THESIS APPROVAL

GRADUATE SCHOOL, KASETSART UNIVERSITY

Doctor of Philosophy (Soil Science)
DEGREE

Soil Science	Soil Science
FIELD	**DEPARTMENT**

TITLE: Carbon Sequestration of Major Upland Agricultural Soils in Northeast Plateau, Thailand

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THESIS

CARBON SEQUESTRATION OF MAJOR UPLAND AGRICULTURAL SOILS IN NORTHEAST PLATEAU, THAILAND

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

Kamolwan Laopoolkit 2011: Carbon Sequestration of Major Upland Agricultural Soils in Northeast Plateau, Thailand. Doctor of Philosophy (Soil Science), Major Field: Soil Science, Department of Soil Science. Thesis Advisor: Professor Irb Kheoruenromne, Ph.D. 183 pages.

Fifteen major upland agricultural soils in Northeast Plateau, Thailand representing soils that cover approximately 26,849 km^2 were used in this carbon sequestration (C_{seq}) study. These soils have ustic soil moisture regime. They include Oxisols, Ultisols and Alfisols. Land uses at the time of sampling were uncultivated lands, corn fields, tree and forage crops and cassava fields. In this study the Ap (D1), base of Ap to 0.6 m (D2), 0.6 to 1 m (D3) and 1 to 2 m (D4) sections of the soil profiles were used to examine the mechanisms and factors controlling C_{seq}. Soils of this region are generally well developed and some of them are sandy. The variation of physical and chemical properties of these soils with depth mainly reflects the different nature of their parent materials.

The water aggregate stability (WAS) of Oxisols, Ultisols and Alfisols are 41-93, 20-84 and 32-84 %, respectively. The size of WAS is largest in Oxisols > Ultisols > Alfisols (1.2, 0.42 and 0.23 mm, respectively). Small macroaggregate in Oxisols (250-2000 μm) makes up the largest proportions ranging from 37-73 g 100 g^{-1} soil whereas Ultisols have microaggregate (53-250 μm) as the dominating fraction (2.3-70 g 100 g^{-1} soil). Land use and management affect aggregate size distribution in Ap horizons whereas clay, sesquioxide and calcium concentration affect aggregate size distribution in subsoils.

The total carbon with depth of these soils is strongly correlated with organic carbon. High decomposition rate of these soils tend to lower C/N to near 10:1. The sequestration of carbon ranges from 6.7-52, 3.0-37, 2.2-28 and 7.5-52 Mg C ha^{-1} in D1, D2, D3 and D4, respectively. Oxisols sequester higher carbon (C) than do Alfisols and Ultisols averaging 112, 85 and 64 Mg C ha^{-1}, respectively. The extreme value of C stored in D1 is in uncultivated lands (52 Mg C ha^{-1}). In surface soils, coarse aggregates have a higher C/N than do the fine aggregates in contrast with the condition in subsoil horizons. Aggregate hierarchy includes microaggregate bound together into macroaggregate by organic binding agents in Ultisols and in surface soils of Oxisols. A relationship between the C enrichment in microaggregate and C in bulk soils of each genetic horizon indicates that stabilization of organic carbon is physical protection in these soils that occurs in the fine aggregates. Carbon in silt and clay fraction has a positive relationship with silt plus clay content.

Topography and land use affect C_{seq} in these soils, while the importance of parent material is shown only in younger soils. The C_{seq} is positively related to silt plus clay content and it is more evident in Oxisols with predominance of iron oxides in the mineral fraction or in Ultisols and Alfisols with predominance of illuviated clay. The estimated carbon stored in D1 is affected by land use, texture and soil aggregation. The estimated carbon stored in D2 and D3 sections reflects their organomineral complex and transformation. The sequestered carbon in D4 section accounts for 51% (28 Mg C ha^{-1}) relative to the carbon storage in the first meter and the carbon stored in the D4 section is related to surface soil management, soil parent material and both transformation and translocation in pedogenesis.

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ACKNOWLEDGMENTS

Firstly, I would like to thank Professor Dr. Irb Kheoruenromne for his continuous support, advice and encouragement throughout. His high commitment given to his graduate students is remarkable and greatly appreciated. Prof., your words mean a lot to me, you raise me up.

I would like to thank thesis co-advisor, Associate Professor Dr. Anchalee Suddhiprakarn, for providing valuable advice on how to improve the dissertation, broadening views and highlighting the importance of the research and the circumspection on my work.

