibbsite and iron oxyhydroxides (Eswaran and Wong, 1978). In humid tropical regions without any distinct dry season, weathering processes are fast and produce kaolinite and gibbsite (Eswaran *et al*., 1990). The dominance of kaolin group minerals and iron oxides in these soils strongly influences the chemical and physical properties of the soils (Schwertmann and Taylor, 1989). Therefore in the current research on Thai sols the properties of these minerals have been investigated in detail.

1. Kaolin Group Minerals

Kaolinite, halloysite and the less common dickite and nacrite are 1:1 layer-structured aluminosilicates of the same ideal composition, they are collectively referred to as kaolin group minerals. Kaolinite and halloysite are commonly products of acid weathering, halloysite is common in soils of volcanic origin. Halloysite is often tubular or spherical in contrast to the platy morphology of kaolinite (Grim, 1968; Dixon, 1989). Kaolinite is one of the most abundant clay minerals in the tropical monsoonal upland soils in Thailand. The properties of kaolins in soils are generally diverse and related to soil parent material (Koppi and Skjemstad, 1981; Hart *et al*., 2003) and climate (Hughes and Brown, 1979; Tawornpruek *et al*., 2006). These properties are not simply related to the age of soils (Chittleborough and Walker, 1988). Basaltic soils commonly contain poorly ordered kaolin, while soils on granite and sedimentary rock may contain more ordered kaolin (Hart *et al*., 2003). McFarlane (1976) reported that kaolin was less ordered in soils formed in more hydrating environments. Hughes and Brown (1979) considered that structural order generally decreased as the length of the dry season decreased and Singh (1996) has proposed that planar kaolinite transforms to tubular halloysite by hydration and exfoliation in wet pedoenvironments.

Properties of the kaolin-group minerals derived from XRD patterns (basal spacing, CSD and HB index) together with SSA, CEC and CD are important indicators of the contributions of kaolin to soil properties. CSD or Coherently

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Scattering Domain size was calculated from the width at half height of the XRD reflections of kaolin using the Scherrer equation (Klug and Alexander, 1974). It provides a measure of crystal size but in compound crystals it is not equivalent to particle size. The 001 CSD size of some Thai soil kaolins is 19.3 nm which is similar to values for Indonesian soil kaolins (mean 10.8 nm) and Western Australian soil kaolins (mean 22.9 nm) (Hart *et al*., 2002). The 060 CSD sizes of the Thai kaolins range from 10.7 to 23.0 nm (mean 17.9 nm) and are also similar to those of Indonesian soil kaolins (11.9 nm) and Western Australian soil kaolins (34.5 nm). The Hughes and Brown index or HB index which is index of crystallinity of kaolin has the same trend as of the CSD. In some red Ultisols and red Oxisols from Thailand, the lowest HB crystallinity index (3.3–5.3) and smallest size (9–11 nm) were reported for kaolin in soil on basalt under very high rainfall (Trakoonyingcharoen *et al*, 2006a).

The particle size of soil kaolins as observed with the TEM is also diverse. Singh and Gilkes (1992a) and Hart *et al*. (2002) observed that sizes of kaolin particles ranges from 0.05–2 µm diameter in soils from tropical and Mediterranean climates. Crystals of kaolinite in saprolite and in kaolin deposits may be much larger, being typically 1–2 µm hexagonal plates (Dixon, 1989), with various shapes including laths and pseudo-hexagonal plates.

There are inverse relationships between Fe concentrations (%Fe_2O_3) and both the 001 and 060 CSD sizes (R^2 = 0.57 and 0.64). For both the Thai and the Western Australian soil kaolins CSD 001 size decreased systematically with increasing Fe_2O_3 concentration. These inverse relationships between crystal size and Fe content may indicate that incorporation of structural Fe in kaolin restricts crystal growth. The decrease in crystal size of kaolinite with increasing structural Fe content has been observed by several authors (Mestdagh *et al*., 1980; Cases *et al*., 1982; Delineau *et al*., 1994).

Kaolin is dominant in all upland soils under monsoon climate in Thailand (Yoothong *et al*., 1997). Many properties of these soils are related, directly or indirectly, to the dominant kaolin mineralogy of the soils. The chemical properties

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include low pH and weak pH buffering, Al toxicity, low available P and high P fixation capacity, deficiencies of Na, Ca, Mg, K and micronutrients, and low cation exchange capacity (CEC). Soil physical processes, particularly those relating to aggregation and dispersion, may depend on the crystal properties of kaolin and some kaolinitic soils exhibit poor structure whereas other kaolinitic soils are well structured (e.g. Oxisols). However, despite the dominance of kaolin in soils of the Tropics with a monsoon climate, little is known of the extent to which the properties of kaolin vary and how this variation affects soil properties. Characteristics of kaolin crystals may influence the physical and chemical properties of these soils (Singh and Gilkes, 1992a; Melo *et al*., 2001) so it is important that the nature of kaolin in soils under this climatic regime is determined.

2. Iron Oxides

Sesquioxides in soils are mostly oxides, oxyhydroxides and hydroxides of iron (Fe), aluminum (Al) and manganese (Mn) (Essoka and Esu, 2001). They may occur in soils as both amorphous and crystalline inorganic compounds. A small fraction of these elements may be present in organic complexes. The crystalline oxides of Fe in tropical soils are mainly hematite and goethite while the aluminum is mainly in gibbsite (Brady and Weil 1999). Amorphous oxides are commonly extracted with ammonium oxalate (Mckeague and Day, 1966) and crystalline oxides are extracted with dithionite-citrate-bicarbonate (Mehra and Jackson 1960).

Iron oxides occur in almost all soils. They may determine soil color; create adsorption sites for various anions and cations; promote aggregation and cementation; and reflect some aspects of soil genesis (Schwertmann and Taylor, 1989). Iron oxides have been considered to be useful indicators of soil forming processes and pedogenetic environments. In the recent decades much work has been carried out on the factors controlling iron oxide formation in soils and the influence of iron oxides on soils properties (Boero *et al*., 1992; Goulart *et al*., 1998).

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Environmental conditions and parent material influence the properties of secondary oxides in soils. In drier and warmer pedoclimates, with a low content of organic matter and slightly alkaline parent material, hematite is favored over goethite whereas goethite occurs in moister and cooler pedoclimates (Schwertmann, 1988). A rapid rate of Fe release favors the precipitation of ferrihydrite, the necessary precursor of hematite (Muggler *et al*., 2001). However, ferrihydrite also can transform to goethite in soils with hues of 2.5YR or yellower (Singer *et al*., 1998).

The degree of Al substitution in iron oxides may reflect the environment in which they form (Schwertmann and Kämpf, 1985; Schwertmann, 1988). High Al goethite may form together with gibbsite under conditions where the activity of Al is high relative to Fe, such as the advanced desilication stage of Oxisols. In contrast, low Al goethite originates under a wetter soil moisture regime where Al is less active and Fe is highly active (Motta and Kämpf, 1992).

Al substitution in soil hematite is usually low, 15 mol% Al was the maximum value for some highly desilicated soils (Motta and Kämpf, 1992; Fontes and Weeds, 1991). Hematite in soils developed from clayey sediment and sandstone showed the lowest Al substitution. Soils formed from mafic rock (basalt) have high Al substitution in hematite (Fontes and Weeds, 1991). Low values of Al substitution in hematite may indicate that hematite formed when Al was less active in soil solution, possibly some time after formation of gibbsite and goethite (Motta and Kämpf, 1992).

Crystal size which is commonly measured as mean coherently diffracting length (MCD) of iron oxides is also influenced by environment factors, for example, larger crystals may form in a xeric soil environment (Boero *et al*., 1992). The extremely small crystal size of pedogenic goethite and hematite in most soil types has been reported in several studies (Schwertmann and Latham, 1986; Singh and Gilkes, 1992b; Prasetsyo and Gilkes, 1994; Anand and Gilkes, 1987) and it has been suggested that small crystal size may be due to the high degree of Al substitution (Fitzpatrick and Schwertmann, 1982).

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Upland soils are widespread in Thailand and the presence of iron oxides has major effects on soil fertility and stability (Schwertmann and Taylor, 1989; Kheoruenromne, 1992). Iron oxides are also useful indicators of soil forming processes and pedogenetic environments but no detailed investigation has been reported on the properties of iron oxides in these Thai soils.

3. Gibbsite

Gibbsite forms under conditions of strong desilication, where H_4SiO_4 activity is low (Huang *et al*., 2002). The X-ray diffraction analyses of Peru upland soils showed that gibbsite was more abundant than mica or goethite in fine-textured soils, while in other soils, non-plinthite horizons have only traces of gibbsite (Osher and Buol, 1998). For Thai upland soils, the end-product of physico-chemical weathering processes is generally kaolinite with various amount of gibbsite and iron hydroxide (Eswaran and Wong, 1978). In humid tropical regions without any distinct dry season, weathering processes are fast and produce kaolinite and gibbsite. Soils containing kaolinite and gibbsite are only found in very limited areas in the northern highlands of Thailand (Tawornpruek, *et al*. 2006; Herrmann *et al*., 2007). Most of the soils are highly weathered and derived from basic or intermediate igneous rocks under udic moisture conditions. Thierry (2001) reported an amount of CDB extractable Al in soil of 45–50 g kg^{-1}, corresponding to Al-substitution in the iron oxide fraction of about 0.35 mol mol^{-1}. This indicates very high Al-substitution in goethite, as is generally observed for highly desilicified, gibbsitic soils. Gibbsite also affects the effective cation exchange capacity (ECEC) of soils. The quantities of gibbsite were negatively correlated with ECEC (r=-0.80) (Shaw, 2001).

Potassium Availability to Plants

Soil K may be divided into four pools: water soluble, exchangeable, non-exchangeable, and matrix K. With K depletion by plants, water soluble and exchangeable K are lowered to minimum levels characteristic of the soil and it has

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been proposed that further K uptake derives solely from the non-exchangeable K and matrix K pools (Johnston and Goulding, 1990).

Exhaustive cropping techniques combined with chemical analyses of soils are useful for relating plant uptake of K to the various forms of soil K (Martin and Sparks, 1985). Results from pot and field experiments determining the availability of nutrients are closely associated (Markewitz and Richter, 2000; Surapaneni *et al*., 2002). For particular soil–plant systems, the suitability of a soil test extractant for predicting K supply depends on how closely the extracted K predicts the actual uptake of K by plants. Several extractants determine readily available K, which is generally assumed to be solution K plus exchangeable K. When this form of K is exhausted the replenishment of plant available K will depend on the release of structural K from minerals (Kirkman *et al*., 1994).

Potassium deficiency is widespread in crops on highly weathered tropical upland soils that may be deficient in K bearing minerals (Ramanathan, 1978). These soils are dominated by sesquioxides and kaolinite (Hart *et al*., 2003; Kanket *et al.*, 2005; Tawornpruek *et al*., 2006). Total K content is generally low and K deficiency frequently occurs after a few years of cropping on such highly developed soils (Ramanathan, 1978; Havlin *et al*., 2005). Significant K may be present in kaolinite particles in highly weathered tropical soils and this K may be available to plants but this proposition remains contentious (Melo *et al*., 2002). Many Thai upland soils under tropical monsoonal climate have quite low exchangeable and non-exchangeable K levels (Darunsontaya *et al.*, 2010) and there are very few studies of the K status of these soils in relation to their mineralogical composition. For more effective K management it is necessary to identify forms of K including mineral species containing structural K (feldspars, micas, etc) in these soils and establish which forms of K may be released to plants over both short and long periods.

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Kinetic of Release of Soils Potassium

The most commonly used analyses of plant available K in soil are water soluble K and exchangeable K, however, crop growth is sometimes poorly correlated with these K forms (Cox *et al*., 1999). This may be due to K being obtained by plants from other K pools, including structural K in minerals, under these circumstances the rate of release of K from minerals will influence plant available K. The long-term plant available K which is derived from structural K can be evaluated by determining the amounts of K dissolved using suitable extractants such as dilute acids (Lopez-Pineiro and Navarro, 1997).

While the majority of measurements of the release of non-exchangeable K have been based on destructive methods such as acid dissolution, less severe extraction procedures that remove K from the slowly/poorly available pool in a similar manner to a plant roots, but at a faster rate, are more indicative of the K that may (eventually) be extracted by plants. Sodium tetraphenylboron (NaTPB) is able to extract fixed interlayer K from micaceous minerals as it maintains an extremely low K concentration in soil solution thereby accelerating exchange of interlayer K. This process resembles the removal of K from mica that may occur in the K depleted soil solution in the rhizosphere (Hinsinger *et al*., 1992). However NaTPB is quite ineffective in removing K from the three-dimensional structure of K-feldspar (Song and Huang, 1988).

The kinetics of K release from the mineral K pool in soils to various extractants has been examined by many authors and a number of models have been evaluated for their suitability for describing K release (Dhillon and Dhillon 1990; Carey and Metherell, 2003). Some of these models are simple and empirical but they have been used with various levels of success to describe the rate of K diffusion from soil constituents to an extracting solution. These models allow soils to be ranked on the basis of differences in the potential rate of release of mineral K to plants. Potassium fertilizers must be used to provide adequate plant nutrition but for some soils the presence of small amounts of feldspar, illite or vermiculite may provide

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plants with significant K. However, little is known of forms of K and the kinetics of K release from kaolinitic soils in this region. This research investigates the kinetics of K release to NaTPB solution from the clay fraction of Thai upland Oxisols and Ultisols in relation to soil mineralogy.

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MATERIALS AND METHODS

Sampling site

The study area encompasses upland areas in Southeast Coast and Peninsular Thailand (Figure 1). Selected areas were Chonburi, Rayong, Chantaburi and Trat provinces in the Southeast Coast. Chumphon and Krabi provinces were selected in Peninsular Thailand. Soil maps at scales of 1:100,000 and 1:50,000 and other maps (topographic map, geological map and isohyet map) were used as base maps to select the study areas. Twenty one soil profiles representing upland soils with various parent materials were selected for this study (Table 1). These regions generally have a summer rainy season with annual rainfall up to 2,900 mm, which generally exceeds evapotranspiration so that the soil moisture regime is udic. The soil temperature regime is isohyperthermic (Köppen, 1931; Soil Survey Staff, 1999).

Field Analyses

Pedon analysis in a soil pit was carried out at each site including detailed profile description and sampling of soil from each genetic horizon by standard field study methods (Soil Survey Division Staff, 1993; Kheoruenromne, 2009).

Bulk samples were air-dried, gently crushed and then passed through a 2-mm sieve. The resultant <2 mm samples were used for general laboratory analysis. The clod samples were used for bulk density measurement.

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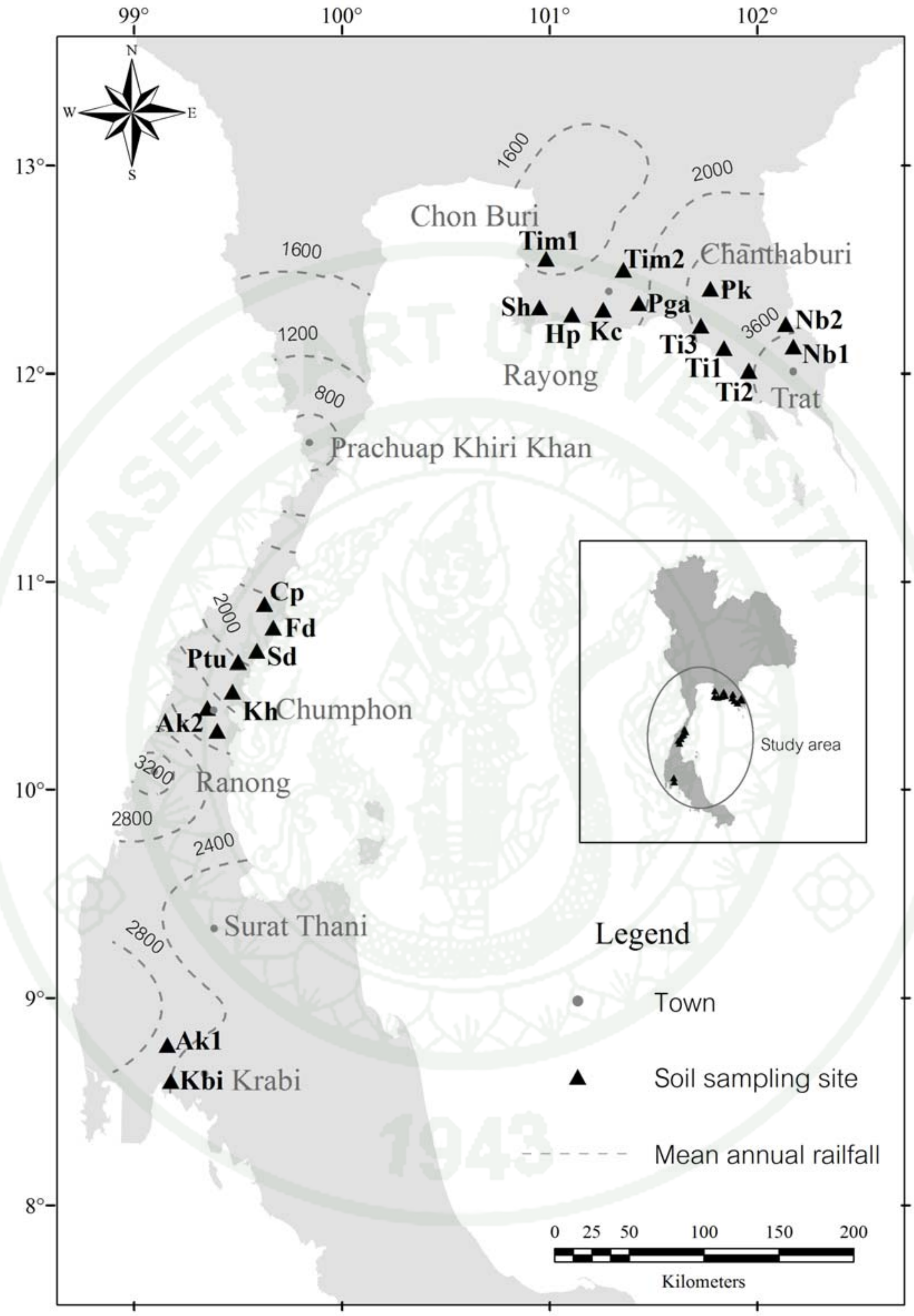

Figure 1 Sampling sites of upland soils under tropical monsoon climate in this study.

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Table 1 Environmental settings of Thai upland Oxisols and Ultisols investigated in this study.

Profile	Parent material	Physiographic position	Surrounding landform	Land use	Elevation MSL (m)	Annual rainfall (mm)
Typic Kandiudox (Ak1)						
Ak1	Residuum derived mainly from limestone	Crestal slope of residual hill in karst corrosion plain	Rolling	Rainforest species, para rubber, papaya, coconut and banana	128	2,171
Typic Kandiudox (Ak2)						
Ak2	Residuum derived from limestone	Karst corrosion plain	Slightly undulating	Tropical rainforest and tropical orchards	78	1,883
Rhodic Kandiudox (Ak3)						
Ak3	Residuum derived from limestone	Rise crestal slope in karst corrosion plain	Undulating	Tropical rainforest and tropical orchards	81	1,883
Kandiudalfic Eutrudox (Ptu)						
Ptu	Residuum and colluvium derived from fine grained clastic rocks and limestone	Footslope in Karst corrosion plain	Undulating	Rainforest species under para rubber, local weeds and fern	82	1,883
Rhodic Kandiudox (Ti1)						
Ti1	Residuum derived from weathered basalt	Upper dissected footslope of lava corrosion hill	Slightly undulating	Tropical orchards and settlements	40	3330
Typic Kandiudox (Ti2)						
Ti2	Residuum derived from weathered basalt	Top of dissected lava corrosion plain	Undulating	Tropical orchards	30	3330
Typic Kandiudox (Ti3)						
Ti3	Residuum derived from weathered basalt	Upper footslope of lava corrosion hill	Undulating	Tropical fruit tree orchard, banana, durian and rambutan	50	3330

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Table 1 **(**Continued).

Profile	Parent material	Physiographic position	Surrounding landform	Land use	Elevation MSL (m)	Annual rainfall (mm)
Typic Kandiudox (Nb1)						
Nb1	Residuum derived from weathered basalt	Shoulder slope on lava corrosion undulating plain	Undulating	Watermelon field (active) left fallow under local grasses	87	3524
Typic Kandiudox (Nb2)						
Nb2	Residuum derived from weathered basalt	Shoulder slope on lava corrosion rolling plain	Rolling	Para rubber plantation	165	3524
Typic Kandiudult (Kh)						
Kh	Colluvium derived from weathered sandstone	Shoulder spur hillslope	Undulating	Tropical orchard, longan, coconut, mangosteen and moist evergreen species remnants	48	1,883
Typic Plinthudult (Kc)						
Kc	Wash and local alluvium derived from meta sedimentary rocks namely quartzite and phyllite	Dissected lower residual footslope	Undulating	Para rubber plantation	14	1,803
Typic Kandiudult (Fd)						
Fd	Residuum derived from clastic sedimentary rocks	Crestal slope of low hill	Undulating	Rainforest and para rubber	81	1,883
Typic Kandiudult (Kbi)						
Kbi	Residuum and colluvium derived from clastic rocks	Shoulder slope of low hill	Mainly rolling	Tropical rainforest, para rubber, rambutan, coconut and tree legume	87	2,171
Typic Kandiudult (Sd)						
Sd	Local alluvium derived from clastic sedimentary rocks	High local alluvial terrace	Undulating	Coconut	72	1,883

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Table 1 (Continued).

Profile	Parent material	Physiographic position	Surrounding landform	Land use	Elevation MSL (m)	Annual rainfall (mm)
Typic Plinthudult (Cp)						
Cp	Local wash over residuum derived from metasedimentary rocks (phyllite and quartzite)	Erosional terrace	Rolling	Para-rubber plantation	125	1,883
Typic Kandiudult (Hp)						
Hp	Residuum derived from weathered granite	Lower midslope of residual hill	Undulating	Cassava field trial plot	37	1,329
Typic Kandiudult (Sh)						
Sh	Mixed wash and local alluvium derived from meta sedimentary rocks and granite	Dissected lower footslope	Flat	Cassava, marigold, para rubber and coconut	80	1,248
Typic Paleudult (Tim1)						
Tim1	Residuum derived from weathered coarse grain granite	Shoulder slope of residual hill	Undulating	Cassava field	137	1,203
Typic Kandiudult (Tim2)						
Tim2	Wash over residuum derived from weathered granite	Upper dissected footslope	Undulating	Para rubber plantation intercropped with pineapple	54	1,850
Typic Kandiudult (Pga)						
Pga	Wash and residuum derived from weathered granite	Lower coalescing footslope	Undulating	Para rubber intercropped with pineapple (young para rubber)	24	1,850
Typic Plinthudult (Pk)						
Pk	Residuum derived from weathered coarse grain granite	Dissected lower footslope	Undulating	Irrigated tropical fruit orchard; Mangosteen, durian and rambutan etc.	67	2,541

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Laboratory Analyses

A summary of methods of physical, chemical, mineralogical and micro-morphological analyses used in the study is shown in Table 2.

Table 2 Laboratory methods.

Analysis	Method	Reference
Whole soil sample		
Physical analysis		
1. Particle size analysis	Pipette method	Gee and Bauder (1986)
2. Hydraulic conductivty	Variable head method	Klute and Dirksen (1986)
3. Bulk density	Clod method	Blake and Hartge (1986)
4. Specific surface area	N_2-BET method	Aylmore *et al.* (1970)
Chemical analysis		
1. Soil pH	1:1 soil:solution in H_2O, 1M KCl and 1:50 soil solution in NaF (pH 8.0) measured by pH meter	National Soil Survey Center (1996), Fieldes and Perrott (1966)
2. Organic carbon	Wet digestion and titration by Walkley-Black method	Nelson and Sommers (1996)
3. Total N	Micro Kjeldahl digestion	National Soil Survey Center (1996)
4. Available P	Bray II	Bray and Kurtz (1945)
5. Available K	1M NH_4OAc at pH 7.0 extraction and measured by AAS	Pratt (1987)
6. Extractable bases (Ca^{2+}, Mg^{2+}, Na^+ and K^+)	1M NH_4OAc at pH 7.0 extraction and measured by AAS	Thomas (1982)
7. Extractable acidity	Barium chloride-triethanolamine solution at pH 8.2	Thomas (1982)
8. Cation exchange capacity (CEC)		
CEC by NH_4OAc	Saturating the exchange site and displacing by 1M NH_4OAc, at pH 7.0	Rhoades (1982), Chapman (1965)
CEC by sum of cations	Sum of extractable bases plus extractable acidity	National Soil Survey Center (1996)
9. Effective cation exchange capacity (ECEC)	Sum of bases plus Al extracted by 1M KCl	National Soil Survey Center (1996)
10. Base saturation percentage (%BS)	By sum of bases extracted by NH_4OAc (pH 7.0), divided by the CEC by sum of cations and multiplied by 100	National Soil Survey Center (1996)
11. Extractable Fe, Al, Mn	Dithionite-citrate-bicarbonate (DCB) and measured by AAS	Mehra and Jackson (1960)
	Extraction in 0.2M ammonium oxalate (pH 3.0) and measured by AAS	McKeague and Day (1966)
	Extraction in 0.1 M sodium pyrophosphate (pH 10.0) and measured by AAS	McKeague (1967)
12. Total analysis of major and minor elements	Fused glass discs by X-ray fluorescence (XRF) using a Philips PW1400 spectrometer	Karathanasis and Hajek (1996); Norrish and Hutton (1969)

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Table 2 (Continued)

Analysis	Method	Reference
Clay fraction sample		
1. Cation exchange capacity (CEC)	Using 0.01 M silver thiourea pH 4.7	Rayment and Higginson (1992)
2. Specific surface area	N_2-BET method	Aylmore *et al.* (1970)
3. Major and minor elements	Aqua regia digestion and measured by a PerkinElmer Optima 5300 DV ICP–OES	Lynch (1999)
4. Major and minor minerals	Oriented clay and powder random X-ray diffraction (XRD) analysis using a Philips PW-3020 diffractometer with a graphite diffracted beam monochromator (CuKα, 50kV 20mA)	Whittig and Allardice (1986), Brown and Brindley (1980), Klug and Alexander (1974)
5. Transmission electron microscope	Dispersed samples on carbon film	Jepson and Rowse (1975)
6. Iron concentrate	Boiling clay in 5 M NaOH	Singh and Gilkes (1991)
7. Kaolin concentrate	Dithionite-citrate-bicarbonate (DCB)	Mehra and Jackson (1960)
Iron concentrate sample		
1. Major and minor minerals	Powder random X-ray diffraction (XRD) analysis using a Philips PW-3020 diffractometer	Whittig and Allardice (1986), Brown and Brindley (1980)
Kaolin concentrate sample		
1. Cation exchange capacity (CEC)	Using 0.01 M silver thiourea pH 4.7	Rayment and Higginson (1992)
2. Analysis of total major and minor elements	Fused glass discs by X-ray fluorescence (XRF) using a Philips PW1400 spectrometer	Karathanasis and Hajek (1996), Norrish and Hutton (1969)
3. Specific surface area	N_2-BET method	Aylmore *et al.* (1970)
4. Major and minor minerals	For oriented clay and random powder by X-ray diffraction (XRD) analysis using a Philips PW-3020 diffractometer	Whittig and Allardice (1986), Brown and Brindley (1980)
5. Crystal morphology	Transmission electron microscope	Jepson and Rowse (1975)
Soil potassium		
1. Water soluble K	Extract soil with deionized water	Pal *et al.* (2001a)
2. Exchangeable K	Extract soil in 1M NH_4OAc at pH 7.0	Thomas (1982)
3. HNO_3-extractable K	Boiling 2 g of soil in 20 mL 1M HNO_3 at 113°C	Pratt (1987)
3. Non-exchangeable K	Difference between HNO_3-K and NH_4OAc-K	Pal *et al.* (2001a)
4. Total K	Fused glass discs by X-ray fluorescence (XRF) using a Philips PW1400 spectrometer	Norrish and Hutton (1969)
5. Kinetic of K release	Extraction in 0.3M sodium tetraphenylboron (NaTPB) solution	Schulte and Corey (1963, 1965)
Statistical analysis		
1. Correlation matrix	Statistical methods	StatSoft, Inc. (2003)
2. Principal component analysis	Statistical methods	StatSoft, Inc. (2003)
3. Cluster analysis	Statistical methods	StatSoft, Inc. (2003)

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RESULTS AND DISCUSSION

Soil Characteristics

1. Field Morphological Characteristics

All soils are Oxisols and Ultisols (Soil Survey Staff, 1999). The Oxisols have developed on colluvium and residuum derived from basalt and limestone, whereas most of the Ultisols have developed on colluvium, residuum and alluvium derived from granite, old local alluvium, sedimentary and metasedimentary rocks. The Oxisols formed on limestone include Typic Kandiudox (Ak1, Ak2), Rhodic Kandiudox (Ak3), and Kandiudalfic Eutrudox (Ptu) (Figure 2) where the Oxisols formed on basalt include Rhodic Kandiudox (Ti1, Ti3) and Typic Kandiudox (Ti2, Nb1, Nb2) (Figure 3). The Ultisols derived from local alluvium, sedimentary and metasedimentary rocks include Typic Kandiudults (Fd, Kbi, Sd, Kh, Suk) and Typic Plinthudults (Cp, Kc), (Figure 4) where the Ultisols derived from granite consist of Typic Kandiudults (Hp, Sh, Tim2, Pga), Typic Peleudult (Tim1) and Typic Plinthudult (Pk) (Figure 5).

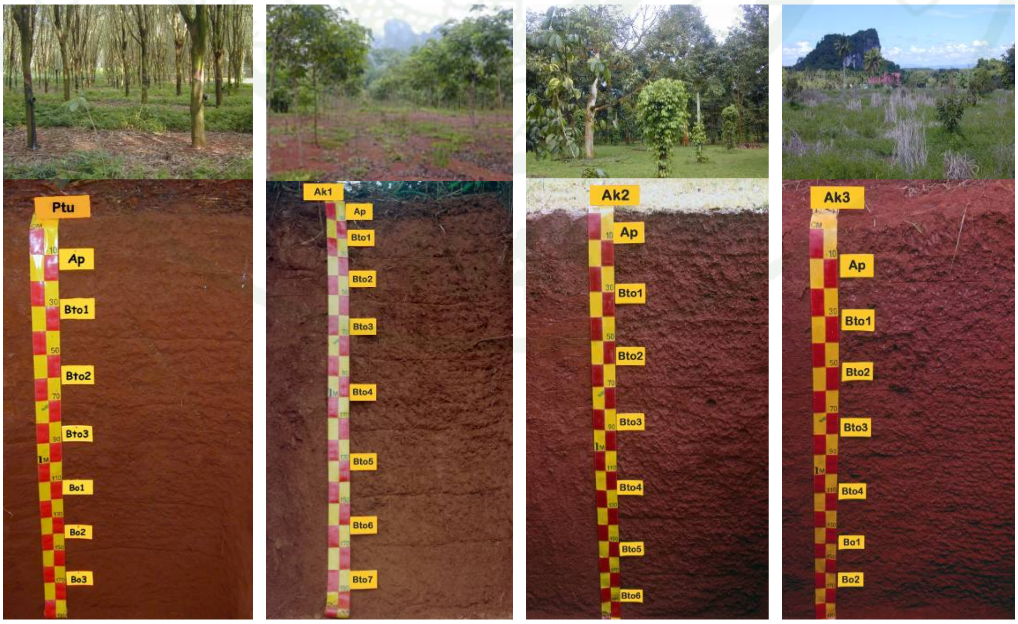

Figure 2 Representative profiles of Oxisols derived from limestone.

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Figure 3 Representative profiles of Oxisols derived from basalt.

The surrounding landforms are mostly undulating having 1–8 percent slope (Appendix A). Horizonation of Oxisols is difficult to identify since iron oxides are consistently dispersed throughout the profile resulting in a uniform color. However, either kandic or oxic horizons do exist. An argillic horizon clearly occurs in Ultisols indicating that extensive illuviation has taken place and a kandic horizon also occurs since the CEC of that horizon is less than 16 $cmol_c\ kg^{-1}$ clay (Soil Survey Staff, 1999). Therefore, the genetic horizons of the Oxisols are Ap, Bt, Bto and Bo, whereas genetic horizons of the Ultisols are Ap, E, Bt, Btc and Bv. These are very deep soils

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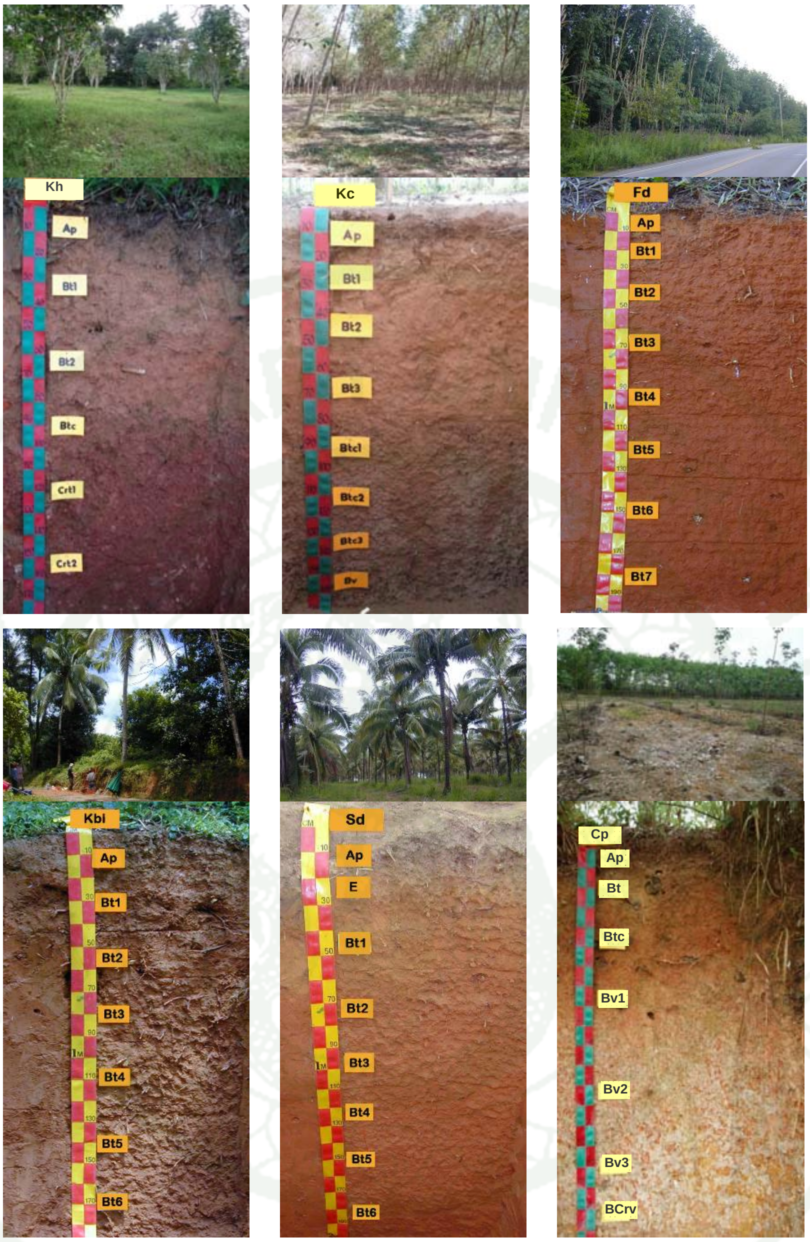

Figure 4 Representative profiles of Ultisols derived from clastic sedimentary rocks.

that are commonly acidic, well drained, with moderate to rapid permeability and moderate to slow runoff. The color of the Oxisols is dusky red to dark yellowish brown, whereas the Ultisols are generally red and occasionally very pale brown.

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Figure 5 Representative profiles of Ultisols derived from granite.

Structure is subangular blocky to strong granular for Oxisols and subangular blocky to semi–angular blocky for Ultisols. Variable amounts and sizes of clay balls occur in all Oxisols. There are few faint/thin clay coatings generally present in all soils except for Ak2 and Ak3, where there are distinct clay coatings.

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Quartz fragments are generally present in Ultisols (Hp, Sh, Tim1, Tim2, Pk, Kh, Fd) in particular for the soils derived from granite. Plinthite bearing layer occurs in the deeper part of Ultisols profiles (Kc, Tim2, Pga, Pk, Cp).

2. Physical Characteristics

2.1 Particle size distribution

Oxisols are clayey throughout the profile except for the surface horizon of Nb1, Nb2, Ti3 and Ptu which has a lighter texture (Figure 6). The texture of Ultisols varies considerably but is mostly sandy loam and sandy clay loam. Subsurface horizons of some profiles have a heavier texture being clay (Pk, Pga, Hp, Kc, Cp, Kh) and sandy clay (Hp, Pga). Clay accumulation in subsoils of all soils is clearly a typical feature of highly developed soils (Buol *et al*., 2003).

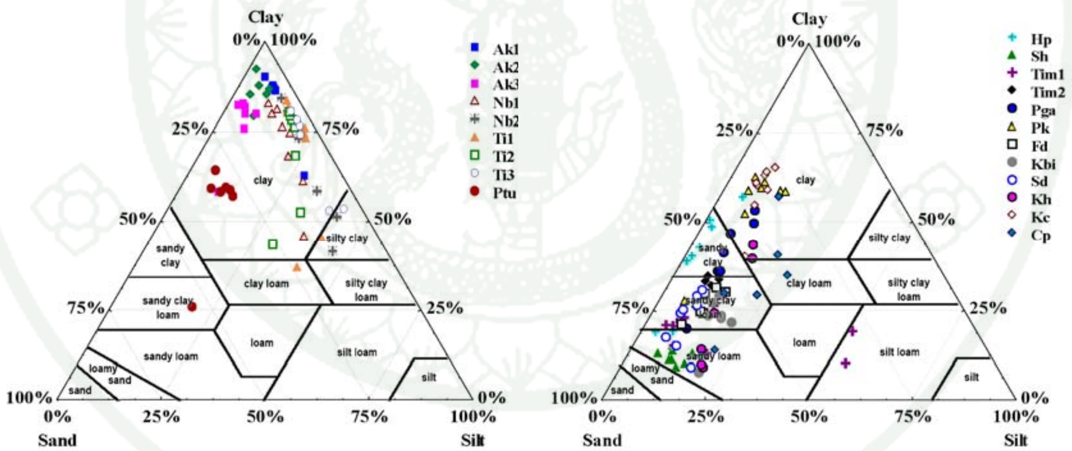

Figure 6 Particle size distribution (sand, silt, clay) of upland Oxisols and Ultisols.

2.2 Bulk density

Bulk density values of Oxisols range from 0.76-1.55 Mg m^{-3}, low to moderate. It is lower than that of Ultisols (1.33-2.03 Mg m^{-3}, moderately low to moderately high). Excellent structure of Oxisols (strong subangular and granular)

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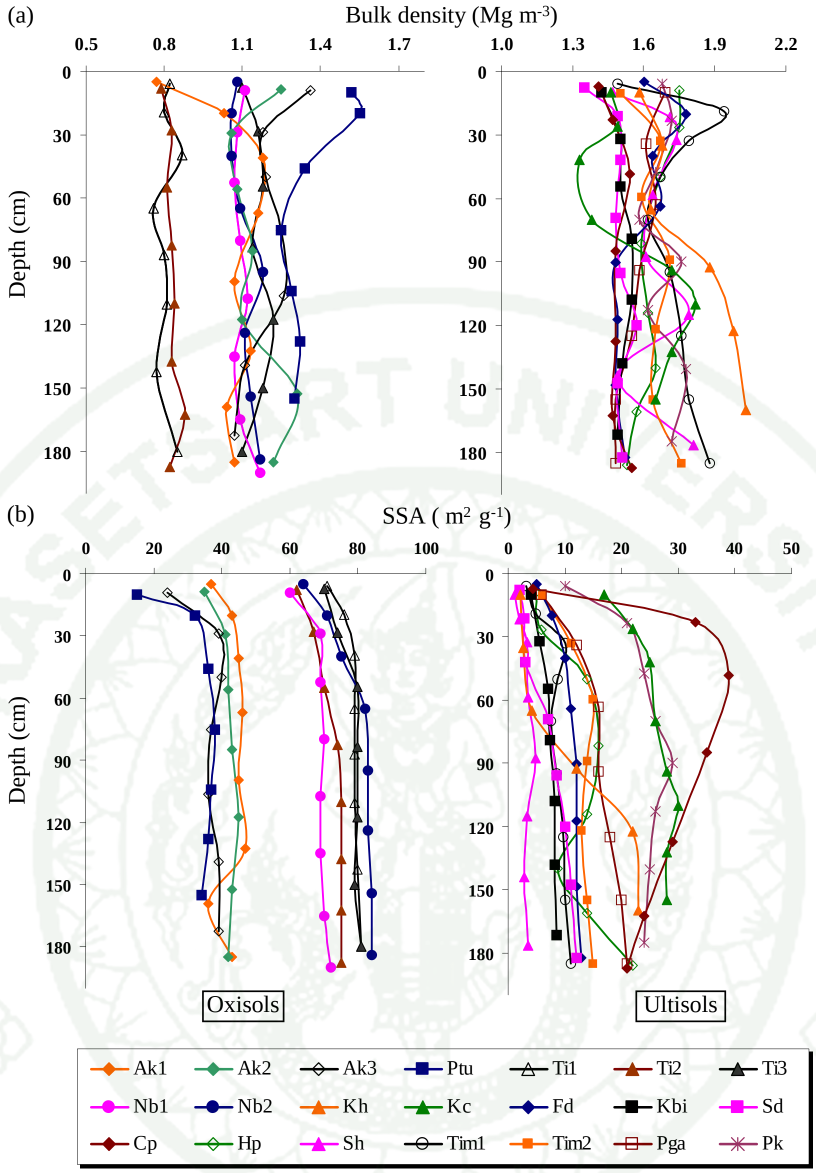

Figure 7 Distribution trend with depth of (a) bulk density and (b) specific surface area in Oxisols and Ultisols.

gives lower bulk density as compared to that of Ultisols even though the soils have a very high clay content. The bulk density of Bt horizons of most Ultisols is higher than of topsoil (Figure 7). This may reflect the high organic matter in the Ap horizon and increasing clay content of Bt due to illuviation (Schaetzl and Anderson, 2005). The bulk density values of Oxisols are quite regular throughout the profile (Figure 7).

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2.3 Specific surface area (SSA)

Values of specific surface area (SSA) for Oxisols are notably greater than for Ultisols reflecting their heavier texture (Figure 7). SSA increases with depth in some Ultisols which have relatively coarser textural surface horizons but essentially constant with depth in red Oxisols which have quite uniform texture trends. The SSA of Oxisols and Ultisols has a significant positive relationship with clay content and negative relationship with sand content. Silt content has no relationship with SSA for both Oxisols and Ultisols.

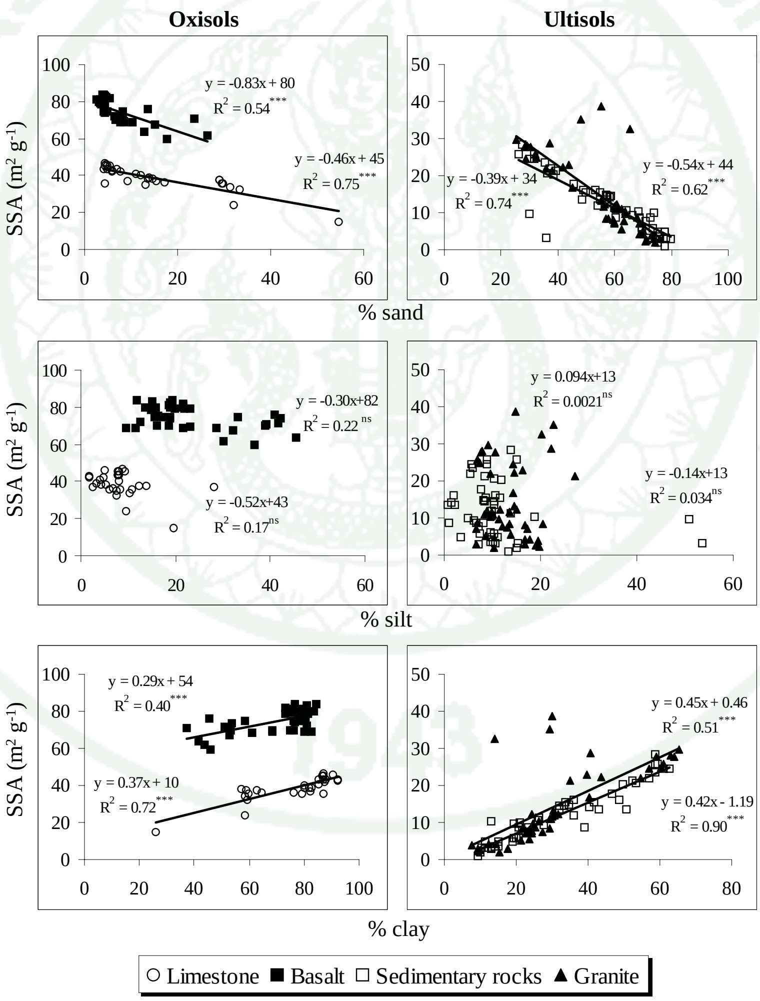

Figure 8 Relationship of SSA with sand, silt and clay in Oxisols and Ultisols. ns = not significant. *** = significant at P<0.001.

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Basaltic Oxisols (Ti, Nb) have the highest SSA value, which is attributed to the dominance of microcrystalline kaolinite and iron oxides and also non-crystalline mineral that may be present in these soils as will be discussed later.

3. Chemical Characteristics

3.1 Soil pH

The pH (1:1 H_2O) ranges from 4.3-6.5 (very strongly acid to slightly acid) for Oxisols and ranges 3.7-6.4 (Extremely acid to slightly acid) for Ultisols. Subsoils of all profiles are very strongly acid to strongly acid. The mean pH value of soils derived from limestone is slightly higher than that of the other soils (Table 3). This is probably due to the soils having received some basic cations from surrounding areas of limestone. However the pH values of the soils developed on limestone are also low due to the loss of cations and accumulation of H^+ by extreme weathering. The pH values measured in KCl are consistently lower than those measured in water. Delta pH of these soils is consequently negative. Therefore, these soils generally have net negative charge which favors cation exchange (Sanchez, 1976).

3.2 Organic matter (OM)

Organic matter content in Ultisols is lower than in Oxisols. OM contents of these soils varies greatly (0.11–79 g kg^{-1}), with values for basaltic Oxisols being higher than for the other soils (Table 3). The surface soils have high OM content, which decreases with depth being characteristic of well developed soils in the Tropics (Soil Survey Staff, 2010). Total nitrogen of these soils clearly correlates with OM ($r = 0.88$, $p<0.001$; Table 4). This is due to the soil OM typically contains about 5%N (Tiessen et al., 2002). However the amounts of N are mostly low as this element can be lost (as nitrate) by leaching (Brady and Weil, 1999).

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Table 3 Mean and SD values for chemical properties of Thai upland soil on various parent materials under a tropical monsoonal climate.