My sincere thanks are to Miss Jindaratana Chuenrung, Dr. Chutharmard Kaewmano and Dr. Punyisa Trakoonyingcharoen for their valuable advice for aggregate laboratory, and to Mr. Rattanon Jaroenchasri, Assistant Professor Dr. Somchai Anusonpornperm and Dr. Suphicha Thanachit for their great assistance.

A deep gratitude goes to Dr. Natthapol Chittamart, Dr. Worachart Wisawapipat, Miss Thanyathorn Jitorwan, Dr. Napaporn Wongpokhom and Dr. Nattaporn Prakongkep for their sincerity, great suggestions and tirelessly support. I would like to thank Miss Khwunta Khawmee, Mr. Wittaya Jindaluang, Miss Daojarus Ketrot, Miss Boontarik Chimchart and Arjan Wipawan Thaymuang who made great contributions to the research projects. Your kindness and generosity is highly admired. I would like to thank all of my friends at the Soil Survey Group (412 room) especially May, Oad, Ohm, Oil, Kam and Kate for their warm support.

I owe my deep appreciations to two persons who are always support and stand beside me “my lovely sister, Miss Timtong Darunsontaya” and “my best friend, Miss Chaweewan Klangpet” for everything that both of you do for me. Thank you very much.

This thesis could not be completed without the support from my family. With the encouragement and support from my parents, I had decided to pursue my further education under Ph.D. program. Thus, this work is dedicated to them, Mr. Surachai and Mrs. Darin Laopoolkit. My parents are my heroes and my role models. I am so proud to be their daughter. Thank you very much for their patience and financial support. My special thanks are to all my younger siblings, Miss Pattra, Mr. Nattawut and Miss Kanokwan Loapoolkit, Miss Amornrattana and Miss Hatairattana Laoboonsuk for the morale support. They never stop loving me and supporting me through all these years.

Kamolwan Laopoolkit
May 2011

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CARBON SEQUESTRATION
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IN NORTHEAST PLATEAU, THAILAND

INTRODUCTION

Soil carbon sequestration (C_{seq}) is an important process to reserve carbon (C) as a form that is not immediately reemitted and as organic carbon (Gibson *et al.*, 2002). Soil organic carbon (OC) is the C component of soil organic matter (OM) directly derived from plants and animals (Charman and Roper, 1991) and plays a central role in soil quality and the sustainability of soil fertility (Chan, 2001). In agricultural soils, OC contributes positively to soil fertility, soil tilth, crop production, and overall soil sustainability (Bauer and Black, 1994). Therefore, C_{seq} in soil helps off-set emissions of carbon while enhancing soil quality and long-term agronomic productivity (Watson *et al.*, 2000). This C_{seq} is still not well understood, being influenced by the composition of OC itself, by its protection against decomposition through various soil constituents and by environmental conditions (Baldock and Skjemstad, 2000). Knowledge of the mechanisms of OC stabilization is needed.

In the humid Tropics, the climatic conditions favor decomposition of OM, so tropical soils are generally very poor in OM (Van Noordwijk *et al.*, 1996). The concentration and turnover rate of OC are influenced by a large number of soil forming factors (Greenland *et al.*, 1992). There should be a greater potential for OC preservation in the subsoil, where the OC saturation of mineral particles is small (Rumpel *et al.*, 2002). Management of soils and land use change can also produce significant alterations in OC levels (Cole *et al.*, 1993). Therefore, understanding on factors controlling depth fractionation of C_{seq} in tropical region and specific mechanism for depth fractionation of C_{seq} in the Tropics needs be explored.

In Thailand, there are several studies on C_{seq}. Findings on emission and turnover rates of OC were from studying soils in forest and slope complex areas (Janmahasatien *et al.*, 1998). However, there was not any detailed report discussing mechanisms and factors influencing OC protection. This study aims at determining how much OC a given soil can protect by investigating physicochemical properties and mineralogical characteristics of soil and its environment factors. These data will provide a broad understanding of the relationship between C_{seq}, OC and its controlling factors.

Most of soils in Northeast Plateau Thailand are highly developed and having low fertility status (Kheoruenromne, 1991). For agricultural development it is very important to study nature of these soils relating to stabilization process of OC. This study would help in formulating appropriate amending and management practices for agricultural soils in the Northeast Plateau.