Property	Mean±SD			
	Limestone	Basalt	Sedimentary rock	Granite
pH (1:1 H_2O)	5.6±0.27	4.8±0.28	5.0±0.36	4.5±0.42
pH (1:1 1M KCl)	4.3±0.64	4.4±0.22	3.7±0.28	3.8±0.37
OM (g kg^{-1})	6.6±5.6	14±19	6.0±4.9	3.0±2.8
Total N (g kg^{-1})	3.2±2.2	6.2±6.9	2.7±1.4	1.3±1.4
Avail. P (mg kg^{-1})	6.0±24	47±27	2.6±6.4	8.0±12
Avail. K (mg kg^{-1})	12±7.7	25±22	18±14	17±6.9
BS (%)	21±12	5.0±4.6	19±12	18±12
CEC (cmol kg^{-1})	7.8±2.2	13±5.2	4.1±2.4	2.6±1.6
Fe_d (g kg^{-1})	86±31	97±25	32±49	7.3±7.5
Fe_o (g kg^{-1})	2.1±0.62	16±3.1	2.9±4.6	1.2±0.85
Fe_p (g kg^{-1})	0.29±0.58	2.9±4.7	0.74±2.5	0.54±1.7
Al_d (g kg^{-1})	12±8.9	21±2.8	3.6±1.4	2.5±2.0
Al_o (g kg^{-1})	9.2±3.7	9.7±3.7	3.1±1.7	1.2±0.59
Al_p (g kg^{-1})	2.3±1.1	5.1±5.6	1.5±1.4	1.3±0.82
Mn_d (g kg^{-1})	0.80±0.35	2.9±0.83	0.14±0.14	0.066±0.086
Mn_o (g kg^{-1})	0.29±0.32	2.0±1.0	0.086±0.12	0.074±0.086
Mn_p (g kg^{-1})	0.079±0.11	0.071±0.11	0.027±0.027	0.010±0.012
Fe_o/Fe_d	0.028±0.016	0.21±0.28	0.33±0.70	0.37±0.43

3.3 Available phosphorus

Available phosphorus has a wide range of values (0.10–131 mg kg^{-1}) and the higher values are for the surface horizon which may be partly due to intensive fertilization. For surface soils, the highest values of available P are for Ti3, Nb1 and Nb2 (>45 mg kg^{-1}) where land uses are tropical orchards and water melon while the low values of available P in surface soils are for Fd, Kbi, Sd where land uses are para rubber and coconut . The subsoils generally have low available phosphorus values reflecting the low native P in these soils.

3.4 Available potassium

Values of available potassium range widely (0.48-99 mg kg^{-1}). Oxisols derived from basalt contain higher amounts of available K due to the higher CEC arising from the relatively smaller crystals of minerals in the clay fraction. This observation is consistent with the significant positive relationship between available K

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Table 4 Correlation matrix (r) for relationships between properties of Thai upland soils.

Variable	pH (H_2O)	pH (KCl)	OM	Total N	Avail.P	Avail.K	EA	CEC	BS	Sand	Silt	Clay
pH(H_2O)	1.00											
pH(KCl)	-0.12	1.00										
OM	0.05	-0.02	1.00									
Total N	0.02	-0.02	**0.88**	1.00								
Avail. P	0.02	0.07	**0.36**	**0.44**	1.00							
Avail. K	-0.01	0.00	**0.38**	**0.44**	**0.39**	1.00						
EA	-0.07	-0.03	**0.48**	**0.48**	**0.59**	0.22	1.00					
CEC	0.12	-0.04	**0.63**	**0.76**	**0.59**	**0.32**	**0.74**	1.00				
BS	**0.36**	-0.01	-0.06	-0.05	-0.21	0.11	**-0.47**	**-0.27**	1.00			
Sand	-0.20	0.08	-0.18	**-0.29**	**-0.40**	-0.08	**-0.61**	**-0.70**	**0.34**	1.00		
Silt	0.05	-0.03	**0.57**	**0.55**	**0.46**	**0.32**	**0.56**	**0.57**	-0.03	**-0.27**	1.00	
Clay	0.19	-0.07	-0.03	0.09	0.24	-0.04	**0.42**	**0.51**	**-0.34**	**-0.93**	-0.10	1.00
SSA	0.06	-0.05	0.25	**0.35**	**0.61**	0.17	**0.82**	**0.78**	**-0.46**	**-0.90**	**0.39**	**0.78**

Bold letter indicates significance at $P < 0.001$.

and CEC (r=0.32, p<0.001) (Table 4). Most of surface soils have higher values of available K due to the higher OM, or fertilizer application and also replenishment from the litter on the surface soils. These soils generally have low values of available K due to advanced weathering stage. However some available K may be contributed by other K forms in the soils and its availability depends on soil properties (refer to the chapter on form and availability of K).

3.5 Base saturation percentage by sum (PBS)

The base saturation percentage of these soils ranges from low (<35%) to moderate (35-75%) (Appendix C, Table 2). The high PBS values are for the surface horizon and it tends to decrease with depth. PBS of Oxisols ranges between 1-43 percent whereas in Ultisols it ranges between 4-66 percent. Most of these soils have low PBS (<40%). This is due to high leaching and extreme stage of development of the soils (Brady and Weil, 1999).

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3.6 Cation exchange capacity (CEC)

Cation exchange capacity of Oxisols ranges from 3.2-34 cmol kg^{-1} and is higher than that of Ultisols for which values range from 0.62-12 cmol kg^{-1}. The higher CEC reflects the heavier texture of Oxisols. The CEC has significant positive relationships with OM (r=0.63), total N (r=0.76), Available P (r=0.59), silt content (r=0.57), clay content (r=0.51) and SSA (r=0.78) (Table 4). There is a significant negative relationship between CEC and sand (r=-0.70).

3.7 Extractable iron and aluminum

Extractable Fe and Al concentrations in Oxisols are higher than in Ultisols for all three extractants (Table 3). Crystalline iron oxides as estimated by DCB extraction (Fe_d) are the dominant form of iron oxide in these soils and amounts differ greatly between soils. Values of Fe_d of Ultisols (0.27-151 g kg^{-1}, mean=19 g kg^{-1}) are much smaller than that of Oxisols (11-150 g kg^{-1}, mean=92 g kg^{-1}). Amounts increase with depth in Ultisols which have relatively coarser surface horizons but are essentially constant with depth in Oxisols which have quite uniform texture trends. The Fe_o which indicates the noncrystalline iron oxide (e.g. ferrihydrite) is much higher for the basaltic soils (Ti and Nb series) than for soils formed on limestone (Ak and Ptu) and Ultisols. However values of Fe_o/Fe_d for Ultisols are higher than for Oxisols indicating that there is a larger proportion of noncrystalline iron oxides in Ultisols and possibly indicating a lower degree of development of these soils (Lair *et al.*, 2009). Al extracted by the three extractants shows the same trend as the corresponding iron values.

Sesquioxide minerals have high SSA values which is responsible for the higher SSA of Oxisols relative to Ultisols. There are a significant positive relationships between SSA and both Fe_d+Al_d and Fe_o+Al_o for Oxisols whereas there is no relationship for Ultisols (Figure 9). The R^2 values for the linear relationships between SSA and iron content (Fe_d and Fe_o) are very high but the distribution of data is bimodal so the statistical relationships are unreliable indicators of continuous

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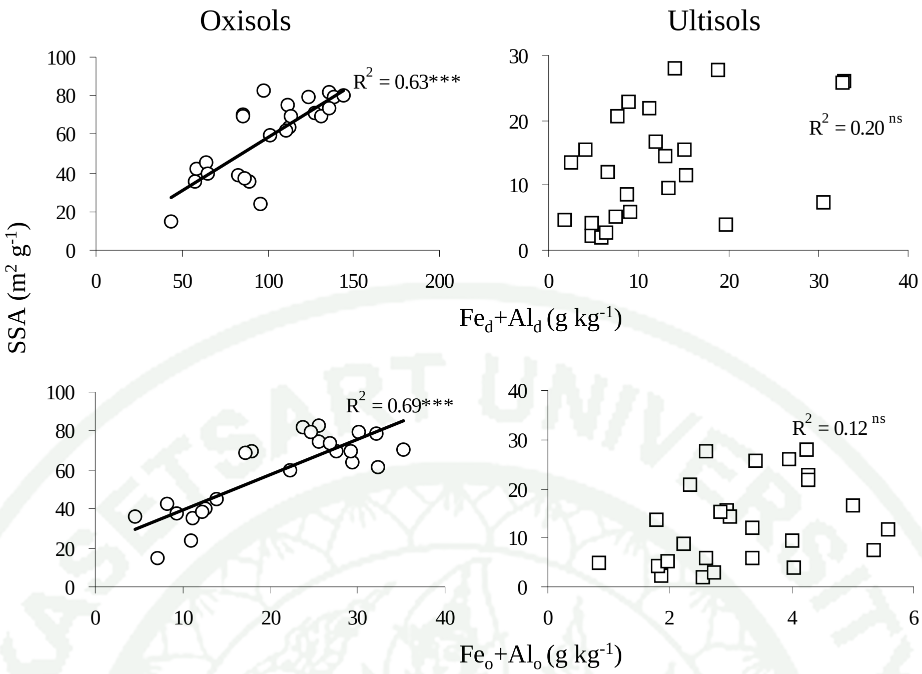

Figure 9 Relationships between SSA of soil samples and Fe plus Al extracted from soil by dithionite-citrate-bicarbonate and ammonium oxalate solutions for Oxisols and Ultisols**.** ns = not significant. *** = significant at P<0.001.

relationships. Including the extractable Al (i.e. Fe_o+Al_o, Fe_d+Al_d) provides more statistically robust relationships. Compared to crystalline iron oxides such as goethite and hematite, amorphous Fe and Al oxides have larger surface area values (Borggaard, 1990) as indicated by these relationships.

4. Mineralogical Characteristics

4.1 Mineralogy of whole soils and silt fraction

XRD patterns were obtained for randomly oriented whole soil and the silt fraction and for basally oriented clay. Results are expressed as the semi quantitative mineralogy (Table 5). The whole soil samples of Oxisols contain much kaolinite with moderate amount of quartz whereas quartz is the dominant mineral and kaolinite is subordinate for Ultisols. Goethite, hematite, maghemite and gibbsite are significant

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constituents of Ti and Nb which are derived from basalt. A trace amount of anatase occurs in all soils. Sh soil contains moderate amount of feldspar and a little occurs in Cp soil. The random powder X-ray diffraction patterns of the silt fraction of all soils give strong reflections of quartz indicating that it is the dominant mineral. Quartz is present in all fractions of these soils as it is a resistant mineral (Stiles *et al*., 2003). Anatase, zircon and rutile are minor minerals in the silt of all Oxisols and Ultisols. Kaolinite, maghemite, gibbsite and hematite are present as minor minerals in the silt of Oxisols. The inclusion of clay size minerals in the silt fraction is interpreted as a consequence of cementation by iron oxides creating stable silt size aggregates (Schaefer, 2001). K-feldspar is present in the silt fraction of Cp, Sh and Tim1, contributing to the higher content of total K in the soil. Feldspar is inherited from the parent rocks (Schaefer, 2008) and its persistence may indicate the lower weathering stage of these soils.

4.2 Clay mineralogy

The clay fraction of these soils contains a large amount of kaolinite with various amounts of minor accessory minerals including smectite, illite, and hydroxy-Al interlayered vermiculite together with feldspar, quartz, goethite, hematite, maghemite, gibbsite, boehmite and anatase (Table 6). Boehmite is only present in Ak1 which formed on limestone under a high rainfall condition. Gibbsite is dominant in Oxisols derived from limestone (Ak1) and basalt (Ti and Nb). Maghemite occurs only in the Oxisols derived from basalt under humid conditions (Ti and Nb). Illite and feldspar are more abundant in Ultisols (Sh, Tim1, Tim2 and Cp profiles) indicating the less intense weathering of the mica (biotite, muscovite, sericite) and feldspar in the parent materials (Kew and Gilkes, 2007). HIV occurs in moderate amounts in the Oxisols and in minor amounts in the Ultisols. The abundant kaolinite and iron oxides in these soils strongly influence the chemical and physical properties of the soils (Schwertmann and Taylor, 1989). Therefore the properties of these minerals have been investigated in detail.

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Table 5 Semi-quantitative mineralogy of whole soil and silt fraction of Thai upland soils on diverse parent materials.

Soil series	Whole soil				Silt fraction			
	Very much	Much	Moderate	Little	Very much	Much	Moderate	Little
Limestone								
Ak1	-	Kao, Qtz	Qtz, Goe	Hem, Boe, Ant	Qtz	-	-	Kao, Gib, Goe, Hem, Ant, Rut
Ak2	-	Kao, Qtz	-	Ant	Qtz	-	-	Kao, Ant, Rut
Ak3	-	Qtz	Kao	Ant	Qtz	-	-	Kao, Goe, Ant, Rut
Ptu	Qtz	-	-	Kao, Ant	Qtz	-	-	Kao, Ant, Rut, Zr
Basalt								
Ti1	-	Kao	Qtz, Goe	Gib, Hem, Mh, Ant	-	Qtz	Hem, Mh, Rut, Zr	Kao Gib, Hem
Ti2	-	Kao	Qtz, Goe	Gib, Hem, Mh, Ant	-	Qtz	Hem, Mh	Kao,Gib
Ti3	-	Kao	Qtz, Goe	Gib, Hem, Mh, Ant	-	Qtz	Mh	Kao,Gib, Hem, Ant
Nb1	-	Kao	Qtz, Goe	Gib, Mh, Ant	-	Kao	Qtz, Goe	Gib, Mh, Ant
Nb2	-	Kao	Qtz,Mh	Gib, Goe, Hem, Ant	-	Kao	Qtz,Mh	Gib, Goe, Hem, Ant
Clastic sedimentary rocks								
Kh	Qtz	-	-	Kao, Ant, Goe	Qtz	-	-	Kao, Ant
Kc	-	Qtz	Kao	Ant	Qtz	-	-	Ant, Rut
Fd	Qtz	-	-	Kao, Ant	Qtz	-	Ant	Zr
Kbi	Qtz	-	-	Kao, Ant	Qtz	-	-	Kao, Ant, Rut, Zr
Sd	Qtz	-	-	Kao, Ant	Qtz	-	-	Ant, Zr
Cp	Qtz	-	-	Kao, Feld	Qtz	-	-	Feld
Granite								
Hp	Qtz	-	-	Kao, Ant	Qtz	-	-	Ant, Rut
Sh	Qtz	-	Feld	Kao, Ant	-	Qtz	Feld	Ant
Tim1	Qtz	-	-	Kao, Ant	Qtz	-	-	Feld, Ant, Rut
Tim2	Qtz	-	-	Kao, Ant	Qtz	-	-	Ant, Rut
Pga	Qtz	-	-	Kao, Ant	Qtz	-	-	Ant, Rut
Pk	-	Qtz, Kao	-	Ant	Qtz	-	-	Kao

Very much=> 60%; Much=20-60%; Moderate=5-20%; Little=<5%
Kao=kaolinite; Qtz=quartz; Feld=feldspar; Goe=goethite; Hem=hematite; Mh=maghemite; Gib=gibbsite; Boe=boehmite; Ant=anatase, Rut=rutile; Zr=zircon

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Table 6 Mineralogy of the clay fraction of Thai upland soils on diverse parent materials.

Soil names	Horizon	Depth (cm)	Kao	Goe	Hem	Qtz	HIV	Sme	Ill	Ant	Gib	Mh	Fel	Boe
Limestone														
Ak1	Ap	0-10	xx	x	x	–	–	–	–	–	xx	–	–	x
	Bto2	30-52	xx	x	x	–	–	–	–	–	xx	–	–	x
	Bto4	80-117	xx	x	x	–	–	–	–	–	xx	–	–	x
Ak2	Ap	0-17	xxxx	tr	tr	x	–	–	–	tr	–	–	–	–
	Bto2	42-70	xxxx	tr	tr	x	tr	–	–	tr	–	–	–	–
	Bto4	100-135	xxxx	tr	x	x	tr	–	–	tr	–	–	–	–
Ak3	Ap	0-18	xxxx	tr	x	tr	tr	–	–	tr	–	–	–	–
	Bto3	60-90	xxxx	tr	x	tr	tr	–	–	tr	–	–	–	–
	Bo1	123-155	xxxx	tr	x	tr	tr	–	–	tr	–	–	–	–
Ptu	Ap	0-20	xxxx	tr	x	x	x	–	–	tr	–	–	–	–
	Bto2	46-75	xxxx	tr	x	x	x	–	–	tr	–	–	–	–
	Bo3	155-190+	xxxx	tr	x	x	x	–	–	tr	–	–	–	–
Basalt														
Ti1	Ap1	0-12	xxxx	tr	tr	x	tr	–	–	tr	tr	x	–	–
	Bto1	27-52	xxxx	x	tr	tr	tr	–	–	tr	tr	x	–	–
	Bo1	96-125	xxxx	x	x	tr	tr	–	–	tr	tr	x	–	–
Ti2	Ap	0-14/16	xxxx	x	tr	tr	tr	–	–	tr	–	tr	–	–
	Bto2	40-70	xxxx	x	tr	tr	tr	–	–	tr	–	tr	–	–
	Bo1	95-125	xxxx	x	tr	tr	tr	–	–	tr	–	tr	–	–
Ti3	Ap	0-15	xxxx	x	tr	tr	tr	–	–	tr	tr	tr	–	–
	Bo1	15-40	xxxx	x	tr	tr	tr	–	–	tr	tr	tr	–	–
	Bto1	67-100	xxxx	x	tr	x	tr	–	–	tr	tr	tr	–	–
Nb1	Ap	0-18	xxxx	x	tr	tr	tr	–	tr	tr	x	tr	–	–
	Bt3	18-40	xxxx	x	tr	x	x	–	tr	tr	x	tr	–	–
	Bto1	95-120	xxxx	x	tr	x	tr	–	tr	tr	x	tr	–	–
Nb2	Ap	0-10	xxx	xx	tr	x	x	–	–	tr	x	tr	–	–
	Bt3	10-30	xxxx	x	tr	tr	x	–	–	tr	x	tr	–	–
	Bto1	80-110	xxxx	x	tr	tr	x	–	–	tr	x	tr	–	–
Clastic sedimentary rocks														
Kh	Ap	0-15/20	xxxx	tr	tr	x	tr	–	–	tr	–	–	–	–
	Bt2	50-80	xxxx	tr	tr	x	tr	–	tr	tr	–	–	–	–
	Btc	80-105	xxxx	tr	tr	x	tr	–	tr	tr	–	–	–	–
	Crt1	105-140	xxxx	tr	tr	x	x	–	tr	tr	–	–	–	–
Kc	Ap	0-15/20	xxxx	tr	tr	tr	tr	–	–	tr	–	–	–	–
	Bt1	20-32	xxxx	tr	tr	tr	tr	–	–	tr	–	–	–	–
	Btc1	88-100	xxxx	tr	tr	–	tr	–	–	tr	–	–	–	–
	Bv	145-165+	xxxx	tr	tr	–	–	tr	–	tr	–	–	–	–
Fd	Ap	0-10	xxxx	tr	tr	tr	tr	–	–	tr	–	–	–	–
	Bt4	78-103	xxxx	tr	tr	tr	tr	–	–	tr	–	–	–	–
Kbi	Ap	0-20	xxxx	tr	tr	x	tr	–	–	tr	–	–	–	–
	Bt3	65-93	xxxx	tr	tr	x	tr	–	–	tr	–	–	–	–
Sd	Ap	0-15	xxxx	tr	tr	tr	x	–	–	tr	–	–	–	–
	E	15-27	xxxx	tr	tr	x	x	–	–	tr	–	–	–	–
	Bt3	81-110	xxxx	tr	tr	tr	tr	–	–	tr	–	–	–	–
Cp	Ap	0-14	x	–	–	x	tr	tr	x	–	–	–	–	–
	Bt	14-32	x	–	–	x	–	tr	x	–	–	–	–	–
	Btc	32-65	xx	–	–	x	–	–	x	–	–	–	–	–
	Bv1	65-105/107	xx	–	–	x	–	–	x	–	–	–	–	–
	BCrv	175-200+	xx	–	–	tr	–	–	x	–	–	–	–	–

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Table 6 (Continued).

Soil names	Horizon	Depth (cm)	Kao	Goe	Hem	Qtz	HIV	Sme	Ill	Ant	Gib	Mh	Fel	Boe
Granite														
Hp	Ap1	0–18	xxxx	–	–	x	tr	–	tr	tr	–	–	–	–
	Bt2	65–98	xxxx	–	–	tr	tr	–	tr	tr	–	–	–	–
Sh	Ap1	0–10	xxx	–	–	xx	–	–	x	tr	–	tr	x	–
	AB	23–42	xxx	–	–	x	–	–	x	tr	–	tr	x	–
	Bt1	42–75	xxx	–	–	xx	–	–	x	tr	–	tr	x	–
Tim1	Ap1	0–12	xxx	tr	tr	x	–	–	x	tr	–	–	–	–
	Bt1	26–40	xxx	tr	tr	x	–	–	x	tr	–	–	–	–
	Bt3	60–80	xxx	tr	tr	x	–	–	x	tr	–	–	–	–
Tim2	Ap	0–21	xxxx	tr	tr	tr	tr	–	tr	tr	–	–	–	–
	Bt3	74–104	xxxx	tr	tr	tr	tr	–	tr	tr	–	–	–	–
	Bv	170–200+	xxxx	tr	tr	tr	tr	–	tr	tr	–	–	–	–
Pga	Ap	0–20	xxxx	tr	tr	tr	tr	–	tr	tr	–	–	–	–
	Bt3	78–110	xxxx	tr	tr	tr	tr	–	tr	tr	–	–	–	–
	Bv	170–200+	xxxx	tr	tr	tr	–	–	tr	tr	–	–	–	–
Pk	Ap	0–10/12	xxxx	tr	tr	tr	tr	–	–	tr	–	–	tr	–
	Bt3	60–80	xxxx	tr	tr	tr	tr	–	–	tr	–	–	tr	–
	Bv1	100–126	xxxx	tr	tr	tr	–	–	–	tr	–	–	tr	–

xxxx = > 60%; xxx = 40–60%; xx = 20–40%; x = 5–20%; tr = <5%; Kao = kaolinite; Goe = goethite; Hem = hematite; Qtz = quartz; HIV = hydroxy-Al interlayered vermiculite; Sme = smectite; Ill = illite; Ant = anatase; Gib = gibbsite; Mh = maghemite; Fel = feldspar; Boe = boehmite

5. Classification and Pedogenesis of Thai Upland Soils Under a Monsoonal Climate

The taxonomic names of these soils including the family name are shown in Table 7. Characteristics of these upland soils indicate that parent materials and environmental factors have had a consistent effect on their properties. Influences of parent rocks mainly control their texture and concentrations of major and trace elements. Mixed and irregular colors in soils developed under a udic soil moisture regime reflect climatic conditions, as color is mostly a consequence of differences in the content and mineralogy of iron oxides with goethite dominating the iron oxides in the clay fraction. The clay mineral assemblages are dominated by kaolinite.

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Table 7 Taxonomic classification of the studied soils (Soil Survey Staff, 2010).

Soil series	Classification
Ao Luek1 (Ak1)	Typic Kandiudox, very-fine, ferruginous, isohyperthermic
Ao Luek2 (Ak2)	Typic Kandiudox, very-fine, kaolinitic, isohyperthermic
Ao Luek3 (Ak3)	Rhodic Kandiudox, very-fine, kaolinitic, isohyperthermic
Pathio (Ptu)	Kandiudalfic Eutrudox, fine, kaolinitic, isohyperthermic
Tha Mai1 (Ti1)	Rhodic Kandiudox, very-fine, kaolinitic, isohyperthermic
Tha Mai2 (Ti2)	Typic Kandiudox, very-fine, kaolinitic, isohyperthermic
Tha Mai3 (Ti3)	Rhodic Kandiudox, very-fine, kaolinitic, isohyperthermic
Nong Bon1 (Nb1)	Typic Kandiudox, very-fine, kaolinitic, isohyperthermic
Nong Bon2 (Nb2)	Typic Kandiudox, very-fine, kaolinitic, isohyperthermic
Kohong (Kh)	Typic Kandiudult, coarse-loamy, kaolinitic isohyperthermic
Khlong Chak (Kc)	Typic Plinthudult, fine, kaolinitic, isohyperthermic
Fang Daeng (Fd)	Typic Kandiudult, fine-loamy, kaolinitic, isohyperthermic
Krabi (Kbi)	Typic Kandiudult, fine-loamy, kaolinitic, isohyperthermic
Sadao (Sd)	Typic Kandiudult, fine-loamy, kaolinitic, isohyperthermic
Chumphon (Cp)	Typic Plinthudult, loamy-skeletal, mixed, semiactive, isohyperthermic
Huai Pong (Hp)	Typic Kandiudult, fine, kaolinitic, isohyperthermic
Sattahip (Sh)	Typic Kandiudult, coarse-loamy, kaolinitic, isohyperthermic
Thai Mueang1 (Tim1)	Typic Peleudult, fine-loamy, siliceous, subactive, isohyperthermic
Thai Mueang2 (Tim2)	Typic Kandiudult, fine-loamy, kaolinitic, isohyperthermic
Phang–nga (Pga)	Typic Kandiudult, fine, kaolinitic, isohyperthermic
Phuket (Pk)	Typic Plinthudult, fine, kaolinitic, isohyperthermic

The dominant pedogenic processes for these upland soils are desilication, ferrugination, illuviation and leaching which have operated to different degrees. Desilication has caused gibbsite formation and dissolved aluminum from gibbsite in these soils may penetrate the interlayer of vermiculite creating HIV. Illuviation and leaching create an argillic and/or a kandic horizon or oxic horizon with low CEC clay ($\leq$16 cmol(+) kg^{-1}), ECEC clay ($\leq$12 cmol(+) kg^{-1}) and low base saturation percentage (< 35%) in the subsoil. Thus, Oxisols and Ultisols have relatively low chemical fertility, particularly their subsurface horizons. Laterization has occurred in deeper parts of some Ultisols, which may reflect fluctuations of reduction and oxidation of Fe under the moist and warm environment of the Tropics.

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Properties of Kaolin Group Minerals

Fifty samples from genetic horizons of 17 soils were analyzed for chemical and mineralogical properties of the kaolin minerals. The Ak1, Cp, Sh and Tim1 soils were not included in this study as they contain moderate amount of the other minerals (e.g. illite and gibbsite) in the clay fraction (Table 6). Iron oxides were removed from the clay fraction by dithionite–citrate–bicarbonate extraction. The residue consisted almost entirely of kaolin group minerals (kaolinite and halloysite) and these concentrates will be referred henceforth to as kaolin. The kaolin samples contain minor amounts of quartz and gibbsite, particularly for soils derived from basalt in the case of gibbsite. Minor amount of anatase, hydroxy-Al interlayered vermiculite and illite are also present in some kaolin samples.

1. Morphology

The shape of kaolin crystals observed by TEM varies substantially between soils (Figure 10). Perfect euhedral hexagonal crystals are common for kaolin derived from granite (e.g. Hp, Pga, Pk and Tim2), sedimentary rocks (e.g. Kc and Sd) and limestone (e.g. Ak2) whereas they are rare in basaltic soils. This trend has been observed by other workers (Hughes and Brown, 1979; Hart *et al.*, 2003). There is a wide range of crystal sizes for kaolin in Kbi and Kh soils. The small crystals may have formed directly during pedogenesis whereas the large crystals may have been inherited from the parent sedimentary rock where diagenesis commonly produces large crystals of kaolin (Montes *et al.*, 2002). Alternatively large kaolin crystals may have formed in saprolite that occurs beneath the present soil profile.

Halloysite tubes occur together with hexagonal platy crystals in Kh, Kbi and Sd soils and in all basaltic soils. Many studies indicate that basaltic soils in warm and wet climates contain halloysite (Kautz and Ryan, 2003; Zhang *et al.*, 2007; Rasmussen *et al.*, 2010). Halloysite being less ordered with less 3-dimensional bonding than kaolinite may be more susceptible to weathering. In some strongly weathered soils, halloysite is more common than kaolinite but it is less stable and it

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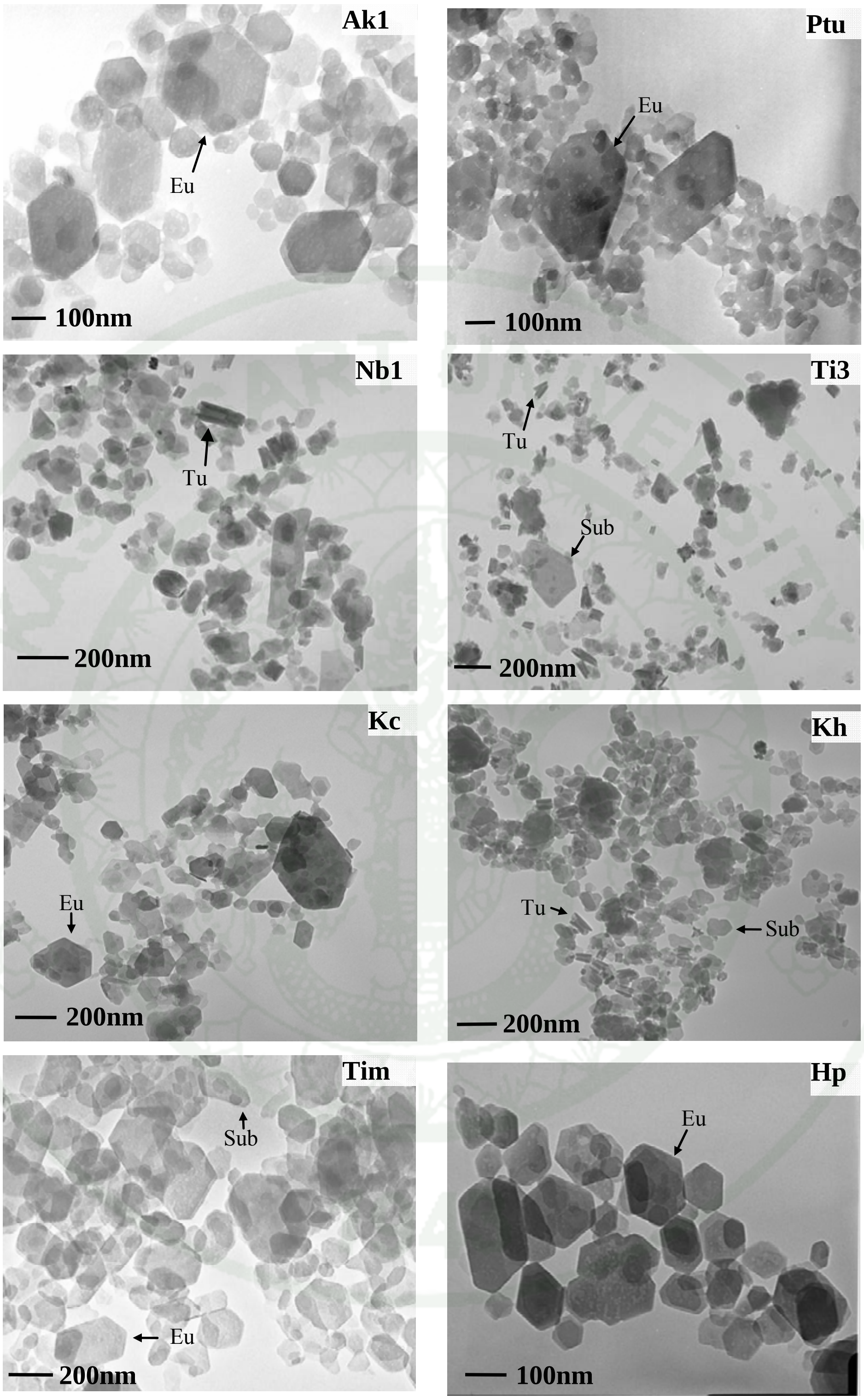

Figure 10 Transmission electron microscope (TEM) micrographs of deferrated kaolins from soils derived from various parent materials showing the wide variation of crystal morphology and size. Sub = subhedral faces, Eu = euhedral faces and Tu = tubes.

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may be replaced by kaolinite with time (Quantin, 1990; Navarrete *et al.,* 2007). Halloysite and gibbsite, although known to require quite different conditions for their formation, typically occur together in the Oxisols derived from basaltic parent materials. Halloysite in these basaltic Oxisols may be formed by resilication of gibbsite and might eventually transform into kaolinite (Furian *et al.*, 1999; Furian *et al.*, 2002; Islam *et al.*, 2002).

Histograms of the frequency of values of the shape ratio (SR= length/width) of platy kaolinite crystals (Figure 11) derived from TEM micrographs indicate that the mean value is considerably greater than one because some kaolinite crystals are elongated. The mean value of shape ratio ranges from 1.26 to 1.47 for Ultisols and from 1.31 to 1.51 for Oxisols. The proportions of lath shaped and equant particles were calculated with a SR value = 2.0 being taken as the boundary between the two shapes. Thus SR > 2.0 identifies a lath and SR < 2.0 identifies an equant crystal. The proportion of lath shaped particle is highest in Nb1 (10%) and consequently the mean value of shape ratio for this soil is the highest (Table 8). Laths are a common morphological feature of kaolin pseudomorphs after mica (Pei Yuan Chen *et al.,* 2004) and this soil although primarily developed over basalt contains minor amount of a micaceous mineral.

Coherently scattering domain (CSD_{001}) sizes of kaolin crystals derived from the width at half height (WHH) of XRD reflections and calculated using the Scherrer equation indicate that the average size of soil kaolin crystals along the c-axis ranges from 10.1 to 20.4 nm for Oxisols and from 14.0 to 41 nm for Ultisols. The kaolins derived from basalt have the smallest crystal size (mean=11.8 nm) whereas kaolin in all other soils has a similar mean value of crystal size after omitting outlier data for Kbi soil (i.e. granite=16.9 nm, limestone and other sedimentary rock=18.5 nm).

2. Chemical Composition

The chemical composition of kaolin bulk samples determined by XRF shows that considerable titanium (Ti) is present in all kaolin samples and amounts of Ti are

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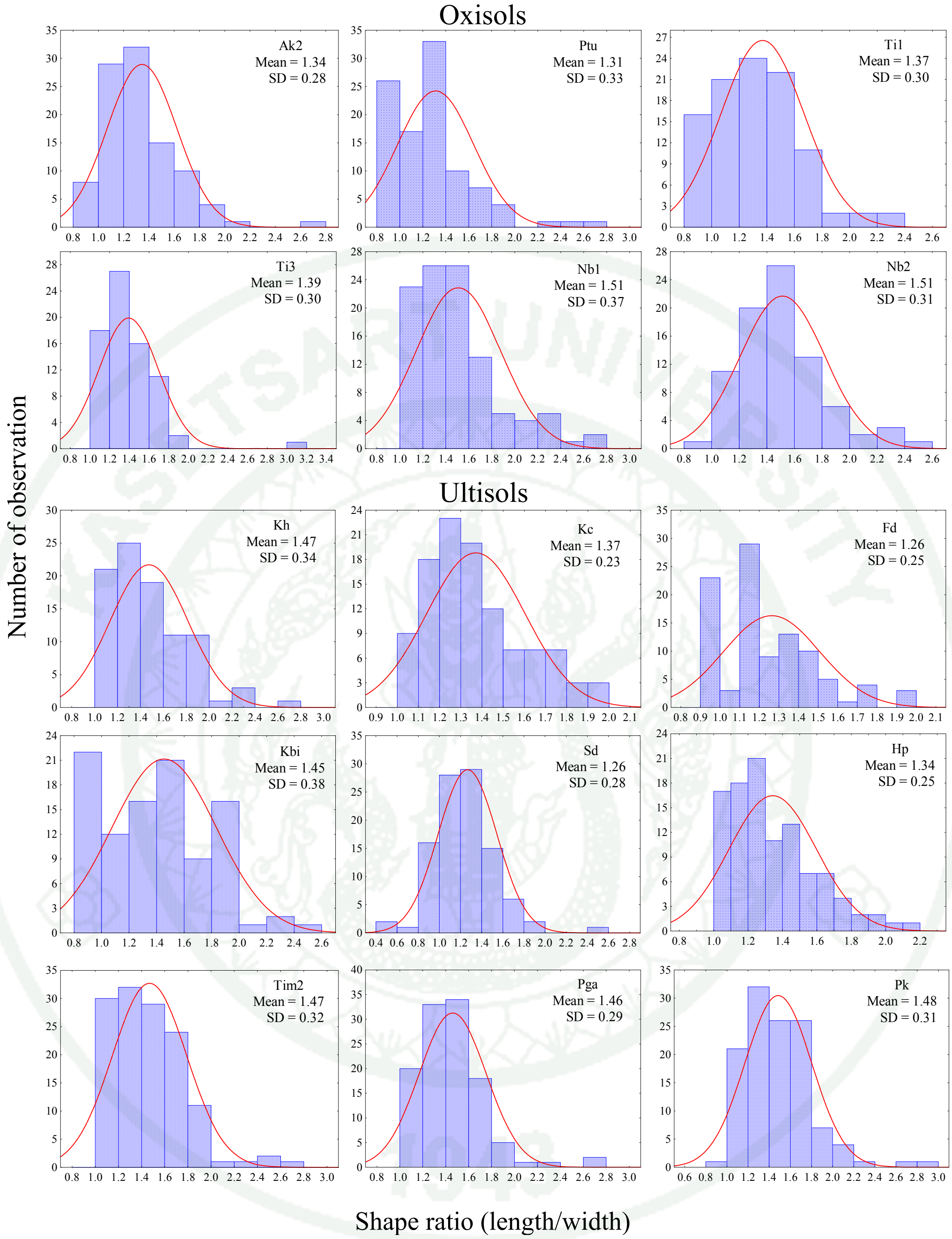

Figure 11 Histograms of the frequency of occurrence of kaolin crystals with various values of shape ratio (length/width) determined by TEM for deferrated kaolins from representative Thai Ultisols and Oxisols.

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Table 8 Some properties of purified kaolin and iron oxides in Thai Oxisols and Ultisols.

soil name /horizon	Depth (cm)	Kaolin													Goethite		Hematite	
		TiO_2	Fe_2O_3	K_2O	CSD_{001}	CSD_{060}	HB	SSA	CEC	Length	Width	Lath	Equant	Tube	Mole Al	MCD_{110}	mole Al	MCD_{110}
		(-------g kg^{-1}-----)			(--------nm-------)		index	(m^2 g^{-1})	(cmol kg^{-1})	(------nm-----)		(---------%-----------)			(%)	(nm)	(%)	(nm)
Oxisols																		
Ak2/Bto2	42-70	9.2	10.3	nd	17.3	28.7	4.7	22	7.0	101	77	4	96	0	15	22	11	29
Ak3/Bto3	60-90	26.7	9.8	0.47	17.8	32.4	5.2	22	6.4	110	82	7	93	0	17	28	9	25
Ptu//Bto2	46-75	13.8	14.5	1.2	20.4	21.7	5.6	26	7.6	78	60	6	94	0	15	30	10	29
Ti1/Bto1	27-52	45.9	27.0	0.45	10.4	16.4	5.3	48	18	69	52	5	90	5	19	12	15	16
Ti2/Bto2	40-70	43.7	19.9	0.41	11.5	18.5	4.5	64	19	99	74	9	82	9	17	12	10	15
Ti3/Bto1	67-100	45.4	27.5	0.65	10.1	7.9	7.5	65	19	99	73	2	79	9	23	9	7	15
Nb1/Bt3	65-95	46.1	18.3	4.9	13.4	12.1	7.1	48	15	84	57	10	79	10	21	11	nd	nd
Nb2/Bt3	50-80	35.5	15.2	3.2	11.5	11.2	9.5	51	19	91	61	6	87	7	10	17	6	13
Mean	-	33.3	17.8	1.4	14.1	18.9	6.2	43	14	91	67	-	-	-	17	18	9.7*	20*
Ultisols																		
Kh/Bt2	50-80	11.3	11.8	8.2	24.2	13.6	10.4	31	16	109	77	7	75	8	14	18	12	18
Kc/Bt2	32-52	13.8	22.4	0.27	17.3	18.1	6.1	41	6.5	106	79	2	98	0	18	8	6	19
Fd/Bt4	78-103	15.0	14.5	0.81	17.1	28.3	5.0	23	14	110	89	3	97	0	16	23	7	33
Kbi/Bt3	65-93	16.5	10.6	1.3	40.6	31.8	9.2	17	9.2	219	152	4	91	5	16	26	9	44
Sd/Bt3	81-110	17.5	16.7	1.7	15.2	24.6	5.7	28	7.4	131	106	3	96	1	13	34	10	33
Hp/Bt1	35-65	18.4	19.7	16.4	14	12.4	8.5	34	8.0	115	87	2	98	0	nd	nd	nd	nd
Tim2/Bt3	74-104	15.9	19.8	3.6	16.5	16.8	9.0	36	9.0	124	86	5	95	0	11	11	6	19
Pga/Bt3	78-110	10.7	21.4	3.3	19.1	20.5	9.2	34	12	128	89	3	97	0	nd	nd	nd	nd
Pk/Bt3	60-80	4.7	11.6	1.7	17.9	18.2	10.7	40	6.0	150	105	7	93	0	19	17	6.7	15
Mean	-	13.7	16.5	4.1	19.7	21.3	7.9	32	9.0	132	97	-	-	-	13*	17*	7.5*	27*

* The calculated mean excludes not detectable (nd) goethite/hematite

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higher in kaolin from Oxisols (mean 33 g kg^{-1}) than from Ultisols (mean=14 g kg^{-1}) (Table 8). Concentrations of Ti are particularly high for kaolin samples from basaltic soils. Significant amount of potassium are present in all kaolin samples except for Ak2 profile where K was not detected by XRF. The K_2O in kaolin is less than 10 g kg^{-1} for all soils except for Hp Ultisol which has the highest K_2O (16 g kg^{-1}) and Nb1 and Nb2 kaolins contain more K than do other Oxisols. These kaolin samples contain small amounts of illite. Kaolin crystals in tropical soils may contain a minor amount of interlayer K in rare illite layers but this proposition has yet to be confirmed as a common occurrence (Melo *et al.*, 2001).

A striking feature of the chemical composition of soil kaolin compared with ideal kaolinite is the presence of considerable amounts of Fe despite free iron oxides having been removed by the DCB treatment. The Fe_2O_3 content in the deferrated kaolin ranges from 1.0 to 28 g kg^{-1}. The mean Fe_2O_3 content of kaolin in Oxisols (mean=18 g kg^{-1}) is the same as for Ultisols (mean=17 g kg^{-1}) indicating that the substitution of Fe in kaolin does not simply depend on the Fe content of the parent rock or the total Fe content of the soils, both of which are largest for the basaltic soils. Thus Fe_2O_3 values of 15 to 18 g kg^{-1} in kaolin from Nb1 and Nb2, (basalt-derived soils), are lower than the mean value (≈ 20 g kg^{-1}) for kaolin from granitic soil profiles (Hp, Pga and Tim2).

Several workers have demonstrated a significant negative relationship between the crystal size of kaolin and Fe_2O_3 concentration (Hart *et al.,* 2003; Hughes *et al.,* 2009). This study also observed significant negative relationships between kaolin crystal size CSD_{001} and Fe content for kaolin in Oxisols. (R^2 = 0.56***, p=<0.001) and Ultisols (R^2 = 0.29**, p=<0.01). However, no relationship exists between CSD_{060} and Fe content for Ultisols (Figure 12).

Kaolin in these soils is highly disordered with a mean HB crystallinity index value for Oxisols of 6.2 and for Ultisols of 8.2 indicating a lack of structural order and these HB values are much less than HB index values for reference mineral kaolinite which range from 38 to 83 (Hughes and Brown, 1979; Singh and Gilkes, 1992a).

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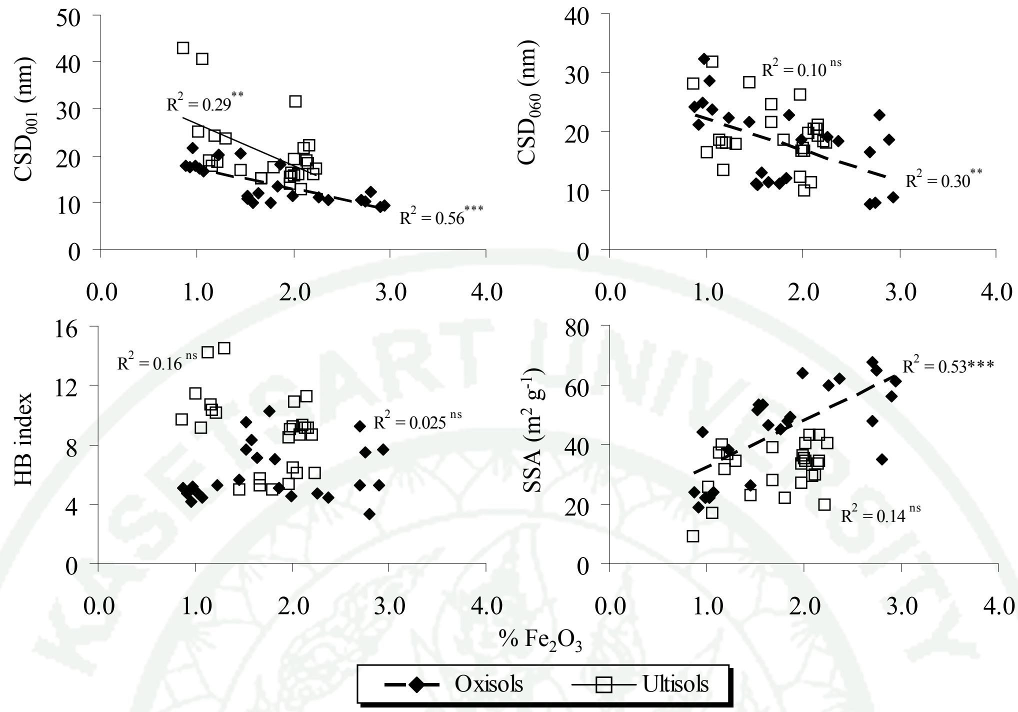

Figure 12 Relationships of CSD_{001}, CSD_{006}, crystallinity index and SSA with $\%Fe_2O_3$ for deferrated soil kaolins. ns = not significant. ** and *** = significant at $P<0.01$ and $P<0.001$.

Although some studies have shown negative relationships between the Fe content of soil kaolin and crystallinity (Hart *et al.*, 2002; Singh and Gilkes, 1992a) other workers have not found this relationship (Trakoonyingcharoen *et al.,* 2006a) as is the case for the present study (Figure 12).

3. Specific Surface Area (SSA) and Cation Exchange Capacity (CEC)

The specific surface area of these kaolins has a wide range (17–65 m^2 g^{-1}). The highest surface area is for Ti3 kaolin which is consistent with its very small crystal size. The low SSA for kaolin in profile Kbi relates to the large crystal size of kaolin in this soil. The SSA of kaolin in Oxisols has a weak positive relationship with Fe content but this relationship does not exist for Ultisols (Figure 12). The lack of clear relationships may reflect the quite small range of Fe concentrations in these kaolins.