OBJECTIVES

This study was carried out on carbon sequestration of major upland agricultural soils in Northeast Plateau with the following objectives;

1. To study the mechanisms that sequester organic carbon in soil based on soil properties.

2. To establish relationship between environmental conditions and physical protection of organic carbon in upland agricultural soils in Northeast Plateau, Thailand.

3. To define the major factors affecting organic carbon sequestration of upland agricultural soils in Northeast Plateau, Thailand.

Hypothesis

Environmental condition and soil properties affect soil organic carbon content of upland agricultural soils in Northeast Plateau, Thailand.

LITERATURE REVIEW

Carbon Sequestration in Soil

1. Definition

Soil carbon sequestration (C_{seq}) is the process of transferring CO_2 from the atmosphere into the soil through crop residues and other organic solids, and in a form that is not immediately remitted (Sundermeier *et al*., 2005). Gibson *et al*. (2002) reported that C_{seq} occurs through direct and indirect fixation of CO_2. Direct C_{seq} occurs by inorganic chemical reactions that convert CO_2 into soil inorganic carbon (IC) compounds such as calcium and magnesium carbonates. Indirect C_{seq} occurs by decomposition processes that convert CO_2 into OC. The amount of C sequestered at a site reflects the long-term balance between C uptake and release mechanisms. Many agronomic, forestry, and conservation practices, including best management practices, lead to a beneficial net gain in C fixation in soil (Skjemstad *et al*., 2001).

2. Distribution

Soils contain approximately 75 percent of the terrestrial C pool (Houghton, 1985). Therefore, soils play a major role in the global C cycle. Soils contain about 1500 Pg (1 Pg= 1 Gt = 10^{15} g) of OC worldwide (Batjes, 1996), which is about three times the amount of C in vegetation and twice the amount in the atmosphere (IPCC, 2000a). The pool of OC in agricultural soils averages 10.2 kg C/m^2 to a depth of 1 m or close to seven times the content of the atmosphere above field (Wood *et al*., 2000). The soils in North America, Asia and Europe are considerably richer in OC (12.2, 12.6 and 14.6 kg C/m^2, respectively) than in Sub-Saharan Africa (7.7 kg C m^{-2}). The mean OC content of Oxisols, Ultisols, Alfisols and Mollisols are similar in the Tropics (8.3 kg OC m^{-2} to a 1-m depth) and in the temperate region (7.4 kg OC m^{-2} to a 1-m depth). Tropical Oxisols and temperate Mollisols have the highest total OC (11.3 and 10.1 kg OC to a 1-m depth respectively) (Sanchez *et al*., 1982). Globally, agricultural soils account for only under one fourth of the OC pool (Gibson *et al*., 2002). However, these soils represent the part of OC pool that is most readily active to management.

A summary on distribution of OC stock in Thailand indicated that soil in 1 meter depth contain OC approximately 6.21×10^{15} gram (Moncharoen, 2001). The majority of soils under sugarcane plantation in Chonburi and Rayong provinces, East of Thailand are low in total OC content (4-9 mg C g $soil^{-1}$ in the upper 30 cm). The soil C stock in the area (22,164 ha) was estimated at 59.43 Tg C (Tg = 10^{12} g C) (Yuttitham, 2006).

Mechanism of Soil Carbon Sequestration

The basic mechanism of C_{seq} is the balance between inputs and outputs of OC (Rasmussen *et al*., 1998). Protection of OC is an integral part of C_{seq} (Jenkinson, 1988). Mechanisms of stabilization of OC can be generally divided into two broad categories: biochemical recalcitrance and physical protection (Krull *et al*., 2003). It is important to note that these mechanisms are not separate entities and instead should be viewed as processes that interact with one another.

1. Biochemical recalcitrance

Biochemical recalcitrance is the inherent chemical and structural stability of biomolecule which is a function of the intra- and inter- structural bound strengths, the degree of regularity of occurrence of structural units and the degree of aromaticity (Gleixner *et al*., 2001). The biological stability of OC is influenced by the physical and chemical environment of the soils (e.g. moisture, temperature, pH, and aeration), the chemical structure of OC (i.e. its susceptibility to decay) and the physical accessibility of the organic matter to microbes and enzyme, i.e. mechanisms of protection offered by soil minerals (Sollins *et al*., 1996; Jastrow and Miller 1997; Baldock and Skjemstad, 2000). In order to understand the interactions between OC and mineral surface, it is fundamental to review the processes that occur during decomposition of plant material and formation of soil humus.