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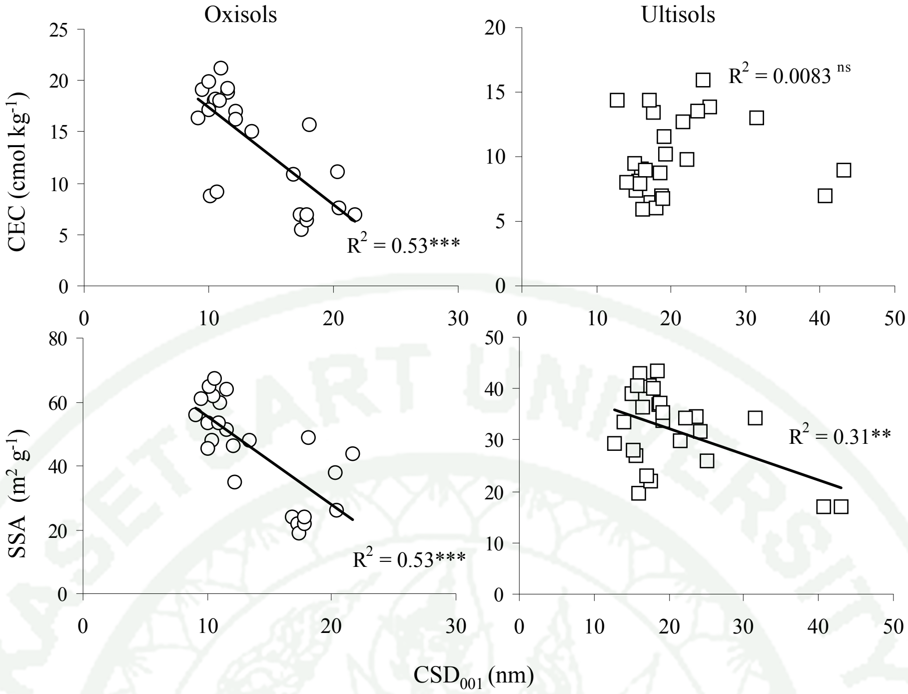

Figure 13 Relationships between SSA, CEC and CSD_{001} for soil kaolins. ns = not significant. ** and *** = significant at P<0.01 and P<0.001.

The cation exchange capacity of the kaolins ranges from 7–19 cmol kg^{-1}. The CEC is closely related to crystal size of kaolin as there is a general trend for CEC to increase with decreasing crystal size and increasing SSA (Figure 13). Halloysite tubes contribute to the higher SSA and CEC of kaolin concentrates from Oxisols relative to that from Ultisols as halloysite exhibits larger surface area (Bigham *et al.,* 2002) and cation exchange capacity than does kaolinite (Delvaux *et al.,* 1990).

Properties of Iron Oxides

1. Al Substitution in Goethite and Hematite

The degree of Al substitution in iron oxides in soils reflects the environment in which they formed and in particular the relative activities of Al and Fe in soil solution (Schwertmann and Kämpf, 1985; Schwertmann, 1988). Iron oxide in the clay

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fractions from 15 representative samples from each profile were concentrated by dissolving kaolin in 5M NaOH. Hp and Pga soils were not investigated as they contain little or no iron oxides in the clay fraction (Table 6). Measurement of Al substitution based on precise values of XRD spacing indicates 10-23 mole% Al in goethite and 6-15 mole% Al in hematite (Table 8). The values of mole% Al substitution in both goethite and hematite in Oxisols are slightly higher than that in Ultisols. Goethite in profile Ti3 has the highest level of Al substitution. Basaltic soils have high Al substitution in goethite and hematite and these soils contain gibbsite, which may indicate that the pedogenic environment promotes desilication of primary minerals and release of abundant free Al which substitutes for Fe in iron oxides (Motta and Kämpf, 1992). There is no relationship between mole% Al substitution in goethite and hematite for these soils (Figure 14) in contrast with observations by many workers (Siradz, 2000; Prasetyo and Gilkes, 1994; Schwertmann and Kämpf, 1985) who showed that a strong positive relationship existed for some tropical soils. The poor statistical strength of this relationship in the present research is probably partly due to the small range of Al substitution values for both iron oxides.

2. Mean Coherently Diffracting Length (MCD)

As postulated by Schwertmann (1988), a small level of Al substitution may stabilize the structure of iron oxide minerals by releasing structural strain, so that a small amount of Al is readily accepted by the iron oxide structure. However, increasing substitution of Al may increase structural strain, slow the rate of crystal growth and reduce crystal size. However this study shows no relationship between mole% Al substitution and crystal size (MCD) for both hematite and goethite (Figure 14). The MCD of goethite in Oxisols follows the sequence basalt< granite< clastic sedimentary rocks = limestone and a similar trend occurs for hematite.

3. Amorphous Fe Oxides

Amorphous Fe oxides (Fe_o) are considered unstable under most soil conditions and significant amounts are expected to be present only during initial stage of soil

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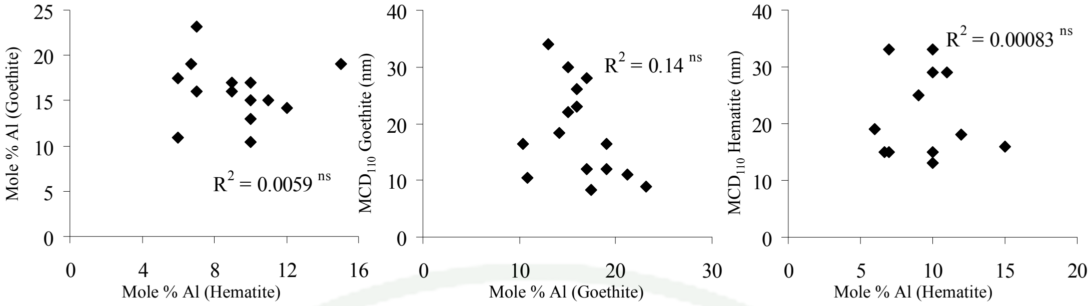

Figure 14 Bivariate plots showing the absence of relationships between mole% Al substitution in goethite and hematite and between MCD_{110} of goethite and hematite versus mole% Al for iron oxide concentrates. ns = not significant.

formation. However, the mature highly weathered soils derived from basalt (Ti and Nb) contain much amorphous Fe, probably as ferrihydrite and possibly due to the presence of abundant dissolved silica and organic matter impeding formation of crystalline Fe oxides (Cornell and Schwertmann, 2003). The high annual rainfall of the region where the basaltic soils profiles occur (~ 3300 to 3500 mm of annual rainfall) may result in the rate of dissolution of the parent rock exceeding the rate of formation of kaolin and crystalline iron oxide resulting in the presence of non-crystalline forms of Fe and Al in the soil (Arieh, 1966). Higher values of Fe_o may also be due to the greater solubility in oxalate of crystalline iron oxides in these basaltic soils which have much smaller iron oxide crystals than that present in the other soils (Trakoonyingcharoen *et al.,* 2006b). With increasing soil age, Fe compounds accumulate and noncrystalline forms including ferrihydrite transform into more stable crystalline minerals particularly goethite and hematite. Ti and Nb clays contain relatively higher amounts of goethite in the clay fraction indicating that ferrihydrite may transform to goethite rather than to hematite.

4. TEM-EDS Analysis

The composition of single clay-size, complex particles from the nondeferrated clay fraction of several samples as determined by TEM-EDS (energy dispersive

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spectrometry) analysis (Figure 15a) have been expressed as normalized percentages of SiO_2, Al_2O_3 and Fe_2O_3 on a water-free basis and are plotted in a triangular graph (Figure 15b). Analyses of ideal kaolin crystals should be located on the horizontal axis of the triangular graph at 55% SiO_2 and 45% Al_2O_3. The small quantities of structural iron present in kaolin crystals will result in analysis being slightly displaced from this point towards the Fe_2O_3 apex as is seen in Figure 15c for DCB treated clay. The nondeferrated clay particles include very small particles of iron oxides attached to kaolin crystals (samples Nb1 and Ti3) and this iron is included in the analyzed volume (Figure 15a). Consequently the analyses of particles plotted in Figure 15b are displaced towards the Fe_2O_3 apex along what is defined as the kaolin line. However the analyses for the particularly Fe rich Nb1 and Ti3 kaolins (i.e. for basaltic soils) actually fall on another line which is displaced from the kaolin line towards the Al_2O_3 apex and the amount of displacement (excess %Al_2O_3) increases with Fe_2O_3 concentration. This displacement is due to the iron oxides particle attached to kaolin crystals being Al-substituted. The degree of Al substitution in goethite in Nb1 and Ti3 clays was estimated by XRD measurements to be about 21% mole (Table 8), the corresponding displaced line is shown in Figure 15b.

After removal of iron oxides from Nb1 and Ti3 by DCB treatment, the low or nil value of Fe_2O_3 (0-1.6 %) in kaolin crystals (Figure 15c) confirms that there is little Fe substitution in kaolin although these soils are Fe-rich and derived from high Fe basalt. The Si/Al ratio for some particles is higher than that for ideal kaolin, this is partly due to Fe substitution for Al but may also be a consequence of damage to particles in the TEM beam which causes preferential Al loss, especially for small and thin kaolin crystals (Ma and Eggleton, 1999).

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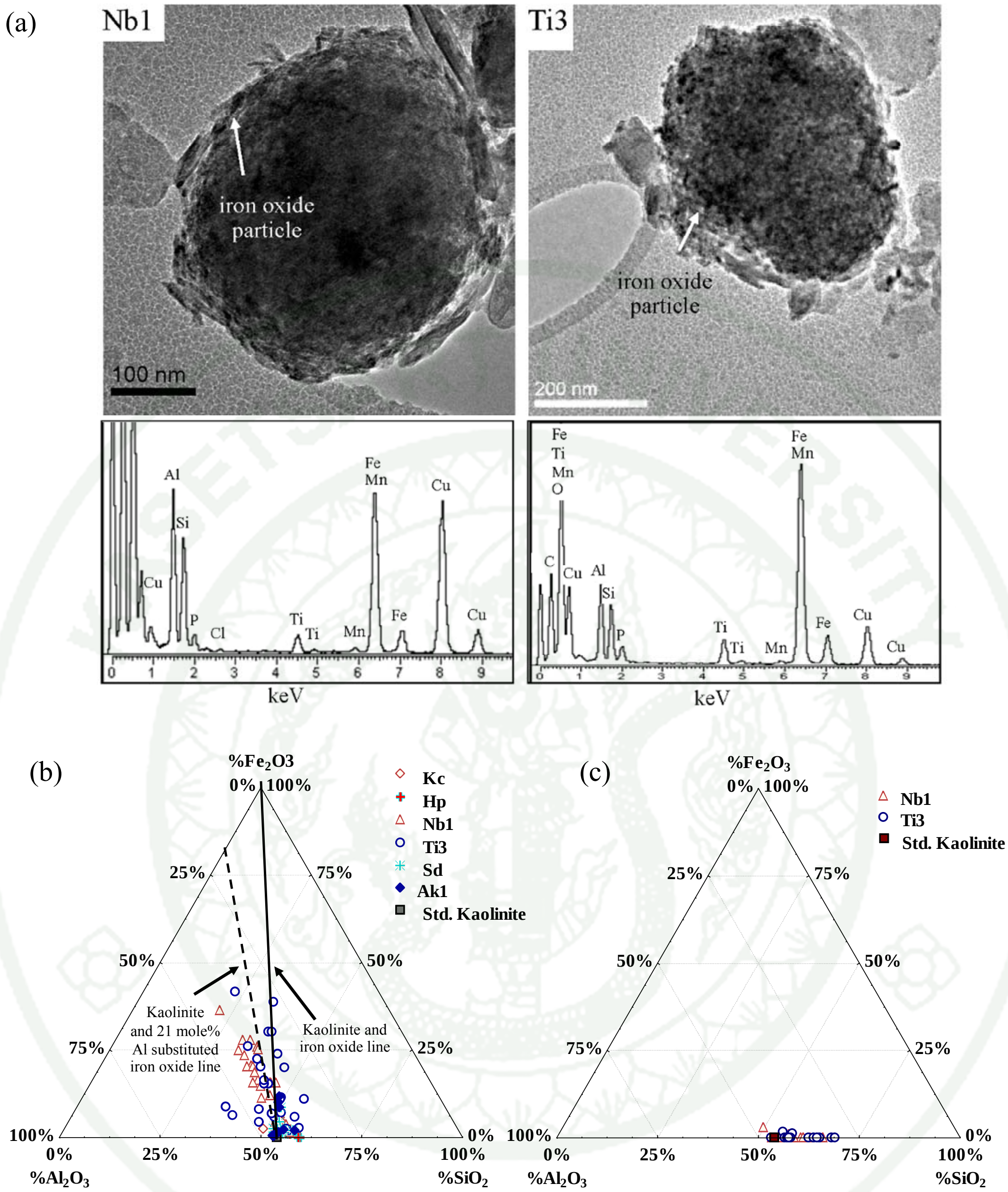

Figure 15 (a) Micrographs and X-ray spectra from clay particles from Nb1 and Ti3 (not deferrated) showing abundant small (about 10 nm) particles of iron oxides attached to complex aggregated kaolin particle, (b) Triangular graph of elements (SiO_2, Al_2O_3, and Fe_2O_3, normalized composition) from TEM-EDS analyses of clay particles for 6 representative clay samples that are not deferrated, (c) Triangular graph for deferrated kaolin particles from Nb1 and Ti3.

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Cluster Analysis of Clay Properties

Properties of the clay fraction including properties of kaolin and iron oxides and the SSA and CEC of three fractions (kaolins, clay sample and whole soil samples) for 17 representative soil samples were subjected to cluster analysis and the results are presented as dendrograms (Figure 16).

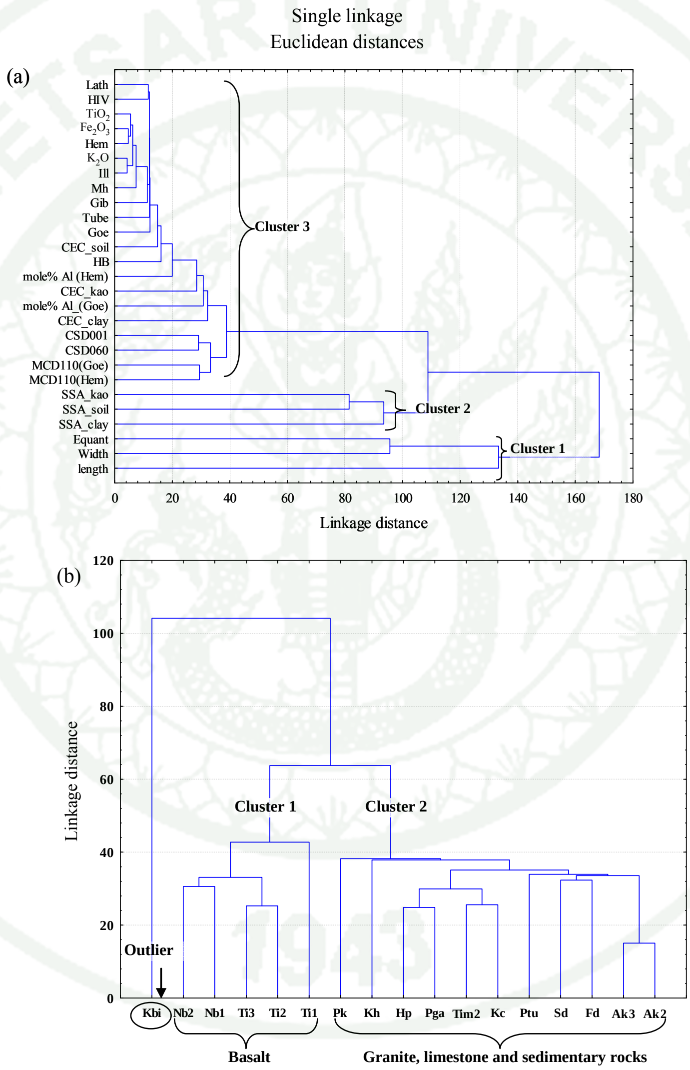

Figure 16 (a) Cluster analysis for properties of whole soils (CEC and SSA), clay before DCB treatment (mineralogy, CEC and SSA), deferrated clay (crystal shape and size, major elements, CEC and SSA) and iron oxides concentrate (crystal size and %Al substitution) for 17 soils. (b) Cluster analysis for the soil samples using the 27 variables shown in (a).

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The dendrogram for 27 properties identifies 3 discrete groups of properties (Figure 16a). Cluster 1 consists of variables describing the shape and size of kaolin crystals, cluster 2 consists of the specific surface area of soil, kaolin and clay and cluster 3 consists of various, diverse mineralogical and chemical properties. Cluster 1 is related to cluster 2 in that the size of kaolin crystals has a strong influence on the specific surface area of soil and clay. The amount of illite in the clay is strongly related to the concentration of K_2O in the kaolin. The concentration of TiO_2 and Fe_2O_3 in kaolin are related the percentage of hematite in the clay fraction. Lath shape which is common morphological feature of kaolin pseudomorphs after mica is closely related to HIV content. HIV in these soils may be an intermediate step in mica weathering to kaolinite (Cho and Komarneni, 2007). Both HIV and lath shape kaolin are features of Oxisols rather than of Ultisols for these Thai soils.

The cluster for the 17 soil samples (Figure 16b) was produced using 27 variables as shown in Figure 16a. The outlier soil Kbi contains particularly large kaolinite crystals that may have been inherited from the parent material (Table 8). The cluster analyses show a clear distinction between the basaltic soils (all in cluster 1) and the other soils (all except Kbi in cluster 2). The cluster of basaltic soils is characterized by small crystals of both kaolin and iron oxides, and high SSA values for soil, kaolin and clay. Granitic soils clustered together with soils on limestone and other sedimentary rocks.

Geochemistry of the Clay Fraction

All soil clays contain much Al, Si and Fe with minor amounts of Ti and Mn (Table 9). For soils formed from basalt, the Fe and Ti concentrations in the clay are larger than for other soil clays reflecting the influence of Fe, Ti-rich basalt which contains abundant ferromagnesian minerals and ilmenite. The clay of basaltic soils has more Al than Si whereas the other clays have less Al than Si. The higher proportion of Al in clay of basaltic Oxisols is partly due to desilication under a humid tropical climate with free drainage conditions (Schaefer *et al.*, 2008) causing formation of gibbsite from kaolinite (Muggler *et al.*, 2007). Consequently significant

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Table 9 Range and average concentrations (mean±SD) of elements in the clay fraction for upland Oxisols derived from basalt and limestone and upland Ultisols derived from sedimentary rock and granite.

Element	Oxisols (basalt) (n= 15)			Oxisols (limestone) (n= 9)			Ultisols (sedimentary rock) (n=15)			Ultisol (granite) (n=11)		
	Min	Max	Mean±SD	Min	Max	Mean±SD	Min	Max	Mean±SD	Min	Max	Mean±SD
(g kg^{-1})												
Al	128	173	148±13	152	181	169±10	141	202	172±18	159	195	186±11
Si	122	147	133±7.2	154	188	177±10	171	217	197±13	177	212	202±10
Ti	20	31	23±3.1	4.0	11	6.9±2.0	5.3	11	7.7±1.9	2.3	9.2	5.3±2.2
Fe	107	169	135±21	53	107	82±22	21	92	50±22	14	40	29±11
Mn	1.2	3.3	2.4±0.63	0.31	2.0	0.85±0.61	0.1	1.0	0.37±0.23	0.08	0.15	0.11±0.025
Ca	0.32	2.6	0.92±0.53	0.14	2.3	0.76±0.61	0.11	1.5	0.56±0.38	0.24	0.81	0.48±0.18
K	0.40	2.7	1.4±0.86	0.51	1.1	0.70±0.19	0.24	6.0	2.3±2.1	1.4	6.4	3.4±1.9
Mg	1.6	2.5	2.1±0.22	1.4	2.4	1.8±0.44	0.26	2.3	1.5±0.53	0.84	1.8	1.2±0.32
P	4.6	18	8.2±3.3	0.14	43	5.0±14	0.083	40	4.2±11	nd	41	6.6±14
(mg kg^{-1})												
S	4.2	329	111±96	10	116	41±34	14	508	74±124	7.6	311	67±99
As	nd	3.2	0.5±2.0	21	221	100±81	1.7	84	24±24	1.7	23	8.3±7.5
Ba	329	792	515±154	10	37	19±8.8	12	69	31±18	8	47	30±15
Be	0.73	2.6	1.5±0.69	0.31	1.2	0.61±0.32	0.15	0.41	0.25±0.08	0.13	0.28	0.19±0.040
Bi	6.7	22	13±4.2	2.4	4.3	3.2±0.7	0.61	3.9	1.9±0.92	0.59	3.7	1.7±1.1
Ce	115	174	148±17	30	100	67±25	13	123	54±34	1.7	66	28±23
Co	19	49	36±11	4.8	35.4	12±9.5	3.4	20	8.9±5.2	1.2	2.8	1.9±0.61
Cr	89	192	124±31	55	157	98±40	43	115	73±24	15	60	36±14
Cu	47	75	58±9.6	11	27	19±5.0	12	34	22±7.8	7.7	20	14±4.2
Ga	25	63	44±8.8	24	32.9	28±3.2	14	47	24±7.8	21	58	35±14
La	56	80	69±7.1	12	36	23±8.3	7.0	29	21±7.0	1.1	34	16±11
Mo	1.5	3.9	2.2±0.67	2.2	3.6	2.8±0.48	0.6	8.2	3.1±2.2	0.37	2.1	1.2±0.65
Nd	47	70	59±6.6	10	33	20±7.1	6.9	28	17±6.7	0.72	19	9.5±7.2
Ni	118	283	189±57	19	54	31±13	7.6	32	17±7.2	2.3	9.3	6.3±2.5
Pb	8.2	14	11±1.7	19	51	33±9.8	2.6	38	22±12	4.1	47	17±13
Rb	10	42	22±10	2.8	17	8.0±5.2	2.0	101	37±36	13	72	40±20
Sc	20	30	25±2.6	13	18	15±2.3	3.8	24	14±6.0	1.9	12	7.2±3.6
Sr	244	437	322±56	3	5.9	4.1±1.1	1.9	22	9.7±6.6	2	9.7	6.0±2.7
Th	11	17	14±1.9	18	26	21±2.4	5.7	29	18±8.5	18	70	33±18
V	108	214	155±27	185	299	233±39	34	281	113±69	11	70	33±22
Zn	70	150	105±23	25	90	51±18	20	104	51±31	15	132	40±33
Zr	1.2	6.6	3.0±1.5	5.4	6.8	5.9±0.50	0.82	9.6	4.0±2.4	0.12	3.1	1.7±1.1

nd= not detected

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amounts of gibbsite occur in the clay fraction of the Ti and Nb soils. Calcium, Mg and Mn are also present in relatively high concentrations in the clay from basaltic rock as compared to other soil clays. The differences in concentrations of elements in the clay partly reflect the presence of primary minerals inherited from the parent rock (Thanachit *et al.,* 2006). The K concentration in the clay of Ultisols is higher than for Oxisols which is consistent with the presence of illite in some clay fractions (Table 9). Both P and S are much more abundant in the clay from basaltic soils. Both elements occur in soils as oxyanions that are adsorbed by the abundant sesquioxide minerals in these clays so that their greater abundance does not correspond to a greater abundance of these elements in parent rocks.

Clay minerals and iron oxides are effective sinks for many trace elements in soils (Singh and Gilkes, 1992b; Becquer *et al.*, 2006) resulting in greater concentrations of trace elements in Oxisols than in Ultisols. The clay fraction of basaltic soils contains significantly higher amounts of Ba, Be, Bi, Ce, Co, Cr, Cu, Ga, La, Nd, Ni, Sc, Sr and Zn. Clays from limestone derived soils contain higher concentrations of As, Pb, V and Zr whereas clays from granitic soils contain higher concentrations of Rb and Th (Table 9).

Principal component analysis of the elemental and mineralogical analyses of the clay fraction was used to identify elements of similar geochemical behavior and also to group clay samples on the basis of their geochemical and clay mineralogical properties. Two factors explain 62.6% of the variation in the data (Figure 17a). The elements and clay mineralogy can be allocated to four main groups of similar geochemical behavior, with some variables not belonging to any group. Group 1 is composed of many major and minor elements (Fe, Ti, Mg, Mn, Ba, Be, Bi, Ce, Co, Cr, Cu, Ga, La, Nd, Ni, Sc, Sr, Zn) together with amounts of maghemite and goethite in the clay fraction. These variables have large values for clays from basaltic soil (Figure 17b). Many metals are associated with Fe because the metals can substitute for Fe in oxide structures (Kabata-Pendias and Pendias, 2001). Both P and S are quite closely associated with Group 1 elements as they may be adsorbed on sesquioxides as oxyanions (Fontes and Weed, 1996; Wisawapipat *et al.,* 2010).

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Group 2 consists of As, Pb, V, Zr and percentages of hematite and HIV. These properties are related to soil clays derived from limestone and also Kbi soil formed on clastic sedimentary rocks. The concentration of As and Pb is quite high in this soil group (Table 9). Zirconium is classed as residual element in soils and commonly occurs in zircon which is highly resistant to weathering (Cornu *et al.,* 1999; Stiles *et al.,* 2003). Vanadium is frequently found to be associated with Fe oxides and can substitute for Fe in iron oxide minerals (Singh and Gilkes, 1992b, Schwertmann and Pfab 1996). In the present work, V is most related to hematite. Group 3 composes of K, Rb and illite content and relates to clay samples from granitic soils and Kh soil which was derived from sandstone (Figure 17b). Soil clays from sedimentary rocks show a broad distribution in the opposite quadrant to basaltic soils (Figure 17b). Group 4 of properties contains %kaolin together with the abundances of Al and Si which are the major constituents of kaolin. It is the dilution of the kaolin content of the clay by abundant iron oxides for basaltic soils that separates basaltic soils from all other soils in Figure 17b.

Analyses on properties and geochemistry of these Oxisols and Ultisols reveal a classic example of lithosequence under tropical monsoonal climate. Under similar topographic condition, natural vegetation and land uses, parent material show a dominant influence on the mineralogical and chemical properties of these soils. Though the clay mineralogy of all soils is similar in being dominated by kaolin group minerals and sesquioxides, the properties of these minerals are different. Oxisols derived from basalt contain kaolin group minerals and iron oxides of smaller crystal size and lower crystallinity and with a higher proportion of amorphous material than do soils on other parent materials. Due to their higher content of iron oxides and high clay content, Oxisols derived from basalt have relatively higher contents of most elements. Exceptions are K and Rb which are most abundant in clays from granitic soils. This information on the nature of secondary minerals and the concentrations and associations of elements will be useful for soil fertility management.

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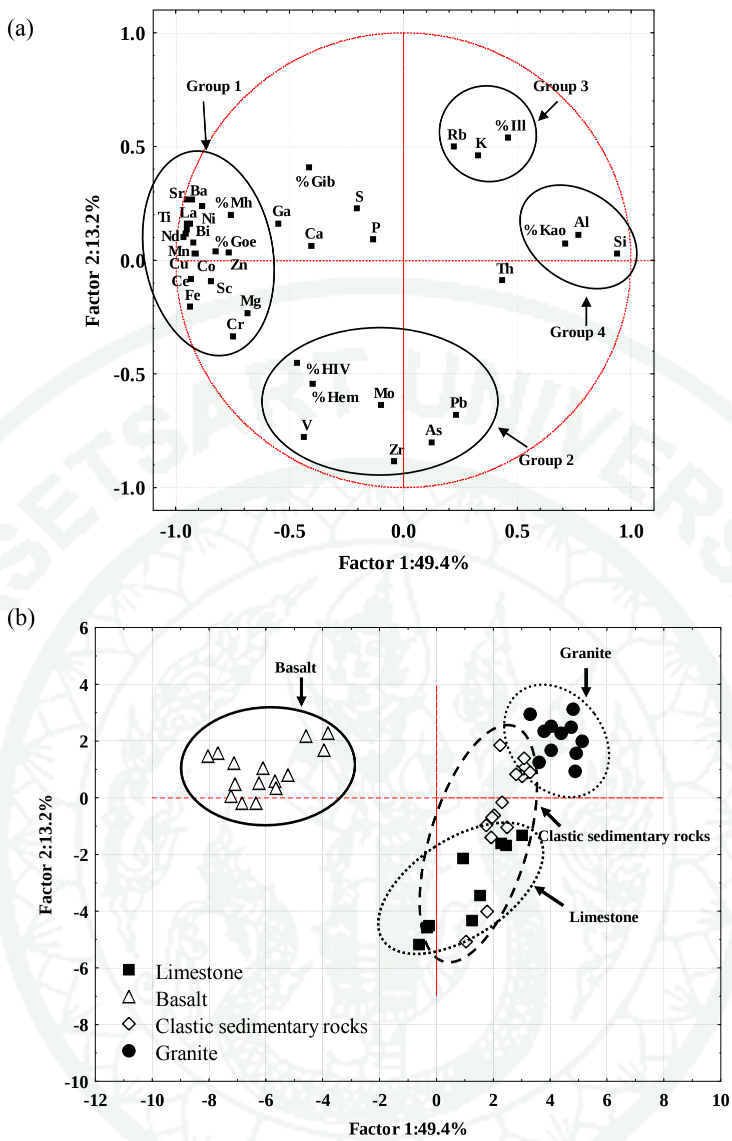

Figure 17 Factor analysis for mineral and element analyses of the clay fraction of Oxisols and Ultisols developed on diverse parent materials: (a) distribution of mineral analyses and elements; (b) distribution of soils.

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The Kinetics of Potassium Release

1. Properties of Clay

Soil clay samples from surface and subsurface horizons of representative soils were examined for K release to 0.3M sodium tetraphenylboron (NaTPB) solution for periods up to 168 hours. Total K and exchangeable K content of the clay fraction range from 243 to 25115 mg $kg^{-1}$and 41 to 226 mg kg^{-1} respectively (Table 10). Total K in the clay of Ultisols is much higher than that of Oxisols due to the higher illite content of Ultisols but the exchangeable K does not differ systematically between Oxisols and Ultisols. The exchangeable K on the clay will not be identical to the initial amount as sodium hexametaphosphate solution was used to disperse the clay which would have contributed Na to the exchangeable cation suite and displaced K. The Oxisol clays have higher values of SSA and CEC than the Ultisol clays. Values of the surface charge density (CD) of the clay fraction calculated from CEC and SSA range from 0.12 to 3.0 C m^{-2}. The larger values of CD for Ultisol clays are likely to reflect the more common presence of small amounts of illite, vermiculite and/or smectite which may have higher values of surface charge density than does kaolinite. For Sh, Tim1 and Cp clays, minor amounts of illite (5-20%) are evident and these clays have the highest total K and Mg concentrations. XRD indicates that trace amounts of illite occur in Nb1, Pk, Pga and Tim2 clays which have higher total K and Mg values than the clays with no illite. Both K and Mg are constituents of illite (Wilson, 1999).

Table 10 Range,mean and SD value of some properties of soil and clay samples for 18 Thai upland Oxisols and Ultisols.

Clay property	Oxisols		Ultisols	
	Range	Mean±SD	Range	Mean±SD
Total K (mg kg^{-1})	276-2581	919±788	243-25115	6370±7999
Exch. K (mg kg^{-1})	44-200	105±44	41-226	99±42
Total Mg (mg kg^{-1})	1180-2234	1823±314	893-5848	1841±1082
Exch. Mg (mg kg^{-1})	2.0-187	41±32	3.8-214	73±67
SSA (m^2 g^{-1})	15-81	48±21	8.6-51	30±15
CEC (cmol kg^{-1})	19-44	35±7.2	5.7-39	21±13
CD (C m^{-2})	0.2-2.1	0.91±0.4	0.12-3.0	1.1±1

SSA=specific surface area; CEC=cation exchange capacity; CD=charge density

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2. Kinetic of K Release

Sodium tetraphenylboron was originally proposed as an analytical reagent for determining K because when the K^+ ion is introduced into NaTPB solution, almost all dissolved K precipitates as KTPB. The solubility of KTPB is very low in water but is much higher in acetone and other organic solvents**.** The present study of K release kinetics was carried out on the clay fraction using 0.3M NaTPB extractant for 0 to 168 hours. The amount of non-exchangeable K released from Oxisol and Ultisol clays at 168 hours ranges from 18.3 to 46.6 mg kg^{-1} (mean=32.4) and from 22.4 to 383 mg kg^{-1} (mean=99.1) respectively. The highest values are for surface and subsurface samples of Sh, Tim1 and Cp clays (Figure 18) which contain minor amounts of illite. NaTPB is clearly effective in releasing K from the interlayer site in this illite (Dhillon and Dhillon, 1992; Rao *et al*., 2001).

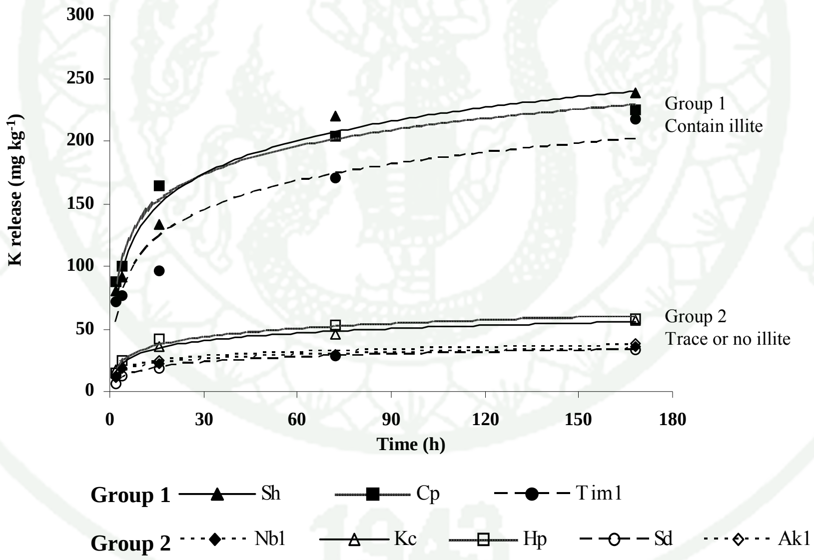

Figure 18 Potassium release to 0.3M NaTPB between 0 and 168 hours for clay from eight surface soil samples

The K release data for all clay samples have been fitted to three kinetic models: parabolic diffusion, power function and Elovich equations (Figure 19). These models have been selected on the basis of their common use in the literature to describe K release kinetics (Sparks *et al*., 1980; Jardine and Sparks, 1984; Havlin and

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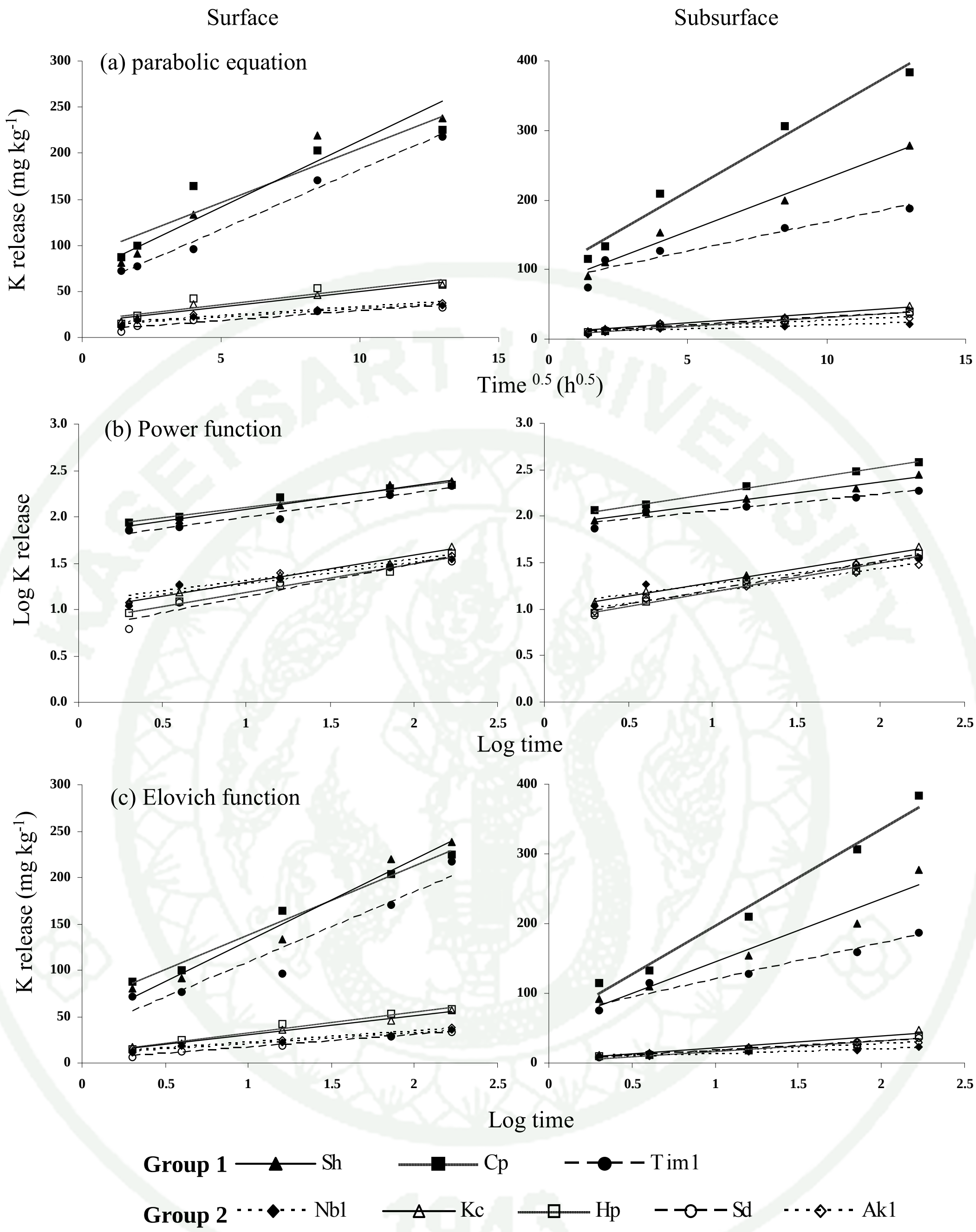

Figure 19 Data fitted to three models describing K release to 0.3M NaTPB for clay from eight surface and eight subsurface soil samples.

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Table 11 Parameters in models used to describe the kinetics of release of non-exchangeable K in clays to 0.3M NaTPB.

Soil series	Horizon	Parabolic equation			Power function			Elovich equation		
		Slope (b)	Intercept (a)	R^2	Slope (b)	Intercept log (a)	R^2	Slope (b)	Intercept (a)	R^2
Oxisols										
Ak1	Top	1.98	13.3	0.92	0.23	1.07	0.94	12.2	9.54	0.97
	Sub	1.70	9.10	0.97	0.25	0.93	0.99	10.3	6.41	0.99
Ak2	Top	2.24	10.6	0.88	0.29	0.96	0.94	14.2	6.06	0.97
	Sub	3.00	9.27	0.97	0.32	0.96	0.99	18.2	4.08	0.99
Ak3	Top	2.15	12.7	0.94	0.24	1.06	0.98	13.3	8.70	0.99
	Sub	2.35	11.1	0.92	0.28	1.00	0.98	14.7	6.48	0.99
Ptu	Top	1.28	8.07	0.91	0.23	0.87	0.95	7.84	5.76	0.95
	Sub	1.42	8.35	0.97	0.23	0.90	0.99	8.51	6.00	0.97
Ti3	Top	1.47	14.0	0.82	0.20	1.08	0.93	9.56	10.6	0.97
	Sub	2.72	10.3	0.99	0.26	1.05	0.98	15.7	6.61	0.91
Nb1	Top	1.83	12.3	0.92	0.23	1.04	0.91	11.3	8.97	0.96
	Sub	1.14	8.10	0.90	0.23	0.85	0.94	7.14	5.84	0.97
Nb2	Top	1.01	7.62	0.91	0.22	0.83	0.94	6.28	5.66	0.98
	Sub	1.01	6.15	0.86	0.27	0.70	0.87	6.45	4.00	0.97
Ultisols										
Kc	Top	3.30	16.6	0.94	0.27	1.18	0.98	20.3	10.4	0.99
	Sub	2.86	9.32	0.98	0.29	1.00	0.99	16.8	5.06	0.94
Fd	Top	1.02	9.37	0.93	0.18	0.93	0.92	6.20	7.57	0.95
	Sub	1.38	7.62	0.95	0.25	0.84	0.94	8.00	5.18	0.97
Kbi	Top	1.29	7.53	0.93	0.25	0.82	0.95	8.02	5.04	0.99
	Sub	1.51	7.54	0.90	0.29	0.81	0.88	9.37	4.63	0.96
Sd	Top	2.18	7.16	0.91	0.35	0.79	0.93	13.7	2.79	0.99
	Sub	2.24	8.16	0.94	0.31	0.90	0.97	13.8	4.41	0.99
Cp	Top	11.7	88.1	0.88	0.22	1.89	0.96	74.5	63.6	0.99
	Sub	23.2	95.5	0.98	0.28	1.97	0.99	140	56.5	0.98
Hp	Top	3.49	18.5	0.83	0.30	1.17	0.91	22.7	10.5	0.97
	Sub	2.50	6.55	0.98	0.31	0.88	0.99	14.6	2.94	0.92
Sh	Top	14.4	69.5	0.94	0.26	1.82	0.99	88.1	43.5	0.97
	Sub	15.2	78.5	0.98	0.24	1.89	0.99	89.8	55.3	0.95
Tim1	Top	13.1	50.7	0.99	0.26	1.74	0.96	76.0	32.4	0.92
	Sub	8.33	84.3	0.90	0.26	1.66	0.99	51.6	68.5	0.95
Tim2	Top	2.64	12.3	0.88	0.30	1.02	0.94	16.8	6.69	0.99
	Sub	4.30	14.0	0.96	0.32	1.13	0.98	26.1	6.46	0.98
Pk	Top	3.12	11.8	0.99	0.27	1.09	0.98	18.3	7.19	0.94
	Sub	1.55	18.5	0.74	0.17	1.20	0.75	9.86	15.3	0.83
Pga	Top	2.74	11.3	0.92	0.29	1.02	0.91	16.6	6.56	0.94
	Sub	2.35	6.47	0.97	0.34	0.82	0.99	14.3	2.33	0.99
Mean										
Oxisols		1.81	10.1	0.92	0.25	0.95	0.95	11.1	6.80	0.97
Ultisols		5.66	29.1	0.93	0.27	1.21	0.95	34.3	19.2	0.96
All samples		4.20	21.7	0.93	0.26	1.11	0.95	25.3	14.4	0.96

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Westfall, 1985). The linear plots of K released vs. $time^{1/2}$ for clay (Figure 19a) indicate that this parabolic diffusion equation provides a moderately accurate description of the K release kinetics for these soil clays (r=0.91-0.99; mean 0.98) which is in accordance with the behaviour of K in highly weathered Western Australian soils (Pal *et al*., 2001b) and Chinese soils (Tu *et al.*, 2007). Release of K from these clays may be a two dimensional diffusion-controlled process (i.e. square root law) (Havlin and Westfall, 1985). Pure micas such as phlogopite, biotite, and muscovite also release K as a linear function of the square root of time (Feigenbaum *et al.*, 1981).

The K release data for these soil clays are also well described by the power function (Figure 19b) (r=0.87-0.99; mean 0.97). The slope derived from this model was less than 1 for all soils (Table 11), indicating that the K release rate decreases with time. This result is in agreement with reports of several researchers (Carey and Metherell, 2003; Nilawonk *et al.*, 2008).

The Elovich model also provides a close fit to the experimental data (r=0.86-0.99, mean=0.96) (Table 11). This model also provided an excellent description of K release from a young soil from Germany (Mengel and Uhlenbecker, 1993) and calcareous soil from Iran (Jalali, 2006) which are very different soils from these highly weathered Thai soils. The slope constant b of the Elovich equation can be used as an index of K release rate and the large differences in slope value indicate that the K supplying power of these clays is highly diverse. There is considerable variation between soils in values of the various slope and intercept constants of the three models, however higher values occur for the Ultisol clays (Table 11).

3. Kinetics of K Release in Relation to Clay Properties

The slope and intercept constants for the three linear models which are indicators of the amount of K released from the clay have been statistically related to clay properties (Table 12). The results show that the total K, total Mg, exchangeable K and the ratio of illite to kaolinite have highly significant ($p<0.01$) positive

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Table 12 Correlation coefficients (r) for relationships between the parameters of the three K-release models and clay properties.

Clay property	Parabolic equation		Power function		Elovich equation	
	Slope	Intercept	Slope	Intercept	Slope	Intercept
SSA	-0.37	-0.32	-0.29	-0.34	-0.38	-0.27
CEC	0.04	0.03	-0.31	-0.05	0.05	0.01
Total K	**0.91**	**0.88**	-0.03	**0.87**	**0.91**	**0.84**
Exch. K	**0.54**	**0.50**	0.12	**0.49**	**0.55**	**0.45**
Total Mg	**0.74**	**0.68**	-0.13	**0.61**	**0.74**	**0.64**
Exch. Mg	0.34	0.37	0.08	0.39	0.34	0.37
I/K	**0.79**	**0.87**	-0.13	**0.83**	**0.80**	**0.85**
CD	**0.45**	0.40	0.02	0.34	**0.46**	0.35

Bold coefficients indicate significance at $P \leq 0.01$ (n = 36)
I=illite; K=kaolinite, Exch. K=exchangeable K, Exch. Mg=exchangeable Mg, CD=charge density

relationships with intercept values of the equations. These attributes are related to the amounts of illite in the clays so that it can be concluded that illite is the major source of the K released to NaTPB solution by these clays. The same conclusion was reached by Havlin *et al.* (1985) who reported that the constants from the three equations were highly correlated with the mica content of calcareous soils in the Great Plains, USA. In marked contrast to these USA soils, illite is only a minor clay mineral in these Thai upland soils but the same relationships with illite (mica) content persist.

The rate coefficient (slope) of parabolic and Elovich equations are also positively related to total Mg, total K, exchangeable K and the illite to kaolinite ratio of the clay which again reflects the illite content of the clays. Havlin and Westfall (1985) and Rao *et al.* (2001) also observed a relationship between rate of K release to NaTPB and initial NH_4OAc-K. However, there are no relationships between the slope values of the power function and any clay property. The constants of the three equations were not related to CEC and SSA of the clays. This together with the diffusion-based kinetics indicates that non-exchangeble K is mostly from interlayer sites in illite and not from the external surface of kaolinite which is the dominant clay mineral in these soils and provides most of the SSA and CEC.

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Principal component and classification analysis were used to provide a better understanding of relationships between the kinetics of K release to NaTPB from clay and clay properties. Two factors explain 65.8% of the variation in data describing K release, which may be considered as an acceptable prediction considering the diverse nature of these clays (Figure 20). A distinct group of variables is recognized with some outliers. This group consists of total K and Mg, exchangeable K and Mg, the ratio of illite to kaolinite and the constant values for the three models except for the slope value of the power function (Figure 20a). This group is related to the amounts of K in the clay fraction with the illite-containing Ultisols (Sh, Tim1 and Cp) having high values of these attributes and consequently these Ultisols represent a discrete population of samples (Figure 20b). The other outlying variables (Figure 20a) are not related and mostly do not strongly influence the kinetics of K release from these clays. The variable CSD 001 of kaolinite is strongly negatively related to the strongly grouped variables.

4. TEM Analysis

For some samples the ratio of illite to kaolinite is zero based on XRD results. However some illite may be present within kaolin crystals and rare illite layers would not be detected by XRD. This interpretation is supported by the X-ray spectra of single kaolinite crystals obtained by transmission electron microscopy – EDS which show that K appears to be present in some kaolinite crystals (Figure 21). K_2O concentrations of crystals range from 0 to 2.4 % (Table 13) with the highest values being consistent with the presence of about 25% muscovite-like layers. This result is also consistent with the report of Melo *et al*. (2001) of K in kaolinite crystals in tropical soils from Brazil. Thus it is possible that K in kaolinite crystals consists of small packets of residual mica layers between kaolinite layers. Discrete illite crystals in these Thai soils give EDS analyses with K_2O concentrations similar to values for illite reported in the literature (Deer *et al*., 1967).