1.1 Particulate form

Most OM enters the soils is in '*particulate form*' (>20 μm) and decomposition into the soil. Undergoing many structural changes as it is covered by aggregates, associated with clay minerals and is incorporated into soil microbial biomass and metabolites (Golchin *et al*., 1997). The initial composition of free particulate OC is characterized by high content of polysaccharides, typically found in fresh plant and microbial tissues (cellulose, hemicelluloses, chitin, peptidoglycan) and C/N ratio are between 12-40 (Krull *et al*., 2003).

1.2 Active or labile pool

With continued decomposition, the chemically labile (easily bioavailable) component such as carbohydrates and proteinaceous materials are preferentially utilized, C/N ratios decrease to 12 or less and particle size decreases to 2-20 µm. In OC models, carbohydrates are usually assigned to the fast degrading '*active* or *labile pool*' which turnover in month or few years (Baldock and Skjemstad, 2000)

1.3 Stable or passive pools

In ^{13}C-NMR studies observed decrease in O-alkyl material and increase in the chemically more recalcitrant substances such as aromatic C (lignin) and alkyl C (lipid structures) (Baldock *et al*., 1992; Zech *et al*., 1997). The OC containing alkyl and lignin-derived aromatic C are thought to have turnover times between 10s to 100s of years and assigned to the '*stable* or *passive pools*' (Coleman and Jenkinson, 1995).

1.4 Inert or highly recalcitrant pool

Charcoal or black C is considered the most recalcitrant structure of OC due to its high degree of aromaticity and highly condensed chemical structure. They have an estimated turnover time of 5000 to 10000 years and are finely divided (<53 µm). And they transported along with other soil particles during erosional events and are therefore particularly abundant in alluvial soils as these forms in zones of accumulation (Skjemstad *et al*., 1990). Skjemstad *et al*. (1999) even found that up to 57% to the total OC was composed of charcoal and this pool are '*inert or highly recalcitrant pool*'.

The most important chemical parameters influencing litter decomposition, nutrient release and OM dynamics are C/N ratio, lignin and polyphenols (Anderson and Flanagan, 1989). Biochemical processes include recalcitrant litter chemistries that slow down or inhibit microbial degradation (Scholes *et al*., 1997), and chemical protection is through bonding between minerals, and formation of recalcitrance compounds (Bayer *et al*., 2001), which can limit accessibility of decomposers to the organic inputs. Even labile organic material that would otherwise decompose quickly can be protected from decomposition by close association with silt and clay particles (Sorensen, 1972). Analyses synthesizing multiple studies suggest that stabilization capacity is dictated by soil silt and clay content and the surface area and reactivity of mineral soil particles (Six *et al*., 2002).

2. Physical Protection

Physical protection is defined as the interaction of OC with the soil minerals matrix, which results in physical or chemical inaccessibility of soil C to decomposer organisms by the formation of closed environments or strong chemical bonds (Krull *et al*., 2003). It is important to note that these mechanisms should be viewed as processes that interact with one another.

2.1 Physicochemical stabilization

Physicochemical stabilization which refers to the association form between soil minerals and organic materials (adsorption to clay minerals, formation of complexes). Physicochemical stabilization is based on adsorption and chemical binding of OC onto mineral surfaces. In soils, layer silicates as well as sesquioxides constitute the majority of materials that provide a reactive surface onto OC can be adsorbed. These interactions are defined by the chemical nature of organic material (functional group content, molecular size), type of clay minerals and specific surface area of mineral particles is a function of particle size (Feller and Beare, 1997; Sorensen, 1972; Torn *et al*., 1997). The presence of multivalent cations, for example Ca^{2+} and Al^{3+}, can enhance the affinity of OC towards mineral surfaces by cation bridges if the surfaces of the mineral and the OC carry like charges (Schlautman and Morgan, 1994). If a soil contains a great amount of $CaCO_3$, a lot of Ca^{2+} is in solution and therefore the charged of OC is able to be sorbed to mineral surface by polyvalent cation bridges (Baldock and Skjemstad, 2000). Flocculation and subsequent precipitation of complexes of Ca^{2+} and aromatic OM can also explain the enhanced sorption in $CaCl_2$ background (Mikutta and Mikutta, 2007). The addition of cations to the soil solution increased the sorption of humic acid to the surfaces of illite, kaolinite or montmorillonite in the order Al > Ca > Mg > K, Na (Varadacheri and Mondal, 1991).