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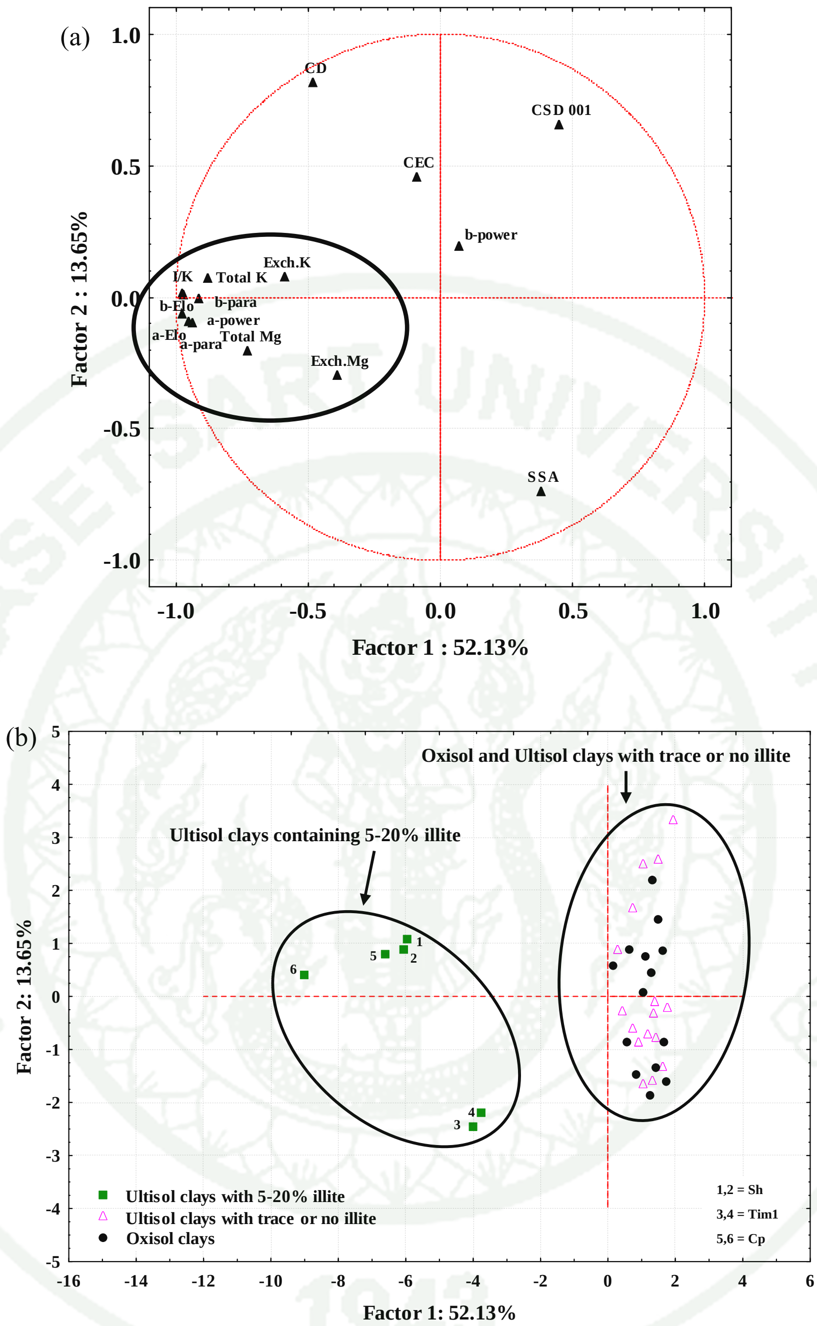

Figure 20 Factor analysis for clay properties and constants from the three equations describing K release: (a) distribution of clay properties and constants; (b) distribution of clay samples.

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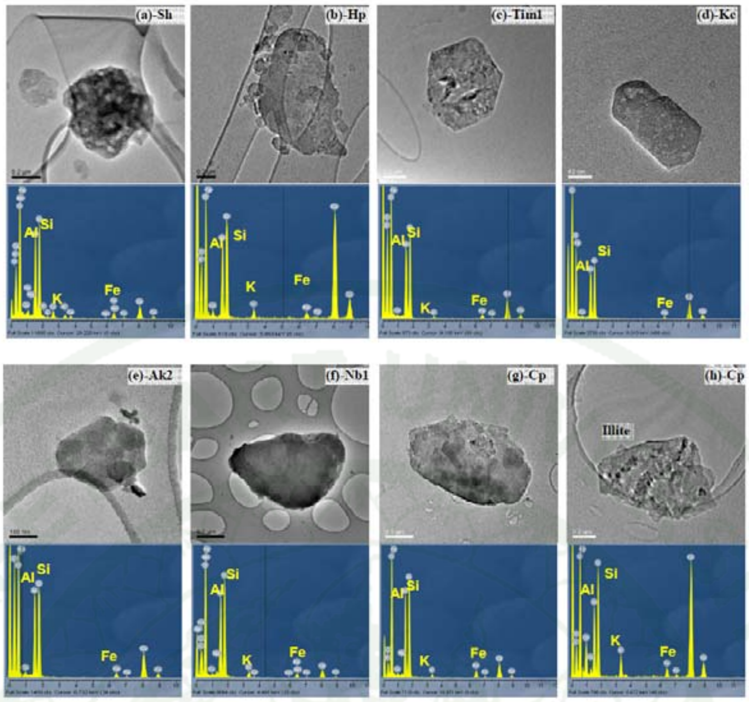

Figure 21 Transmission electron micrographs and X-ray spectra of anhedral to euhedral crystals of kaolinite (a)-(h) and illite (i) from Thai soils. Many kaolinite crystals appear to contain small amounts of potassium.

5. Mineralogical Changes as Affected by Extraction of K by NaTPB

XRD patterns of basally oriented Mg-saturated clays were modified by dividing intensities by the Lorentz-polarisation (LP) factor to provide greater clarity in the low 2θ region (Brown and Brindley, 1980). The three XRD patterns of the Mg saturated clay, namely before extraction, at 16 hours and 168 hours of extraction by NaTPB were identical for most soils. In particular, the basal reflection of kaolinite did not change. However for Sh, Tim1 and Cp soils, extraction of K led to a substantial decrease in the intensity of illite basal reflections and to an increase for vermiculite (Figure 22). Evidently the use of NH_4^+ solution to quench K exchange in the aliquot removed for XRD analysis did not cause irreversible collapse of vermiculite. These results are consistent with findings of Hinsinger *et al*. (1992) and Singh and Goulding (1997) who observed that K-depletion resulted in a decrease in the intensity of reflections for illite and an increase for interstratified clay minerals, vermiculite and smectite.

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Table 13 Energy dispersive spectrometry (EDS) analysis of single crystals of kaolinite or illite from the clay fraction of Thai soils. The composition (%) was normalized to 100% on a water free basis.

Sample	$\%Al_2O_3$	$\%SiO_2$	$\%K_2O$	$\%Fe_2O_3$	SiO_2/Al_2O_3
Sh (kao)	42.6	54.2	1.1	2.1	1.27
Hp (kao)	39.4	56.5	2.4	1.7	1.44
Tim1(kao)	42.4	53.6	2.1	1.8	1.26
Kc (kao)	43.1	56.0	nd	0.9	1.30
Ak2 (kao)	44.8	53.7	nd	1.5	1.20
Nb1(kao)	41.4	55.7	1.6	1.3	1.34
Cp-a (kao)	42.1	54.4	0.8	2.7	1.29
Cp-b (ill)	33.5	57.8	5.5	3.2	1.73

kao = kaolinite, ill = illite, nd = not detected

The extent and rate of potassium release to NaTPB from these soil clays is highly dependent on the clay mineralogy. The amounts and rates of K release from illite-containing clay are much higher than for clay containing only kaolinite with or without inhibited vermiculite. Potassium release for all clays is well described by the parabolic diffusion, power and Elovich equations. For these Thai soil clays in which kaolinite is the dominant clay mineral, the release to NaTPB of significant amounts of K is indicative of the presence of long-term available K in the soil. It is notable that several soils contained significant NaTPB extractable K despite no K-containing mineral being detected in the clay by XRD. Kaolinite crystals may contain minor amount of interlayer K in rare illite layers which cannot be detected by XRD. The low values of exchangeable K indicate that most soils have low plant-available K reserves but this interpretation may need to be revised on the basis of the presence of significant amounts NaTPB extractable-K in illite that may be liberated in the K-depleted rhizophere solution.

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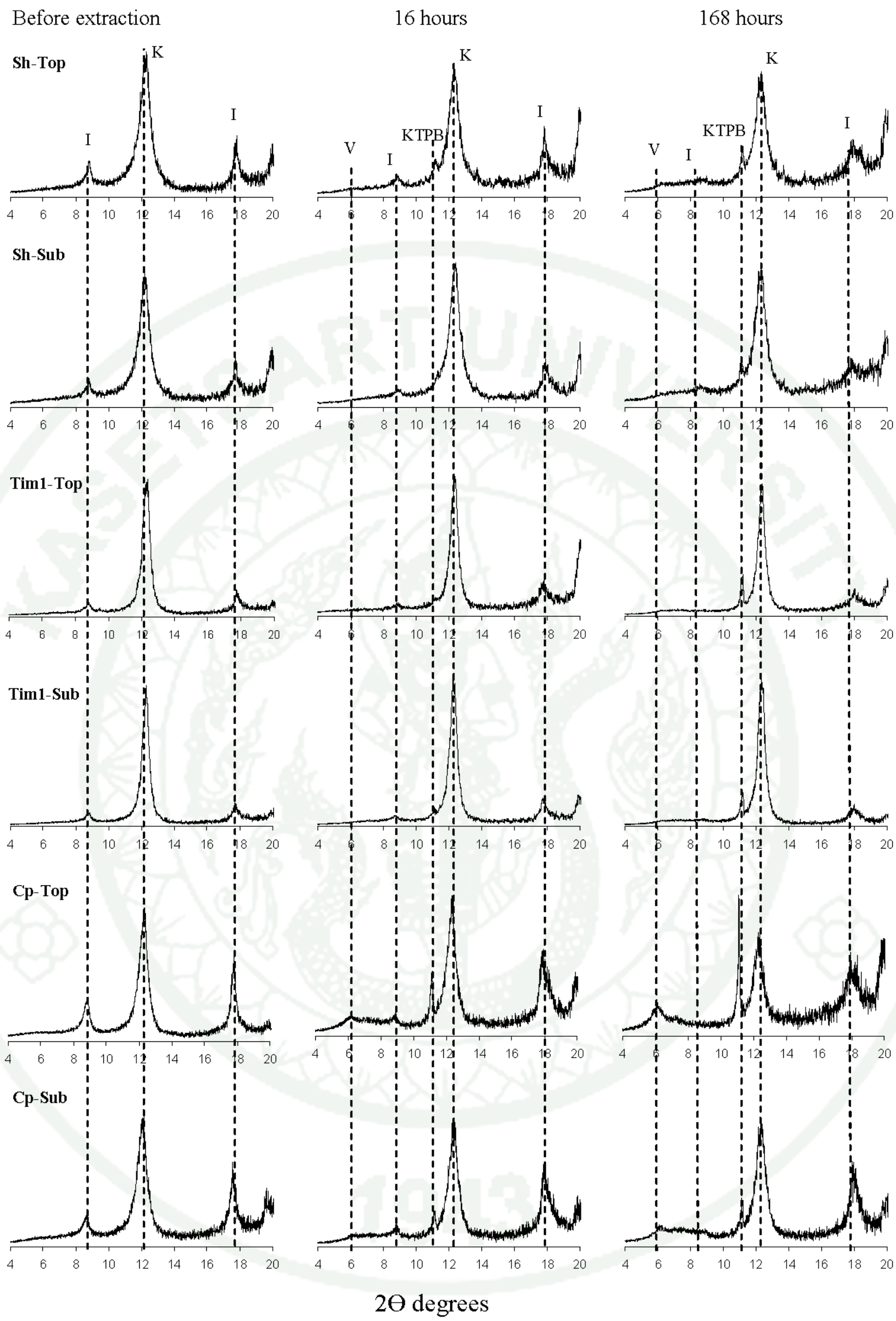

Figure 22 Diffraction patterns of six basally oriented, Mg-saturated soil clays modified using the LP factor showing changes in the relative peak intensities for vermiculite and illite for 16 and 168 hours of shaking with 0.3M NaTPB. (V=vermiculite, I= illite, K= kaolinite). The reflection at 11˚ 2θ is due to KTPB.

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The Forms and Availability to Plants of Soil K

1. K-bearing Minerals

The relationships between different pools of K were investigated as a function of silt and clay mineralogy for these Thai upland soils. Conventional XRD patterns for whole soils show that feldspar occurs in Sh and Cp soils (Figure 23a) and was not detected in Oxisols. However, the patterns obtained from a very high intensity synchrotron x-ray show trace amount of feldspar in Ak1 soils (Figure 23b). Silt fraction from Sh, Tim1 and Cp contains significant amounts of feldspar. Illite occurred in trace amounts in clay fraction of some Ultisols and in moderate amount (5-20%) for Sh, Tim1 and Cp (Table 6). Several soils contain no illite despite synchrotron x-ray being used to obtain XRD patterns (Figure 23b).

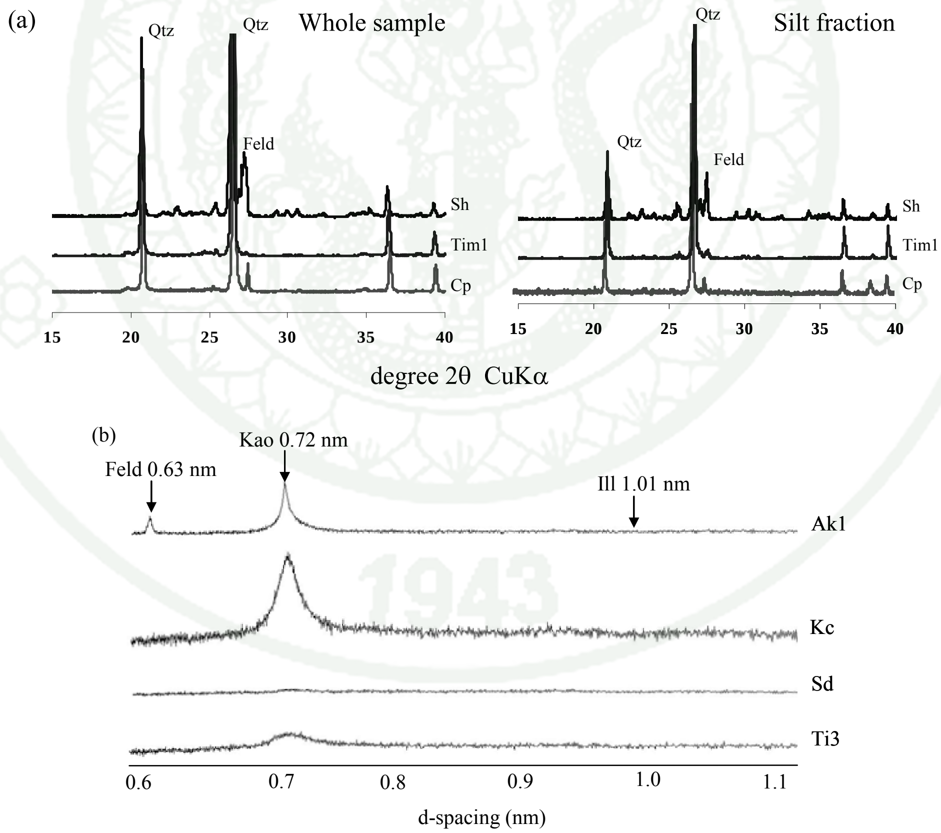

Figure 23 (a) Conventional XRD patterns (XRD) of whole soil and silt fraction from Sh, Tim1 and Cp soils (b) Synchrotron XRD pattern (SXRD). Qtz=quartz; Feld=feldspar; Kao=kaolinite; Ill=illite.

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2. TEM-EDS-EFTEM Analysis of Clay Fraction

Representative soil clays were used for the determination of the composition of K-containing single clay size particles using TEM-EDS and EFTEM. For Hp, Nb1, Sd, Ti3 soils discrete illite crystals are present (Figure 24) although the concentration of K_2O (3.9-6.4%) in these crystals is much smaller than that of ideal muscovite (10% K_2O). Values of 4 to 7% K_2O in the single crystals of illite are comparable to published values for bulk analyses of illite (Newman, 1987). For Sd and Ti3 clays that contained no illite on the basis of XRD analysis it was possible to locate illite crystals using analytical TEM with EDS (Figure 24). For the Kc soil which has the lowest total K value (66 mg kg^{-1}) illite was not found by analytical TEM.

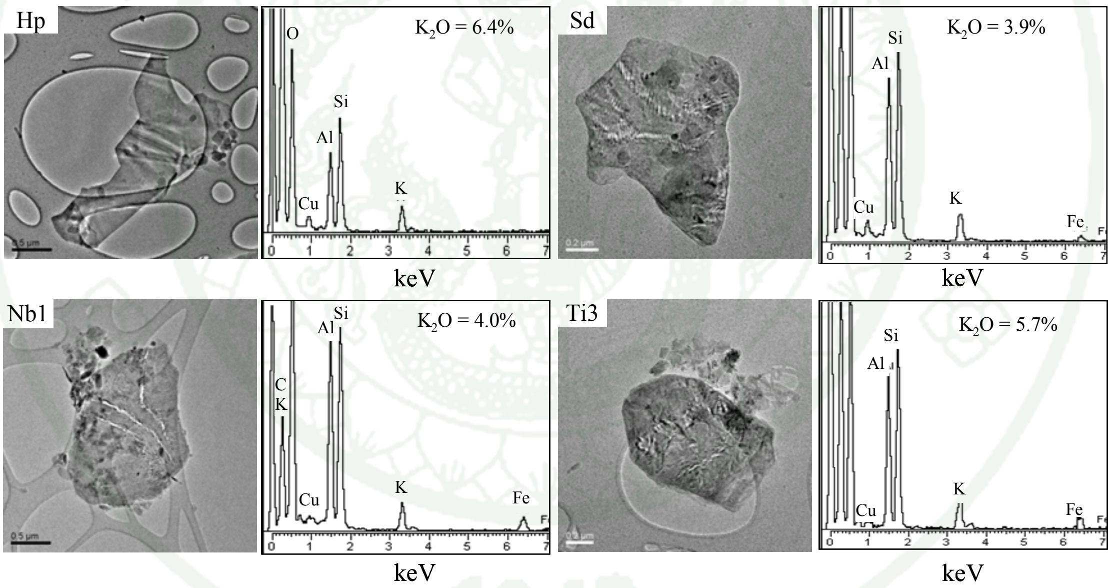

Figure 24 Transmission electron micrographs, X-ray spectra and K_2O contents of crystals of mica (illite) from the clay fraction of four Thai upland soils.

The composition (% SiO_2, Al_2O_3 and Fe_2O_3) obtained by Energy Dispersive Spectrometry (EDS) analysis of clay size particles from several samples was normalized to 100% representing a structural water free basis and plotted in a triangular graph (Figure 25). The analyses were classified according to the K concentration in the particles and were limited to particles containing <2.5% K_2O

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which cannot be pure illite. There were 2 populations of particles; the first and larger group contained no K and is assumed to be kaolinite associated with various amounts of 21 mole % Al substituted iron oxide. The second represents kaolinite/ muscovite particles with various amounts of iron oxide. Analyses of kaolinite particles should be located on the horizontal axis of the triangular graph at about 55% SiO_2 and 45% Al_2O_3. Muscovite analyses will also be located at or near this point as the data have been expressed on a K_2O-free basis (i.e. SiO_2+Al_2O_3+Fe_2O_3 =100%). Consequently particles containing both minerals (kaolinite and muscovite) will also be located at this point and analyses of many potassium containing crystals (up to 2.5% K_2O) are located at this point.

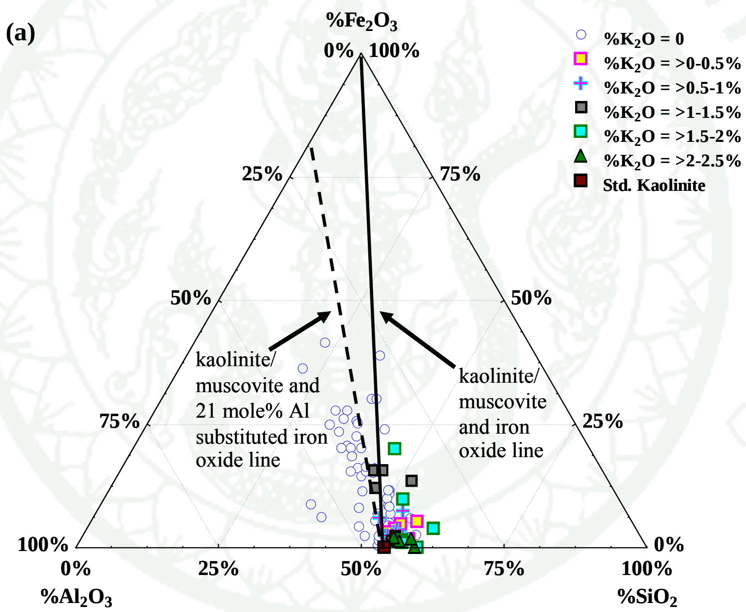

Figure 25 Triangular graph of major oxide constituents (SiO_2, Al_2O_3, and Fe_2O_3) from TEM-EDS normalized compositions and grouped by %K_2O in particles from 9 representative clay samples of Thai upland soils.

Element mapping of single crystals using EFTEM was conducted to locate the K present in discrete crystals in the clay fraction. The K map of a crystal from Cp soil containing 5.5% K_2O (Figure 26a) shows that K is distributed homogeneously in the crystal rather than there being discrete mica/kaolinite zones visible in this (001) projection of the crystal.

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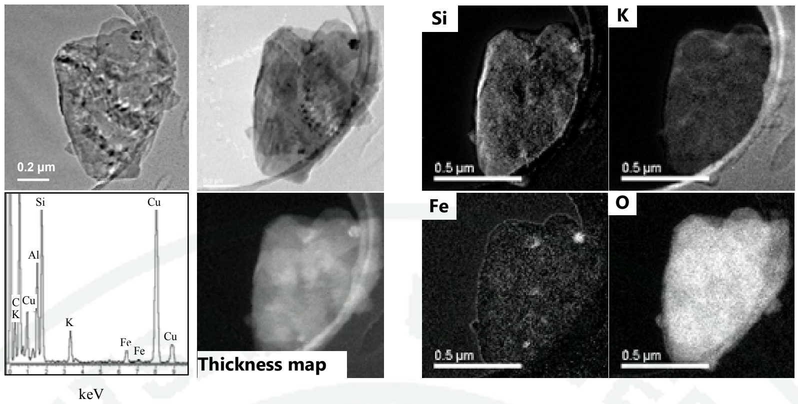
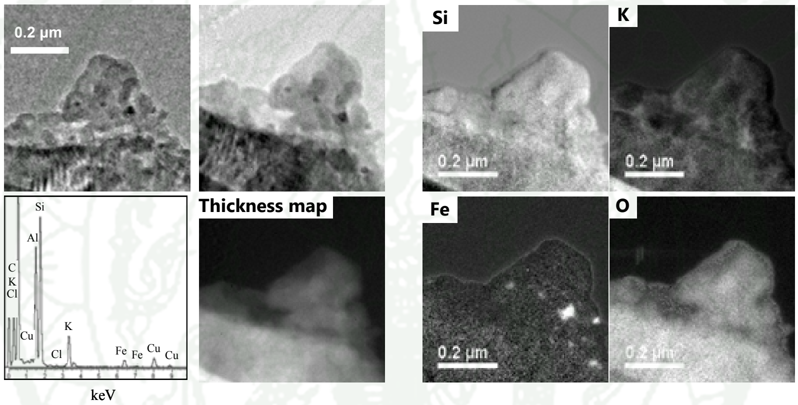
(a) Cp-surface soil

Composition	Al_2O_3	SiO_2	K_2O	Fe_2O_3
%	33.5	57.8	5.5	3.2



(b) Tim1 –subsurface soil

Composition	Al_2O_3	SiO_2	K_2O	Fe_2O_3
%	39.2	53.8	5.4	1.6



(c) Ti3 –subsurface soil

Composition	Al_2O_3	SiO_2	K_2O	Fe_2O_3
%	42.8	52.8	2.8	1.6

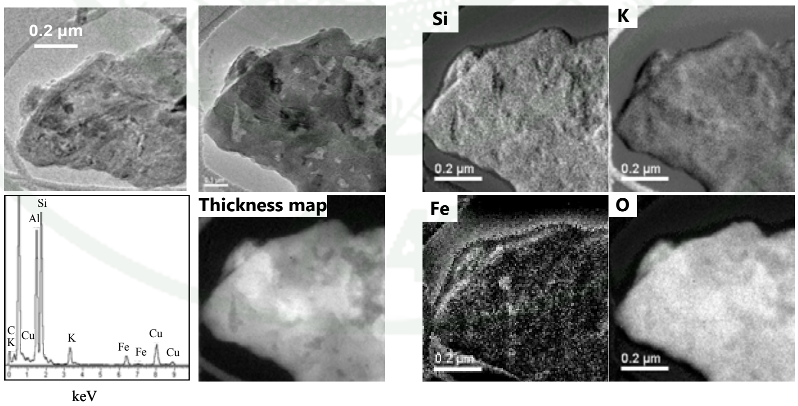


Figure 26 Micrographs, thickness map, X-ray spectrum analysis and EFTEM element maps for Si, Fe, K and O for discrete mica crystals from (a) Cp top soil (b) Tim1 subsurface soil and (c) a compound particle from Ti3 subsurface soil.

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A crystal from Tim1 soil shows a non-uniform distribution of K with the brighter areas in the K image corresponding to thicker regions of the crystal containing more K rather than there being discrete K-rich illite regions (Figure 26b). A particle from the Ti3 soil which is probably an aggregate of crystals gives similar results (Figure 26c). These results indicate that K in these crystals is not localized in discrete zones when observe along the c axis of crystals however there may be discrete zones of mica and kaolinite arranged perpendicular to the c* axis which would not be resolved for this view of the crystals. Consequently aggregates of basally oriented crystals were impregnated with resin and sections were cut parallel to c* using a diamond knife microtome. These images of the organization of layers perpendicular to the c axis show lattice fringes and discrete 0.7 nm (kaolinite) and 1.0 nm (illite) crystals in compound particles. The clay particles shown in Figure 27 are from the Ti3 soil which gave no 1.0 nm reflection of illite/ muscovite in conventional and synchrotron XRD patterns.

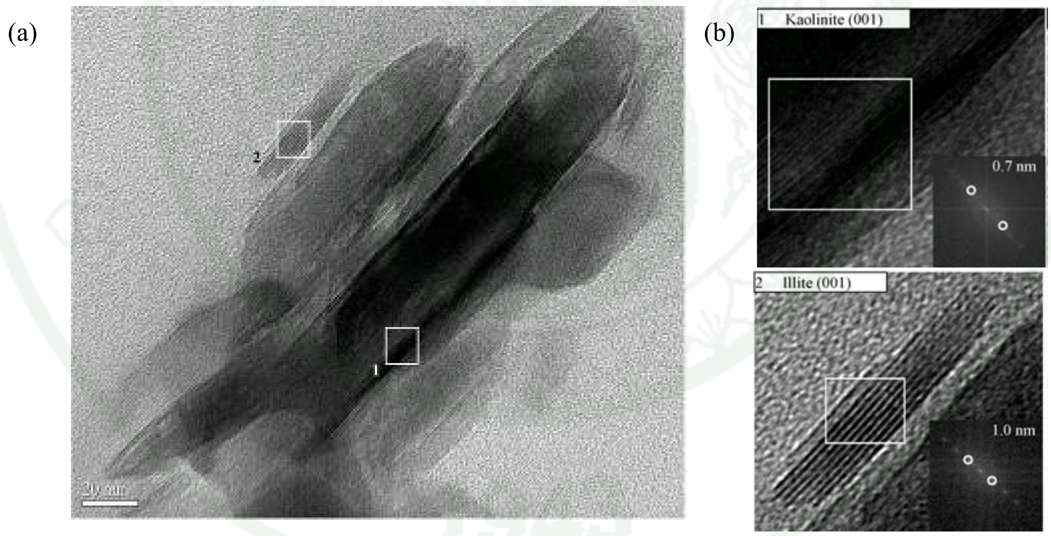

Figure 27 TEM image of clay particles from Ti in a basally oriented clay aggregate prepared by the ultramicrotome technique and viewed along (001); (b) High-resolution electron micrographs of the areas in the white rectangles in (a) showing lattice fringes.

Thus this TEM technique has provided a more sensitive method for detecting illite and the location of K in these clays. The finding that very small amounts of illite

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are present in clays of group 2 which mostly contain kaolinite in the clays fraction provides an explanation for the release of K to NaTPB extraction following the same parabolic equation for group 2 as for group 1 (considerable illite) samples (Figure 18). The capacity of HRTEM to identify very small quantities of illite crystals associated with the dominant kaolinite crystals may indicate that K is not present within the kaolinite structure as was proposed by Melo *et al*. (2001).

3. Water Soluble K and Exchangeable K

The potassium concentration in soil solution influences the rate and extent of K uptake by plants (Pal *et al*., 1999). Amounts of water-soluble K range widely with a mean value of 32 mg kg^{-1} for Oxisols and 17 mg kg^{-1} for Ultisols (Table 14). Water-soluble K has a negative relationship with sand content (r=-0.40) but has positive relationships with pH H_2O (r=0.36), pH KCl (r=0.43), clay (r=0.45) and CEC (r=0.34) (Table 15). These associations are consistent with more water soluble K being present in more heavily textured soils.

Table 14 Mean values of several forms of K for soils analyzed at the commencement of the plant growth experiment and after the final harvest.

K content (mg kg^{-1})	Before cropping	After cropping	Difference
Oxisols			
H_2O-K	32	5	27
EXK	64	8	56
NEK	30	22	8
HNO_3-K	96	30	66
Ultisols			
H_2O-K	17	7	10
EXK	19	9	10
NEK	46	28	18
HNO_3-K	65	37	37

NEK=non-exchangeable K; EXK=exchangeable K; H_2O-K=water soluble K

Exchangeable K is held by the negative surface charges on organic matter and clay minerals. It is easily exchanged with other cations and is quite readily available to plants (Havlin *et al*., 2005). Values of exchangeable K range widely with a mean

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Table 15 Correlation coefficients (r) for linear relationships of various forms of soil K versus soil properties.

K form	pH (1:1)		Sand	Silt	Clay	CEC	EA	OM	N	Avail.P	I/K
	H_2O	KCl									
H_2O-K	**0.36**	**0.43**	**-0.40**	0.02	**0.45**	**0.34**	0.25	0.12	0.01	-0.07	0.13
EXK	**0.45**	**0.47**	**-0.49**	-0.09	**0.60**	0.30	0.15	0.07	-0.05	-0.13	0.00
NEK	0.07	0.05	**0.32**	-0.10	**-0.32**	-0.22	-0.19	-0.24	0.15	0.08	**0.71**
HNO_3-K	**0.38**	**0.39**	-0.18	-0.13	0.26	0.09	0.00	-0.09	0.06	-0.05	**0.42**
Total K	0.11	0.10	0.24	0.02	-0.28	-0.18	-0.13	-0.16	0.04	0.06	**0.59**

Bold letter indicate significance at $P \leq 0.05$ ($n = 38$).

value of 64 mg kg^{-1} for Oxisols and 19 mg kg^{-1} for Ultisols (Table 14). Oxisols contain higher amounts of exchangeable K than do Ultisols due to their higher clay contents. There is a positive relationship between exchangeable K and clay content (r=0.60) (Table 15). A similar result was reported by Sharply (1989) for kaolinitic soils in the USA and Puerto Rico.

The exchangeable K accounts for 0.89 to 36.2% of total K for Oxisols and for 0.067 to 16.9 % for Ultisols. Thus the exchangeable K content for both soil orders mostly represents a small proportion of total soil K as has been reported for other highly weathered soils (Markewitz and Richter, 2000; Askegaard *et al.*, 2005; Nilawonk *et al.*, 2008). The proportion of exchangeable K ranges from 40 to 85% of HNO_3-K (mean=62%) for Oxisols and from 11 to 62 % (mean=32%) for Ultisols.

For soils of low to medium CEC, the minimal exchangeable K occupancy supporting optimal K nutrition has been reported to be close to 3% of exchange sites (Schneider and Villemin, 1992). Except for the Ti3, Nb1, Ak1 and Ak2 soils, most of the soils have K occupancy percentages below this value which for example contrasts with virgin soils from Western Australia which mostly have a K occupancy above 3% (Pal *et al.*, 1999). These results indicate that exchangeable K in some Ultisols may not be sufficient to maintain crop production whereas the Oxisols have a higher K-supply potential.

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4. Non-exchangeable K and Total K

Non-exchangeable K, which is the amount of K soluble in molar nitric acid minus exchangeable K, may be sparingly available to plants and may correspond to the clay-size illite which is soluble in strong acids (Snäll and Liljefors, 2000). The data show that values of non-exchangeable K range widely with a mean value of 30 mg kg^{-1} for Oxisols and 46 mg kg^{-1} for Ultisols (Table 14). The Sh, Tim1 and Cp soils contain the highest amounts of non-exchangeable K (>70 mg kg^{-1}) because they have relatively high contents of illite in the clay fraction. These soils also contain silt-size K-rich feldspar which is a potential source of non-exchangeable K. The non-exchangeable K accounts for 4.9 % of total K for Oxisols and 10.6% for Ultisols. Non-exchangeable K has a very weak positive relationship with sand content (r=0.32) (Table 15).

The mean values of total K are 914 mg kg^{-1} for Oxisols and 3492 mg kg^{-1} for Ultisols (Table 14). For Sh and Tim1 soils, the relatively high total K contents relate to the persistence of primary minerals but the exchangeable K values for these soils are low due to the low CEC associated with their low clay content. For all soils the illite/kaolinite peak intensity ratio in XRD patterns of the clay fraction is systematically related to the total K (r =0.59).

5. Tissue K Concentration, Plant Yield and K Uptake by Grass

Tissue K concentration and K uptake by Guinea grass for 6 harvests for the 18 surface and subsurface soils showed large variations between soils (Figure 28). The tissue K concentration in the first cut herbage ranged from 0.25 to 3.23 % with a mean value of 1.21 %. The lowest value of tissue K for the first harvest of 0.25 % K was well below the critical value (1.1 %) for tropical grasses (Martin and Matocha, 1973) and the mean value for all soils of 1.21 % is close to this critical level. Consequently, plant mortality due to K deficiency occurred for some soils after the first 2 harvests. The cumulative dry matter yield from the 6 harvests ranged from 0.43 to 19.2 g kg^{-1} soil with a mean value of 3.98 g kg^{-1} soil and the cumulative K uptake at the sixth

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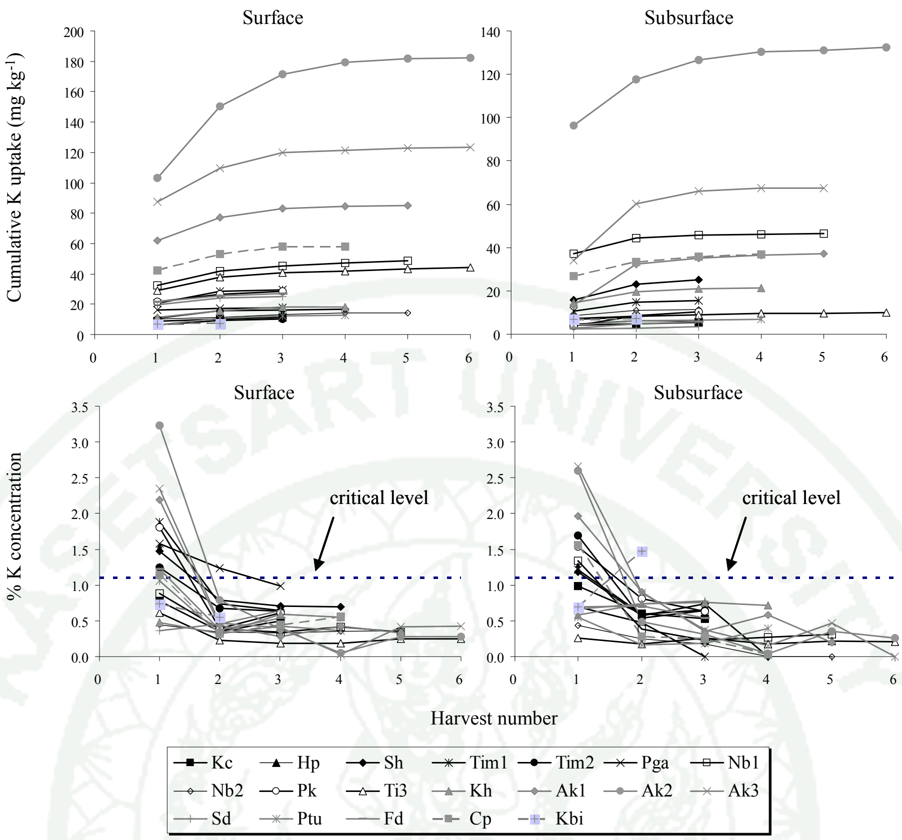

Figure 28 Cumulative K uptake and tissue %K concentration for Guinea grass at each harvest for 19 surface and subsurface soils.

harvest ranged from 3.46 to 182 mg K kg^{-1} soil with a mean value of 31.1 mg K kg^{-1} soil.

For the first harvest, the grass showed K deficiency symptoms for Nb2, Sd and Kbi surface soils and Pga, Nb2, Ti3 and Kh subsurface soils. These soils contain low levels of both exchangeable K and non-exchangeable K. The symptoms appeared first on older leaves, the leaf color changed to yellow and brown, leaf tips and margins became yellowish brown and dried (Dobermann and Fairhurst, 2000). The symptoms developed prior to the first harvest with plants grown on Nb2 and subsurface Ti3 soils and the plants had continued to grow until the fifth harvest, however the yield was greatly reduced.

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Plants on almost all soils showed symptoms of severe K deficiency after the second harvest and K deficiency was severe for all soils for the third harvest. Rusty brown spots appeared on the tips of older leaves and later spread over the whole leaf, which then turned brown and became desiccated as bacterial infection occurred. Plants ultimately died prior to the third harvest for some soils so there are no data for subsequent harvests (Figure 28).

Plants grown on Hp and Kbi soils died after the second harvest due to severe K deficiency. For these soils, the K concentrations in plants were well below the critical concentration (1.1%). This was particularly the case for very sandy soils formed on residuum and colluvium derived from weathered granite and clastic sedimentary rocks as these soils contained less than 15 mg kg^{-1} exchangeable K. These soils contained moderate amount of illite but adequate K was not released from illite over the time of the experiment. After the fifth harvest plants grown on Nb1, Nb2 and Ak1 soils died from K deficiency. Only for Ti3, Ak2 and Ak3 soils, did the plants survive up to the sixth harvest. These three soils are Oxisols which have a clay texture with relatively high CEC and exchangeable K levels. For Ti3 soil which has no illite detectable by XRD, the non-exchangeable K in illite which was detected by TEM-EDS (Figure 24) may be a vital reserve of K. The difference in non-exchangeable K before and after cropping for 180 days for Ti3 soil is about 30 mg kg^{-1} which may be from the small content of illite in the clay.

6. Changes in Forms of Soil K Due to Plant Growth

After cropping with Guinea grass, the contents of water soluble K in the soils ranged from 2.1 to 14 mg kg^{-1} (mean value 6.4 mg kg^{-1}), exchangeable K 4.2 to 14 mg kg^{-1} (mean value 8.3 mg kg^{-1}), non-exchangeable K 8.6 to 94 mg kg^{-1} (mean value, 26 mg kg^{-1}) and HNO_3-K 16 to 101 mg kg^{-1} (mean value, 35 mg kg^{-1}). The contents of water-soluble K were variously affected by the growth of plants (Table 14).

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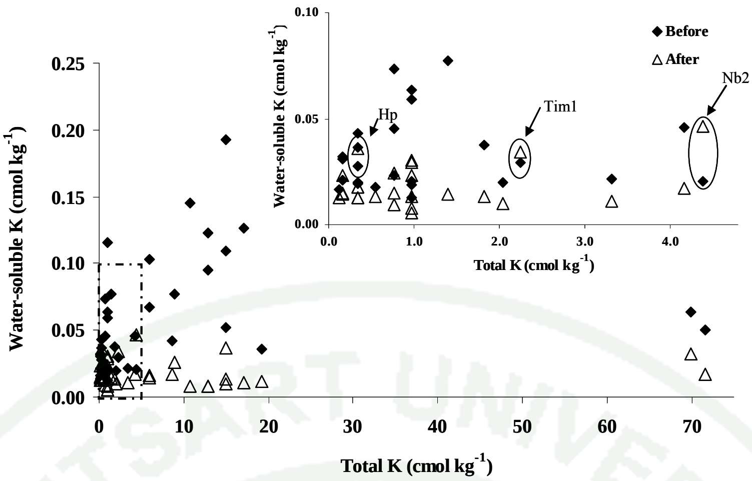

Figure 29 Plot of water-soluble K versus initial total K content for soil sampled before (♦), and after (Δ) plant growth. Samples indicated by an ellipse show an increase in water soluble K due to cropping.

The water soluble K in most soils was reduced considerably by K uptake by Guinea grass. Three soils that initially contained small amounts of water-soluble K (Hp, Tim1 and Nb2) gained a small amount of this form of K (Figure 29) presumably due to rhizosphere effects and root decomposition. We interpret that some of the previously exchangeable K was retained within plant roots, which remained in soil and contributed to the water soluble K. Increased water soluble K may also be due to minor dissolution of non-exchangeable K by rhizosphere activity and there was a small input of K from seeds. Similar gains in water soluble K due to plant growth have been reported by MacKay and Russell (1975) and Pal *et al.* (2001a) and these changes were greatest for highly weathered podzolic soils (Ultisols) which contained little water soluble K.

Plots of cumulative K uptake by grass at each harvest versus initial exchangeable K (including water soluble K) show the progressive utilization of exchangeable K by the grass during the experiment (Figure 30). The slope of relationship for the first harvest indicated that on average about 59% of exchangeable K had been removed from the soil (slope = 0.59) and by the end of the experiment (6^{th} harvest) almost complete removal of exchangeable K (slope=0.94) had occurred and

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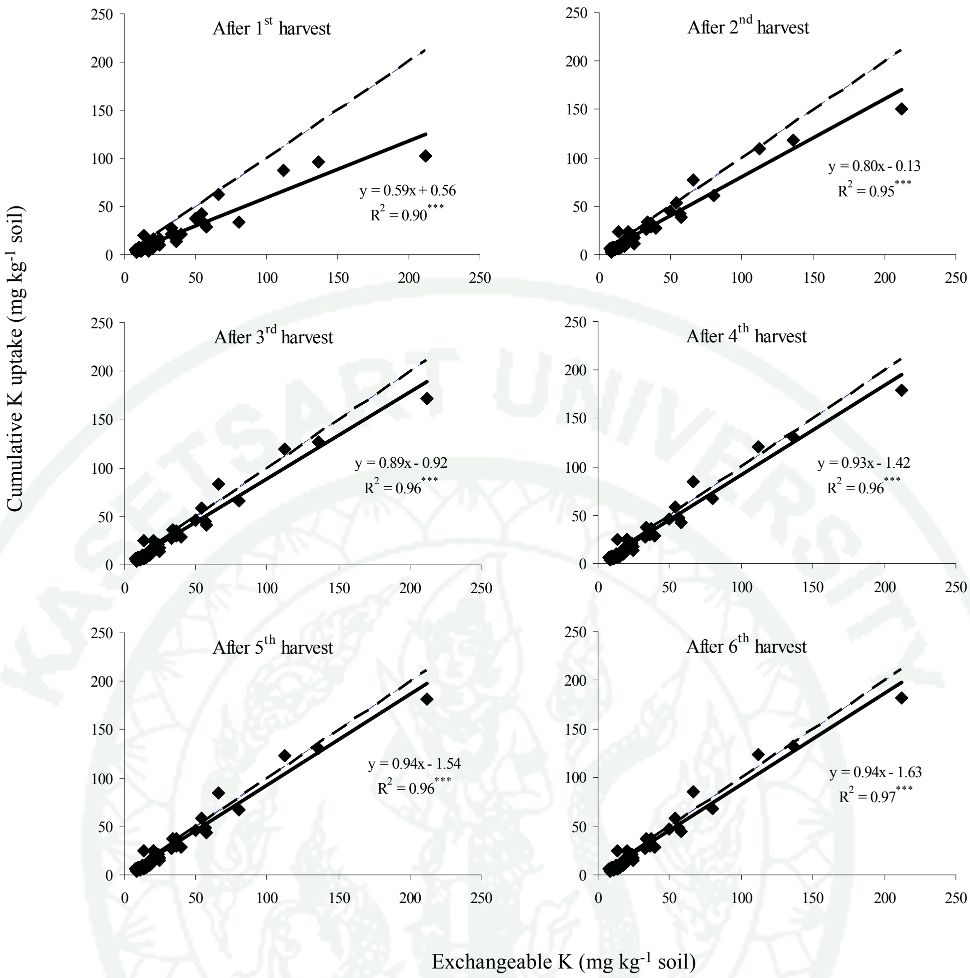

Figure 30 Relationship between exchangeable K (including water-soluble K) and cumulative K uptake by Guinea grass for 6 harvests. Broken lines have slope=1. *** = significant at P<0.001.

most grass had died from K deficiency (except Ti3 and Ak2). Thus the slope of the regression line in Figure 30 increases progressively with harvest number to a value approaching one for the sixth harvest, indicating that exchangeable K was almost the only form of K utilized by Guinea grass. The slope of the regression line is slightly less than 1, as some K would have remained in plant roots that were not analyzed. Similar results have been reported by Kirkman *et al*. (1994) for ryegrass grown on New Zealand soils and for some of their soils mineral K (HNO_3-K, total K) contributed little or no K to plants. Other workers have also reported strong positive relationships between exchangeable K and K uptake by plants (MacKay and Russell, 1975; Mielniczuk and Selbach, 1978; Lopez-Pineiro and Garcia, 1997) but in most

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instances these studies did not achieve the almost complete exhaustion of exchangeable K that occurred for these Thai soils.

Cumulative K uptake by Guinea grass at the final harvest had significant relationships with the reductions in water soluble K, exchangeable K and HNO_3-K (Figure 31). As discussed above the slope of the relationship between K content in plants and exchangeable K (including water soluble K) was approximately unity (0.96), consequently the slope was much higher for water soluble K (2.25) and smaller for HNO_3-K (0.81). These relationships indicate that plants utilized almost all of the exchangeable K and that there was little or no K contributed by other forms. A similar result was obtained for Midwestern USA soils and Western Australian soils where the K content of plants was equal to the NH_4OAc extractable K indicating a low contribution of non-exchangeable K (Cox *et al*., 1999; Pal *et al*., 2001a). In marked contrast to these results, Jalali (2006) showed a stronger correlation between HNO_3-K and plant K uptake than for NH_4OAc-K versus plant K uptake but the data were for juvenile calcareous soils from Iran rather than for the highly weathered soils investigated in the present research.