2.2 Physical stabilization

This physical protection exerted by macro- and/or micro-aggregates on OC is attributed to: (i) reduced access of microbes to the center of the aggregates where most of the OC is located (ii) reduced diffusion of oxygen into macro- especially micro-aggregates and (iii) spatial localization and therefore inaccessibility of enzymes to intra-aggregate spaces (Six *et al*., 2002). The capacity of a soil to stabilize OC by this mechanism depends on its structural properties, including the degree and stability of aggregates (Krull *et al*., 2003).

In most soil types and management systems, aggregate formation follows a hierarchical order (Tisdall and Oades, 1982): primary particles associate into microaggregates (<250 µm), which in turn associate into macroaggregates (>250 µm). The smaller the aggregate hierarchical level, the higher is its physical stability because the binding agents involved in aggregate formation change with the spatial scale. Clay-sized associations are bound together by sesquioxides, humic materials, and polysaccharides. These associations are further bound into microaggregates by bacterial and fungal debris which may further be bound into macroaggregates mostly by temporary agents derived from plant residues (Cosentino *et al*., 2006). Therefore the rate of macroaggregate formation can be enhanced by returning more crop residues to soil. Macroaggregate stability is very sensitive to changes in land use and cultivation practices (Puget *et al*., 2000). In contrast, OC stabilization is greater within microaggregates and is only slowly influenced by management systems (Six *et al*., 2000b). Puget *et al*. (2000) estimated a turnover time of only a few years for OC in macroaggregates compared with a turnover time of hundreds of years for OC in microaggregates. Nonetheless, macroaggregates still play an important role in C_{seq} as they promote the formation and seclusion of microaggregates within the macroaggregate structure (Six *et al*., 2000b).

Factors Affecting Mechanism of OC Stabilization in Tropical Soils

1. Effect of soil forming factors

1.1 Climate

Climate strongly affects the decomposition and mineralization rates of OM (Ladd and Amato, 1985). In natural ecosystems, temperature and precipitation are the main factors affecting both inputs and losses of organic materials in soil ecosystems (Alvarez and Lavado, 1998). They control the boundaries for maximum C_{seq} in soils in a given area (Australian Greenhouse Office, 2000). Temperature has a direct effect on the rate of decomposition of organic materials and OC (Jenkinson, 1991) and precipitation has an effect on plant productivity (Dalal and Mayer, 1986). Especially, OC content in the top 0–50 cm soil layer is positively correlated with the precipitation and temperature ratio (Alvarez and Lavado, 1998). The amounts of OC and nitrogen have been found to be positively correlated with precipitation, and negatively correlated with temperature at any particular amount of precipitation (Burke *et al*., 1989). The correlation between OC and soil types is partly due to zonal distribution of soil in the world in relation to climatic factors (Gibson *et al*., 2002). The decomposition of OC in tropical regions is normally more rapid than in temperate regions (Dalal and Chan, 2001).

1.2 Parent materials

The OC content of a soil is influenced by its parent material thickness, texture and mineral content (Baldock and Skjemstad, 2000). Parent material influences OC accumulation not only through its effect on soil texture but also on type of clay mineralogy (Saggar *et al*, 1996; Wattel-Koekkoek *et al*., 2001). Soils developed from inherently rich material, such as basalt, are more fertile than soils formed from granitic material, which contains less mineral nutrients. The former experiences more OC accumulation because of abundant vegetative growth (Food and Agriculture Organization [FAO], 2005). In tropical soils, minerals in clay fractions are dominated by 1:1 phyllosilicates, as kaolinite, associated with crystallized and poorly or non-crystallized iron (Fe) and aluminum (Al) oxides and hydroxides (Segalen, 1994).

1.3 Topography

Topography modifies the microclimate and influences the vegetation, thereby producing a strong effect on the amount of OC. The OC accumulation is often favored at the bottom of the hills. There are two reasons for this accumulation. Firstly its conditions are wetter than at mid- or upper-slope positions, and secondly, OC is transported to the lowest point in the landscape through runoff and erosion (Quideau, 2002).

1.4 Vegetation

Plant production and decomposition determine C inputs to the soil profile (Brady and Weil, 2008). The quality of C inputs, often characterized by lignin content, is another important control of decomposition rates (Menteemeyer, 1978). Under tropical conditions, applications of readily degradable materials with low C:N ratios, such as green manure and leguminous cover crops favor decomposition and a short-term increase in the labile nitrogen pool during the growing season. Plant constituents such as lignin and other polyphenols retard decomposition (Juo and Lal, 1977). Palm and Sanchez (1990) reported that both the decomposition rate and the nitrogen release patterns of three tropical legumes are related to the amount of polyphenol compounds such as lignin in the leaf. Leaves with the lowest concentrations of polyphenols have the fastest decomposition rate. Root turnover also constitutes an important addition of humus into the soils, and consequently it is important for C_{seq} (FAO, 2005). In forests, most OM is added as superficial litter. However, in grassland ecosystems, up to two-thirds of OM is added through the decay of roots (Quideau, 2002). Vegetation is a major determinant of the vertical distribution of OC as related to plant root zone. A report on vegetation change and surface erosion in desert grasslands in Southern New Mexico indicated that the OC distributions are deepest in shrubs where their root zone is deepest, intermediate in grasslands and shallowest in forest (Ludwig and Esteban, 2000).

1.5 Time

The stage of OM accumulation can be divided into five phases (Eswaran *et al*., 1995). The first phase (0-6 years) is the gradual improvement of physical condition and accumulation of enough nitrogen to support a cover of vegetation. The second phase (10-40 years) is an accelerated rate of OM accumulation. The third phase (40-1,000 years) is the slowing down of the annual rate of OM accumulation. The fourth phase (1,000-10,000 years) is the equilibrium phase of maturity, where the amount of OM remains nearly constant over a very long period of time. Eventually a fifth phase (> 10,000 years) occurs in which declining soil fertility leads to decreased plant growth and gradual decrease in OM. That maturity phase lasts so long that some of other factors influencing OM may change during changes the time and type of vegetation, harvest removal, cultivation and erosion (Troeh and Thompson, 1993).

2. Effect of physicochemical properties

2.1 Soil structure and aggregation

Soil structure and organic matter are properties that often change simultaneously. Factors affecting soil aggregation vary according to soil order and type, but OC is a common one (Bronick and Lal, 2005). Soil structure, the result of the process by which primary soil particles (sand, silt and clay) are aggregated with organic and amorphous materials controls aeration, water infiltration, water, gas and solute transport, drainage, soil fertility, and the ease of soil tillage (Dexter, 1988). Soil aggregate size distribution and stability are important indicators of soil physical quality and C_{seq}. The aggregate distributions were expressed as mean weight diameter (MWD) (Kemper and Rosenau, 1986). A number of soil properties contribute to the formation and stabilization of aggregates including OM, clay mineralogy, soil texture, exchangeable cations and salt content, $CaCO_3$ content and Fe and Al oxides (Tisdall and Oades, 1982). Silicate clays, calcium carbonate and sexquioxides cement particles together but their binding effect is much less than that of humus (Boix-Fayos *et al*., 2001). The formation and stabilization of macroaggregates tend to be dependent on OC, except in certain highly weathered soils in which Fe and/or Al oxides provide the main agent that binds particles into aggregates (Six *et al*., 2000b).