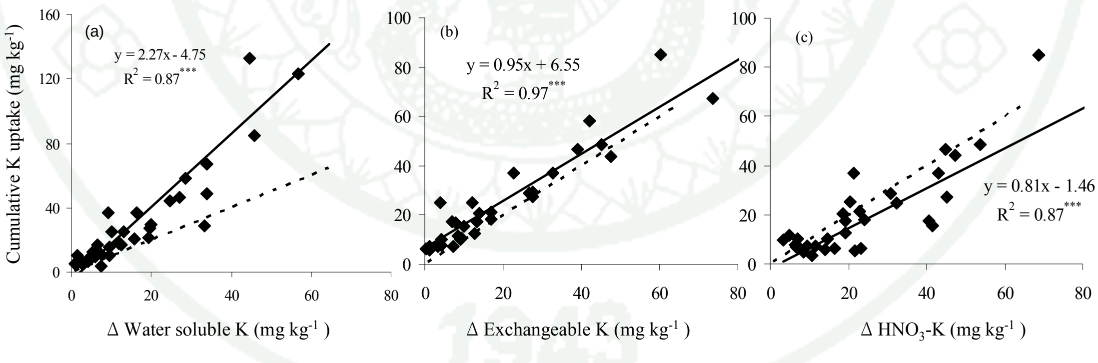

Figure 31 Relationships between changes in various forms of K (ΔK) due to cropping and cumulative K uptake (mg kg^{-1}) by Guinea grass after six harvests. Broken line has slope=1. *** = significant at $P<0.001$.

These data demonstrate that for these highly weathered soils, K release from non-exchangeable forms to plants is of minor importance yet some authors have concluded that for some soils non-exchangeable K forms do contribute K to plants

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(Cox *et al*., 1999; Rao *et al*., 1999; Askegaard *et al*., 2005). For these Thai soils, there is no relationship between exchangeable and non-exchangeable K (r=0.08). This may indicate that the exchangeable K is not simply dependent on amounts of non-exchangeable K. In contrast, Pal *et al*. (2001a) reported close relationships (r = 0.84–0.90) between these forms for Western Australian soils.

7. Mineralogical Changes Produced by Plant Growth

The random powder XRD pattern of whole soils and silt fraction after cropping were compared with the corresponding patterns for the uncropped soils. The patterns showed no change for any sample even for those soils which contain feldspar and mica which might provide a source of K to plants. A comparison of the XRD patterns of clays showed that there was no change in clay mineralogy due to plant growth indicating that the structure of the clay minerals (hydroxy-Al interlayered vermiculite, illite and kaolinite) was not affected by K depletion due to plant growth. This is consistent with K being provided to plants from exchange sites and not from structural sites in layer silicates. However, for clay from Cp surface soil that contains moderate amounts of illite, the illite to kaolinite peak area ratio decreased from 0.37 to 0.26 due to cropping (Figure 32), indicating that some K was released from the interlayer cation site. The reduction in the strength of the illite 001 diffraction line was associated with the development of a broad smectite reflection (Figure 32). This result is consistent with findings of Hinsinger *et al*. (1992) and Singh and Goulding (1997) who also observed that K-depletion resulted in a decrease in illite and an increase in interstratified clay minerals, vermiculite and smectite.

Some workers hold the view that there is not a general transformation sequence (e.g. illite → vermiculite) that is valid for all soils, because clay mineral transformations depend on various soil conditions (Wilson, 1999; Rasmussen *et al*., 2007). This view is supported by the result of a K release study of these soils that completely removed K from the illite interlayer site by chemical extraction. The extraction of K by 0.3M sodium tetraphenylboron solution from Cp soil clays led to a substantial decrease in the intensity of illite basal reflections and to an increase for

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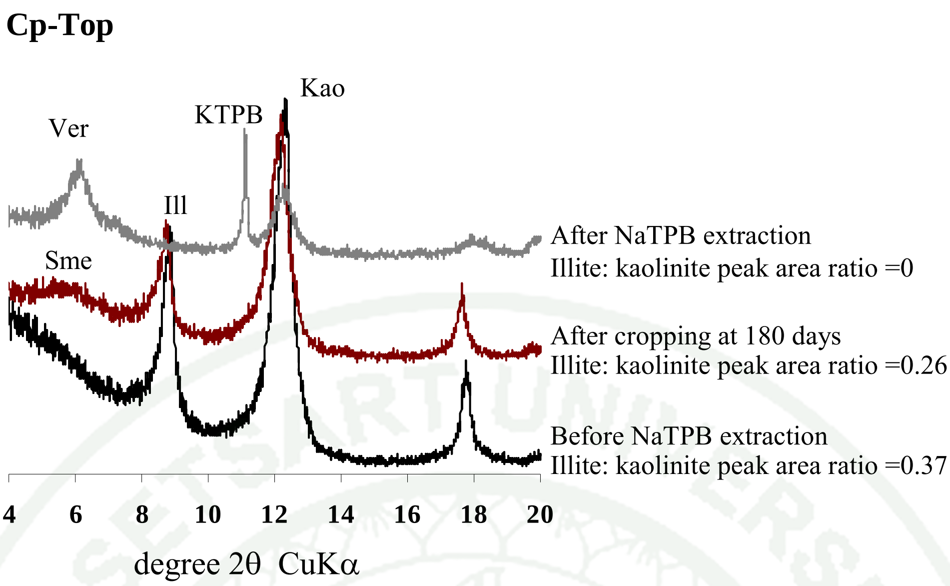

Figure 32 Diffraction patterns of the Mg saturated clay fraction of Cp surface soil before extraction or cropping, after cropping and after extraction by 0.3M NaTPB for 168 hours (Ver=vermiculite, Sme= smectite, Ill= illite, Kao= kaolinite).

vermiculite. However, in the present plant growth experiment with Cp soil where K was removed from illite in the rhizosphere the reduction in strength of the illite 001 diffraction line was associated with the development of a broad smectite reflection rather than a formation of vermiculite as occurred for the corresponding clay with NaTPB extraction (Figure 32). The transformation of illite to smectite in this soil clay may be due to mineralogical changes in the rhizosphere occurring in response to attack by H^+ and complexing agents from plant roots rather than being only due to simple interlayer cation exchange (Tributh *et al*., 1987).

This study has identified exchangeable K as being highly and quantitatively predictive of the availability of K to plants grown in the glasshouse. The NH_4OAc extractable K is the major form of plant-available K in these upland Oxisols and Ultisols. For some soils, a little K was supplied by the non-exchangeable K pools, probably from illite that is present in all clays albeit being undetectable by XRD techniques for some soils. Analytical TEM of clay particles indicates that K is not

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present within the kaolinite structure but as very small illite crystals which are associated with the dominant kaolinite crystals.

Only one soil (Cp surface) showed a mineralogical change that indicated that non-exchangeable K was released from the interlayer site in illite. K in Ultisols is less available than K in Oxisols where the higher clay content is related to higher exchangeable K. This K exhaustion experiment involved small volumes of soil that were intensively exploited by roots and the removal of plant tops ensured that there was limited recycling of K. Under field conditions plant roots can exploit a much larger volume of soil and recycling of K from foliage can occur. Consequently, K exhaustion of soils will occur at a slower rate in the field. However these soils clearly contain little exchangeable K and the low availability of non-exchangeable K indicates that soil K will eventually become too low to support annual field crops if a K fertilizer is not provided.

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CONCLUSIONS

Upland Oxisols and Ultisols under tropical monsoonal climate are intensively weathered due to the high rainfall and high temperature. The major processes in these well drained soils are desilication, ferrugination and leaching combined with illuviation. The differences in their parent materials provided various soil characteristics. Oxisols have distinctly higher clay and Fe contents than do the Ultisols. Clay and Fe contents are also the main properties that influence other soil properties including CEC, AEC and SSA.

Kaolin group minerals are major clay minerals for these Thai upland soils with moderate to trace amounts of illite and HIV. Goethite, hematite, quartz and anatase are also present in most soils. This study shows a lithosequence where soil parent material is the main factor influencing the mineralogical and chemical properties of the clay fraction which strongly affects other soil properties. The minerals in clay fraction of basaltic soils have the smallest crystal size, the largest crystal size is for soils formed on sedimentary rocks. The smaller crystals are generally poorly ordered and the degree of Al substitution in iron oxides is also highest in basaltic soils.

The large surface area and chemical reactivity of clay, which results from small size and defect crystal structure will be important for sorption reactions in these soils which are often sandy and contain little organic matter to sorb plant nutrients and other ions. Consequently, kaolin and iron oxides may provide a substantial part of the capacity of the soil profile to retain anions and cations. This research has also identified a possible role for kaolin as a host for trace elements as structural ions such which has significant implications for soil fertility and geochemical exploration.

Many highly weathered soils in Thailand are believed to have a good supply of K. Some studied soils have quite high level of total K and exchangeable K in the absence of K-bearing minerals, such as illite, micas and feldspars. The results from this study show that these highly weathered kaolinitic soils often have adequate levels of K to support plant growth but only if K can be liberated from mineral structures and there

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is little evidence for this process.. TEM can detect illite beyond the XRD range for some kaolinitic soil clays. Illite crystals are present associated with kaolinite but may contributed little K to plants. Low K concentrations in coarse-textured soils with low CEC have a high risk of K loss after fertilisation and a low inherent capacity to release K from mineral sources. This study clearly shows differences between soil texture classes with respect to available K and crop K concentrations, consequently different K fertilization strategies and cropping systems will be required for different soils. The long-term K release capacity through mineral weathering, should be estimated, and should be included in field balance calculations. The potential of certain crops to extract K from slowly available fractions should be explored; for example species that are good at extracting K from soil should be introduced and used as green manure in the crop rotation.

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APPENDICES

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Appendix A

Soil Profile Description

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Ao Luek 1 series

I Information on the site

Profile symbol	:	Ak1
Soil name	:	Ao Luek series (Ak)
Classification	:	Typic Kandiudox, very-fine, kaolinitic
Date of examination	:	September 23, 2002
Described by	:	Irb Kheoruenromne, Piboon Kanghae, Saowanuch Tawornpruek, Punyisa Trakoonyingcharoen, Sumitra Watana, Suphicha Thanachit and Thanapol Srisupha-olarn
Location	:	Adjacent to Wang Tarn Tip Resort and Restaurant, 1.6 km from Ban Nai Sa-Ban Thung road (4033), Ban Nai Sa, Tambon Kaotoug, Amphoe Muang, Changwat Krabi
Elevation	:	Approximately 128 m (MSL)
Map sheet number	:	4725II Coordination : 47Q 477649E, 0902500N

Landform

1. Physiographic position	:	Crestal slope of residual hill in Karst corrosion plain
2. Surrounding land form	:	Rolling
3. Slope on which profile site	:	8% Aspect : East
Land use	:	Rain forest species, para rubber, papaya, coconut, banana
Annual rainfall	:	Approximately 2,171 mm
Mean temperature	:	Approximately 28^{o}C
Climate	:	Tropical Monsoonal
Others	:	Agricultural and borrowing pit area

II General information on the soil

Parent material	:	Residuum derived mainly from limestone
Drainage	:	Well drained
Permeability	:	Moderate
Runoff	:	Moderate
Depth of ground water	:	Deeper than 2 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-10	Yellowish red (5YR 4/6); clay; strong fine and medium granular structure; soft dry, friable moist, slightly sticky and moderately plastic; many very fine, fine vesicular pores; many very fine, fine and common medium roots; present of some clay balls; neutral (field pH 7.0); clear, smooth boundary to Bto1.
Bto1	10-30	Red (2.5YR 4/6); clay; moderate fine and medium semi-angular blocky parting to strong very fine and fine granular structure; slightly hard dry, friable moist, slightly sticky and moderately plastic; common distinct clay coats on ped faces and pore walls; common very fine and fine vesicular and few fine simple and dendritic tubular pores; many very fine, fine and common medium roots; very few fine rounded rock fragments; slightly acid (field pH 6.5); gradual, smooth boundary to Bto2.

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Bto2	30-52	Red (2.5YR 4/6); clay; moderate fine and medium semi-angular blocky parting to strong very fine and fine granular structure; slightly hard dry, friable moist, slightly sticky and moderately plastic; common distinct clay coats on ped faces and pore walls; common very fine, fine and few medium vesicular and few fine simple tubular pores; many very fine, fine and common medium roots; present of few fine clay balls; few termite nest; slightly acid (field pH 6.5); gradual, smooth boundary to Bto3.
Bto3	52-80	Red (2.5YR 4/6); clay; moderate fine and medium subangular blocky parting to fine and medium granular structure; soft dry, friable moist, slightly sticky and moderately plastic; common distinct clay coats on ped faces and pore walls; many very fine and few medium vesicular and few very fine simple tubular pores; many very fine, fine and common medium roots; present of few fine clay balls and few medium size (0.5 cm) of clay balls, few fine crack; moderately acid (field pH 6.0); gradual, smooth boundary to Bto4.
Bto4	80-117	Red (2.5YR 4/6); clay; moderately weak fine and medium subangular blocky parting to fine and medium granular structure; soft dry, friable moist, slightly sticky and moderately plastic; common distinct clay coats on ped faces and pore walls; common very fine, fine and very few medium vesicular and few fine simple and dendritic tubular pores; many very fine, fine and common medium roots; few fine black spot of unknown nature and very few fine rounded rock fragments; moderately acid (field pH 6.0); clear, smooth boundary to Bto5.
Bto5	117-148	Red (2.5YR 4/6); clay; weak fine and medium semi-angular blocky parting to mainly moderate very fine granular structure; soft dry, friable moist, slightly sticky and moderately plastic; common distinct clay coats on ped faces and pore walls; many very fine, fine and medium vesicular and few fine simple tubular pores; common very fine, fine and few medium roots; few fine cracks, few very fine rounded unknown nature and present of 0.5 cm clay balls; moderately acid (field pH 6.0); gradual, smooth boundary to Bto6.
Bto6	148-170	Red (2.5YR 4/6); clay; weak fine and medium subangular blocky parting to mainly fine, moderate fine and very fine granular structure; soft dry, friable moist, slightly sticky and very plastic; common faint clay coats on ped faces and pore walls; many very fine, fine and medium vesicular pores; common very fine, fine and few medium roots; moderately acid (field pH 6.0); clear, smooth boundary to Bto7.
Bto7	170-200	Red (2.5YR 4/6); clay; moderately weak fine and medium semi-angular blocky parting to mainly fine, moderate fine and very fine granular structure; soft dry, friable moist, slightly sticky and very plastic; common faint clay coats on ped faces and pore walls; many very fine, fine and few medium vesicular and few fine simple tubular pores; few very fine and fine roots; present of very few fine (0.1-0.2 cm) clay balls; moderately acid (field pH 6.0).

Remark: clay coats area are smaller size from Bto1 to Bto5.
(Bto1=Bto2>Bto3>Bto4=Bto5)

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Ao Luek 2 series

I Information on the site

Profile symbol : Ak2
Soil name : Ao Luek series (Ak)
Classification : Typic Kandiudox, very-fine, kaolinitic
Date of examination : September 25, 2002
Described by : Irb Kheoruenromne, Piboon Kanghae, Saowanuch Tawornpruek, Punyisa Trakoonyingcharoen, Sumitra Watana, Suphicha Thanachit and Thanapol Srisupha-olarn
Location : At 3.5 km, road to Ban Tam Singh from Petchakasem road (41) (Chumphon to Sawi), Ban Huay Non, Tambon Khun Krating Amphoe Muang, Changwat Chumphon
Elevation : Approximately 78 m (MSL)
Map sheet number : 4829 IV Coordination : 47Q 511129E, 1156948N

Landform
1. Physiographic position : Karst corrosion plain
2. Surrounding land form : Slightly undulating
3. Slope on which profile site : 3% Aspect : East-west
Land use : Tropical Rainforest species, durian and pepper
Annual rainfall : Approximately 1,883 mm
Mean temperature : Approximately 28^{o}C
Climate : Tropical Monsoonal
Others : Agricultural and sparse settlement

II General information on the soil

Parent material : Residuum derived from limestone
Drainage : Well drained
Permeability : Moderate
Runoff : Slow
Depth of ground water : Deeper than 2 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-17	Red (2.5YR 4/6); clay; strong fine and medium subangular blocky partially parting to strong fine granular structure; hard dry, firm moist, slightly sticky and very plastic; common distinct clay coats on ped faces and pore walls; many very fine, fine and few medium vesicular pores; many very fine, fine roots; few traces of charcoal fragments, few fine cracks, few fine quartz fragments and few traces of dead roots; neutral (field pH 7.0); clear, smooth boundary to Bto1.
Bto1	17-42	Red (2.5YR 4/6); clay; moderate fine and medium subangular blocky structure; hard dry, firm moist, slightly sticky and moderately plastic; many prominent clay coats on ped faces and pore walls; common very fine, many fine and few medium vesicular and few fine simple tubular pores; common very fine, fine roots; few small concretions and nodules of Mn oxide; neutral (field pH 7.0); gradual, smooth boundary to Bto2.

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Bto2	42-70	Red (2.5YR 4/6); clay; moderate fine and medium subangular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; common distinct clay coats on ped faces and pore walls; common very fine, fine vesicular and few fine simple tubular pores; few very fine, fine roots; very few small variegated sand, very few small concretions and nodules, traces of dead roots; very strongly acid (field pH 5.0); gradual, smooth boundary to Bto3.
Bto3	70-100	Red (2.5YR 4/6); red (2.5YR5/8) 3%, and reddish yellow (7.5YR6/8) 2% mottles; clay; moderate fine and medium subangular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; common distinct clay coats on ped faces and pore walls; common very fine, fine and few medium vesicular and few fine simple tubular pores; few very fine, fine roots; few fine cracks, few clay balls; traces of dead roots; very strongly acid (field pH 5.0); gradual, smooth boundary to Bto4.
Bto4	100-135	Red (2.5YR 4/6); clay; moderately weak fine and medium subangular blocky readily parting to strong fine and very fine granular structure; slightly hard dry, friable moist, slightly sticky and moderately plastic; common faint clay coats on ped faces and pore walls; many very fine, common fine and few medium vesicular and few fine and medium simple tubular pores; very few fine, very fine and fine roots; few fine cracks, few clay balls, few fine nodules and concretions, traces of dead roots; strongly acid (field pH 5.0); clear, smooth boundary to Bto5.
Bto5	135-170	Red (2.5YR 4/6); slightly gravelly clay; moderately weak fine and medium subangular blocky readily parting to strong fine and very fine granular structure; slightly hard dry, friable moist, slightly sticky and moderately plastic; common faint clay coats on ped faces and pore walls; many very fine, fine and common medium vesicular pores; practically no roots; few fine cracks, few clay balls, common small nodules and concretions; strongly acid (field pH 5.0); clear, smooth boundary to Bto6.
Bto6	170-200	Red (2.5YR 4/6); slightly gravelly clay; moderate fine and medium subangular blocky partially parting to strong fine granular structure; slightly hard dry, friable moist, slightly sticky and moderately plastic; common faint clay coats on ped faces and pore walls; many very fine, fine and common medium vesicular pores; practically no roots; common fine concretions (MnO_2) (5YR3/2, 5YR 2.5/1) strongly acid (field pH 5.0).

Remark: few clay balls throughout from Bto3 downward, be easy to wash hands.

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Ao Luek 3 series

I Information on the site

Profile symbol	:	Ak3
Soil name	:	Ao Luek series (Ak)
Classification	:	Rhodic Kandiudox, very-fine, kaolinitic
Date of examination	:	October 2, 2002
Described by	:	Irb Kheoruenromne, Piboon Kanghae, Saowanuch Tawornpruek, Punyisa Trakoonyingcharoen, Sumitra Watana, Suphicha Thanachit and Thanapol Srisupha-olarn
Location	:	Ban Thala Sub, Tambon Thala Sub, Amphoe Pathiu, Changwat Chumphon
Elevation	:	Approximately 81 m (MSL)
Map sheet number	:	4830 III Coordination : 47Q 526529E, 1182434N

Landform

1. Physiographic position	:	Rise crestal slope in karst corrosion plain
2. Surrounding land form	:	Undulating
3. Slope on which profile site	:	1% Aspect : East-west
Land use	:	Tropical Rain forest species, Durian, Pepper (Tropical orchards)
Annual rainfall	:	Approximately 1,883 mm
Mean temperature	:	Approximately 28^{o}C
Climate	:	Tropical Monsoonal
Others	:	Agricultural and sparse settlement

II General information on the soil

Parent material	:	Residuum derived from limestone
Drainage	:	Well drained
Permeability	:	Rapid
Runoff	:	Slow
Depth of ground water	:	Deeper than 2 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-18	Dark reddish brown (2.5YR 3/4); clay; strong fine and medium subangular blocky structure; slightly hard dry, firm moist, slightly sticky and moderately plastic; many distinct clay coats on ped faces and pore walls; many very fine, common fine and few medium vesicular and few fine simple tubular pores; many very fine, fine roots; few traces of dead roots, few small clay balls; strongly acid (field pH 5.5); clear, smooth boundary to Bto1.
Bto1	18-40	Dark reddish brown (2.5YR 3/4); clay; strong fine and medium semi-angular blocky structure; hard dry, firm moist, slightly sticky and moderately plastic; many prominent clay coats on ped faces and pore walls; many very fine, fine and common medium vesicular, few fine simple and dendritic tubular pores; many very fine, fine roots; few traces of dead roots; very strongly acid (field pH 5.0); gradual, smooth boundary to Bto2.

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Bto2	40-60	Dark reddish brown (2.5YR ¾); clay; moderate fine and medium semi-angular blocky structure; slightly hard dry, firm moist, slightly sticky and moderately plastic; many prominent clay coats on ped faces and pore walls; common very fine, fine and medium vesicular, common fine simple and dendritic tubular pores; common very fine, fine roots; common clay balls (2mm), plasticity somewhat slightly sticky plastic; very strongly acid (field pH 5.0); clear, smooth boundary to Bto3.
Bto3	60-90	Dark red (2.5YR 3/6); clay; moderate fine and medium subangular blocky partially parting to moderate fine granular structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; common faint clay coats on ped faces and pore walls; many very fine, fine and medium vesicular, few fine simple and dendritic tubular pores; few very fine, fine roots; few fine clay balls (smaller than Bto2), plasticity somewhat slightly sticky plastic, small termite nest; very strongly acid (field pH 4.5); gradual, smooth boundary to Bto4.
Bto4	90-123	Dark red (2.5YR 3/6); clay; moderate fine and medium semi-angular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; common distinct clay coats on ped faces and pore walls; many very fine, fine and common medium vesicular, few fine simple and dendritic tubular pores; few very fine, fine roots; few clay balls (2 mm), plasticity somewhat slightly sticky plastic; very strongly acid (field pH 5.0); clear, smooth boundary to Bo1.
Bo1	123-155	Dark red (2.5YR 3/6); clay; moderately weak fine and medium semi-angular blocky partially parting to mainly fine granular structure; soft dry, friable moist, slightly sticky and moderately plastic; common faint clay coats on ped faces; many very fine, fine and common medium vesicular, common fine simple and dendritic tubular pores; few very fine, fine roots; few small clay balls; very strongly acid (field pH 5.0); gradual, smooth boundary to Bo2.
Bo2	155-190+	Dark red (2.5YR 3/6); clay; moderately weak fine and medium semi-angular blocky partially parting to mainly fine granular structure; soft dry, friable moist, slightly sticky and moderately plastic; common faint clay coats on ped faces; many very fine, fine and common medium vesicular, common fine simple and dendritic tubular pores; very few very fine, fine roots; few small clay balls; very strongly acid (field pH 5.0).

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Pathio series

I Information on the site

Profile symbol	:	Ptu
Soil name	:	Pathio (Ptu)
Classification	:	Kandiudalfic Eutrudox, fine, kaolinitic
Date of examination	:	October 1, 2002
Described by	:	Irb Kheoruenromne, Piboon Kanghae, Saowanuch Tawornpruek, Punyisa Trakoonyingcharoen, Sumitra Watana, Suphicha Thanachit, Thanapol Srisupha-olarn
Location	:	Ban Mab Amarit, Tambon Don Yang, Amphoe Pathiu, Changwat Chumphon
Elevation	:	Approximately 82 m (MSL)
Map sheet number	:	4830 IV Coordination : 47536253E, 1202658N

Landform

1. Physiographic position	:	Footslope in karst corrosion plain
2. Surrounding land form	:	Undulating
3. Slope on which profile site	:	4-5% Aspect : North-west
Land use	:	Rainforest species under para rubber local weeds and fern
Annual rainfall	:	Approximately 2,500 mm
Mean temperature	:	Approximately 28 ^{o}C
Climate	:	Tropical Monsoonal
Others	:	Agricultural

II General information on the soil

Parent material	:	Residuum and colluvium derived from fine grained clastic rocks and limestone
Drainage	:	Well drained
Permeability	:	Moderate
Runoff	:	Moderate
Depth of ground water	:	Deeper than 2 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-20	Dark reddish brown (2.5YR 3/4); sandy clay; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; few faint clay coats on ped faces and pore walls; common very fine, fine and medium vesicular and few fine simple tubular pores; many very fine, fine and medium roots; common fine rounded sand grains, few traces of dead roots; moderately acid (field pH 6.0); abrupt, smooth boundary to Bto1.
Bto1	20-46	Dark red (2.5YR 3/6); sandy clay; moderately weak fine and medium subangular blocky partially parting to coarse and medium granular structure; slightly hard dry, firm moist, slightly sticky and moderately plastic; many prominent clay coats on ped faces and pore walls; common very fine, fine and few medium vesicular and few fine simple tubular pores; common very fine, fine and medium roots; few fine rock fragments, few traces of dead roots and large termite nests; moderately acid (field pH 6.0); gradual, smooth boundary to Bto2.

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Bto2	46-75	Dark red (2.5YR 3/6); sandy clay; moderately weak fine and medium subangular blocky partially parting to coarse and medium granular structure; slightly hard dry, firm moist, moderately sticky and moderately plastic; many distinct clay coats on ped faces and pore walls; many very fine, fine and medium vesicular and few fine simple tubular pores; common very fine, fine and medium roots; large termite nests; strongly acid (field pH 5.5); clear, smooth boundary to Bto3.
Bto3	75-104	Dark red (2.5YR 3/6); sandy clay; moderate fine and medium semi-angular blocky structure; slightly hard dry, firm moist, slightly sticky and moderately plastic; few distinct clay coats on ped faces and pore walls; common very fine, fine and medium vesicular and few fine simple tubular pores; few very fine and fine roots; strongly acid (field pH 5.5); gradual, smooth boundary to Bto4.
Bto4	104-128	Dark red (2.5YR 3/6); sandy clay; moderately weak fine and medium subangular blocky partially parting to medium and fine granular structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; few distinct clay coats on ped faces and pore walls; many very fine, common fine and few medium vesicular and few fine simple and dendritic tubular pores; few very fine and fine roots; smaller quartz sand fragments (grains); moderately acid (field pH 6.0); gradual, smooth boundary to Bto5.
Bto5	128-155	Dark red (2.5YR 3/6); sandy clay; moderately weak fine and medium subangular blocky structure partially parting to medium and fine granular structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; few distinct clay coats on ped faces and pore walls; common very fine, fine and few medium vesicular and few fine simple tubular pores; few very fine and fine roots; smaller quartz sand fragments (grains); strongly acid (field pH 5.5); clear, smooth boundary to Bo.
Bo	155-190+	Dark red (2.5YR 3/6); sandy clay; moderately weak fine and medium semi-angular blocky partially parting to medium and fine granular structure; slightly hard dry, friable moist, slightly sticky and moderately plastic; few faint clay coats on pore walls; many very fine, fine and few medium vesicular and few fine simple tubular pores; very few very fine and fine roots; smaller quartz sand fragments (grains); strongly acid (field pH 5.5).

Remark: Few fine to very fine quartz sand grains in all horizons.

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Tha Mai 1 series

I Information on the site

Profile symbol	:	Ti1
Soil name	:	Tha Mai series (Ti)
Classification	:	Rhodic Kandiudox, very-fine, kaolinitic
Date of examination	:	February 8, 2003
Described by	:	Irb Kheoruenromne, Piboon Kanghae, Saowanuch Tawornpruek, Punyisa Trakoonyingcharoen, Suphicha Thanachit, Thanapol Srisupha-olarn and Tonglor Suttisong
Location	:	At 3.5 km, road to Ban Tam Singh from Petchakasem road (41) (Chumphon to Sawi), Ban Cham Ko, Tambon Ploy Whan Amphoe Tha Mai, Changwat Chantaburi
Elevation	:	Approximately 40 m (MSL)
Map sheet number	:	5434III Coordination : 48Q 0179202E, 1395764N

Landform

1. Physiographic position	:	Upper dissected footslope of lava corrosion hill
2. Surrounding land form	:	Slightly undulating
3. Slope on which profile site	:	3% Aspect : North-west
Land use	:	Tropical orchards and settlement/ durian, langsat, mangosteen, banana, evergreen species
Annual rainfall	:	Approximately 3,030 mm
Mean temperature	:	Approximately 26°C
Climate	:	Tropical monsoonal
Others	:	Agricultural and sparse settlement

II General information on the soil

Parent material	:	Residuum derived from weathered basalt
Drainage	:	Well drained
Permeability	:	Rapid
Runoff	:	Slow
Depth of ground water	:	Deeper than 2 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap1	0-12	Dark reddish brown (5YR 3/4); clay; strong fine and medium subangular blocky parting to strong very fine and fine granular structure; loose dry, friable moist, slightly sticky and moderately plastic; few fine faint clay coats on ped faces and pore walls; many very fine, fine vesicular pores; many very fine, fine and medium roots; common fine clay balls, few traces of dead roots, very few very fine rock fragments; slightly acid (field pH 6.5); clear, smooth boundary to Ap2.
Ap2	12-27	Dark reddish brown (5YR 3/4); clay; strong fine and medium subangular blocky parting to strong very fine and fine granular structure; loose dry, friable moist, slightly sticky and moderately plastic; very few very fine faint clay coats on pore walls; common very fine, fine vesicular pores; many very fine, fine and medium roots; common fine clay balls, few traces of dead roots and charcoal fragment, few fine rock fragments; very strongly acid (field pH 5.0); clear, smooth boundary to Bto1.

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Bto1	27-52	Dark reddish brown (5YR 3/4); clay; strong medium and coarse semi-angular blocky partially parting to granular structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; common distinct clay coats on ped faces and pore walls; many very fine, fine vesicular and common fine simple tubular pores; very few very fine and fine roots; common fine clay balls, few traces of dead roots, few fine rock fragments; very strongly acid (field pH 5.0); gradual, smooth boundary to Bto2.
Bto2	52-78	Dusky red (2.5YR 3/4); clay; strong medium and coarse subangular blocky parting to granular structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; common distinct clay coats on ped faces and pore walls; many very fine, fine vesicular and common fine simple tubular pores; few fine and medium roots; common fine clay balls, few fine rock fragments; very strongly acid (field pH 5.0); gradual, smooth boundary to Bto3.
Bto3	78-96	Dusky red (2.5YR 3/4); clay; strong medium and coarse semi-angular blocky parting to medium and fine granular structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; common distinct clay coats on ped faces and pore walls; many very fine, fine and few medium vesicular and common fine simple and dendritic tubular pores; few fine and medium roots; common fine clay balls, few traces of dead roots, few fine rock fragment, faunal activities; strongly acid (field pH 5.5); clear, smooth boundary to Bo1.
Bo1	96-125	Dusky red (2.5YR 3/4); clay; moderate fine and medium semi-angular blocky parting to granular structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; common fine faint clay coats on pore walls mainly; many very fine, fine and few medium vesicular pores; few fine and medium roots; common clay balls, very few rock fragment; strongly acid (field pH 5.5); clear, smooth boundary to Bo2.
Bo2	125-160	Dusky red (2.5YR 3/4); clay; moderate fine and medium semi-angular blocky parting to granular structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; common fine faint and few distinct clay coats on pore walls mainly; many very fine, common fine and few medium vesicular and few fine simple tubular pores; few fine and medium roots; common clay balls, very few rock fragment; very strongly acid (field pH 5.0); gradual, smooth boundary to Bo2.
Bo3	160-200	Dusky red (2.5YR 3/4); clay; moderate fine and medium semi-angular blocky parting to granular structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; common fine faint and few distinct clay coats on pore walls mainly; many very fine, fine and common medium vesicular and common fine simple tubular pores; very few fine and medium roots; common clay balls, very few rock fragment; very strongly acid (field pH 5.0).

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Tha Mai 2 series

I Information on the site

Profile symbol	:	Ti2
Soil name	:	Tha Mai series (Ti)
Classification	:	Typic Kandiudox, very-fine, kaolinitic
Date of examination	:	February 8, 2003
Described by	:	Irb Kheoruenromne, Piboon Kanghae, Saowanuch Tawornpruek, Punyisa Trakoonyingcharoen, Suphicha Thanachit, Thanapol Srisupha-olarn and Tonglor Suttisong
Location	:	Mr. Sakieum Sathandee' orchards, Ban Moo 1, Tambon Si Phaya, Amphoe Tha Mai, Changwat Chantaburi
Elevation	:	Approximately 30 m (MSL)
Map sheet number	:	5434III Coordination :48Q 0179338E, 1393219N

Landform

1. Physiographic position	:	Top of dissected lava corrosion plain
2. Surrounding land form	:	Undulating
3. Slope on which profile site	:	3% Aspect : North-east
Land use	:	Tropical orchards/ durian, longan langsat, papaya
Annual rainfall	:	Approximately 3,030 mm
Mean temperature	:	Approximately 26^{o}C
Climate	:	Tropical Monsoonal
Others	:	Agricultural

II General information on the soil

Parent material	:	Residuum derived from weathered basalt
Drainage	:	Well drained
Permeability	:	Rapid
Runoff	:	Moderate
Depth of ground water	:	Deeper than 2 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-14/16	Dark reddish brown (5YR 3/4); clay; strong medium and coarse subangular blocky partially parting to strong medium and coarse granular structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; few fine faint clay coats on pore walls; many very fine, fine and few medium vesicular pores; common very fine and fine roots; common clay balls, few traces of dead roots and charcoal fragments, few fine rounded rock fragments; slightly acid (field pH 6.5); clear, smooth boundary to Bto1.
Bto1	16-40	Dark reddish brown (5YR 3/4); clay; strong fine and medium subangular blocky parting to fine granular structure; slightly hard dry, friable moist, moderately sticky and moderately plastic; few fine faint clay coats on pore walls; many very fine, fine and few medium vesicular pores; few very fine and fine roots; common clay balls, few traces of dead roots, few fine rounded rock fragments; strongly acid (field pH 5.5); gradual, smooth boundary to Bto2.

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Bto2	40-70	Dark reddish brown (5YR 3/4); clay; moderate medium and coarse semi-angular blocky parting to medium and fine granular structure; slightly hard dry, friable moist, moderately sticky and moderately plastic; common faint clay coats mostly on pore walls; many very fine, fine and few medium vesicular and few fine simple tubular pores; few very fine, fine and medium roots; common fine clay balls, few charcoal fragments, few fine rounded rock fragments; strongly acid (field pH 5.5); gradual, smooth boundary to Bto3.
Bto3	70-95	Dark reddish brown (5YR 3/4); clay; strong medium and coarse semi-angular blocky parting to medium and fine granular structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; common faint and few distinct clay coats on ped faces and pore walls; many very fine, common fine and few medium vesicular and few fine simple tubular pores; very few very fine, fine and medium roots; common clay balls, few fine rounded rock fragments; very strongly acid (field pH 5.0); clear, smooth boundary to Bo1.
Bo1	95-125	Dusky red (2.5YR 3/4); clay; moderate fine and medium semi-angular blocky parting to fine granular structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; few faint clay coats mostly on pore walls; many very fine, common fine and few medium vesicular and common fine simple and dendritic tubular pores; very few very fine, fine and medium roots; common clay balls, few fine rounded rock fragments; strongly acid (field pH 5.5); clear, smooth boundary to Bo2.
Bo2	125-150	Dusky red (2.5YR 3/4); clay; moderate fine and medium semi-angular blocky parting to fine granular structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; common faint clay coats on ped faces and pore walls; many very fine, common fine and few medium vesicular and common fine simple and dendritic tubular pores; very few very fine, fine and few medium roots; common clay balls, few fine rounded rock fragments; strongly acid (field pH 5.5); gradual, smooth boundary to Bo3.
Bo3	150-175	Dusky red (2.5YR 3/4); clay; moderate fine and medium semi-angular blocky parting to fine granular structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; common faint clay coats on ped faces and pore walls; many very fine, common fine and few medium vesicular and common fine simple and dendritic tubular pores; very few very fine, fine and few medium roots; common clay balls, few fine rounded rock fragments; strongly acid (field pH 5.5); gradual, smooth boundary to Bo4.
Bo4	175-200	Dusky red (2.5YR 3/4); clay; moderate fine and medium semi-angular blocky parting to fine granular structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; common faint clay coats on ped faces and pore walls; many very fine, fine and few medium vesicular and few fine simple and dendritic tubular pores; very few very fine, fine and few medium roots; common fine clay balls, very few fine rock fragments; strongly acid (field pH 5.5).

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Tha Mai 3 series

I Information on the site

Profile symbol	:	Ti3
Soil name	:	Tha Mai series (Ti)
Classification	:	Typic Kandiudox, very-fine, kaolinitic
Date of examination	:	January 6, 2008
Described by	:	Irb Kheoruenromne, Mahitorn Putiso, Worachart Wisawapipat, Timtong Darunsontaya, Chutharmard Kaewmano, Natthapol Chittmart and Bussayarat Mokmoor
Location	:	200 m Northeast of road around Ploywaen Hill, Tropical fruit tree orchards, Moo 3 Ban Cham Ko, Tambon Ploy Whan Amphoe Tha Mai, Changwat Chantaburi
Elevation	:	Approximately 50 m (MSL)
Map sheet number	:	4830 I Coordination: 48Q 0178748E, 1396017N
Landform		
1. Physiographic position	:	Upper footslope of Lava corrosion hill
2. Surrounding land form	:	Undulating
3. Slope on which profile site	:	3% Aspect : North-east
Land use	:	Tropical fruit tree orchard; banana, durian and rambutan
Annual rainfall	:	Approximately 3,030 mm
Mean temperature	:	Approximately 27 ^{o}C
Climate	:	Tropical Monsoonal
Others	:	Agricultural and precious stone mining

II General information on the soil

Parent material	:	Residuum derived from weathered basalt
Drainage	:	Well drained
Permeability	:	Moderate
Runoff	:	Moderate
Depth of ground water	:	Deeper than 2 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-15	Reddish brown (2.5YR 4/4); clay; strong fine and medium subangular blocky partially parting to medium and coarse granular structure; slightly hard dry, firm moist, moderately sticky and moderately plastic; few faint clay coats on ped faces and pore walls; few clay balls and quartz fragments; many very fine and fine, and few medium vesicular and few fine tubular pores; many very fine, fine and medium roots; common traces of dead roots; moderately acid (field pH 6.0); clear, smooth boundary to Bo1.
Bo1	15-42	Red (2.5YR 4/6); clay; moderate weak fine and medium subangular blocky mostly parting to fine and very fine granular structure; soft dry, friable moist, slightly sticky and slightly plastic; very few faint clay coats on ped faces; very few and few fine vesicular pores; many very fine, fine and medium roots and few coarse toots; common traces of dead roots; strongly acid (field pH 5.5); clear, smooth boundary to Bo2.

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Bo2	42-67	Red (2.5YR 4/6); clay; moderate fine and medium subangular blocky mostly parting to fine and very fine granular structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; few faint clay coats on ped faces and pore walls; few clay balls and very few fine cracks; common very fine and many fine vesicular pores; common fine and medium roots; common traces of dead roots; very strongly acid (field pH 5.0); clear, smooth boundary to Bto1.
Bto1	67-100	Red (2.5YR 4/6); clay; moderate fine and medium subangular blocky partially parting to fine and medium granular structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; common faint clay coats on ped faces and pore walls; few clay balls; common very fine and fine and few medium vesicular pores; common fine and medium roots; few traces of dead roots; very strongly acid (field pH 5.0); gradual, smooth boundary to Bto2.
Bto2	100-135	Red (2.5YR 4/6); clay; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; common faint clay coats on ped faces and pore walls; few clay balls and very few quartz fragments; many very fine, fine and common medium vesicular and few fine tubular pores; common fine and medium roots; few traces of dead roots; very strongly acid (field pH 5.0); gradual, smooth boundary to Bto3.
Bto3	135-165	Red (2.5YR 4/6); clay; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; common faint clay coats on ped faces and pore walls; few clay balls; many very fine, fine and common medium vesicular and few fine tubular pores; few fine and medium roots; few traces of dead roots; very strongly acid (field pH 5.0); gradual, smooth boundary to Bto4.
Bto4	165-195+	Red (2.5YR 4/6); clay; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; common faint clay coats on ped faces and pore walls; few clay balls; common very fine, fine and few medium vesicular and fine tubular pores; few fine and medium roots; few traces of dead roots; very strongly acid (field pH 5.0).

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Nong Bon 1 series

I Information on the site

Profile symbol	:	Nb1
Soil name	:	Nong Bon series (Nb)
Classification	:	Typic Kandiduox, very-fine, kaolinitic
Date of examination	:	January 5, 2008
Described by	:	Irb Kheoruenromne, Worachart Wisawapipat, Timtong Darunsontaya, Mahitorn Putiso, Natthapol Chittmart, Chutharmard Kaewmano and Bussayarat Mokmoor
Location	:	Watermelon filed on road from Bo Rai to Nong Bon, Moo 5 Ban Nong Maihom, Tambon Changtoon, Amphoe Bo Rai, Changwat Trad
Elevation	:	Approximately 87 m (MSL)
Map sheet number	:	4830 I Coordination : 48 0226774E, 1398728N

Landform

1. Physiographic position	:	Shoulder slope on lava corrosion undulating plain
2. Surrounding land form	:	Undulating
3. Slope on which profile site	:	4% Aspect : South
Land use	:	Watermelon field (active) left fallow under local grasses
Annual rainfall	:	Approximately 3,524 mm
Mean temperature	:	Approximately 27 ^{o}C
Climate	:	Tropical Monsoonal
Others	:	Agricultural mainly: bamboo, banana, other fruit tree and tropical rainforest species

II General information on the soil

Parent material	:	Residuum derived from weathered basalt
Drainage	:	Well drained
Permeability	:	Moderate
Runoff	:	Moderate
Depth of ground water	:	Deeper than 2 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-18	Brown (7.5 YR 4/4); clay; moderate fine and medium semi-angular blocky structure; slightly hard dry, firm moist, moderately sticky and moderately plastic; large krotovena in lower part of horizons and few fine crack; few vertical narrow cracks running across Ap depth and few clay balls; many very fine and common fine vesicular pores; common fine and fine roots; moderately acid (field pH 6.0); clear, smooth boundary to Bt1.
Bt1	18-40	Mixed strong brown (7.5YR 4/6) 50% and strong brown (7.5YR 5/6) 50%; clay; moderate fine and medium semi-angular blocky parting to fine granular structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; common faint clay coats on pore walls; few quartz fragments and common clay balls; many very fine and common fine vesicular and few fine tubular pores; few very fine and fine roots; few traces of dead roots; moderately acid (field pH 6.0); gradual, smooth boundary to Bt2.

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Bt2	40-65	Strong brown (7.5YR 4/6); clay; moderate fine and medium subangualr blocky parting to fine granular structure; slightly hard dry, firm moist, moderately sticky and moderately plastic; few faint clay coats on pore walls; few clay balls; common very fine and few vesicular and few fine tubular pores; few very fine and fine roots; moderately acid (field pH 6.0); clear, smooth boundary to Bt3.
Bt3	65-95	Dark yellowish brown (10YR 4/4); clay; moderate fine and medium subangualr blocky parting to fine granular structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; few faint clay coats on pore walls and ped faces; few clay balls; common very fine and fine vesicular and few medium vesicular and few fine tubular pores; few very fine and fine roots; moderately acid (field pH 6.0); clear, smooth boundary to Bto1.
Bto1	95-120	Dark yellowish brown (10YR 4/4); clay; moderate fine and medium subangualr blocky parting to fine granular structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; few faint clay coats on pore walls and ped faces; few clay balls; common very fine and fine and few medium vesicular and few various sizes tubular pores; few very fine and fine roots; moderately acid (field pH 6.0); gradual, smooth boundary to Bto2.
Bto2	120-150	Dark yellowish brown (10YR 4/4); clay; moderate fine and medium subangualr blocky parting to fine and medium granular structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; few faint clay coats on pore walls mainly; few clay balls; common very fine and fine and few medium vesicular and few various sizes tubular pores; very few very fine and fine roots; moderately acid (field pH 6.0); gradual, smooth boundary to Bto3.
Bto3	150-180	Mixed dark yellowish brown (10YR 4/4) 90% and (10YR 5/8) 10%; clay; moderate fine and medium subangualr blocky parting to fine and medium granular structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; few faint clay coats on pore walls mainly; few clay balls; few larger clay balls than those upper horizons; common very fine and fine vesicular and few medium vesicular and few fine tubular pores; very few very fine and fine roots; moderately acid (field pH 6.0); gradual, smooth boundary to Bto4.
Bto4	180-200+	Mixed dark yellowish brown (10YR 4/4) 90% and yellowish brown (10YR 5/8) 10%; clay; moderate fine and medium subangualr blocky parting to fine and medium granular structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; few faint clay coats on pore walls mainly; few larger clay balls than those upper horizons; common very fine and fine vesicular and few medium vesicular and few fine tubular pores; very few very fine and fine roots; moderately acid (field pH 6.0).

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Nong Bon 2 series

I Information on the site

Profile symbol	:	Nb2
Soil name	:	Nong Bon series (Nb)
Classification	:	Typic Kandiduox, very-fine, kaolinitic
Date of examination	:	January 5, 2008
Described by	:	Irb Kheoruenromne, Worachart Wisawapipat, Timtong Darunsontaya, Mahitorn Putiso, Natthapol Chittmart, Chutharmard Kaewmano and Bussayarat Mokmoor
Location	:	Para rubber plantation on road from Bo Rai to Nong Bon, Ban Trakoon Patana Moo 6, Tambon Chang Toon, Amphoe Bo Rai, Changwat Trad
Elevation	:	Approximately 165 m (MSL)
Map sheet number	:	4830 I Coordination : 48 0227269E, 1400542N

Landform

1. Physiographic position	:	Shoulder slope on lava corrosion rolling plain
2. Surrounding land form	:	Rolling
3. Slope on which profile site	:	3% Aspect : North
Land use	:	Para rubber plantation
Annual rainfall	:	Approximately 3,524 mm
Mean temperature	:	Approximately 27 ^{o}C
Climate	:	Tropical Monsoonal
Others	:	Agricultural mainly: bamboo and tropical orchards

II General information on the soil

Parent material	:	Residuum derived from weathered basalt
Drainage	:	Well drained
Permeability	:	Moderate
Runoff	:	Moderate
Depth of ground water	:	Deeper than 2 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-10	Mixed reddish brown (5YR 4/4) 80% and dark reddish gray (5YR 4/2) 20%; clay; moderate coarse and medium subangular blocky parting to fine granular structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; few clay balls; many very fine and fine vesicular and few fine tubular pores; common very fine, fine and medium roots; few traces of dead roots; moderately acid (field pH 6.0); clear, smooth boundary to Bt1.
Bt1	10-30	Reddish brown (5YR 4/4); clay; moderate fine and medium semi-angular blocky parting to fine granular structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; very few faint clay coats on pore walls; few clay balls; common very fine and fine vesicular and few fine tubular pores; common very fine, fine and medium roots; few traces of dead roots; moderately acid (field pH 6.0); clear, smooth boundary to Bt2.