Recent researches have focused on the role of soil structure in controlling the dynamics of OC by physical protection (Balesdent *et al*., 1998; Christensen, 2000). Balabane (1996) and Besnard *et al*. (1996) showed that OC within a given particle-size fraction has different turnover rates in relation to differing locations within or between soil aggregates. Anderson *et al*. (1981) described the differences of soil humus associated with primary particle-size separates as essential to understanding the dynamic of OM. Tisdall and Oades (1982) presented a conceptual, hierarchical model for soil aggregate formation that describes the association of OC with three different soil physical units, silt and clay particles (SC, <53 µm), microaggregates (MiA, 53-250 µm), and macroaggregates (MA, >250 µm). Macroaggregates are very sensitive to land use changes and agricultural practices since they are less stable than microaggregates, due to the stronger binding of the latter (Tisdall and Oades, 1982). Macroaggregates (>2 mm) are abundant in forest soils (41–70 %) while micro aggregates (<0.5 %) are abundant (56–63 %) in cultivated soils (Shrestha *et al*., 2007). In Nepal, organic carbon concentration in aggregate was reported that macroaggregates in the surface layers contained 14.9 to 24.8 and 5.5 to 20.7 g kg^{-1} OC in cultivated and forest soils, respectively, while microaggregates contained 12.5 to 30.8 and 11.9 to 25.4 g kg^{-1} OC, respectively (Shrestha *et al*., 2007). In addition, cultivated soils contained higher amounts of clay but less clay-associated OC than do forest soils. Clay and silt fractions associated with OC can consist of both labile and stable fractions (Balabane and Balesdent, 1995; Balesdent *et al*., 1998). Six *et al*. (2000b) suggested that microaggregates are the primary sites of OC preservation from mineralization. However, the stability of soil OC and aggregation as well as relationships between OC and aggregation are affected by the presence of sesquioxides (Dalal and Bridge, 1996). The importance of aggregation in the stability of OC should also be re-examined for soils that are rich in sesquioxides (Barthès *et al*., 2008).

2.2 Effect of soil texture and clay mineralogy

Mineralization of OC is generally more rapid in coarse texture than in fine texture soils and the protection of OC by silt and clay particles is well established (Sorensen, 1972; Ladd *et al*., 1985; Hassink, 1997). The ability of soils to retain OC is most likely limited by the surface area available for sorption (Guggenberger and Kaiser, 2003) that depends on two mechanisms. Firstly, bonds between the surface of clay particles and OM retard the decomposition process. Secondly, soils with higher clay content have a higher potential for aggregate formation (Rice, 2002). Under similar climate conditions, OC content in fine-textured (clayey) soils is 2-4 times that of coarse-textured (sandy) soils (Prasad and Power, 1997). In contrast, OC content in fine-textured soils in the Tropics is different since the clay minerals are generally dominated by the one with less surface area (kaolinite) (Barthès *et al*., 2008). Clay content is the best predictor in the soil deeper layers. This may be due to the increased proportion of slower cycling OC pools at depth (Trumbore, 2000) since there are C pool strongly associated with clay particles and noncrystalline minerals that stabilize and protect OC (Torn *et al*., 1997). McLauchlan (2006) however reported that clay concentration has no effect on total soil C pool sizes or rate of accumulation. Many studies have shown that clay content influences aggregation (Schlecht-Pietsch *et al*., 1994) that increased clay contents were associated with increased aggregation or aggregate stability. The soil clay content indirectly affects soil C storage by occluding organic materials. Clay correlates positively with aggregate size and the rate of aggregate accumulation, and it correlate negatively with potential net N mineralization rates regardless of field age (Zinn *et al*., 2007). Therefore, soil texture (particularly soil clay content) plays direct and indirect roles in chemical and physical protection mechanisms (Gale *et al*., 2000a). Organic carbon retention can be affected by soil texture and mineralogy directly, through sorption by clays (Zinn *et al*., 2007), and indirectly through soil structure.

Kaolinite, the main clay mineral in many upland soils in the Tropics, has a much smaller specific surface and nutrient exchange capacity than do most other clay minerals (Yoothong *et al*., 1997). Therefore, kaolinitic soils contain considerably fewer clay-humus complexes. This is because the OC in kaolinite is rich in polysaccharides whereas that in smectite is abundant in aromatic compounds (Wattel-Koekkoek *et al*., 2001). For, kaolinitic soils, pH affects surface charge due to the variable charge nature of clay crystal edges. Increasing pH leads to a charge reversal on the edges of the kaolinitic clay particles, from positive to negative (Tombacz and Szekeres, 2006). This, in turn, weakens the bonds between positive and negatively charged surface sites on adjacent particles and thus has an adverse effect on the stability of the aggregates (Chang *et al.*, 1987). Sesquioxides affect the stability of OC and aggregation (Barthès *et al.*, 2008). The aggregating role of OC could be less effective in soils that are rich in sesquioxides (Tisdall and Oades, 1982; Six *et al.*, 2002) due to the role of sesquioxides in the stabilization of OC (Dalal and Bridge, 1996). The strong bonds between organic anion and clay crystals derived from the action of the polyvalent cations prevent the organic materials from microbial decomposition (Shukla and Lal, 2004). The strength of bonds depends on the valence of the metals bridging the inorganic and organic anions in the following order: $Al^{+3} > Fe^{+3} > Ca^{+2} > Na^{+}$ (Tisdall, 1996).