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Bt2	30-50	Reddish brown (5YR 3/3); clay; moderate fine and medium subangular blocky parting to fine granular structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; very few faint clay coats on pore walls; few clay balls; common very fine and fine vesicular and few fine tubular pores; common very fine, fine and medium roots and few coarse roots; few traces of dead roots; moderately acid (field pH 6.0); clear, smooth boundary to Bt3.
Bt3	50-80	Reddish brown (5YR 3/4); clay; moderate fine and medium subangular blocky parting to fine granular structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; very few faint clay coats on pore walls; few clay balls of various sizes; common very fine and fine vesicular and few fine tubular pores; common very fine, fine and medium roots; few traces of dead roots; moderately acid (field pH 6.0); clear, smooth boundary to Bto1.
Bto1	80-110	Reddish brown (5YR 3/4); clay; moderate fine and medium subangular blocky parting to fine granular structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; very few faint clay coats on pore walls; few clay balls of various sizes; large basalt gravel in the horizon; common very fine and fine vesicular and few fine tubular pores; few very fine, fine and medium roots; few traces of dead roots; moderately acid (field pH 6.0); gradual, smooth boundary to Bto2.
Bto2	110-138	Reddish brown (5YR 3/4); clay; moderate fine and medium subangular blocky parting to fine and medium granular structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; few faint clay coats on pore walls; few clay balls; common very fine and fine vesicular and few fine tubular pores; few very fine, fine and medium roots; few traces of dead roots; moderately acid (field pH 6.0); gradual, smooth boundary to Bto3.
Bto3	138-170	Reddish brown (5YR 3/4); clay; moderate fine and medium subangular blocky parting to fine and medium granular structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; few faint clay coats on pore walls; few clay balls; common very fine and fine vesicular and few fine tubular pores; few very fine, fine and medium roots; few traces of dead roots; moderately acid (field pH 6.0); gradual, smooth boundary to Bto4.
Bto4	170-198+	Reddish brown (5YR 3/4); clay; moderate fine and medium semi-angular blocky parting to fine granular structure mainly; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; very few faint clay coats on pore walls; few clay balls; common very fine and fine vesicular and few fine tubular pores; few very fine, fine and medium roots; moderately acid (field pH 6.0).

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Kohong series

I Information on the site

Profile symbol	:	Kh
Soil name	:	Kohong series (Kh)
Classification	:	Typic Kandiudult, coarse-loamy, kaolinitic
Date of examination	:	February16, 2008
Described by	:	Irb Kheoruenromne, Worachart Wisawapipat, Natthapol Chittmart Timtong Darunsontaya and Darakorn Akahadsri
Location	:	Noen Ta Thoeng Hill Moo 8 Ban Bon Don, Tambon Na Chanang, Amphoe Meang, Changwat Chumporn
Elevation	:	Approximately 48 m (MSL)
Map sheet number	:	4830 I Coordination : 47 0526706E, 1166063N

Landform

1. Physiographic position	:	Shoulder spur hill slope
2. Surrounding land form	:	Undulating
3. Slope on which profile site	:	4-5% Aspect : 310
Land use	:	Tropical orchard, Longang, coconut, mangosteen and moist evergreen species remnant
Annual rainfall	:	Approximately 2,500 mm
Mean temperature	:	Approximately 27oC
Climate	:	Tropical Monsoonal
Others	:	Agricultural and settlements

II General information on the soil

Parent material	:	Colluvium derived from weathered sandstone
Drainage	:	Well drained
Permeability	:	Moderate
Runoff	:	Moderate
Depth of ground water	:	Deeper than 2 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-15/20	Mixed yellowish brown (10YR 5/6) 85% and brown (7.5YR 4/3) 15%; sandy loam; moderate weak fine and medium subangular blocky structure; slightly hard dry, friable moist, slightly sticky and non plastic; few variegated sands; few very fine and common fine vesicular and very few fine tubular pores; many very fine , fine and few medium and coarse roots; few traces of dead roots; strongly acid (field pH 5.5); clear, wave boundary to Bt1.
Bt1	20-50	Mixed reddish yellow (7.5YR 6/6) 85%, reddish yellow (5YR 6/8) 10% and brown (7.5YR 5/4) 5%; sandy loam; moderate weak fine and medium subangular blocky structure; slightly hard dry, friable moist, slightly sticky and non plastic; few faint clay bridges among sand grains; few variegated sands; few very fine and common fine vesicular and few tubular pores; common very fine, fine and medium and few coarse roots; very strongly acid (field pH 5.0); clear, smooth boundary to Bt2.
Bt2	50-80	Mixed reddish yellow (5YR 6/6) 50% and red (2.5 YR 5/6) 50%; sandy loam; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; few faint clay coats on pore walls and common faint clay bridges among sand grains; few variegated sands; very few very fine and common fine and common tubular pores; few very fine, fine, medium and coarse roots; few traces of dead roots; very strongly acid (field pH 5.0); clear, smooth boundary to Btc.

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Btc	80-105	Mixed red (2.5YR 5/6) 85%, reddish yellow (5YR 6/6) 10% and red (10R 4/8) 5%; very gravelly sandy clay loam; moderate fine and medium subangular blocky structure parting along medium surface; slightly hard dry, firm moist, moderately sticky and moderately plastic; common faint clay bridges among sand grains and common faint clay coats on pore walls; few variegated sands; very few very fine and few fine vesicular and tubular pores; few very fine and fine roots; common ferruginized rock fragments of various sizes and iron oxides nodules and few traces of dead roots; very strongly acid (field pH 5.0); clear, smooth boundary to Crt1.
Crt1	105-140	Mixed red (2.5YR 5/6) 90% and red (10R 4/8) 10%; very gravelly sandy clay loam; moderate fine and medium subangular blocky structure parting along fine surface; hard dry, firm moist, moderately sticky and moderately plastic; common faint clay coats on pore walls and ped faces; few variegated sands and few fine cracks; very few very fine and few fine vesicular and tubular pores; very few very fine and fine roots; few iron oxides nodules and common large weathered sandstone fragments and few traces of dead roots; very strongly acid (field pH 4.5); gradual, smooth boundary to Crt2.
Crt2	140-180+	Mixed red (2.5YR 5/6) 90% and red (10R 4/8) 10%; very gravelly sandy clay loam; moderate fine and medium subangular blocky structure parting along fine surface; hard dry, firm moist, moderately sticky and moderately plastic; common faint clay coats on pore walls and ped faces; few variegated sands and few fine cracks; very few very fine and few fine vesicular and tubular pores; very few very fine and fine roots; few traces of dead roots and common weathered ferruginized rock fragments very strongly acid (field pH 5.0)

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Khlong Chak series

I Information on the site

Profile symbol	:	Kc
Soil name	:	Khlong Chak series (Kc)
Classification	:	Typic Plinthudult, fine, kaolinitic
Date of examination	:	December 8, 2007
Described by	:	Irb Kheoruenromne, Mahitorn Putiso, Worachart Wisawapipat, Timtong Darunsontaya, Chutharmard Kaewmano, Natthapol Chittmart and Bussayarat Mokmoor
Location	:	Approximately 30 meters North of road from Sukhemvitt at Km 262.7, Ban Khao Wang Hin, Tambon Huai Yang, Amphoe Klang, Changwat Rayang
Elevation	:	Approximately 14 m (MSL)
Map sheet number	:	4830 I Coordination :47 0782291E, 1410991N
Landform		
1. Physiographic position	:	Dissected lower residual footslope
2. Surrounding land form	:	Undulating
3. Slope on which profile site	:	3% Aspect : 150o Azimuth
Land use	:	Para rubber plantation
Annual rainfall	:	Approximately 2,500 mm
Mean temperature	:	Approximately 27oC
Climate	:	Tropical Monsoonal
Others	:	Agricultural and settlements; Tropical fruit tree orchards: durian and lansat mainly, banana and betal nut

II General information on the soil

Parent material	:	Wash and local alluvium derived from meta sedimentary rocks namelyQuartzite and Phyllite
Drainage	:	Well drained
Permeability	:	Moderate
Runoff	:	Moderate
Depth of ground water	:	Deeper than 1.7 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-15/20	Mixed yellowish brown (10YR 5/4) 80% and brown (7.5YR4/2) 20%; sandy clay; strong fine and medium subangular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; few variegated sands; common very fine and fine vesicular and few fine tubular pores; common very fine, fine and medium roots; few traces of dead roots; very strongly acid (field pH 4.5); clear, abrupt boundary to Bt1.
Bt1	20-32	Mixed strong brown (7.5YR 5/6) 60%, light yellowish brown (10YR 6/4) 33%, brown (7.5YR 5/2) 5% and reddish yellow (5YR 6/6) 2%; sandy clay; strong medium and coarse semi-angular blocky structure; very hard dry, firm moist, moderately sticky and moderately plastic; common faint clay bridges among sand grains, and few faint clay coats on ped faces and pore walls; few variegated sands; few very fine and medium vesicular, few fine simple and dendritic tubular pores; few very fine, fine, medium and coarse roots; few traces of dead roots; very strongly acid (field pH 4.5); clear, smooth boundary to Bt2.

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Bt2	32-52	Mixed reddish yellow (7.5YR 6/6) 50% and yellowish red (5YR 5/6) 50%; sandy clay; strong fine and medium angular blocky structure; hard dry, slightly firm moist, moderately sticky and moderately plastic; common faint clay coats on pore walls and ped faces and few faint clay coats among sand grains; common variegated sands and few rock fragments; few very fine and fine vesicular and fine tubular pores; few very fine and fine roots; few traces of dead roots; very strongly acid (field pH 4.5); clear, smooth boundary to Bt3.
Bt3	52-88	Mixed yellowish red (5YR 5/6) 70%, reddish yellow (7.5YR 6/6) 25% and brown (7.5YR 5/2) 5%; sandy clay; strong fine and medium angular blocky structure; hard dry, slightly firm moist, moderately sticky and moderately plastic; common faint clay coats on pore walls and ped faces and few faint clay coats among sand grains; common variegated sands, few rock fragments and few very fine cracks; very few very fine and few fine vesicular tubular pores; few very fine and fine roots and few medium roots; very few traces of dead roots; very strongly acid (field pH 5.0); abrupt, smooth boundary to Btc1.
Btc1	88-100	Mixed yellowish red (5YR 5/6) 85% and reddish yellow (7.5YR 6/6) 15%; very gravelly sandy clay; weak fine and medium subangular blocky parting along nodules and concretion surfaces; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; few faint clay coats on pore walls, nodules and concretion surfaces; many Fe-Mn oxides nodules and concretions; common very fine and fine vesicular pores; very few very fine and fine roots; very few traces of dead roots; very strongly acid (field pH 5.0); gradual, smooth boundary to Btc2.
Btc2	100-120	Mixed reddish yellow (5YR 6/6) 85% and reddish yellow (7.5YR 6/6) 15%; very gravelly sandy clay; weak fine and medium subangular blocky parting along nodules and concretion surfaces; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; few faint clay coats on pore walls, nodules and concretion surfaces; many Iron-Manganese oxides nodules and concretions; sizes of nodules and concretions increase with depth; common very fine and fine vesicular pores; very few very fine and fine roots; very strongly acid (field pH 5.0); clear, smooth boundary to Btc3.
Btc3	120-145	Mixed light reddish brown (5YR 6/4) 82%, light gray (5YR 7/1) 10%, yellowish brown (10YR 5/8) 5% and red (2.5YR 4/6) 3%; very gravelly sandy clay; weak fine and medium subangular blocky parting along nodules and concretion surfaces; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; few faint clay coats on pore walls, nodules and concretion surfaces; many Iron-Manganese oxides nodules and concretions; sizes of nodules and concretions increase with depth; common very fine and fine vesicular pores; very few very fine and fine roots; very strongly acid (field pH 4.5); clear, smooth boundary to Bv.
Bv	145-165+	Mixed light reddish brown (5YR 6/4) 75%, light gray (5YR 7/1) 15%, yellowish brown (10YR 5/8) 5%, red (2.5YR 4/6) 3% and dark reddish brown (2.5YR 3/4) 2%; very gravelly sandy clay; weak fine and medium subangular blocky parting along nodules and concretion surfaces; hard dry, firm moist, slightly sticky and moderately plastic; few faint clay coats on pore walls, nodules and concretion surfaces; many Manganese oxides nodules and concretions; increase amounts of nodules and concretions from Btc3; common very fine and fine vesicular pores; very few very fine and fine roots and one coarse roots; very strongly acid (field pH 4.5).

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Fang Daeng series

I Information on the site

Profile symbol	:	Fd
Soil name	:	Fang daeng series (Fd)
Classification	:	Typic Kandiudult, fine-loamy, kaolinitic
Date of examination	:	October 2, 2002
Described by	:	Irb Kheoruenromne, Piboon Kanghae, Saowanuch Tawornpruek, Punyisa Trakoonyingcharoen, Sumitra Watana, Suphicha Thanachit, Thanapol Srisupha-olarn
Location	:	Ban Bang Jak, Tambon Chum Kho, Amphoe Pathiu, Changwat Chumphon
Elevation	:	Approximately 81 m (MSL)
Map sheet number	:	4830 I Coordination : 47 540716E, 1191351N

Landform

1. Physiographic position	:	Crestal slope of low hill
2. Surrounding land form	:	Undulating
3. Slope on which profile site	:	2% Aspect : North-east
Land use	:	Rainforest species under para rubber
Annual rainfall	:	Approximately 2,500 mm
Mean temperature	:	Approximately 28^{o}C
Climate	:	Tropical Monsoonal
Others	:	Agricultural

II General information on the soil

Parent material	:	Residuum derived from clastic sedimentary rock
Drainage	:	Well drained
Permeability	:	Moderate
Runoff	:	Moderate
Depth of ground water	:	Deeper than 2 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-10	Mixed yellowish red (5YR 5/8) 50% and red (2.5YR4/6) 50%; sandy loam; moderate fine and medium subangular blocky structure; hard dry, firm moist, slightly sticky and slightly plastic; common very fine, fine and few medium vesicular and few fine simple tubular pores; common very fine and fine roots; few traces of dead roots; neutral (field pH 7.0); clear, smooth boundary to Bt1.
Bt1	10-30	Red (2.5YR 4/8); sandy clay loam; moderate fine and medium subangular blocky structure; hard dry, firm moist, slightly sticky and moderately plastic; common faint clay coats mainly on pore walls; common very fine, fine and few medium vesicular and few fine simple tubular pores; common very fine, fine and medium roots; few variegated sands; very strongly acid (field pH 5.0); clear, smooth boundary to Bt2.
Bt2	30-50	Red (2.5YR 4/8); sandy clay loam; moderate fine and medium subangular blocky structure; hard dry, firm moist, slightly sticky and moderately plastic; common faint clay coats on ped faces and mainly on pore walls; common very fine, fine and medium vesicular and few fine simple tubular pores; common very fine, fine and medium roots; very strongly acid (field pH 5.0); clear, smooth boundary to Bt3.

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Bt3	50-78	Red (2.5YR 4/8); sandy clay loam; moderately weak fine and medium subangular blocky structure; hard dry, slightly firm moist, slightly sticky and moderately plastic; common faint clay coats on ped faces and mainly on pore walls; many very fine, fine and common medium vesicular and few fine simple tubular pores; common very fine, fine and medium roots; few fine quartz fragments and variegated sands; very strongly acid (field pH 5.0); gradual, smooth boundary to Bt4.
Bt4	78-103	Red (2.5YR 4/8); sandy clay; moderately weak fine and medium subangular blocky; hard dry, slightly firm moist, slightly sticky and moderately plastic; few faint clay coats on ped faces and pore walls; common very fine, fine and few medium vesicular and few fine simple tubular pores; common very fine, fine and medium roots; few fine variegated sands; very strongly acid (field pH 5.0); clear, smooth boundary to Bt5.
Bt5	103-132	Red (2.5YR 4/8); sandy clay; moderately weak fine and medium subangular blocky structure; hard dry, firm moist, slightly sticky and moderately plastic; few faint clay coats on ped faces and pore walls; common very fine, fine and medium vesicular and very few fine simple tubular pores; common very fine, fine and medium roots; few fine variegated sands; very strongly acid (field pH 5.0); gradual, smooth boundary to Bt6.
Bt6	132-165	Red (2.5YR 4/8); sandy clay; moderately weak fine and medium semi-angular blocky structure; hard dry, firm moist, slightly sticky and moderately plastic; few faint clay coats on ped faces and pore walls; many very fine, fine and common medium vesicular and few fine simple tubular pores; few very fine and fine roots; very few fine variegated sands; very strongly acid (field pH 5.0); gradual, smooth boundary to Bt7.
Bt7	165-200	Red (2.5YR 4/8); sandy clay; moderately weak fine and medium semi-angular blocky structure; hard dry, firm moist, slightly sticky and moderately plastic; few faint clay coats on ped faces and pore walls; many very fine, fine and common medium vesicular and few fine simple tubular pores; very few very fine and fine roots; few trace of dead roots, few fine variegated sands; very strongly acid (field pH 5.0).

Remark: Generally, there are termite nest holes in all horizons and highly concentrated in Ap.

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Krabi series

I Information on the site

Profile symbol	:	Kbi
Soil name	:	Krabi series (Kbi)
Classification	:	Typic Kandiudult, fine-loamy, kaolinitic
Date of examination	:	September 24, 2002
Described by	:	Irb Kheoruenromne, Piboon Kanghae, Saowanuch Tawornpruek, Punyisa Trakoonyingcharoen, Sumitra Watana, Suphicha Thanachit and Thanapol Srisupha-olarn
Location	:	Oil palm possessing platform, Ban Nai Rai, Tambon Nong Talay, Amphoe Muang, Changwat Krabi
Elevation	:	Approximately 87 m (MSL)
Map sheet number	:	4725 II Coordination : 47 478114E, 0897565N

Landform

1. Physiographic position	:	Shoulder slope of low hill
2. Surrounding land form	:	Mainly rolling
3. Slope on which profile site	:	7% Aspect : South-east
Land use	:	Tropical rainforest species, para rubber, rambutan, coconut, tree legume
Annual rainfall	:	Approximately 2,600 mm
Mean temperature	:	Approximately 28^{o}C
Climate	:	Tropical Monsoonal
Others	:	-

II General information on the soil

Parent material	:	Residuum and colluvium derived from clastic rocks
Drainage	:	Well drained
Permeability	:	Moderate
Runoff	:	Moderate
Depth of ground water	:	Deeper than 2 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-20	Yellowish red (5YR 4/6); sandy clay loam; moderate fine and medium subangular blocky structure; slightly hard dry, firm moist, slightly sticky and moderately plastic; common distinct clay bridges among sand grains and clay coats on ped faces and pore walls; common very fine, fine vesicular and few fine simple tubular pores; many very fine, fine and common medium and coarse roots; common traces of dead roots; very strongly acid (field pH 5.0); clear, smooth boundary to Bt1.
Bt1	20-44	Red (2.5YR 4/6); sandy clay loam; moderate fine and medium semi-angular blocky structure; slightly hard dry, firm moist, slightly sticky and moderately plastic; common distinct clay bridges among sand grains and clay coats on ped faces and pore walls; common very fine, fine vesicular and few fine simple tubular pores; common very fine, fine, medium and coarse roots; few fine variegated sands, large termite nest across; very strongly acid (field pH 4.5); clear, smooth boundary to Bt2.

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Bt2	44-65	Yellowish red (5YR 4/6); sandy clay loam; moderate fine and medium semi-angular blocky structure; slightly hard dry, firm moist, slightly sticky and moderately plastic; common distinct clay bridges among sand grains and clay coats on ped faces and pore walls; common very fine, fine vesicular and common fine simple tubular pores; common very fine, fine, medium and many coarse roots; few fine variegated sands; very strongly acid (field pH 4.5); clear, smooth boundary to Bt3.
Bt3	65-93	Red (2.5YR 4/8); sandy clay loam; moderate fine and medium semi-angular blocky structure; slightly hard dry, firm moist, slightly sticky and moderately plastic; common distinct clay bridges among sand grains and clay coats on ped faces and pore walls (similar to Bt2 but more clay coats on ped faces and pore walls); common very fine, fine, medium vesicular and few fine simple tubular pores; common very fine, fine and many medium and coarse roots; few fine variegated sands; very strongly acid (field pH 4.5); clear, smooth boundary to Bt4.
Bt4	93-123	Red (2.5YR 4/8); sandy clay loam; moderately weak fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; common distinct clay bridges among sand grains and clay coats on ped faces and pore walls (similar to Bt3 but size of clay bridges is smaller than appears than that it); many very fine, fine and medium vesicular pores; common very fine, fine and many medium and coarse roots; few fine variegated sand; strongly acid (field pH 5.5); clear, smooth boundary to Bt5.
Bt5	123-153	Red (2.5YR 4/8); clay loam; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; common distinct clay coats on ped faces and pore walls and common spots of distinct clay bridges among sand grains; many very fine, fine, common medium vesicular and common very fine and fine simple tubular pores; common very fine, fine, medium and coarse roots; few very fine variegated sand; strongly acid (field pH 5.5); clear, smooth boundary to Bt.
Bt6	$153\text{-}190^{+}$	Red (2.5YR 4/6); sandy clay; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; common distinct clay bridges among sand grains and clay coats on ped faces and pore walls; many very fine, fine, common medium vesicular and few fine simple tubular pores; few very fine, fine, common medium and few coarse roots; few very fine variegated sands; strongly acid (field pH 5.5).

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Sadao series

I Information on the site

Profile symbol	:	Sd
Soil name	:	Sadao series (Sd)
Classification	:	Typic Kandiudult, fine-loamy, kaolinitic
Date of examination	:	October 2, 2002
Described by	:	Irb Kheoruenromne, Piboon Kanghae, Saowanuch Tawornpruek, Punyisa Trakoonyingcharoen, Sumitra Watana, Suphicha Thanachit, Thanapol Srisupha-olarn
Location	:	East of Nong Sai-Thung Wao Lan road at 3.5 km in KMITL (Chumphon Campus), Tambon Chum Kho, Amphoe Pathiu, Changwat Chumphon
Elevation	:	Approximately 72 m (MSL)
Map sheet number	:	4829 IV Coordination : 47 540123E, 186051N

Landform

1. Physiographic position	:	High local alluvial terrace
2. Surrounding land form	:	Undulating
3. Slope on which profile site	:	2% Aspect : West
Land use	:	Coconut
Annual rainfall	:	Approximately 2,500 mm
Mean temperature	:	Approximately 28°C
Climate	:	Tropical Monsoonal
Others	:	Agricultural

II General information on the soil

Parent material	:	Local alluvium derived from clastic sedimentary rock
Drainage	:	Well drained
Permeability	:	Moderate
Runoff	:	Moderate
Depth of ground water	:	Deeper than 2 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-15	Dark yellowish brown (10YR 4/4); sandy loam; moderate fine and medium subangular blocky structure; soft dry, friable moist, slightly sticky and slightly plastic; many very fine and fine vesicular pores; many very fine, fine and medium, few coarse roots; traces of dead roots, few charcoal fragments; slightly acid (field pH 6.5); clear, smooth boundary to E.
E	15-27	Yellowish red (5YR 4/6); sandy loam; moderately weak fine and medium subangular blocky structure; soft dry, friable moist, slightly sticky and slightly plastic; many very fine, fine and common medium vesicular and few fine simple tubular pores; many very fine, fine and medium, few coarse roots; very few very fine variegated sands; strongly acid (field pH 5.5); clear, smooth boundary to Bt1.

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Bt1	27-57	Yellowish red (5YR 5/8); sandy loam; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; few faint clay coats mostly on pore walls and common faint clay bridges among sand grains; common very fine, fine and few medium vesicular and few fine simple tubular pores; common very fine, fine and medium, few coarse roots; few fine variegated sands; strongly acid (field pH 5.5); clear, smooth boundary to Bt2.
Bt2	57-81	Yellowish red (5YR 5/8); sandy clay loam; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; few faint clay coats mostly on pore walls and common faint clay bridges among sand grains (similar to Bt1 but clay coats and clay bridges more than that it); common very fine, fine and medium vesicular and few fine simple tubular pores; common very fine, fine and medium, few coarse roots; few fine variegated sands; strongly acid (field pH 5.5); gradual, smooth boundary to Bt3.
Bt3	81-110	Red (2.5YR 5/8); sandy clay loam; strong fine and medium semi-angular blocky structure; slightly hard dry, firm moist, slightly sticky and slightly plastic; few faint clay coats on ped faces and pore walls and few faint clay bridges among sand grains; many very fine, fine and common medium vesicular and few fine simple tubular pores; common very fine, fine and medium, few coarse roots; few spots of fecal accumulation of soil fauna, few fine variegated sands; strongly acid (field pH 5.5); gradual, smooth boundary to Bt4.
Bt4	110-130	Red (2.5YR 5/8); sandy clay loam; moderate fine and medium semi-angular blocky structure; slightly hard dry, firm moist, slightly sticky and moderately plastic; few faint clay coats mostly on pore walls and few faint clay bridges among sand grains; many very fine, fine and common medium vesicular and few fine simple tubular pores; common very fine, fine and medium, few coarse roots; few fine variegated sands; very strongly acid (field pH 5.0); clear, smooth boundary to Bt4.
Bt5	130-165	Red (2.5YR 4/8); sandy clay loam; strong fine and medium semi-angular blocky structure; hard dry, firm moist, slightly sticky and moderately plastic; few faint clay coats mostly on pore walls and few faint clay bridges among sand grains; common very fine, fine and few medium vesicular and few fine simple tubular pores; few very fine, common fine and medium roots; few traces of dead roots, few fine variegated sands; very strongly acid (field pH 5.0); gradual, smooth boundary to Bt6.
Bt6	165-202	Red (2.5YR 4/8); sandy clay loam; moderate fine and medium semi-angular blocky structure; slightly hard dry, firm moist, slightly sticky and moderately plastic; few faint clay coats mostly on pore walls and few faint clay bridges among sand grains; many very fine, common fine and medium vesicular and few fine simple tubular pores; few very fine, common fine and medium roots; few fine variegated sands; very strongly acid (field pH 5.0).

Remark: Bt2 has a light sandy clay loam texture.

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Chumphon series

I Information on the site

Profile symbol	: Cp
Soil name	: Chumphon series (Cp)
Classification	: Typic Plinthudult, loamy-skeletal, mixed, semiactive
Date of examination	: February 3, 2001
Location	: Approximately 30 km. West of Phetchakasem road at Km 441.7, Ban Tam Chaiyapruek, Tambon Khao Chaiyaraj, Amphoe Pathiu, Chumphon Province
Elevation	: Approximately 125 m (MSL)
Map sheet number	: 4830 IV Coordination: 47 532040E, 1209079N
Landform	
1. Physiographic position	: Erosional terrace
2. Surrounding land form	: Rolling
3. Slope on which profile site	: 11% Aspect: E 35o S (NW-facing)
Land use	: Para-rubber plantation
Annual rainfall	: 1,883 mm Mean temperature: 26.8°C
Climate	: Tropical monsoon

II General information on the soil

Parent material	: Local wash over residuum derived from metasedimentary rocks (phyllite and quartzite)
Drainage	: Well drained
Permeability	: Moderate
Runoff	: Medium
Depth of ground water	: Deeper than 2 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-14	Dark yellowish brown (10YR 4/4); clear many fine distinct strong brown (7.5YR 5/8) mottles; sandy loam; moderate fine and medium subangular blocky structure; slightly hard dry, firm moist, slightly sticky and slightly plastic; few faint clay coats on ped faces and pore walls; common very fine and fine vesicular and few fine simple tubular pores; many very fine, fine and medium roots; some traces of dead roots; strongly acid (field pH 5.5); clear and smooth boundary to Bt.
Bt	14-32	Mixed light yellowish brown (10YR 6/4) 60% and brownish yellow (10YR 4/6) 40%; sandy clay loam; moderate fine and medium subangular blocky structure; hard dry, firm moist, slightly sticky and slightly plastic; few faint clay coats on ped faces and pore walls; many very fine and fine vesicular and few fine simple tubular pores; common very fine, fine and medium roots; few fine iron oxide nodules and concretions; strongly acid (field pH 5.5); clear and smooth boundary to Btc.

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Btc	32-65	Mixed light yellowish brown (10YR 6/4) 30% and red (10R 4/8) 20%; weak red (10R 4/4) 15%, red (10R 4/6) 15%, dusky red (10R 3/3) 10% and black (10YR 2/1) 10% nodules; gravelly sandy clay; moderate fine and medium subangular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; common distinct clay coats and ferri-argillan on ped faces, pore walls and some on nodules and concretions surfaces; few very fine, fine vesicular pores; few very fine, fine roots; common 0.5-0.8 cmrounded to subrounded shaped hardened lateritic nodules; very strongly acid (field pH 5.0); clear and smooth boundary to Bv1**.**
Bv1	65-105/107	Mixed strong brown (7.5YR 4/6) 25%, light brownish gray (10YR 6/2) 15%, pale yellow (2.5Y 7/3) 15%, red (10R 4/8) 10%; dusky red (10R 3/2) 10%, dusky red (10R 3/3) 10% and brownish yellow (10YR 6/8) 5% nodules; very gravelly sandy clay; strong fine and medium subangular blocky structure parting along ped surfaces and ped (semi-hardened) accumulation surfaces; hard dry, firm moist, moderately sticky and moderately plastic; common distinct clay coats and ferri-argillan on ped faces and pore walls; few very fine, common fine, few medium vesicular and few very fine simple tubular pores; few very fine, fine roots; common 0.3-0.5 cm rounded shaped semi-hardened and hardened lateritic nodules; very strongly acid (field pH 5.0); clear and smooth boundary to Bv2.
Bv2	107-150	Mixed pale brown (10YR 6/3) 25% and yellowish brown (10YR 5/8) 10%, strong brown (7.5YR 4/6) 10%, 10YR 7/2, 5% and 10YR 2/1, 5%; red (10R 4/6) 20% and red (10R 4/8) 15% soft plinthites; dusky red (10R 3/3) 10% semi-hardened nodules; gravelly sandy clay; moderate fine and medium subangular blocky structure parting along ped and semi-hardened accumulation surfaces; hard dry, firm moist, moderately sticky and moderately plastic; common distinct clay coats and ferri-argillan on ped faces and pore walls; few very fine, common fine, few medium vesicular pores; few very fine, fine roots; partially soft plinthite segregations along few 0.3-0.5 cm rounded shaped semi-hardened lateritic nodules; very strongly acid (field pH 5.0); clear and smooth boundary to Bv3.
Bv3	150-170/175	Mixed light gray (2.5Y 7/1) 50%, yellowish brown (10YR 5/8) 5% and strong brown (7.5YR 4/6) 5%; red (10R 4/8) 15%, dark red (2.5YR 4/8) 10%, brownish yellow (10YR 6/8) 10% and yellowish red (5YR 4/6) 5% soft plinthites; sandy clay; moderate fine and medium subangular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; common distinct clay coats and ferri-argillan on ped faces and pore walls; few very fine, fine vesicular pores; few very fine, fine roots; common fine cracks; common generally various size of soft plinthite separations; very strongly acid (field pH 5.0); clear and smooth boundary to BCrv.
BCrv	175-200+	Light gray (2.5Y 7/1) 70%; red (10R 4/8) 15% and yellowish brown (10YR 5/8) 10% and reddish yellow (7.5YR 6/8) 5% soft plinthites; gravelly sandy clay; strong medium and coarse semiangular blocky structure partially retaining weathered rock structure; hard dry, very firm moist, moderately sticky and moderately plastic; common distinct clay coats and ferri-argillan on ped faces and pore walls; few very fine, common fine vesicular pores; practically no roots; distinct soft plinthite separations with common retain weathered rock structure; very strongly acid (field pH 5.0).

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Huai Pong series

I Information on the site

Profile symbol	:	Hp
Soil name	:	Huai Pong series (Hp)
Classification	:	Typic Kandiudult, fine, kaolinitic
Date of examination	:	December 8, 2007
Described by	:	Irb Kheoruenromne, Mahithon Putiso, Worachart Wisawapipat, Timtong Darunsontaya, Chutamart Kaewmano, Natthapol Chittamart and Bussayarat Mokmoor
Location	:	At Cassava Field Trial Area in Huai Pong Field Crop Station, 1 km from Sukhumvit, Huai Pong crop station, Tambon Huai Pong, Amphoe Muang, Changwat Rayong
Elevation	:	Approximately 37 m (MSL)
Map sheet number	:	- Coordination : 47 0732184E, 1408969N
Landform		
1. Physiographic position	:	Lower midslope of residual hill
2. Surrounding land form	:	Undulating
3. Slope on which profile site	:	2% Aspect : 30˚ Asimuth
Land use	:	Cassava field trial plot
Annual rainfall	:	Approximately 1,329 mm
Mean temperature	:	Approximately 28^{o}C
Climate	:	Tropical Monsoonal
Others	:	Settlement and agricultural uses

II General information on the soil

Parent material	:	Residuum derived from weathered granite
Drainage	:	Well drained
Permeability	:	Moderate
Runoff	:	Moderate
Depth of ground water	:	210 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap1	0-18	Light brownish gray (10YR 6/2); sandy loam; moderate fine and medium subangular blocky structure; hard dry, slightly firm moist, slightly sticky and slightly plastic; common variegated sands; common very fine and fine vesicular pores; common very fine and fine roots; few traces of dead roots; very strongly acid (field pH 4.5); clear, smooth boundary to Ap2.
Ap2	18-35	Mixed pale brown (10YR 6/3) 60% and grayish brown (10YR 5/2) 40%; sandy loam; moderate fine and medium subangular blocky structure; hard dry, slightly firm moist, slightly sticky and slightly plastic; few faint clay bridges among sand grains; common variegated sands; common very fine and fine vesicular pores; common very fine and fine roots; few traces of dead roots; extremely acid (field pH 4.0); abrupt, smooth boundary to Bt1.

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Bt1	35-65	Mixed pale brown (10YR 6/3) 85% and light brownish gray (10YR 6/2) 15%; sandy clay loam; moderate fine and medium angular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; few clay bridges among sand grains, faint clay coats on pore walls and ped surfaces; common variegated sands, few quartz fragments; common very fine, fine vesicular and few fine tubular pores; few very fine, fine and medium roots; few traces of dead roots; extremely acid (field pH 4.0); gradual, smooth boundary to Bt2.
Bt2	65-98	Mixed Pale brown (10YR 6/3) 85% and light gray (10YR 7/2) 15%; sandy clay; moderate medium and coarse semi-angular blocky structure; hard dry, firm moist, very sticky and very plastic; common clay bridges among sand grains, common faint clay coats on pore walls and ped faces; common variegated sands, few quartz fragments; few very fine, common fine vesicular and few fine tubular pores; very few very fine, fine roots; few traces of dead roots; extremely acid (field pH 4.0); gradual, smooth boundary to Bt3.
Bt3	98-130	Mixed pale brown (10YR 6/3) 68% and light gray (10YR 7/2) 20%; few fine yellowish brown (10YR 5/6) < 12% mottles; sandy clay loam; moderate fine and medium semi-angular blocky structure; slightly hard dry, firm moist, moderately sticky and moderately plastic; few clay bridges among sand grains, faint clay coats on pore walls and ped faces; common variegated sands, few quartz fragments and few fine cracks; common very fine, fine vesicular and few fine tubular pores; very few very fine, fine roots; few traces of dead roots; very strongly acid (field pH 4.5); clear, smooth boundary to Bt4.
Bt4	130-150	Mixed pale brown (10YR 6/3) 78% and light gray (10YR 7/2) 20%; few fine yellowish brown (10YR 5/6) 2% mottles; sandy clay loam; moderate medium and coarse semi-angular blocky structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; few clay bridges among sand grains, faint clay coats on pore walls and ped faces; many variegated sands and few fine cracks; few very fine, common fine vesicular and few fine tubular pores; very few very fine, fine roots; few traces of dead roots; neutral (field pH 4.5); clear, smooth boundary to Bt5.
Bt5	150-172	Mixed pale brown (10YR 6/3) 70% and light gray (10YR 7/2) 20% ; common medium and coarse yellowish red (5YR 5/6) 10% and common medium brownish yellow (10YR 6/8) 10% mottles; sandy clay loam; moderate medium and coarse semi-angular blocky structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; few faint clay coats on pore walls mainly; many variegated sands, few fine cracks and few large spots of iron oxides coated sands; few very fine, common fine vesicular and few fine tubular pores; very few very fine, fine roots; few traces of dead roots; very strongly acid (field pH 4.5); clear, smooth boundary to Bt6.
Bt6	172-200+	Mixed very pale brown (10YR 7/4) 55% and light gray (10YR 7/2) 20%; common medium and coarse brownish yellow (10YR 6/8) 10% and common medium and coarse red (2.5YR 4/8) 15% mottles; slightly gravelly sandy 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, faint clay coats on pore walls and ped faces; few variegated sands and quartz fragments; few very fine, common fine medium vesicular and few fine tubular pores; practically no roots; common large spots of iron oxides coated sands; very strongly acid (field pH 4.5).

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Sattahip series

I Information on the site

Profile symbol	:	Sh
Soil name	:	Sattahip series (Sh)
Classification	:	Typic Kandiudult coarse-loamy, kaolinitic
Date of examination	:	December 22, 2007
Described by	:	Irb Kheoruenromne, Mahitorn Putiso, Worachart Wisawapipat, Timtong Darunsontaya, Chutharmard Kaewmano, Natthapol Chittmart and Bussayarat Mokmoor
Location	:	Ban Mab Fug Thong, Tambon Huay Yai, Amphoe Bang La Moong, Changwat Chonburi
Elevation	:	Approximately 80 m (MSL)
Map sheet number	:	4745 IV Co-ordinate: 47P 0718656E, 1411195N
Landform		
1. Physiographic position	:	Dissected lower Footslope
2. Surrounding landform	:	Undulating
3. Slope on which profile site	:	1% Aspect : 110° Azimuth (East south)
Land use	:	Cassava, Marigold, Pararubber, Coconut
Annual rainfall	:	Approximately 1,203 mm
Mean temperature	:	Approximately 28.7 °C
Climate	:	Tropical Monsoonal
Others	:	Settlement and agricultural

II General information on the soil

Parent material	:	Mixed wash and local alluvium derived from meta sedimentary rocks and granite
Drainage	:	Well drained
Permeability	:	Moderate
Runoff	:	Moderate
Depth of ground water	:	Deeper than 2.0 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap1	0-10	Mixed grayish brown (10YR 5/2) 80% and very dark gray (10YR 3/1) 20%; loamy fine sand; moderate weak fine and medium subangular blocky structure; slightly hard dry, friable moist, slightly sticky and slightly plastic; common variegated sand; many very and fine vesicular pores; many very fine roots, few traces of dead roots; strongly acid (field pH 5.5); clear, smooth boundary to Ap2
Ap2	10-23	Mixed brown (10YR 5/3) 65%, very pale brown (10YR 7/4) 20% and very dark gray (10YR 3/1) 15%; loamy fine sand; moderate fine and medium semi-subangular blocky structure; slightly hard dry, friable moist, slightly sticky and very plastic; common variegated sand and spot accumulation of organic matter; few very fine and common fine vesicular pores; few very fine and fine roots, few traces of dead roots; strongly acid (field pH 5.5); clear, smooth boundary to AB

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AB	23-42	Mixed brown (10YR 5/3) 60%, dark grayish brown (10YR 4/2) 20% and light brown (7.5YR 6/4) 20%; sandy loam; moderate fine and medium semi-angular blocky structure; hard dry, friable moist, slightly sticky and slightly plastic; few faint spotted clay bridges among sand grains; common variegated sands and spotted accumulation of organic matter, few vary fine and common fine vesicular pores, few very fine and fine roots; few charcoal fragments; strongly acid (field pH 5.5); clear, smooth boundary to Bt1.
Bt1	42-75	Mixed brown (10YR 5/3) 90% and light yellowish brown (10YR 6/4) 10%; sandy loam; moderately weak fine and medium subangular blocky structure; slightly hard dry, friable moist, slightly sticky and slightly plastic; few faint spotted clay bridges among sand grains; common variegated sands and spotted accumulation of organic matter, few vary fine and common fine vesicular pores, few very fine and fine roots; strongly acid (field pH 5.5); clear, smooth boundary to Bt2.
Bt2	75-100	Mixed pale brown (10YR 6/3) 70%, brown (10YR 5/3) 20% and very dark gray (10YR 3/1) 10%; sandy loam; moderately weak fine and medium subangular blocky structure; slightly hard dry, friable moist, slightly sticky and slightly plastic; few faint spotted clay bridges among sand grains; common variegated sands, few vary fine and common fine vesicular pores, few very fine and fine roots, a large krotovinas as a longitudinal band; moderately acid (field pH 6.0); clear, smooth boundary to Bt3.
Bt3	100-130	Mixed very pale brown (10YR 7/3) 70% and brown (10YR4/3) 30%; sandy loam; moderately weak fine and medium subangular blocky structure; soft dry, friable moist, slightly sticky and slightly plastic; few faint spotted clay bridges among sand grains; common variegated sands and spot accumulation of quartz fragments and sizes of quartz fragments increase; few very fine and common fine vesicular pores, few very fine and fine roots, a; very strongly acid (field pH 5.0); gradual, smooth boundary to Bt4.
Bt4	130-158	Mixed very pale brown (10YR 7/4) 70% and brown (10YR 5/3) 30%; sandy loam; weak fine and medium subangular blocky structure; soft dry, friable moist, slightly sticky and slightly plastic; few faint spotted clay bridges among sand grains; common variegated sands and spot accumulation of quartz fragments and sizes of quartz fragments increase; few very fine and common fine vesicular pores, very few very fine and fine roots; very strongly acid (field pH 5.0); clear, smooth boundary to Bt5.
Bt5	158-195+	Mixed light yellowish brown (10YR 6/4) 80% and brown (10YR 5/3) 20%; slightly gravel sandy loam; weak fine and medium subangular blocky structure; soft dry, friable moist, slightly sticky and slightly plastic; few faint clay coating on pore walls and nodule surfaces; common variegated sands, spot accumulation of quartz fragments and sizes of quartz fragments increase, and few spotted accumulation of iron and manganese oxides; few very fine and common fine vesicular pores; very few very fine and fine roots; a sizes of quartz fragments increase; very strongly acid (field pH 5.5).

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Thai Mueang1 series

I Information on the site

Profile symbol	:	Tim1
Soil name	:	Thai Mueang series (Tim)
Classification	:	Typic Peleudult, fine-loamy, siliceous, subactive
Date of examination	:	January 4, 2008
Described by	:	Irb Kheoruenromne, Mahitorn Putiso, Worachart Wisawapipat, Timtong Darunsontaya, Chutharmard Kaewmano, Natthapol Chittmart and Bussayarat Mokmoor
Location	:	Approximately 1 km South of Bowin Village turn off, Moo 5 Ban Khao Kayay, Tambon Bowin, Amphoe Sri Racha, Changwat Chon buri
Elevation	:	Approximately 137 m (MSL)
Map sheet number	:	4830 I Coordination : 47P 0722487E 1443621N
Landform		
1. Physiographic position	:	Shoulder slope of residual hill
2. Surrounding land form	:	Undulating
3. Slope on which profile site	:	4% Aspect : North
Land use	:	Cassava field
Annual rainfall	:	Approximately 1,203 mm
Mean temperature	:	Approximately 28.7^{o}C
Climate	:	Tropical Monsoonal
Others	:	Agricultural and settlements

II General information on the soil

Parent material	:	Residuum derived from weathered CG granite
Drainage	:	Well drained
Permeability	:	Moderate
Runoff	:	Moderate
Depth of ground water	:	Deeper than 2 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap1	0-12	Mixed brownish yellow (10YR 6/8) 50%, very pale brown (10YR 7/4) 45% and dark grayish brown (10YR 4/2) 5%; sandy loam; moderate fine and medium subangular blocky structure; hard dry, slightly firm moist, slightly sticky and slightly plastic; few variegated sands and common quartz fragments; common very fine, fine and few medium vesicular and fine tubular pores; common very fine and fine roots and few coarse roots; common traces of dead roots; moderately acid (field pH 6.0); clear, smooth boundary to Ap2.
Ap2	12-26	Mixed light yellowish brown (10YR 6/4) 70%, reddish yellow 7.5YR 6/6 20% and yellowish red 5YR 5/6 10%; sandy loam; moderate fine and medium semi-angular blocky structure; hard dry, slightly firm moist, slightly sticky and slightly plastic; few faint clay coats on pore walls; few variegated sands and common quartz fragments; common very fine and fine vesicular pores, few medium vesicular and fine tubular pores; common very fine and fine roots; few traces of dead roots; strongly acid (field pH 5.5); clear, smooth boundary to Bt1.

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Bt1	26-40	Mixed reddish yellow (5YR 6/8) 70% and reddish yellow (5YR 6/6) 30; sandy loam; moderate fine and medium semi-angular blocky structure; hard dry, slightly firm moist, slightly sticky and slightly plastic; few faint clay bridges among sand grains and few faint clay coats on pore walls; very few variegated sands and common quartz fragments; few very fine and common fine vesicular and few fine tubular pores; few very fine and fine roots; few traces of charcoal fragments; very strongly acid (field pH 5.0); clear, smooth boundary to Bt2.
Bt2	40-60	Mixed reddish yellow (5YR 6/8) 80% and reddish yellow (7.5YR 6/6) 20%; sandy loam; moderate fine and medium semi-angular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; few faint clay bridges among sand grains and few faint clay coats on pore walls; very few variegated sands and common quartz fragments; few very fine, fine and medium vesicular and few fine tubular pores; few very fine and fine roots; few charcoal fragments and few traces of dead roots; very strongly acid (field pH 5.0); gradual, smooth boundary to Bt3.
Bt3	60-80	Reddish yellow (5YR 6/8); coarse 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 and few faint clay coats on pore walls; very few variegated sands and common quartz fragments; few very fine, fine and medium vesicular and few fine tubular pores; few very fine and fine roots; few charcoal fragments and few traces of dead roots; strongly acid (field pH 5.5); gradual, smooth boundary to Bt4.
Bt4	80-110	Mixed reddish yellow (5YR 6/8) 90% and yellowish red (5YR 5/6) 10%; coarse 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 and few faint clay coats on pore walls; very few variegated sands and common quartz fragments; very few very fine, few fine and medium vesicular and very few fine tubular pores; few very fine and fine roots; very few traces of dead roots; strongly acid (field pH 5.5); clear , smooth boundary to Bt5.
Bt5	110-140	Reddish yellow (5YR 6/8); slightly gravelly coarse sandy loam; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; very few faint clay coats on pore walls; very few variegated sands and common quartz fragments; very few very fine, few fine and medium vesicular and very few fine tubular pores; few very fine and fine roots; very few traces of dead roots; strongly acid (field pH 5.5); clear, smooth boundary to Bt6.
Bt6	140-170	Mixed reddish yellow (5YR 6/8) 90% and brown (7.5YR 5/3) 10%; gravelly coarse sandy loam; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; very few faint clay coats on pore walls; very few variegated sands and common quartz fragments; very few very fine, few fine and medium vesicular and very few fine tubular pores; practically no roots; moderately acid (field pH 6.0); clear, smooth boundary to Bt7.
Bt7	170-200+	Mixed reddish yellow (5YR 6/8) 90% and reddish yellow (7.5YR 6/6) 10%; gravelly coarse sandy loam; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; very few faint clay coats on pore walls; very few variegated sands and many quartz fragments; very few very fine and fine, common medium vesicular and very few fine tubular pores; practically no roots; moderately acid (field pH 6.0)

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Thai Mueang2 series

I Information on the site

Profile symbol	:	Tim2
Soil name	:	Thai Mueang series (Tim)
Classification	:	Typic Kandiudult, fine-loamy, kaolinitic
Date of examination	:	January 4, 2008
Described by	:	Irb Kheoruenromne, Mahitorn Putiso, Worachart Wisawapipat, Timtong Darunsontaya, Chutharmard Kaewmano, Natthapol Chittmart and Bussayarat Mokmoor
Location	:	Approximately 200 m Northeast of road, Moo 2 Ban Khao Talad, Tambon Prong Ta Oeamw, Amphoe Wang Chan, Changwat Rayong
Elevation	:	Approximately 54 m (MSL)
Map sheet number	:	4830 I Coordination : 47P 0775040E 1428966N
Landform		
1. Physiographic position	:	Upper dissected footslope
2. Surrounding land form	:	Undulating
3. Slope on which profile site	:	2% Aspect : 140^{o} Azimuth
Land use	:	Para rubber plantation intercropped with pineapple
Annual rainfall	:	Approximately 1,850 mm
Mean temperature	:	Approximately 28.4^{o}C
Climate	:	Tropical Monsoonal
Others	:	Agriculture and settlements, banana, bamboo and local weeds

II General information on the soil

Parent material	:	Wash over residuum derived from weathered granite
Drainage	:	Well drained
Permeability	:	Moderate
Runoff	:	Moderate
Depth of ground water	:	Deeper than 2 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-21	Mixed brown (10YR 4/3) 70% and light yellowish brown (10YR 6/4) 30%; sandy loam; moderate fine and medium subangular blocky structure; slightly hard dry; slightly firm moist; slightly sticky and slightly plastic; many variegated sands; common very fine and fine vesicular pores; common very fine, fine and few medium and coarse roots; few charcoal fragments, few traces of dead roots; moderately acid (field pH 6.0); abrupt, smooth boundary to Bt1.
Bt1	21-45	Mixed light yellowish brown (10YR 6/4) 40%, brownish yellow (10YR 6/6) 40% and brown (10YR 4/3) 20%; sandy clay loam; moderate fine and medium semi-angular blocky structure; hard dry; slightly firm moist; sticky and plastic; few faint clay coats on pore walls and clay bridges among sand gains; common variegated sands; few very fine, common fine and few medium vesicular pores; common very fine, fine and few medium roots; few small ant's nests and few traces of dead roots; strongly acid (field pH 5.5); clear, smooth boundary to Bt2.

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Bt2	45-74	Mixed reddish yellow (7.5YR 6/6) 90% and brown (7.5YR 5/3) 10%; sandy clay loam; moderate fine and medium subangular blocky structure; hard dry; slightly firm moist; moderately sticky and moderately plastic; few faint clay coats on pore walls and clay bridges among sand gains; few variegated sands and quartz fragments; few very fine and common fine vesicular and few fine tubular pores; few very fine and common fine roots; very few small ant's nests; very strongly acid (field pH 5.0); gradual, smooth boundary to Bt3.
Bt3	74-104	Mixed reddish yellow (7.5YR 6/8) 80% and strong brown (7.5YR 5/6) 20%; sandy clay loam; moderate fine and medium subangular blocky structure; hard dry; slightly firm moist; moderately sticky and moderately plastic; common faint clay coats on ped faces and pore walls, and clay bridges among sand grains; common variegated sands and few quartz fragments; few very fine and common fine vesicular and few fine tubular pores; few very fine and fine roots; common large termite's nests; very strongly acid (field pH 5.0); gradual, smooth boundary to Bt4.
Bt4	104-140	Mixed reddish yellow (7.5YR 6/8) 71%, strong brown (7.5YR 5/6) 20%, yellowish red (5 YR 5/8) 7% and yellow (10 YR 7/6) 2%; sandy clay loam; moderate fine and medium subangular blocky structure; hard dry; firm moist; moderately sticky and moderately plastic; few faint clay coats on pore walls and common clay bridges among sand grains; common variegated sands and few quartz fragments and few krotovina; few very fine and fine and medium vesicular and few fine tubular pore; few very fine and fine roots; few large ant's nests and sand pockets; strongly acid (field pH 5.5); gradual, smooth boundary to Bt5.
Bt5	140-170	Mixed strong brown (7.5YR 5/6) 63%, reddish yellow (5 YR 6/8) 30%, yellowish red (5 YR 5/8) 5% and yellow (10 YR 7/6) 2%; slightly gravelly sandy clay loam; moderate fine and medium subangular blocky structure; slightly hard dry; slightly firm moist; moderately sticky and moderately plastic; few faint clay coats on pore walls and common clay bridges among sand grains; common variegated sands and few quartz fragments; few very fine and fine and medium vesicular and few fine tubular pores; few very fine and fine roots; few large ant's nests and few iron oxide nodules; strongly acid (field pH 5.5); clear, smooth boundary to Bv.
Bv	170-200+	Mixed brownish yellow (10YR 6/6) 91%, yellowish red (5 YR 5/8) 7% and yellow (10 YR 7/6) 2%; gravelly sandy clay; moderate fine and medium subangular blocky structure; very hard dry; firm moist; moderately sticky and moderately plastic; few faint clay coats on pore walls and common clay bridges among sand grains; few variegated sands and common iron oxides separations and nodules; very few very fine and few fine vesicular and tubular pores; few very fine and fine roots; strongly acid (field pH 5.5).

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Phang-nga series

I Information on the site

Profile symbol : Pga
Soil name : Phang-nga series: (Pga)
Classification : Typic Kandiudult, fine, kaolinitic
Date of examination : January 5, 2008
Described by : Irb Kheoruenromne, Mahithon Putiso, Worachart Wisawapipat, Timtong Darunsontaya, Chutamart Kaewmano, Natthapol Chittamart and Bussayarat Mokmoor
Location : Approximately 700 m Northwest of road from WC-K to Ban Chumchon Nai
Elevation : Approximately 24 m (MSL)
Map sheet number : Coordination : 47P 0779643E, 1423161N
Landform
1. Physiographic position : Lower coalescing
2. Surrounding land form : Undulating
3. Slope on which profile site : 3% Aspect : 230˚ Azimuth
Land use : Para rubber intercropped with pineapple (young para rubber)
Annual rainfall : Approximately 1,850 mm
Mean temperature : Approximately 28.4°C
Climate : Tropical Monsoonal
Others : Agricultural

II General information on the soil

Parent material : Wash and residuum derived from weathered granite
Drainage : Well drained
Permeability : Moderate
Runoff : Moderate
Depth of ground water : More than 2 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-20	Mixed grayish brown (10YR 5/2) 68%, light yellowish brown (10YR 6/4) 30% and very pale brown (10YR 7/2) 2%; 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 clay bridges among sand grains; few fine variegated sands; few very fine and common fine vesicular and few fine tubular pores; common very fine, fine and medium roots; common medium and few large pores and few traces of dead roots; extremely acid (field pH 4.0); abrupt, smooth boundary to Bt1
Bt1	20-48	Mixed very pale brown (10YR 7/4) 92%, grayish brown (10YR5/2) 5% and very pale brown (10YR 8/2) 3%; sandy clay loam; moderate fine and medium semi-angular blocky structure; hard dry, slightly firm moist, moderately sticky and moderately plastic; few faint clay coats on pore walls and clay bridges among sand grains; few fine variegated sands; few very fine and fine vesicular pores and few fine tubular pores; few very fine and fine roots; two large remnant of ant’s rest and few large pores and few trace of dead roots; extremely acid (field pH 4.5); clear, smooth boundary to Bt2

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Bt2	48-78	Mixed light yellowish brown (10YR 6/4) 80% and very pale brown (10YR 8/2) 20%, common fine and medium prominent reddish yellow (5YR 6/8), few fine distinct strong brown (7.5 YR 5/8) and few fine distinct brownish yellow (10YR 6/8) nodule; sandy clay loam; moderate fine and medium semi-angular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; common faint clay coats on ped faces and pore walls and few faint clay bridges among sand grains; few variegated sands, few fine cracks and charcoal fragments; few very fine and fine vesicular and few fine tubular pores; few very fine and fine roots; few traces ant's nest; extremely acid (field pH 4.5); clear, smooth boundary to Bt3.
Bt3	78-110	Mixed very pale brown (10YR 7/4) 75% and white (2.5Y 8/1) 10%; common fine distinct yellowish brown (10YR 5/8), common fine and medium distinct brownish yellow (10YR 6/8) and common fine and medium prominent reddish yellow (5 YR 6/8) nodules; sandy clay; moderate fine and medium semi-angular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; common faint clay coats on pore walls and ped faces and few faint clay bridges among sand grains; few variegated sands, few fine cracks and few fine soft iron oxides nodules; few very fine and fine vesicular and few fine tubular pores; very few very fine and fine roots; few vertical cracks across horizon thickness; extremely acid (field pH 4.0); clear, smooth boundary to Bt4.
Bt4	110-140	Mixed very pale brown (10YR 7/3), light gray (10YR 7/2) 10%, white (10YR 8/1) 7% and white (2.5Y 8/1) 3%, common fine distinct reddish yellow (7.5YR 6/8), few fine distinct brownish yellow (10YR 6/8) and common fine and medium prominent reddish yellow (5YR 6/8) nodule; sandy clay; moderate fine and medium subangular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; common faint clay coats on pore walls and ped faces and few faint clay bridges among sand grains; few fine variegated sands and few fine iron oxides nodules; common indistinct separations of clays and iron oxides; common very fine and fine vesicular, few medium vesicular and few fine tubular pores; very few very fine and fine roots; very strongly acid (field pH 5.0); clear, smooth boundary to Bt5.
Bt5	140-170	Mixed very pale brown (10YR 7/4) 62%, white (10YR 8/1) 15% and light brownish gray (10YR 6/2) 3%, common medium and coarse prominent red (2.5YR 5/6), few medium prominent yellowish red (5YR 5/8) and common fine and medium distinct yellowish brown (10YR 5/8) nodule; sandy clay; moderate fine and medium semi-angular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; common faint clay coats on pore walls and ped faces and few faint clay bridges among sand grains; few fine variegated sands, few fine iron oxides nodules and few fine cracks; common very fine and fine vesicular, few medium vesicular and few fine tubular pores; partically no roots; common indistinct separations of clays and iron oxides; very strongly acid (field pH 4.5); clear, smooth boundary to Bv.
Bv	170-200+	Mixed very pale brown (10YR 7/4) 50% and white (10YR 8/1) 20%, common medium prominent red (2.5YR 5/6), few fine distinct strong brown (7.5YR 5/8), and common fine and medium distinct yellowish brown (10YR 5/8) plinthite; slightly gravelly sandy clay; moderate fine and medium semi-angular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; common faint clay coat and ferri-argillan coats on pore walls and ped faces; few fine variegated sands, few fine iron oxides nodules and few fine cracks; few very fine, common fine and few medium vesicular and few fine tubular pores; partically no roots; common distinct separations of clays and iron oxides and some parts are semi-hardened; very strongly acid (field pH 5.0).

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Phuket series

I Information on the site

Profile symbol	:	Pk
Soil name	:	Phuket series (Pk)
Classification	:	Typic Plinthudult, fine, kaolinitic
Date of examination	:	January 6, 2008
Described by	:	Irb Kheoruenromne, Mahitorn Putiso, Worachart Wisawapipat, Timtong Darunsontaya, Chutharmard Kaewmano, Natthapol Chittmart and Bussayarat Mokmoor
Location	:	Mr. Narongwit's tropical fruit tree orchards, Ban Klong Nam Yen, Tambon Ta Khean Tong, Amphoe Khao Kitchagooch, Changwat Chantaburi
Elevation	:	Approximately 67 m (MSL)
Map sheet number	:	4830 I Coordination : 48 0178273E, 1424664N

Landform

1. Physiographic position	:	Dissected lower footslope
2. Surrounding land form	:	Undulating
3. Slope on which profile site	:	3% Aspect : 310
Land use	:	Irrigated tropical fruit orchard; Mangosteen, durian and rambutan etc.
Annual rainfall	:	Approximately 2,541 mm
Mean temperature	:	Approximately 27.5^{o}C
Climate	:	Tropical Monsoonal
Others	:	Agricultural

II General information on the soil

Parent material	:	Residuum derived from weathered CG granite
Drainage	:	Well drained
Permeability	:	Moderate
Runoff	:	Moderate
Depth of ground water	:	Deeper than 1.9 m at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-10/12	Mixed grayish brown (10YR5/2) 60% and yellowish brown (10YR 5/4) 40%; coarse sandy clay; moderate fine and medium subangular blocky structure; hard dry, slightly firm moist, moderately sticky and moderately plastic; very few faint clay coats on pore walls; very few variegated sands and few quartz fragments; common very fine, few fine vesicular and few fine tubular pores; common very fine and fine roots; few traces of dead roots; very strongly acid (field pH 5.0); clear, smooth boundary to Bt1.
Bt1	12-35	Mixed reddish yellow (7.5YR 6/8) 50%, yellowish brown (10YR 5/4) 40% and reddish yellow (5YR 6/6) 10%; gravelly coarse sandy clay; moderate fine and medium subangular blocky structure; hard dry, slightly firm moist, moderately sticky and moderately plastic; common faint clay coats on pore walls and ped faces; very few variegated sand and common quartz fragments; few very fine and few medium vesicular and fine tubular pores; few very fine and fine roots; very strongly acid (field pH 5.0); clear, smooth boundary to Bt2.

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Bt2	35-60	Mixed reddish yellow (7.5YR 6/6) 80% and reddish yellow (5YR 6/6) 20%; slightly gravelly coarse sandy clay; moderate fine and medium subangular blocky structure; hard dry, slightly firm moist, moderately sticky and moderately plastic; common faint clay coats on pore walls and ped faces; common quartz fragments and few coarse ferruginized rock nodules; few very fine, fine and medium vesicular and few fine tubular pores; very few very fine and fine roots; strongly acid (field pH 5.5); clear, smooth boundary to Bt3.
Bt3	60-80	Mixed yellowish red (5YR 5/6) 60% and strong brown (7.5YR 6/6) 20%, common fine distinct red (2.5YR 4/8) and common fine prominent yellow (10YR 7/8) plinthite; gravelly coarse sandy clay; moderate fine and medium subangular blocky structure; hard dry, slightly firm moist, slightly sticky and moderately plastic; common faint clay coats on pore walls and ped faces; common quartz fragments and few ferruginized rock nodules; few clay and iron oxides separations; few very fine, fine and medium vesicular and few fine tubular pores; very few very fine and fine roots; strongly acid (field pH 5.5); gradual, smooth boundary to Bt4.
Bt4	80-100	Mixed yellowish red (5YR 5/6) 75%, reddish yellow (7.5YR 6/6) 15%, brownish yellow (10YR 6/8) 5% and very pale brown (10YR 8/3) 5%, common medium distinct red (2.5YR 4/8) plinthite; very gravelly coarse sandy clay; moderate fine and medium subangular blocky structure also parting along ferruginized rock surfaces; hard dry, slightly firm moist, slightly sticky and moderately plastic; common faint clay coats and distinct ferri-argillan coats on pore walls and ped faces; common ferruginized rock nodules and quartz fragment; common clays and iron oxides separations; few very fine, fine and medium vesicular and few fine tubular pores; very few very fine and fine roots; strongly acid (field pH 5.5); clear, smooth boundary to Bv1.
Bv1	100-126	Mixed strong brown (7.5YR 5/6) 40% and yellowish red (5YR 5/6) 30%, common medium distinct red (2.5YR 4/6) and red (2.5YR 5/8), and common fine prominent yellowish red (10YR 5/8) plinthite; very gravelly coarse sandy clay; moderate fine and medium subangular blocky structure generally parting along nodules surfaces; hard dry, firm moist, moderately sticky and moderately plastic; common faint clay coats and distinct ferri-argillan coats on pore walls and ped faces; many iron oxides hard fragments and nodules; many clays and iron oxides separations and few fine cracks; few very fine, fine and medium vesicular and few fine tubular pores; practically no roots; strongly acid (field pH 5.5); clear, smooth boundary to Bv2.
Bv2	126-155	Mixed strong brown (7.5YR 5/6) 35% and yellowish red (5YR 5/6) 35%, common fine prominent red (10R 4/8) and common fine distinct yellowish red (10YR 5/8) plinthite; very gravelly coarse sandy clay; moderate fine and medium subangular blocky structure generally parting along nodules surfaces; hard dry, firm moist, moderately sticky and moderately plastic; common faint clay coats and distinct ferri-argillan coats on pore walls and ped faces; many iron oxides hard fragments and nodules; many clays and iron oxides separations and few fine cracks; few very fine, fine and medium vesicular and few fine tubular pores; practically no roots; strongly acid (field pH 5.5); clear, smooth boundary to Bv3.
Bv3	155-195+	Mixed strong brown (7.5YR 5/6) 30% and yellowish red (5YR 5/6) 30%, common distinct dark yellowish brown (10YR 4/6) and yellowish brown (10YR 5/8), common prominent yellow (10YR 8/8) and common faint strong brown (7.5YR 5/8) plinthite; very gravelly coarse sandy clay, very little fine earths; moderate fine and medium subangular blocky structure generally parting along nodules surfaces, typical plinthite sheet structure mainly; hard dry, firm moist, moderately sticky and moderately plastic; common faint clay coats and distinct ferri-argillan coats on pore walls and ped faces; many iron oxides hard fragments and nodules; few very fine, fine and medium vesicular and few fine tubular pores; practically no roots; very strongly acid (field pH 5.0).

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Appendix B
Methods of Laboratory Analyses

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Analysis of Whole Soil Samples

Physical Analyses

1. Particle size analysis

Particle size analysis was carried out to evaluate soil texture. A mass of 10 g air dried soil sample was pretreated with 30% 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^{o}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 millilitres of suspension was pipetted out from a depth of 10 cm for clay at appropriate times based on Stoke's Law (i.e. at 28^{o}C for <0.002 mm sized fraction sampling time at 10 cm depth is 6.5 hr). Suspensions were dried at 105^{o}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 ^{o}C for further analysis.

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2. Bulk density (BD)

Bulk density is the mass of dry solid per unit bulk volume of the soil. The bulk volume includes the volume of both solid and pore space. Bulk density varies with structural condition of the soil. It is often used as a measure of soil structure. The undisturbed clod sample (size of about 40 g oven–dry weight) was oven dried at 105°C. The clod and attached thread were weighed in and air the clod was then dipped into paraffin wax. The paraffin wax–coated clod was weighed in air and in water. The difference in these weights provides the weight of water that has same volume as the bulk volume of the paraffin wax–coated clod. The density of water and paraffin, weights of oven–dry clod, in air, clod plus paraffin coating in air and in water were used to calculate the bulk density which is reported in units of Mg m^{-3} (Blake and Hartge, 1986).

3. Specific surface area (SSA)

Specific surface area (SSA) of whole soil was measured using the N_2–BET method (Aylmore *et al*., 1970) with a Micrometric Gemini III 2375 surface analyzer. Accurately weighed with 4 decimals empty test tube and approximately weighed 0.5 g air–dry soil into the test tube. Degased the soil samples overnight and reweighed the soil sample plus tube. Load the sample tube on the surface area analyzer using the software.

Chemical Analyses

1. Soil pH

Soil pH was determined in water and 1 M KCl at a solid to solution ratio of 1:1. The contents were stirred with a glass rod for 30 minutes before measuring the pH by a standardized pH meter (Thomas, 1996; 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 Walkley 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

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sulphate (Nelson and Sommers, 1996). A weight of 0.5 g of soil (< 0.5 mm) was placed in a 250 mL Erlenmeyer flask. Five mL of 0.5 M $K_2Cr_2O_7$ 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 a 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 0.5 M $FeSO_4$ 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 5 mL of digestion mixture solution 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 add 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 M NaOH was added. Distill for 7 minutes, add 5 mL H_3BO_3 acid indicator for containing NH_3. Determine ammonium–N in the distillate by titration with 0.025 M H_2SO_4 until color changed from green to an end point of pink color.

4. Available phosphorus

A soil sample weighing 3 g was placed in the 250 mL flask and added Bray II extracting solution 30 mL, shake 40 second. 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 wave length 882 mili–micron. Standard solution at different concentrations also was determined.

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5. Extractable bases

The bases (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) that are extracted by NH_4OAc 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 1M NH_4OAc, 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 ($BaCl_2$–TEA) at pH 8.2 (Thomas, 1982). 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 (0.025M $BaCl_2$ H_2O and 0.2M 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 washings with 20 mL buffer solution and 5 washing with 20 mL of the replacing solution (0.25 M $BaCl_2$ H_2O and 0.4 mL of buffer solution in 1L). 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 M HCl. The acid was added drop by drop until the color changed from green to an end point of purplish red color. The amount of HCl consumed was used to calculate the extractable acidity expressed as cmol H^{+} 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, 1982; National Soil Survey Centre, 1996):

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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 10 g was placed in an Erlenmeyer flask, to which 50 mL of 1 M 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 washings with 25 mL of 1 M 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 washings 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 0.005 M H_2SO_4 until color changed from green to the pink end point. The volume of H_2SO_4 was 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 NH_4OAc extractable bases plus the $BaCl_2$–TEA extractable acidity (at pH 8.2) (National Soil Survey Center, 1996).

8. Effective cation exchange capacity (ECEC)

The ECEC was computed from the sum of NH_4OAc extractable bases plus the KCl extractable Al (National Soil Survey Centre, 1996).

9. Base saturation percentage (%BS)

Base saturation percentage by NH_4OAc at pH 7.0 is equal to the sum of bases extracted by NH_4OAc, divided by the CEC by NH_4OAc, and multiplied by 100. Base saturation percentage by sum of cations is equal to the sum of bases extracted by NH_4OAc, divided by the CEC by sum of cations, and multiplied by 100 (National Soil Survey Center, 1996).

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10. Extractable Al

Extractable Al is exchangeable aluminum extracted by 1 M KCl. It is a major constituent of exchangeable cations only in strongly acid soils with pH less than 5.0. It contributes to the effective cation exchangeable capacity (ECEC). A soil sample weighing 10 g was placed in 125 mL Erlenmeyer flask and 15 mL of 1 M KCl were added. The contents were stirred and allowed to equilibrate for 30 min. The contents were filtered by the Buchner funnel procedure and washed 3 times with 5–10 mL 1 M KCl before making the volume to 100 mL. An aliquot of 5 mL was pipetted into a 50–mL volumetric flaks, to which 2 mL of 1% Thioglycolic acid and 10 mL of aluminon reagent were added before making the volume to 50 mL with deionized water. The contents were placed in a boiling–water bath for 4 min and cooled down to room temperature, and then transferred to reading tube. Light transmittance was measured with a spectrophotometer at 535 µm and Al determined by reference to a standard curve.

11. Extractable Fe, Al, Mn

11.1. Dithionite–Citrate–Bicarbonate (DCB) extractable Fe, Al, Mn

The amounts of iron extracted from soils by various dissolution methods (so called specific reagents) are commonly taken to indicate particular forms of this element in soil. The results are useful in studies of soil classification, soil genesis and soil behavior. The method extracts virtually no Fe, Al or Mn from most crystalline silicate minerals, and thus provides an estimate of "free oxide" (i.e. non silicate Fe) in soils.

One gram of soil (< 0.5 mm) was weighed into a 100 mL centrifuge tube to which 45 mL of buffer solution (0.3 M Na–citrate + 0.1 M Na–bicarbonate) were added. The tube was then placed in a water bath at 80 °C. One gram of Na–dithionite powder was added to the tube, the mixture was stirred constantly for 1 minute and occasionally during next 15 minutes. Ten mL of NaCl saturated solution and 10 mL acetone were added to promote flocculation. The tube contents were centrifuged for 15 minutes at 2000 rpm. Clear supernatant was decanted into a 250 mL volumetric flask. This extraction procedure was repeated

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twice, then the volume was made up to 250 mL with deionized water and the solution was kept for further analysis. For determinination of iron by atomic absorption spectrophotometry (AAS), standard solutions of these elements were prepared in a matrix of extracting solution (Mehra and Jackson, 1960).

11.2. Oxalate extractable Fe, Al, Mn

A subsample of one gram of soil (< 0.5 mm) was weighed into a 250 mL centrifuge tube. 50 mL of 0.2 M ammonium oxalate solution at pH 3.0 were added to the tube. The tube was shaken for 4 h in darkness. Next five drops of 0.4% Superfloc were added to the tube, which was swirled and then centrifuged. Clear supernatant was kept for further analysis by AAS (McKeague and Day, 1966).

11.3. Pyrophosphate extractable Fe, Al, Mn

Crystalline oxides and silicates of Fe, Al and Mn, various organic complexes occur in soils. Pyrophosphate solution has been used to extract organic complexes of iron (McKeague, 1967).

A subsample of 1 g of soil (< 0.5 mm) was weighed into a 200 mL shaking tube and 100 mL of 0.1 M sodium pyrophosphate solution were added before shaking overnight. Fifty mL of solution were transferred into a 50 mL centrifuge tube, 3 drops of 0.4% Superfloc were added, and mixed thoroughly before centrifuging the tubes. Clear supernatant was kept for measuring iron by AAS.

12. Mineralogical analysis

Random powder XRD patterns of silt and grounded whole soil samples were scanned from 4–70° 2θ using a scan speed of 0.02^{o} min^{-1} on Philips PW–3020 diffractometer equipped with a graphite diffracted beam monochromater (CuKα operating at 50 kV and 20 mA). A semi–quantitative estimate of the relative proportions of minerals was obtained by comparing the ratio of integrated intensities of major reflections. Relative proportions of various minerals were calculated by comparing XRD peak intensities with the intensities of standard minerals. Minor corrections of spacing for peak shifts due to instrumental error were made by

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reference to reflections due to quartz, which was normally present in all samples (Klug and Alexander, 1974).

Analysis of Clay Samples

Cation Exchange Capacity (CEC)

Cation exchange capacity (CEC) was measured using 0.01 M silver thiourea solution at pH 4.7 to displace the exchangeable cations (Rayment and Higginson, 1992). This CEC method involves the equilibration of 0.1 g air-dry clay and 0.01 M $(AgTU)^+$ for 16 h, with end-over-end shaking, followed by centrifugation and analysis of the residual Ag^+ by AAS in the presence of La. It should not be used on samples where CEC values above ~30 cmol kg^{-1} are expected.

Specific Surface Area

The surface area of the kaolinite and iron concentrate samples was determined by BET nitrogen sorption method (Aylmore *et al*., 1970). Sample was degassed overnight at 105 ^{o}C and measurements made using a Micromeritrics Gemini III 2375 surface area analyzer

Mineralogical Analysis

X–ray diffraction analysis was used to identify and to make semiquantitative measurements of the crystalline mineral components of clay fraction. The clay fraction from sedimentation was pretreated using 4 treatments. The clay after Mg^{2+} and K^+ saturation were placed on the ceramic plates, dropped with ≈10% glycerol on the Mg^{2+} saturation plates for the glycerol treatment, and heated to 550 ^{o}C on K^+ saturation slide for heat treatment (Brown and Brindley, 1980). Minerals were determined for all horizons with X–ray diffraction (XRD) analysis using a Philips PW–3020 diffractometer with a graphite diffracted beam monochromator (CuKα 50 kV 20 mA). Clay fractions were scanned respectively from 4 to 45° 2θ and 4 to 65° 2θ, using a step size of 0.02° 2θ and a scan speed of 0.04° 2θ sec^{-1}. Relative proportions of various minerals were calculated by comparing the XRD peak intensity

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with the intensity for standard minerals (Klug and Alexander, 1974; Whittig and Allardice, 1986; Brown and Brindley, 1980).

Preparation of Kaolinite Concentrate

Free iron oxides were removed from the whole soil samples by a series of dithionite–citrate–bicarbonate (DCB) extractions following the procedure of Mehra and Jackson (1960). At this stage the sample was examined by XRD to confirm that it consisted almost entirely of kaolin group minerals and henceforth these purified soil materials are referred to as kaolins.

Preparation of Iron Concentrate

Soil samples were boiled in 5 M NaOH until complete dissolution of kaolinite, which is confirmed by X–ray diffraction patterns. And then, the samples are washed three times by 0.5 M HCl to ensure the complete removal of both sodalite and kaolinite. As a result of this work we became aware of the presence of considerable amounts of poorly crystalline material in the iron oxide concentrate produced by the caustic treatment.

Analysis of Iron Concentrate

X–Ray Diffraction (XRD) and Structuaral Analysis

X–ray diffraction (XRD) patterns of iron oxide concentrates were obtained using CuKα radiation with a Philips PW–3020 diffractometer equipped with a graphite diffracted beam monochromator.

Random powder patterns of kaolinites were obtained over the range of 4–70° 2θ with a step size of 0.02° 2θ and a scan speed of 0.04° per second to determine the degree of structural order of the kaolinite which is expressed as the HB index (Hughes and Brown, 1979). Accurate measurements of d values of kaolinite and iron oxides were made using the quartz present in samples as an internal standard. The semi–quantitative proportions of minerals were estimated by comparison of integrated areas of reflections with XRD patterns of standard minerals.

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Al Substitution in Iron Oxides

Random powder patterns of iron oxide concentrates were recorded from 4–70^o 2θ using a step size of 0.01^o and a scan speed of 0.25^o 2θ/min. For calculation of Al substitution in goethite, the *c* dimension (Å) was derived from d(110) and d(111) (Schulze 1984) and was used in the relationship molar Al/(Al+Fe) = 1462–483*c* (Schwertmann and Carlson 1994). For hematite, the *a* dimension was derived from d(110) and was used in the relationship molar Al/(Al+Fe) = 3141–623*a* (Schwertmann, 1988).

Crystal Size

Mean coherently diffracting length (MCD) for kaolinite and iron oxides was calculated from the width of reflections at half maximum using the Scherrer formula, after correction for instrument broadening (Schulze, 1984).

Analysis of Kaolinite

Cation Exchange Capacity (CEC)

Cation exchange capacity (CEC) was measured using 0.01 M silver thiourea solution at pH 4.7 to displace the exchangeable cations (Rayment and Higginson, 1992). This CEC method involves the equilibration of 0.1 g air-dry kaolin and 0.01 M $(AgTU)^+$ for 16 h, with end-over-end shaking, followed by centrifugation and analysis of the residual Ag^+ by AAS in the presence of La. It should not be used on samples where CEC values above ~30 cmol kg^{-1} are expected.

X-ray Fluorescence (XRF) Analysis

Major elements in the kaolin samples were determined using a Phillips PW1400 X-ray fluorescence (XRF) spectrometer fitted with a rhodium tube. 0.700 g of sample was fused with 7.000 g of lithium meta/tetraborate flux at 1050°C in a platinum crucible. The molten mixture was cast into a disc in a platinum-gold alloy mold. The element composition was determined by comparison with certified reference materials and the minimal spectrometer drift corrected by regular measurements of an external monitor sample. Matrix effects were corrected using α-factor provided by Phillips and adjusted

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for this sample preparation procedure (Karathanasis and Hajek, 1996; Norrish and Hutton, 1969).

Specific Surface Area

Specific surface area (SSA) of kaolin sample was measured using the N_2-BET method (Aylmore *et al.,* 1970) with a Micrometric Gemini III 2375 surface analyzer. Accurately weighed with 4 decimals empty test tube and also approximately 0.300 g air-dry kaolin sample into the test tube. Degased the soil samples overnight and reweighed the kaolin sample plus tube. Load the sample tube on the surface area analyzer using the software.

X-Ray Diffraction (XRD)

X-ray diffraction (XRD) patterns of the kaolins were obtained using CuKα radiation with Philips PW-3020 diffractometer equipped with a graphite diffracted beam monochromator. Random powder patterns were obtained over the range 4–65^o 2θ with step size of 0.02^o 2θ and a scan speed of 0.04^o per second to determine the degree of structural order of the kaolins expressed as the HB index (Hughes and Brown, 1979). Oriented kaolins were prepared on ceramic plates and XRD patterns 4–30^o 2θ were obtained after various pretreatments to aid identification of accessory minerals (Brown and Brindley, 1980). Accurate measurements of *d* values of kaolins were made using both NaCl and octacosane as internal standards (Brindley and Wan, 1974). Coherently scattering domain (CSD) size of kaolins was calculated from the width at half height of XRD reflections using the Scherrer equation (Klug and Alexander, 1974).

Transmission Electron Microscope (TEM) for Kaolin Samples

For analytical transmission electron microscopy (TEM), specimens were prepared by dispersed samples. A highly diluted suspension of the iron concentrated sample was prepared in distilled water and kaolin particles were dispersed by ultrasonic treatment. A drop of the suspension was deposited on a carbon-coated supported on a Cu grid and examined using a Jeol 2000 FX II electron microscope operated at 80 kV.

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Analysis of Soil Potassium

Forms of Soil Potassium

A sample of soil was then collected from each pot for chemical determination of various K forms and for XRD analysis of the clay fraction. Water soluble K was determined by extraction of 4 g soil with 20 mL deionized water for 1h with end-over-end shaking. Exchangeable K was determined by extraction in 1M NH_4OAc at pH 7.0 (Thomas, 1982). The NH_4OAc-K consisted of exchangeable K and water soluble K and will henceforth be referred to as exchangeable K in this paper. HNO_3-extractable K (HNO_3-K) was determined by boiling 2 g of soil in 20 mL 1M HNO_3 at 113°C for 25 min, followed by washing with 0.1M HNO_3 and making the final volume to 100 mL with deionized water (Pratt, 1987). The HNO_3-K includes exchangeable K. A measure of potentially available K defined as non-exchangeable K was determined as the difference between HNO_3-K and NH_4OAc-K (Pal et al., 2001). Total K in soils was determined using X-ray fluorescence spectrometry (Norrish and Hutton, 1969).

K Released by 0.3M NaTPB

Sodium tetraphenyl boron (NaTPB) is commonly used to study the kinetics of release of non-exchangeable K and the method used in the present research was modified from that of Schulte and Corey (1963, 1965). Potassium was extracted by shaking 1g of clay in 10 ml of 0.3M NaTPB for periods up to 168 hours. After the desired extraction period (2, 4, 16, 72 and 168 hours), a 1 ml aliquot of the extract with suspended clay was separated in order to determine mineralogical changes and K release. One milliliter of 1M NH_4OAc was immediately added to the aliquot to prevent continuing K exchange from the suspended clay and to block subsequent fixation of dissolved K. The KTPB precipitate was then dissolved in 50 ml of 70% acetone. The acetone was then collected from the sample by filtration and acidified with 5 ml 6M H_2SO_4. The resulting solution was heated on a hot plate for 2 hours at 60°C to concentrate the H_2SO_4 and was then made up to a final volume of 100 ml with deionized water. Potassium in this solution was determined with a flame photometer.

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Modelling K Release

The value of the exchangeable K in clay which was extracted by NH_4OAc was subtracted from the NaTPB-extractable K which includes exchangeable K and the data were then fitted to the following equations using Statistica software (Statsoft Inc, 2003):

Parabolic diffusion $k = a + bt^{1/2}$

Power function $k = at^b$ or $\log (k) = \log (a) + b \log (t)$

Elovich equation $k = a+b \log (t)$

where k is the amount of released K at time t, a and b are constants which are different for each equation. In these equations, the constant a will be referred to as the magnitude of the non-exchangeable K released from clay, the constant b is indicative of the rate of release of K and will be referred to as the rate constant.

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Appendix C
Table

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Appendix Table C1 Physical properties of Thai upland soils soils under tropical monsoonal climate.

Horizon	Depth (cm)	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Textural class[1/]	Bulk density (Mg m^{-3})	SSA[2/] (m^2 g^{-1})
Typic Kandiudox (Ak1)							
Ap	0-10	92	280	628	C	0.77	37
Bto1	10-30	48	80	872	C	1.03	43
Bto2	30-52	48	80	872	C	1.18	45
Bto3	52-80	47	49	904	C	1.16	46
Bto4	80-117	43	93	864	C	1.07	45
Bto5	117-148	44	89	868	C	1.13	47
Bto6	148-170	44	84	872	C	1.04	36
Bto7	170-200+	42	79	880	C	1.07	43
Typic Kandiudox (Ak2)							
Ap	0-17	132	76	792	C	1.25	35
Bto1	17-42	109	39	852	C	1.06	41
Bto2	42-70	59	17	924	C	1.08	42
Bto3	70-100	60	17	924	C	1.14	43
Bto4	100-135	55	77	868	C	1.10	45
Bto5	135-170	70	78	852	C	1.31	43
Bto6	170-200+	76	48	876	C	1.22	42
Rhodic Kandiudox (Ak3)							
Ap	0-18	320	96	584	C	1.36	24
Bto1	18-40	137	43	820	C	1.18	39
Bto2	40-60	120	80	800	C	1.19	40
Bto3	60-90	153	24	824	C	1.25	37
Bto4	90-123	171	69	760	C	1.26	36
Bo1	123-155	147	53	800	C	1.11	39
Bo2	155-190+	139	33	828	C	1.07	39
Kandiudalfic Eutrudox (Ptu)							
Ap	0-20	545	195	260	SCL	1.52	15
Bto1	20-46	333	75	592	C	1.55	32
Bto2	46-75	296	108	596	C	1.34	36
Bto3	75-104	291	137	572	C	1.25	38
Bo1	104-128	289	123	588	C	1.29	37
Bo2	128-155	297	59	644	C	1.32	36
Bo3	155-190$^+$	314	102	584	C	1.30	34
Rhodic Kandiudox (Ti1)							
Ap1	0-12	237	391	372	CL	0.82	71
Ap2	10-27	136	408	456	C	0.80	76
Bto1	27-52	44	153	804	C	0.87	79
Bto2	52-78	35	149	816	C	0.76	79
Bto3	78-96	35	232	733	C	0.80	79
Bo1	96-125	33	219	748	C	0.81	79
Bo2	125-160	30	135	836	C	0.77	80
Bo3	160-200	25	215	760	C	0.85	81
Typic Kandiudox (Ti2)							
Ap	0-14/16	264	301	436	C	0.79	62
Bto1	16-40	152	322	527	C	0.83	67
Bto2	40-70	84	231	685	C	0.81	70
Bto3	70-95	44	188	768	C	0.83	74
Bo1	95-125	48	188	764	C	0.84	75
Bo2	125-150	44	173	783	C	0.83	75
Bo3	150-175	42	162	796	C	0.88	75
Bo4	175-200	40	156	804	C	0.82	75

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Appendix Table C1 (Continued)

Horizon	Depth (cm)	Sand (g kg^{-1})	Silt	Clay	Textural class[1/]	Bulk density (Mg m^{-3})	SSA[2/] (m^2 g^{-1})
Typic Kandiudox (Ti3)							
Ap	0-15	81	389	531	C	1.10	70
Bo1	15-40	43	421	535	SiC	1.16	74
Bo2	42-67	44	215	741	C	1.18	80
Bto1	67-100	33	188	780	C	1.14	80
Bto2	100-135	34	159	807	C	1.22	80
Bto3	135-165	34	199	767	C	1.18	79
Bto4	165-195+	32	185	782	C	1.10	81
Typic Kandiudox (Nb1)							
Ap	0-18	176	366	458	C	1.11	60
Bt1	18-40	101	286	612	C	1.08	69
Bt2	40-65	101	216	683	C	1.07	69
Bt3	65-95	76	160	763	C	1.09	70
Bto1	95-120	84	116	800	C	1.12	69
Bto2	120-150	77	95	828	C	1.07	69
Bto3	150-180	66	186	748	C	1.09	70
Bto4	180-200+	65	125	811	C	1.17	72
Typic Kandiudox (Nb2)							
Ap	0-10	129	453	417	SiC	1.08	64
Bt1	10-30	72	416	512	SiC	1.06	71
Bt2	30-50	82	332	586	C	1.06	75
Bt3	50-80	53	215	732	C	1.09	82
Bto1	80-110	47	188	765	C	1.18	83
Bto2	110-138	43	149	808	C	1.11	83
Bto3	138-170	41	193	766	C	1.13	84
Bto4	170-198+	38	119	843	C	1.17	84
Typic Kandiudult (Kh)							
Ap	0-15/20	710	199	92	SL	1.58	2.2
Bt1	20-50	711	189	100	SL	1.68	2.7
Bt2	50-80	690	168	142	SL	1.63	4.2
Btc	80-105	607	150	243	SCL	nd	12
Crt1	105-140	417	146	437	C	1.98	22
Crt2	140-180+	440	163	397	C	2.03	23
Typic Plinthudult (Kc)							
Ap	0-15/20	452	144	404	C	1.46	17
Bt1	20-32	358	96	546	C	1.49	22
Bt2	32-52	324	75	602	C	1.33	25
Bt3	52-88	322	68	610	C	1.38	26
Btc1	88-100	290	79	631	C	1.72	28
Btc2	100-120	254	92	654	C	2.02	30
Btc3	120-145	282	78	640	C	1.72	28
Bv	145-165+	304	106	589	C	1.65	28
Typic Kandiudult (Fd)							
Ap	0-10	702	86	212	SCL	1.60	5.1
Bt1	10-30	634	122	244	SCL	1.78	7.8
Bt2	30-50	639	113	248	SCL	1.64	10
Bt3	50-78	604	100	296	SCL	1.67	11
Bt4	78-103	563	137	300	SCL	1.48	12
Bt5	103-132	567	117	316	SCL	1.49	12
Bt6	132-165	601	99	300	SCL	1.48	12
Bt7	165-200	551	145	304	SCL	1.52	13

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Appendix Table C1 (Continued)

Horizon	Depth	Sand	Silt	Clay	Textural class[1/]	Bulk density	SSA[2/]
	(cm)		(g kg^{-1})			(Mg m^{-3})	(m^2 g^{-1})
Typic Kandiudult (Kbi)							
Ap	0-20	729	195	76	SL	1.42	4.0
Bt1	20-44	626	138	236	SCL	1.50	5.6
Bt2	44-65	599	173	228	SCL	1.50	7.1
Bt3	65-93	598	130	272	SCL	1.55	7.4
Bt4	93-123	580	204	216	SCL	1.55	8.3
Bt5	123-153	595	169	236	SCL	1.51	8.2
Bt6	153-190$^+$	571	137	292	SCL	1.49	8.5
Typic Kandiudult (Sd)							
Ap	0-15	744	104	152	SL	1.35	2.0
E	15-27	739	169	92	SL	1.49	2.8
Bt1	27-57	758	66	176	SL	1.50	3.1
Bt2	57-81	689	67	244	SCL	1.48	7.0
Bt3	81-110	678	70	252	SCL	1.50	8.6
Bt4	110-130	639	97	264	SCL	1.57	10
Bt5	130-165	624	84	292	SCL	1.49	11
Bt6	165-202	604	88	308	SCL	1.51	12
Typic Plinthudult (Cp)							
Ap	0-14	700	178	122	GC	1.41	4.3
Bt	14-32	656	203	141	GC	1.47	33
Btc	32-65	554	147	299	GC	1.54	39
Bv1	65-105/107	479	227	294	GC	1.48	35
Bv2	107-150	371	222	407	GC	1.48	29
Bv3	150-170/175	287	142	571	GC	1.47	24
BCrv	175-200+	378	272	350	GC	1.55	21
Typic Kandiudult (Hp)							
Ap1	0-18	775	35	190	SL	1.75	4.8
Ap2	18-35	732	74	194	SL	1.75	5.9
Bt1	35-65	550	21	429	SC	1.67	14
Bt2	65-98	491	21	488	SC	1.59	16
Bt3	98-130	581	14	405	SC	1.62	14
Bt4	130-150	602	9	389	SC	1.65	8.8
Bt5	150-172	486	7	507	SC	1.57	14
Bt6	172-200+	374	55	571	C	1.53	22
Typic Kandiudult (Sh)							
Ap1	0-10	775	132	92	SL	1.47	1.1
Ap2	20-23	749	150	101	SL	1.71	2.0
AB	23-42	717	153	130	SL	1.74	3.3
Bt1	42-75	761	101	139	SL	1.64	3.6
Bt2	75-100	775	111	113	SL	1.61	4.8
Bt3	100-130	781	105	113	SL	1.79	3.4
Bt4	130-158	799	71	130	SL	1.49	2.8
Bt5	158-195+	753	96	151	SL	1.81	3.5
Typic Peleudult (Tim1)							
Ap1	0-12	359	536	104	LS	1.49	3.2
Ap2	12-26	751	98	151	SL	1.94	4.8
Bt1	26-40	682	188	130	SL	1.79	10
Bt2	40-60	686	82	232	SCL	1.67	8.8
Bt3	60-80	710	72	218	SCL	1.62	7.6
Bt4	80-110	726	68	206	SCL	1.71	8.6
Bt5	110-140	299	508	192	SL	1.76	9.7
Bt6	140-170	740	50	210	SCL	1.79	10
Bt7	170-200+	598	138	264	SCL	1.88	11

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Appendix Table C1 (Continued)

Horizon	Depth (cm)	Sand	Silt	Clay	Textural class[1/]	Bulk density ($Mg\ m^{-3}$)	SSA[2/] ($m^2\ g^{-1}$)
		($g\ kg^{-1}$)					
Typic Kandiudult (Tim2)							
Ap	0-21	698	97	205	SL	1.50	6.0
Bt1	21-45	643	98	260	SCL	1.67	11
Bt2	45-74	570	83	348	SCL	1.59	15
Bt3	74-104	585	84	332	SCL	1.71	14
Bt4	104-140	576	104	320	SCL	1.65	13
Bt5	140-170	576	104	321	SCL	1.64	14
Bv	170-200+	547	116	337	SCL	1.76	15
Typic Kandiudult (Pga)							
Ap	0-20	695	104	201	SL	1.69	5.9
Bt1	20-48	541	98	361	SCL	1.61	12
Bt2	48-78	533	106	361	SCL	1.65	16
Bt3	78-110	498	87	415	SC	1.58	16
Bt4	110-140	456	77	467	SC	1.55	18
Bt5	140-170	386	118	496	C	1.48	20
Bv	170-200+	364	104	532	C	1.48	21
Typic Plinthudult (Pk)							
Ap	0-10/12	662	61	277	SCL	1.68	10
Bt1	10/12-35	393	83	524	C	1.72	21
Bt2	35-60	353	60	588	C	1.65	24
Bt3	60-80	316	89	594	C	1.58	26
Bt4	80-100	274	138	587	C	1.76	29
Bv1	100-126	263	151	586	C	1.62	26
Bv2	126-155	316	57	627	C	1.78	25
Bv3	155-195+	301	88	611	C	1.72	24

[1/] SL = sandy loam; LS = loamy sand; SCL = sandy clay loam; CL = clay loam; SiC = silty clay; GC = gravelly clay; C = clay
[2/] SSA = specific surface area

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Appendix Table C2 Chemical properties of Thai upland Oxisols and Ultisols.

Horizon	pH (1:1)		OM	Total N	Avail. P	Avail. K	Extractable bases				Sum bases	EA	CEC NH_4OAC	CEC clay	ECEC clay	BS
	H_2O	KCl					Ca	Mg	Na	K						
			(----g kg^{-1}---)		(------mg kg^{-1}------)		(--cmol kg^{-1}								--)	(%)
Typic Kandiudox (Ak1)																
Ap	6.0	4.6	25	0.30	1.15	10	2.24	0.06	0.42	0.13	2.9	13	13	21	4.6	19
Bto1	5.8	5.1	15	0.20	0.30	2.9	0.19	0.12	0.38	0.04	0.73	12	6.6	7.5	0.89	6
Bto2	5.9	5.2	9.2	0.20	0.25	2.8	0.17	0.12	1.06	0.04	1.4	11	4.1	4.7	1.6	12
Bto3	5.8	5.0	6.7	0.20	0.25	6.3	0.08	0.09	0.32	0.08	0.57	9.0	3.2	3.5	0.66	5.9
Bto4	5.8	5.2	4.9	0.20	0.30	9.4	0.13	0.07	0.49	0.12	0.81	9.8	3.2	3.7	1.0	7.7
Bto5	5.9	5.3	4.3	0.10	0.20	6.4	0.46	0.27	0.74	0.08	1.6	10	6.6	7.6	1.8	13
Bto6	5.7	5.2	4.3	0.10	0.15	5.4	0.10	0.04	0.27	0.07	0.48	12	7.3	8.4	0.60	3.9
Bto7	5.6	5.2	3.7	0.10	0.10	3.7	0.23	0.05	0.40	0.05	0.73	14	6.7	7.6	0.89	5.1
Typic Kandiudox (Ak2)																
Ap	6.5	5.6	18	0.80	131	33	2.56	2.65	0.56	0.42	6.2	8.3	9.2	12	7.9	43
Bto1	5.7	3.8	9.8	0.60	2.7	23	2.60	1.08	0.96	0.29	4.9	10	8.3	10	7.2	33
Bto2	5.5	3.9	7.4	0.40	1.9	22	2.90	1.02	0.63	0.28	4.8	9.5	6.9	7.5	6.7	34
Bto3	5.4	3.5	6.7	0.40	2.6	20	2.90	1.00	0.30	0.26	4.5	10	8.1	8.7	6.2	31
Bto4	5.1	3.8	3.4	0.40	0.45	8.5	0.87	0.53	0.18	0.11	1.7	10	7.7	8.9	5.4	14
Bto5	5.3	3.7	4.6	0.20	0.35	4.2	0.87	0.55	0.20	0.05	1.7	9.0	7.7	9.0	4.8	16
Bto6	5.5	3.5	1.3	0.40	0.30	3.8	0.95	0.59	0.85	0.05	2.4	9.0	7.6	8.6	5.5	21
Rhodic Kandiudox (Ak3)																
Ap	5.3	3.8	12	1.10	20	26	2.90	0.03	0.57	0.34	3.8	11	11	19	7.2	27
Bto1	5.4	4.0	4.3	0.20	3.6	19	1.20	0.41	0.13	0.25	2.0	9.4	10	12	3.0	18
Bto2	5.4	4.0	3.1	0.40	1.0	10	1.24	0.47	0.26	0.13	2.1	8.9	9.3	12	3.2	19
Bto3	5.4	4.0	2.5	0.40	0.60	5.7	0.95	0.40	0.26	0.07	1.7	8.6	11	13	2.6	16
Bto4	5.5	4.1	1.9	0.30	0.70	7.1	0.49	0.24	0.24	0.09	1	9.1	10	13	2.7	10
Bo1	5.4	4.0	1.3	0.30	0.60	7.2	0.48	0.26	0.05	0.09	1	9.1	5.8	7.3	2.4	8.8
Bo2	5.4	4.0	1.3	0.30	0.40	7.5	0.45	0.24	0.30	0.10	1	12	6.3	7.6	2.6	8.5

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Appendix Table C2 (Continued)

Horizon	pH (1:1)		OM	Total N	Avail. P	Avail. K	Extractable bases				Sum	EA	CEC	CEC	ECEC	BS
	H_2O	KCl					Ca	Mg	Na	K	bases		NH_4OAC	clay	clay	
			(----g kg^{-1}---)		(------mg kg^{-1}------)		(--cmol kg^{-1}--)									(%)
Kandiudalfic Eutrudox (Ptu)																
Ap	5.6	3.7	17	0.46	1.30	18	2.90	1.02	0.48	0.05	4.5	6.4	5.1	19	18	41
Bto1	5.6	4.0	5.4	0.46	0.40	13	3.77	1.04	0.14	0.03	5.0	7.4	8.2	14	9.4	40
Bto2	5.5	3.8	4.9	0.32	0.35	16	3.64	1.17	0.17	0.03	5.0	8.1	8.6	14	8.9	38
Bto3	5.5	3.8	4.3	0.14	0.20	10	3.46	1.26	0.25	0.03	5.0	8.4	10	17	10	37
Bo1	5.5	4.0	3.7	0.07	0.20	13	2.76	0.85	0.22	0.03	3.9	9.6	8.4	14	9.4	29
Bo2	5.3	4.0	4.3	0.14	0.60	11	3.91	1.16	0.20	0.03	5.3	11	8.3	13	10	33
Bo3	5.4	4.1	3.1	0.07	0.50	14	2.90	0.86	0.36	0.04	4.2	15	7.8	13	8.5	22
Rhodic Kandiudox (Ti1)																
Ap1	5.1	4.6	45	1.00	99	23	5.62	1.06	0.29	0.29	7.3	67	12	31	20	9.8
Ap2	4.8	4.3	28	0.80	19	11	3.35	0.62	0.05	0.15	4.2	62	15	34	10	6.3
Bto1	4.9	4.5	11	0.30	18	19	0.50	0.52	0.09	0.25	1.4	56	11	14	1.8	19
Bto2	5.1	4.8	6.0	0.30	22	17	0.67	0.35	0.06	0.22	1.3	56	11	13	1.6	24
Bto3	5.2	4.8	5.3	0.20	20	17	0.62	0.26	0.12	0.21	1.2	40	11	15	1.7	29
Bo1	4.9	4.5	4.6	0.20	25	13	0.19	0.31	0.18	0.17	0.85	40	11	15	1.3	12
Bo2	4.8	4.4	4.1	0.20	26	10	0.10	0.26	0.48	0.13	1.0	51	9.4	11	1.3	6.2
Bo3	4.6	4.3	2.7	0.20	18	7.4	0.09	0.18	0.57	0.09	0.93	54	10	14	1.5	5.3
Typic Kandiudox (Ti2)																
Ap	5.3	4.6	34	1.00	72	49	6.40	1.05	0.22	0.63	8.3	47	16	37	19	15
Bto1	4.7	4.1	20	0.50	41	19	0.35	0.24	0.57	0.24	1.4	49	18	34	3.2	2.8
Bto2	4.6	4.3	13	0.50	23	11	0.46	0.35	0.20	0.13	1.1	44	9.4	14	1.8	2.6
Bto3	4.5	4.2	5.0	0.20	21	12	0.22	0.24	0.14	0.16	0.76	40	10	12	1.1	1.9
Bo1	4.5	4.4	4.8	0.20	13	13	0.29	0.33	0.05	0.16	0.83	22	6.5	8.5	1.2	3.7
Bo2	4.6	4.4	2.9	0.10	6.8	4.3	0.43	0.47	0.09	0.05	1.0	22	8.8	11	1.4	4.6
Bo3	4.4	4.7	1.9	0.20	3.8	4.2	0.35	0.23	0.18	0.05	0.81	20	6.4	8.0	1.1	3.9
Bo4	4.4	4.6	3.6	0.10	2.3	4.9	0.25	0.17	0.27	0.06	0.75	21	8.6	11	1.0	3.5

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Appendix Table C2 (Continued)

Horizon	pH (1:1)		OM	Total N	Avail. P	Avail. K	Extractable bases				Sum bases	EA	CEC NH_4OAC	CEC clay	ECEC clay	BS
	H_2O	KCl					Ca	Mg	Na	K						
			(----g kg^{-1}---)		(------mg kg^{-1}------)		(--------------------cmol kg^{-1}--------------------)									(%)
Typic Kandiudox (Ti3)																
Ap	5.7	5.2	30	1.53	62	53	6.85	1.75	0.25	0.13	9.0	26	26	48	17	26
Bo1	5.2	4.9	16	0.77	64	17	1.95	0.61	0.40	0.04	3.0	28	18	33	5.7	9.5
Bo2	4.8	4.5	4.7	0.48	50	15	0.53	0.29	0.17	0.04	1.0	27	14	19	1.5	3.6
Bto1	4.8	4.5	4.0	0.28	51	16	0.51	0.17	0.17	0.04	0.90	26	8.2	11	1.3	3.4
Bto2	4.9	4.5	2.7	0.20	63	14	0.75	0.23	0.14	0.04	1.2	26	12	15	1.6	4.4
Bto3	4.9	4.5	2.4	0.16	78	23	0.79	0.33	0.34	0.06	1.5	26	11	15	2.3	5.6
Bto4	4.9	4.6	3.3	0.20	61	19	1.39	0.26	0.43	0.05	2.1	26	12	15	2.8	7.6
Typic Kandiudox (Nb1)																
Ap	4.5	4.1	81	2.30	51	61	0.55	0.18	0.17	0.16	1.0	36	18	39	4.2	2.8
Bt1	4.6	4.3	26	1.04	32	44	0.46	0.16	0.15	0.11	0.89	33	15	24	2.1	2.7
Bt2	4.9	4.5	17	0.73	44	79	0.45	0.23	0.24	0.20	1.1	29	13	19	1.9	3.7
Bt3	4.7	4.5	6.0	0.55	51	99	0.63	0.17	0.70	0.25	1.8	24	10	14	2.5	6.7
Bto1	4.7	4.5	2.7	0.49	51	56	0.77	0.26	0.14	0.14	1.3	26	9.2	12	1.7	4.7
Bto2	4.8	4.4	2.7	0.41	43	62	0.67	0.13	0.24	0.16	1.2	24	8.7	11	1.5	4.8
Bto3	4.9	4.3	2.0	0.40	45	27	0.48	0.09	0.48	0.07	1.1	22	11	14	1.7	4.8
Bto4	5.3	4.3	2.4	0.41	42	15	0.37	0.11	0.57	0.04	1.1	22	7.9	10	1.6	4.8
Typic Kandiudox (Nb2)																
Ap	4.3	3.9	71	3.57	62	40	0.42	0.15	6.61	0.10	7.3	50	34	81	22	13
Bt1	4.7	4.3	42	1.93	47	17	0.14	0.06	0.16	0.04	0.40	45	20	39	0.90	0.89
Bt2	4.9	4.4	22	0.91	63	12	0.10	0.05	3.20	0.03	3.4	37	16	27	6.3	8.3
Bt3	5.0	4.4	7.4	0.54	91	10	0.42	0.03	0.42	0.02	0.89	33	10	14	1.7	2.7
Bto1	4.9	4.3	4.7	0.33	94	12	0.07	0.04	0.48	0.03	0.63	31	13	17	1.3	2.0
Bto2	4.9	4.3	2.6	0.34	86	10	0.36	0.05	0.25	0.03	0.70	31	12	15	1.2	2.2
Bto3	4.8	4.4	4.1	0.34	91	11	0.35	0.06	0.31	0.03	0.75	28	11	14	1.3	2.6
Bto4	4.8	4.5	4.1	0.27	76	11	0.30	0.16	0.42	0.03	0.91	28	10	12	1.1	3.2

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Appendix Table C2 (Continued)

Horizon	pH (1:1)		OM	Total N	Avail. P	Avail. K	Extractable bases				Sum bases	EA	CEC NH_4OAC	CEC clay	ECEC clay	BS
	H_2O	KCl					Ca	Mg	Na	K						
			(----g kg^{-1}---)		(------mg kg^{-1}------)		(------cmol kg^{-1}------)									(%)
Typic Kandiudult (Kh)																
Ap	5.5	4.0	11	0.51	6.2	15	0.28	0.09	0.44	0.04	0.85	1.9	1.6	18	11	31
Bt1	5.1	3.8	3.4	0.27	1.8	9.1	0.17	0.03	0.34	0.02	0.57	0.5	1.6	16	8.5	55
Bt2	5.1	3.7	2.7	0.35	1.7	13	0.23	0.06	0.12	0.03	0.44	0.9	1.0	7.0	5.2	32
Btc	5.5	3.6	4.0	0.13	1.7	13	0.20	0.03	0.20	0.03	0.47	2.3	5.2	21	9.2	17
Crt1	5.2	3.7	4.0	0.24	1.1	16	0.82	0.09	0.47	0.04	1.4	4.2	2.0	4.6	11	25
Crt2	5.0	3.6	2.7	0.30	0.80	26	1.00	0.08	0.32	0.07	1.5	4.2	6.3	16	12	26
Typic Plinthudult (Kc)																
Ap	4.6	3.6	20	0.52	40	17	0.27	0.09	0.16	0.04	0.57	9.9	5.8	14	6.2	10
Bt1	4.5	3.6	11	0.42	2.6	12	2.14	0.07	0.72	0.03	3.0	9.0	5.1	9.3	9.3	58
Bt2	4.6	3.6	6.5	0.24	2.8	6.9	0.30	0.04	0.17	0.02	0.53	7.0	4.6	7.7	4.5	11
Bt3	4.7	3.6	5.8	0.31	2.9	7.5	0.39	0.06	0.18	0.02	0.65	7.0	3.4	5.5	4.4	19
Btc1	5.0	3.7	2.2	0.14	3.1	7.0	0.41	0.07	0.11	0.02	0.60	7.0	5.6	8.9	4.0	11
Btc2	4.9	3.7	2.2	0.10	2.8	9.4	0.49	0.12	0.32	0.02	0.96	7.0	4.5	6.9	4.7	21
Btc3	4.9	3.7	3.0	0.14	2.8	8.5	0.45	0.13	0.21	0.02	0.81	8.0	4.5	7.0	4.6	18
Bv	4.9	3.7	0.82	0.07	2.6	10	0.29	0.13	0.58	0.03	1.03	7.0	3.1	5.3	5.2	33
Typic Kandiudult (Fd)																
Ap	6.4	4.7	11	0.42	1.3	36	1.10	0.51	0.35	0.09	2.1	2.6	2.4	12	10	44
Bt1	5.3	3.4	5.1	0.25	0.80	13	0.47	0.16	0.46	0.03	1.1	3.6	2.7	11	6.2	24
Bt2	5.0	3.3	4.9	0.28	0.75	10	0.30	0.11	0.29	0.03	0.73	3.6	2.1	8.3	5.0	17
Bt3	4.7	3.3	4.2	0.28	1.1	10	0.31	0.11	0.07	0.02	0.51	4.6	2.4	8.2	3.9	10
Bt4	4.7	3.2	4.3	0.25	0.60	9.3	0.20	0.13	0.40	0.02	0.75	4.9	3.4	11	4.4	13
Bt5	4.6	3.3	3.1	0.14	0.70	13	0.23	0.15	0.47	0.03	0.88	5.4	3.9	12	5.3	14
Bt6	4.6	3.3	3.1	0.18	0.90	14	0.13	0.14	0.46	0.03	0.76	4.4	2.6	8.5	4.8	15
Bt7	4.6	3.5	3.7	0.18	0.70	16	0.13	0.12	0.12	0.04	0.41	4.5	2.9	10	3.7	8.4

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Appendix Table C2 (Continued)

Horizon	pH (1:1)		OM	Total N	Avail. P	Avail. K	Extractable bases				Sum bases	EA	CEC NH_4OAC	CEC clay	ECEC clay	BS
	H_2O	KCl					Ca	Mg	Na	K						
			(----g kg^{-1}---)		(------mg kg^{-1}------)		(----------cmol kg^{-1}----------)									(%)
Typic Kandiudult (Kbi)																
Ap	5.6	4.2	13	0.42	3.7	15	0.40	0.19	0.13	0.04	0.76	4.5	4.9	65	13	15
Bt1	4.7	3.7	19	0.53	1.4	27	0.22	0.09	0.24	0.07	0.62	3.0	4.8	20	3.5	17
Bt2	4.8	3.7	11	0.32	0.80	18	0.23	0.06	0.30	0.05	0.64	4.0	4.4	19	3.7	14
Bt3	5.1	3.8	6.1	0.28	0.70	11	0.09	0.04	0.15	0.03	0.31	4.0	3.1	11	1.9	7.1
Bt4	5.4	4.2	4.9	0.28	0.40	7.3	0.19	0.05	0.16	0.02	0.42	3.5	2.4	11	4.2	11
Bt5	5.4	3.4	4.9	0.18	0.35	12	0.27	0.06	0.32	0.03	0.68	4.0	2.3	10	5.3	15
Bt6	5.3	3.5	4.6	0.11	0.30	6.8	0.33	0.06	0.38	0.02	0.79	4.0	2.6	8.8	4.7	16
Typic Kandiudult (Sd)																
Ap	5.6	3.9	21	0.28	4.1	23	0.64	0.19	0.31	0.06	1.2	14	2.9	19	8.4	8.2
E	5.2	3.8	6.1	0.18	2.2	8.7	0.35	0.08	0.46	0.02	0.91	11	1.6	17	12	7.7
Bt1	5.0	3.8	3.1	0.14	0.5	10	0.38	0.09	0.43	0.03	0.93	11	3.3	19	5.7	8.1
Bt2	4.8	3.9	2.5	0.14	0.30	9.5	0.30	0.09	0.07	0.02	0.48	11	1.9	8.0	4.3	4.2
Bt3	4.9	3.9	3.1	0.14	0.25	7.7	0.32	0.16	0.21	0.02	0.71	12	2.7	11	5.5	5.9
Bt4	4.9	3.9	2.3	0.14	0.25	12	0.39	0.29	0.52	0.03	1.2	13	2.6	10	6.9	9.0
Bt5	5.0	4.0	2.2	0.14	0.35	9.2	0.28	0.52	0.31	0.02	1.1	12	3.1	10	5.3	8.6
Bt6	5.2	3.9	3.1	0.07	0.35	21	0.53	0.03	0.44	0.05	1.1	9.5	4.4	14	4.3	10
Typic Plinthudult (Cp)																
Ap	4.7	4.0	15	0.70	-	59	0.75	0.56	0.23	0.15	1.7	4.4	4.9	40	19	28
Bt	4.8	3.9	6.9	0.40	-	27	0.72	0.43	0.17	0.07	1.4	2.9	3.2	23	14	32
Btc	5.1	3.9	6.5	0.40	-	43	1.09	0.72	0.22	0.11	2.1	7.0	6.5	22	11	24
Bv1	5.0	3.9	3.3	0.30	-	39	0.82	1.24	0.25	0.10	2.4	8.1	8.4	29	15	23
Bv2	5.0	3.8	3.3	0.40	-	39	0.82	1.61	0.24	0.10	2.8	8.4	8.5	21	13	25
Bv3	5.1	3.8	4.0	0.30	-	55	0.38	2.21	0.29	0.14	3.0	11	11	19	14	21
BCrv	5.1	3.7	2.5	0.30	-	59	0.28	3.44	0.27	0.15	4.1	10	12	35	26	29

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Appendix Table C2 (Continued)

Horizon	pH (1:1)		OM	Total N	Avail. P	Avail. K	Extractable bases				Sum bases	EA	CEC NH_4OAC	CEC clay	ECEC clay	BS
	H_2O	KCl					Ca	Mg	Na	K						
			(----g kg^{-1}---)		(------mg kg^{-1}------)		(--cmol kg^{-1}								--)	(%)
Typic Kandiudult (Hp)																
Ap1	4.1	3.5	8.1	0.20	39	20	0.29	0.10	0.51	0.05	0.95	5.6	1.6	8.5	8.3	15
Ap2	4.0	3.4	6.1	0.17	29	15	0.14	0.04	0.59	0.04	0.81	4.7	2.4	12	9.1	15
Bt1	3.7	3.3	6.9	0.10	10	13	0.33	0.05	0.63	0.03	1.0	6.5	0.62	1.5	6.7	14
Bt2	4.0	3.4	6.7	0.17	5.3	10	0.67	0.08	0.25	0.03	1.0	6.5	1.9	3.8	5.2	13
Bt3	4.1	3.4	4.7	0.10	4.5	7.4	0.36	0.05	0.61	0.02	1.0	4.7	1.9	4.6	6.3	18
Bt4	4.2	3.4	4.7	0.03	4.4	11	0.39	0.07	0.56	0.03	1.0	6.5	1.6	4.1	5.8	14
Bt5	4.3	3.4	2.7	0.03	2.5	8.7	0.46	0.06	0.42	0.02	0.97	4.7	2.6	5.1	5.0	17
Bt6	4.4	3.8	2.7	0.07	2.5	12	0.61	0.09	0.41	0.03	1.1	5.6	3.2	5.7	5.2	17
Typic Kandiudult (Sh)																
Ap1	5.2	4.1	6.8	0.13	30	19	0.77	0.10	0.42	0.05	1.3	8.5	2.4	26	16	14
Ap2	5.2	4.2	6.8	0.03	42	20	2.49	0.07	0.23	0.05	2.9	7.4	1.5	15	29	28
AB	5.2	4.2	3.4	0.03	47	29	0.89	0.08	0.64	0.07	1.7	5.6	1.1	8.6	13	23
Bt1	4.8	4.0	2.7	0.03	27	21	0.73	0.05	0.20	0.06	1.0	4.7	1.0	7.2	8.0	18
Bt2	4.6	3.9	2.7	0.03	5.9	17	0.63	0.05	1.10	0.04	1.8	3.8	1.0	8.8	18	32
Bt3	4.5	3.9	2.7	0.03	5.3	13	0.54	0.05	0.45	0.03	1.1	3.7	0.6	5.5	11	22
Bt4	4.9	4.2	1.5	0.03	5.0	15	0.59	0.06	0.25	0.04	0.93	2.8	1.0	7.6	7.9	25
Bt5	4.9	4.0	1.4	0.02	5.7	17	0.58	0.06	0.12	0.04	0.80	2.7	0.62	4.1	6.9	23
Typic Peleudult (Tim1)																
Ap1	5.3	4.3	6.7	0.21	19	42	0.89	0.16	7.82	0.11	1.5	4.7	1.2	12	15	24
Ap2	4.8	3.8	4.1	0.07	4.8	18	0.58	0.09	0.44	0.05	1.2	4.7	1.5	10	10	20
Bt1	4.6	3.7	2.7	0.07	4.3	21	0.80	0.14	0.19	0.05	1.2	5.6	1.4	10	12	17
Bt2	4.8	4.2	2.7	0.03	4.3	28	1.19	0.24	0.71	0.07	2.2	6.6	1.4	5.9	10	25
Bt3	5.0	4.4	4.8	0.03	4.1	23	1.25	0.25	0.45	0.06	2.0	7.5	1.5	6.9	9.2	21
Bt4	5.0	4.4	2.7	0.03	4.4	17	1.08	0.20	0.18	0.04	1.5	4.7	1.2	6.0	7.4	24
Bt5	5.2	4.5	2.2	0.00	4.9	22	1.22	0.40	0.57	0.06	2.2	4.7	1.4	7.1	12	32
Bt6	5.4	4.7	2.1	0.03	4.8	17	0.83	0.44	0.61	0.04	1.9	5.7	1.1	5.3	9.2	25
Bt7	5.5	4.9	2.7	0.07	2.7	21	1.05	0.61	0.79	0.06	2.5	3.8	2.2	8.5	9.5	40

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Appendix Table C2 (Continued)

Horizon	pH (1:1)		OM	Total N	Avail. P	Avail. K	Extractable bases				Sum bases	EA	CEC NH_4OAC	CEC clay	ECEC clay	BS
	H_2O	KCl					Ca	Mg	Na	K						
			(----g kg^{-1}---)		(------mg kg^{-1}------)		(------------------------------------				cmol kg^{-1}				------------------------------------)	(%)
Typic Kandiudult (Tim2)																
Ap	4.3	3.4	12	0.44	6.7	14	0.15	0.06	0.40	0.04	0.64	8.5	3.1	15	9.1	6.9
Bt1	4.4	3.6	6.8	0.10	1.0	11	0.18	0.04	0.66	0.03	0.90	9.4	2.6	10	9.2	8.7
Bt2	4.5	3.5	6.2	0.17	0.76	10	0.34	0.06	0.39	0.02	0.81	8.5	3.2	9.3	7.2	8.7
Bt3	4.4	3.5	4.8	0.17	0.76	12	0.25	0.04	0.45	0.03	0.76	6.6	2.9	8.6	7.8	10
Bt4	4.4	3.5	4.1	0.10	0.76	13	0.20	0.04	0.41	0.03	0.68	7.6	3.0	9.3	7.9	8.2
Bt5	4.6	3.6	3.4	0.10	0.57	5.9	0.00	0.00	1.10	0.02	1.06	7.5	3.2	10	9.0	13
Bv	4.5	3.6	2.7	0.07	0.80	8.9	0.16	0.03	0.29	0.02	0.50	10.4	2.7	8.1	7.3	4.6
Typic Kandiudult (Pga)																
Ap	4.0	3.5	8.2	0.33	8.4	20	0.27	0.07	0.44	0.05	0.83	6.6	2.5	12	8.3	11
Bt1	4.3	3.5	3.4	0.23	1.7	16	0.22	0.04	0.19	0.04	0.50	4.7	2.6	7.2	6.1	9.2
Bt2	4.4	3.6	4.8	0.17	1.6	17	0.15	0.05	0.19	0.04	0.44	7.5	2.5	6.8	6.5	5.3
Bt3	4.4	3.6	3.4	0.07	1.9	16	0.22	0.08	0.53	0.04	0.87	6.6	2.6	6.2	6.3	11
Bt4	4.2	3.6	2.0	0.07	1.9	14	0.20	0.08	0.15	0.04	0.47	5.6	1.7	3.7	5.2	7.4
Bt5	4.1	3.6	2.0	0.20	2.3	15	0.31	0.17	0.44	0.04	0.96	6.6	4.2	8.5	6.1	12
Bv	4.2	3.6	1.4	0.03	1.7	12	0.32	0.24	0.13	0.03	0.71	7.5	4.6	8.6	5.0	8.3
Typic Plinthudult (Pk)																
Ap	4.3	3.9	20	0.77	6.3	33	0.48	0.10	4.50	0.08	5.2	10.3	4.7	17	23	34
Bt1	4.2	3.8	10	0.38	2.2	18	0.21	0.03	6.74	0.05	7.0	10	5.1	10	17	36
Bt2	4.5	3.8	6.7	0.24	1.9	16	0.15	0.03	0.68	0.04	0.91	9	8.9	15	4.8	8.4
Bt3	4.3	3.8	5.4	0.28	7.9	15	0.19	0.03	0.24	0.04	0.50	9.4	5.9	10	4.4	4.9
Bt4	4.3	3.8	4.7	0.13	1.4	14	0.13	0.02	0.36	0.04	0.54	9	5.1	8.7	4.6	4.7
Bv1	4.3	3.8	4.1	0.14	1.6	22	0.61	0.03	0.23	0.06	0.93	8	5.0	8.5	5.3	7.8
Bv2	4.4	3.8	3.3	0.07	1.4	20	0.17	0.03	3.36	0.05	3.6	10	3.4	5.4	9.2	25
Bv3	4.4	3.8	2.0	0.10	1.7	16	0.17	0.03	0.70	0.04	0.94	9.4	3.7	6.1	5.1	11

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Appendix Table C3 Some properties of purified kaolin in upland Oxisols and Ultisols.

soil name	horizon	Al_2O_3	SiO_2	TiO_2	Fe_2O_3	K_2O	SiO_2/Al_2O_3	CSD_{001}	CSD_{060}	HB	SSA	CEC
		(---------------g/kg				-----------------)		(------nm	-----)		m^2g^{-1}	cmol kg^{-1}
Ak2	Ap	453	527	9.9	10.7	nd	1.16	16.8	23.8	4.4	24	11
	Bto2	459	522	9.2	10.3	nd	1.14	17.3	28.7	4.7	22	7.0
	Bto4	455	526	9.8	9.2	nd	1.16	17.4	21.1	4.7	19	5.5
Ak3	Ap	456	518	13.2	12.3	0.40	1.13	20.3	22.4	5.3	38	11
	Bto3	445	518	26.7	9.8	0.47	1.17	17.8	32.4	5.2	22	6.4
	Bo1	459	517	15.6	8.8	nd	1.13	17.8	24.3	5.1	24	7.0
Ptu	Ap	437	534	9.9	18.6	0.81	1.22	18.1	22.7	5.1	49	16
	Bto2	439	531	13.8	14.5	1.2	1.21	20.4	21.7	5.6	26	7.6
	Bo	451	527	11.4	9.6	0.42	1.17	21.7	24.9	4.2	44	7.6
Ti1	Ap1	424	480	58.6	36.2	0.44	1.13	9.1	18.6	5.3	56	16
	Bto1	434	487	45.9	32.7	0.45	1.12	10.4	16.4	5.3	48	18
	Bo1	417	484	63.2	35.6	0.42	1.16	12.2	22.7	3.3	35	17
Ti2	Ap	436	503	38.2	22.6	nd	1.15	11.0	19.0	4.7	60	21
	Bto2	439	497	43.7	19.9	0.41	1.13	11.5	18.5	4.5	64	19
	Bo1	433	491	52.4	23.7	0.41	1.13	10.5	18.3	4.4	62	18.
Ti3	Ap	343	391	46.6	29.4	0.72	1.14	9.5	8.8	7.7	61	19
	Bto1	359	401	45.4	27.5	0.65	1.11	10.1	7.9	7.5	65	8.8
	Bo1	353	402	45.0	27.0	0.65	1.14	10.6	7.7	9.2	67	9.2
Nb1	Ap	368	396	43.0	17.6	4.1	1.07	10.0	11.2	10	45	17
	Bt3	357	395	46.1	18.3	4.9	1.11	13.4	12.1	7.1	48	15
	Bto1	362	416	37.4	16.4	4.2	1.15	12.1	11.3	7.1	46	16
Nb2	Ap	356	405	36.9	15.8	3.1	1.14	10.0	13.0	8.3	54	20
	Bt3	353	406	35.5	15.2	3.2	1.15	11.5	11.2	9.5	51	19
	Bto1	359	406	35.2	15.3	3.6	1.13	10.9	10.9	7.7	53	18
Kh	Ap	363	469	16.0	20.2	3.7	1.29	31.5	16.7	11	34	13
	Bt2	338	488	12.3	10.1	7.4	1.44	24.2	13.6	10	32	16
	Btc2	328	517	11.3	11.8	8.2	1.58	25.1	16.4	12	26	14
	Crt2	352	476	10.5	13.0	8.6	1.35	23.6	17.9	15	35	14
Kc	Ap	385	457	11.8	22.1	0.28	1.19	16.0	18.3	8.7	20	9.1
	Bt1	383	453	13.8	22.4	0.27	1.18	17.3	18.1	6.1	41	6.5
	Btc1	374	443	11.4	20.5	0.20	1.18	16.2	19.8	6.1	43	6.0
	Bv1	384	458	11.7	21.5	0.20	1.19	18.5	19.3	11	43	8.7
Fd	Ap	423	536	18.8	18.0	4.8	1.27	17.6	18.5	5.0	22	13
	Bt4	423	547	15.0	14.5	0.81	1.29	17.1	28.3	5.0	23	14
Kbi	Ap	434	540	16.8	8.6	0.86	1.24	43.1	28.1	9.7	9.0	7.3
	Bt3	438	534	16.5	10.6	1.3	1.22	40.6	31.8	9.2	17	9.2
Sd	Ap	424	537	20.7	16.7	2.0	1.27	15.1	21.7	5.3	39	9.5
	E	425	536	16.5	19.7	2.2	1.26	15.6	26.3	5.4	27	8.1
	Bt3	429	535	17.5	16.7	1.7	1.25	15.2	24.6	5.7	28	7.4
Hp	Ap	377	459	11.1	20.0	3.0	1.22	19.2	17.1	9.3	35	13
	Bt1	362	471	15.9	19.8	3.6	1.30	16.5	16.8	9.0	36	9.0
Tim2	Ap	365	461	16.5	20.8	15.9	1.26	16.0	16.2	11	38	14
	Bt3	375	464	18.4	19.7	16.4	1.24	15.8	18.6	11	42	9.7
	Bv1	376	469	16.9	20.1	16.0	1.25	17.0	19.2	10	40	12

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Appendix Table C3 (Continued)

soil name	horizon	Al_2O_3	SiO_2	TiO_2	Fe_2O_3	K_2O	SiO_2/Al_2O_3	CSD_{001}	CSD_{060}	HB	SSA	CEC
		(---------------g/kg-----------------)						(-----nm-----)			m^2g^{-1}	cmol kg^{-1}
Pga	Ap	360	455	12.2	21.1	3.7	1.26	21.5	20.4	9.4	30	13
	Bt3	370	454	10.7	21.4	3.3	1.23	19.1	20.5	9.2	34	12
	Bv1	371	449	10.4	21.6	3.5	1.21	22.2	21.2	9.1	34	9.8
Pk	Ap	389	469	5.0	12.1	1.8	1.21	18.7	18.2	10	37	7.0
	Bt3	394	469	4.7	11.6	1.7	1.19	17.9	18.2	11	40	6.0
	Bv1	390	462	4.6	11.3	1.6	1.18	18.9	18.5	14	37	6.8
All studied samples												
Max		459	547	63.2	36.2	16.4	1.80	43	32.4	15	67	21
Min		301	391	4.6	8.6	nd	1.07	9.1	7.7	3.3	9.0	6.0
Mean		390	482	22.8	18.1	2.9	1.25	17	18.3	7.7	38	12

CSD_{001}, CSD_{060}=coherently scattering domain size for 001 and 060 reflection respectively; HB=Hughes and Brown crystallinity index; SSA=specific surface area; CEC=cation exchange capacity

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Appendix Table C4 Major element concentrations in the clay fraction of Thai upland soils

Soil name	Horizon	Al	Si	Ti	Fe	Mn	Ca	K	Mg	P
		(------------				g kg^{-1}				------------)
Ak2	Ap	152	154	7.4	53	1.6	2.3	0.54	1.7	4.3
	Bto2	180	188	4.0	54	0.31	0.69	0.54	1.4	0.14
	Bto4	178	187	6.3	56	0.37	0.59	0.71	1.4	0.14
Ak3	Ap	181	182	11	96	0.75	0.14	0.51	1.7	0.65
	Bto3	169	180	6.1	88	0.37	0.69	0.61	1.5	0.33
	Bo1	172	174	6.3	87	0.37	0.58	0.66	1.4	0.16
Ptu	Ap	170	181	9.2	107	2.0	0.19	0.73	2.2	0.61
	Bto2	161	174	5.5	100	0.94	0.86	1.1	2.4	0.31
	Bo	160	173	6.4	101	0.89	0.83	0.90	2.3	0.25
Ti1	Ap1	136	129	27	157	3.3	1.3	0.86	2.3	4.6
	Bto1	139	128	26	156	2.6	1.0	0.72	2.1	4.7
	Bo1	128	122	31	169	3.1	1.0	0.87	2.5	5.2
Ti2	Ap	138	127	23	117	2.2	0.93	0.95	1.9	18
	Bto2	147	137	24	124	2.6	0.79	0.75	1.8	6.5
	Bo1	134	129	21	113	1.2	0.62	0.71	1.6	8.6
Ti3	Ap	148	130	26	154	2.6	2.6	0.56	2.1	8.8
	Bto1	155	136	25	153	2.8	0.88	0.40	2.0	11
	Bo1	143	127	25	153	2.8	1.2	0.71	2.0	8.5
Nb1	Ap	173	147	21	108	2.7	0.32	2.6	2.1	7.3
	Bt3	164	143	21	107	2.3	0.69	2.6	2.0	6.1
	Bto1	163	142	21	108	2.6	1.0	2.7	2.1	8.4
Nb2	Ap	161	136	21	144	1.8	0.35	1.9	2.2	10
	Bt3	145	125	20	136	1.4	0.65	2.0	2.1	7.4
	Bto1	149	132	20	130	1.5	0.65	2.3	2.0	8.3
Kh	Ap	141	205	7.0	42	0.18	1.5	4.2	1.9	1.1
	Bt2	154	217	6.4	54	0.12	1.1	5.6	1.9	1.0
	Btc2	154	197	5.7	64	0.12	0.74	5.9	2.0	0.29
	Crt2	157	189	5.3	73	0.13	0.73	6.0	2.3	0.28
Kc	Ap	199	204	7.1	27	0.58	0.16	0.25	1.5	16
	Bt1	186	190	7.2	25	0.45	0.11	0.24	1.4	0.13
	Btc1	179	188	6.0	21	0.37	0.54	0.54	0.26	0.08
	Bv1	202	216	6.8	25	0.28	0.59	0.60	0.66	0.34
Fd	Ap	184	206	9.6	58	0.45	0.27	3.1	2.0	40
	Bt4	156	171	7.4	46	0.20	0.26	0.62	1.3	0.55
Kbi	Ap	179	184	7.9	86	0.30	0.54	1.0	1.5	0.72
	Bt3	160	182	7.6	92	0.48	0.58	1.3	1.2	0.37
Sd	Ap	183	203	11	47	0.49	0.12	1.8	1.6	0.95
	E	177	209	11	48	0.99	0.37	1.8	1.7	0.53
	Bt3	171	195	9.3	47	0.36	0.74	1.7	1.4	0.20
Hp	Ap	159	177	7.6	14	0.13	0.39	2.6	1.2	41
	Bt1	174	192	9.2	15	0.14	0.24	2.7	1.2	0.62
Tim2	Ap	186	203	5.3	40	0.15	0.32	6.3	1.8	0.62
	Bt3	188	208	4.6	39	0.14	0.64	6.0	1.4	0.26
	Bv1	189	208	5.5	40	0.11	0.67	6.4	1.4	0.17
Pga	Ap	191	209	6.8	22	0.12	0.26	3.0	1.4	2.9
	Bt3	191	212	5.7	20	0.09	0.57	3.1	0.84	0.48
	Bv1	195	212	5.9	22	0.08	0.81	3.3	0.86	0.05
Pk	Ap	195	206	2.9	39	0.08	0.35	1.4	1.3	0.41
	Bt3	187	199	2.4	38	0.11	0.51	1.6	0.90	0.03
	Bv1	188	201	2.3	32	0.08	0.51	1.6	0.84	nd

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Appendix Table C5 Trace element concentrations in the clay fraction of Thai upland soils

Soil name	Horizon	As	Ba	Be	Bi	Ca	Ce	Co	Cr	Cu	Ga	La	Mo	Nd	Ni	Pb	Rb	S	Sc	Sr	Th	V	Zn	Zr
		(mg kg^{-1})																						
Ak2	Ap	24	17	0.5	2.4	391	36	14	66	27	28	21	2.5	16	22	34	4.5	68	12	4.3	20	204	51	5.6
	Bto2	21	11	0.4	2.6	365	30	5.0	55	11	24	18	2.2	15	19	19	3.7	23	13	3.2	18	185	36	5.6
	Bto4	21	13	0.4	2.8	241	53	7.6	58	17	24	25	2.3	22	24	28	4.7	23	13	3.1	20	197	50	5.5
Ak3	Ap	127	21	0.4	4.0	183	71	8.7	157	15	32	13	3.5	10	29	32	11	10	17	3.6	25	299	42	6.8
	Bto3	110	10	0.3	4.3	341	81	4.8	143	16	29	12	2.8	14	22	26	2.8	116	18	3.3	23	249	25	6.1
	Bo1	21	12	0.4	2.5	235	52	7.0	56	16	26	25	2.7	22	23	27	4.2	23	13	3.0	19	197	47	6.4
Ptu	Ap	221	37	1.2	3.7	202	93	35	126	22	29	32	2.8	26	54	51	17	53	17	4.8	24	274	59	5.5
	Bto2	177	26	0.9	3.6	535	84	16	110	19	33	28	3.6	25	45	43	15	31	17	5.9	21	246	90	5.4
	Bo	181	21	1.0	2.9	480	100	13	110	23	30	36	2.8	33	45	39	11	18	16	5.3	22	246	54	6.2
Ti1	Ap1	nd	422	1.9	19	1112	151	47	101	48	34	66	1.6	58	173	11	13	47	25	291	15	123	146	6.6
	Bto1	nd	360	1.9	14	694	141	42	89	47	41	59	1.5	52	167	9.5	10	4.2	25	259	15	142	99	2.5
	Bo1	nd	433	1.7	22	760	150	46	137	50	50	66	2.7	59	164	10	13	194	25	308	15	170	105	2.8
Ti2	Ap	2.3	528	1.7	8.6	664	161	29	115	48	45	74	3.0	64	248	12	19	329	24	341	13	169	98	5.6
	Bto2	0.7	502	1.7	13	520	157	40	127	48	39	71	1.6	61	237	11	12	63	26	319	14	176	95	3.9
	Bo1	nd	483	1.7	14	499	153	43	124	47	51	69	1.7	59	225	11	12	64	26	309	14	176	93	4.1
Ti3	Ap	nd	793	2.6	13	1914	173	49	120	59	43	80	1.7	70	250	12	20	48	24	437	16	108	150	2.6
	Bto1	nd	755	2.5	15	603	161	46	114	57	46	71	1.9	62	283	8.2	19	95	24	377	16	122	110	2.6
	Bo1	nd	785	2.6	15	966	174	49	121	59	63	79	1.9	70	273	9.3	18	100	25	421	17	134	118	2.7
Nb1	Ap	2.7	369	0.9	8.7	388	128	38	98	75	49	63	2.8	52	147	13	42	38	22	273	12	174	95	1.8
	Bt3	3.2	359	0.9	6.7	338	128	27	91	68	47	63	2.2	52	147	13	40	71	21	267	11	149	87	1.2
	Bto1	2.7	329	0.8	7.6	599	115	27	91	65	25	56	2.4	47	135	14	33	221	20	244	11	145	129	1.5
Nb2	Ap	2.4	519	0.7	13	561	142	23	191	71	49	72	3.9	58	135	14	27	253	29	316	12	214	113	2.5
	Bt3	0.4	587	0.8	13	349	151	20	181	64	36	77	2.0	61	132	12	29	6.1	30	353	13	163	70	2.4
	Bto1	2.1	504	0.7	11	328	133	19	155	64	42	66	2.5	54	118	12	29	135	27	315	12	164	72	1.5
Kh	Ap	23	47	0.2	2.4	1996	28	3.8	66	32	18	15	2.8	10	9.3	25	94	508	3.8	22	12	111	102	0.8
	Bt2	27	33	0.2	1.9	923	49	3.4	74	15	20	23	3.2	14	7.6	27	84	110	5.5	17	15	115	25	2.2
	Btc2	33	32	0.2	1.7	446	57	4.1	98	16	28	27	3.7	17	10	31	101	50	6.4	17	22	142	20	2.5
	Crt2	37	32	0.3	2.2	384	65	4.4	109	18	24	25	4.1	14	11	33	95	92	8.0	16	22	154	20	3.2

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Appendix Table C5 (continued)

Soil name	Horizon	As	Ba	Be	Bi	Ca	Ce	Co	Cr	Cu	Ga	La	Mo	Nd	Ni	Pb	Rb	S	Sc	Sr	Th	V	Zn	Zr
		(mg kg^{-1})																						
Kc	Ap	2.2	13	0.2	0.7	219	13	20	77	32	20	7.0	0.8	6.9	27	5.8	14	13	21	3.2	7	43	47	2.3
	Bt1	1.7	12	0.2	0.6	198	17	15	86	34	22	7.3	0.9	7.2	32	4.6	15	28	24	2.3	7	44	37	2.5
	Btc1	2.1	21	0.1	1.0	183	22	14	60	29	18	19	0.6	18	18	3.2	13	41	21	1.9	6	34	28	2.3
	Bv1	2.2	19	0.2	0.6	189	17	7.7	73	30	20	19	0.6	17	20	2.6	14	14	20	2.1	6	35	20	2.0
Fd	Ap	21	69	0.3	2.2	315	53	5.6	49	14	22	29	2.8	28	11	22	14	15	11	8.3	22	111	38	5.3
	Bt4	23	67	0.3	2.7	330	50	5.2	52	12	29	28	2.6	27	11	21	17	16	12	7.1	22	113	39	4.3
Kbi	Ap	84	48	0.4	3.9	767	66	6.5	115	26	47	19	8.2	14	20	38	7.6	51	16	18	29	281	104	10
	Bt3	67	17	0.3	2.8	212	68	5.1	101	23	28	16	7.0	11	14	29	2.0	96	15	11	25	228	37	7.6
Sd	Ap	11	21	0.3	2.5	163	64	15	43	19	14	23	3.5	19	25	32	31	23	12	5.1	25	92	91	4.8
	E	11	20	0.3	2.2	451	121	12	44	15	24	26	3.1	23	16	30	25	28	14	7.3	27	94	79	5.2
	Bt3	12	22	0.3	1.9	460	122	12	47	17	26	27	3.2	24	19	31	31	29	15	8.3	28	97	83	5.3
Hp	Ap	3.0	46	0.3	2.0	354	66	2.7	39	17	22	33	0.4	19	8.9	47	44	18	8.2	10	49	11	55	2.6
	Bt1	3.0	28	0.2	1.2	236	64	1.3	36	12	21	30	0.7	18	7.2	35	34	14	8.1	7.4	34	11	32	2.8
Tim2	Ap	7.2	43	0.2	1.4	893	19	2.8	43	12	47	8.8	2.1	6.0	7.9	16	60	311	7.2	6.3	18	70	132	0.39
	Bt3	7.8	48	0.2	0.6	260	39	2.5	43	20	22	18	1.8	14	9.3	17	61	7.6	11	7.4	19	66	33	1.6
	Bv1	6.7	46	0.2	0.9	307	37	2.1	35	17	58	23	1.7	17	5.7	16	46	8.3	11	6.9	19	59	18	2.2
Pga	Ap	1.7	35	0.2	1.0	191	13	2.1	60	12	30	6.0	2.1	4.1	7.3	11	72	184	7.3	5.7	20	24	23	0.12
	Bt3	2.4	23	0.1	1.2	200	27	1.8	50	7.7	26	13	0.7	11	7.6	10	44	121	11	3.2	22	24	18	0.15
	Bv1	1.7	35	0.1	0.6	493	35	1.2	42	18	22	17	0.6	13	7.6	13	32	27	9.5	10	21	24	53	1.5
Pk	Ap	23	12	0.2	3.7	450	2.6	1.8	19	16	39	22	1.6	1.1	3.4	8	16	18	1.9	5.6	70	32	32	3.1
	Bt3	18	8.0	0.2	3.2	167	1.7	1.2	15	8.8	52	1.1	1.0	0.7	2.3	4	13	15	2.1	2.0	48	22	15	2.3
	Bv1	17	8.1	0.2	2.5	164	1.7	1.4	15	8.9	49	1.1	0.9	0.7	2.5	4	13	13	2.0	2.1	46	21	25	2.2

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Appendix Table C6 Soil pH (soil : water = 1:1).

Rating	Range
Ultra acid	< 3.5
Extremely acid	3.5-4.5
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 C7 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 C8 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 C9 Available phosphorus (Bray II).

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

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Appendix Table C10 Available potassium.

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

Appendix Table C11 Cation exchange capacity (CEC).

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 C12 Base saturation percentage (PSB).

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

Appendix Table C13 Extractable acidity (EA).

Rating	EA (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

Source: Kanchanaprasert (1986)

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Appendix Table C14 Bulk density (BD).

Rating	BD ($Mg\ m^{-3}$)
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: Kanchanaprasert (1986)

Appendix Table C15 X-ray diffraction spacing obtained from (001) planes of layer-silicate species as related to sample treatment

Diffraction spacing (nm)	**Mineral (or minerals) Indicated**
	Mg-saturated, air-dried
1.4 - 1.5	Smectite, vermiculite, chlorite
0.99 - 1.01	Mica (illite), halloysite
0.72 - 0.75	Metahalloysite
0.715	Kaolinite, chlorite (2nd-order maximum)
	Mg-saturated, glyceral-solvated
1.77 - 1.80	Smectite
1.4 - 1.5	Vermiculite, chlorite
1.08	Halloysite
0.99 - 1.01	Mica (illite)
0.72 -0. 75	Metahalloysite
0.75	Kaolinite, chlorite (2nd-order maximum)
	K-saturated, air-dried
1.4 - 1.5	Chlorite, vermiculite (with interlayer aluminium)
1.24 - 1.28	Smectite
0.99 - 1.01	Mica (illite), halloysite, vermiculite (contracted)
0.72 - 0.75	Metahalloysite
0.715	Kaolinite, chlorite (2nd-order maximum)
	K-saturated, heated (550°C)
1.4	Chlorite
0.99 - 1.01	Mica, vermiculite (contracted), smectite (contracted)
0.715	Chlorite (2nd-order maximum)

Source: Whittig and Allardice (1986)

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