Oxides are known to readily bind to both clay minerals and organic material (Goldberg, 1989; Schwertmann and Taylor, 1989) forming mineral complexes which may significantly determine capacity of a soil to sequester C. Iron oxides have been shown to strongly interact with kaolinite, for instance, promoting the formation of aggregates which may help preserve OC (Kitagawa, 1983). Positively charged oxides may form bridges between negatively charged organic compounds and clay minerals, similar to the clay-polyvalent cation OM complexes proposed by Edwards and Bremner (1967). Amorphous Al oxides have a greater capacity to absorb dissolved OC relative to ferrihydrite (Kaiser and Zech, 1998).

3. Effect of chemicophysical properties

The pH affects the surface charge of variable-charge minerals, e.g. Fe and Al (hydr) oxides. On hydroxylated surfaces, the net surface charge becomes increasingly negative as pH increases (Sollins *et al.*, 1996; Krull *et al.*, 2003). The pH also affects the extent of dissociation of the carboxylic acid groups ($COOH^{-} > COO^{-}$) in OM. In many tropical soils, weathering has reached an advanced stage, resulting in clay minerals with low nutrient retention capacities (Sanchez, 1976). Kaewmano *et al.* (2009) shows aggregate stability have a strong negative relationship with soil pH that with increasing soil pH clay dispersion occurs as a result of increased repulsion of negatively charged clay particles. Typical values for the cation exchange capacity (CEC) of soils dominated by kaolinite and amorphous oxides range from 2 to 6 $cmol_c$

kg^{-1} (Gallez *et al*., 1976; Duxbury *et al*., 1989). As permanent charge in these soils is generally only 1 or 2 $cmol_c\ kg^{-1}$, the importance of the CEC due to variable charge is obvious (Oades *et al*., 1989). Variable charge is associated primarily with oxides and OM is the most important contributor to the CEC in these soils. Generally, OM is responsible for 25–90 % of the mineral soil surface horizons (van Dijk, 1971; Oades *et al*., 1989). Some Brazilian soils in tropical humid area have high ECEC value up to 90 $mmol_c\ kg^{-1}$ in the clay fraction of surface horizons (Soares *et al*., 2005). This may indicate the formation of clay–organic matter complexes caused by OM bonding to kaolinite via calcium or aluminum cation bridges (Asadu *et al*., 1997).

The integral charge on soil surfaces is derived from multi-site surfaces, inorganic functional groups (hydroxyl of Si, Al and Fe) and organic functional groups (enolic, phenolic and carboxyl) (Duquette and Hendershot, 1993). The intrinsic charge of soil particles depends on degree of soil weathering and type of mineral constituents (Chorover *et al*., 2004). Soils in the Tropics as indicated by their constituents are dominated by kaolinite and sesquioxides (gibbsite, hematite and goethite) (Fontes *et al*., 1992; Melo *et al*., 2001). These minerals are known to generate mainly variable charge on their surfaces (Schwertman and Taylor, 1989; Zhang and Yu, 1997). As the soil development processes reach an advanced stage of weathering, the variable charge becomes dominant over permanent charge (Hendershot and Lavkulich, 1978). Therefore, charge component in tropical soil is derived from kaolinite, sesquioxides and organic matter (Anda *et al*., 2008). It is very difficult to change soil mineral therefore the retention of plant nutrients may have to depend on OM management (Oades *et al*., 1989).

4. Effect of land use and agricultural management practices

In tropical soils, tillage, irrigation, and chemical fertilizers have been used to complement and enhance the functions of OM (Sanchez and Miller, 1986). Tillage is one of the major practices that increase decomposition rates. Soil tillage practices are of particular significance to the OM status because they affect OC dynamics both directly and indirectly (Dick *et al*., 1986a). Tillage practices which invert or considerably disturb the surface soil reduce OC by increasing decomposition and mineralization of biomass due to increased aeration and mixing of plant residues into the soil, exposing previously protected OC to soil fauna and increasing losses due to soil erosion (Lal, 1984). The OM that binds microaggregates into macroaggregates has been suggested to be a primary source of OM lost upon cultivation (Elliott, 1986). In Saskatchewan, 60 years after changing the land to cultivation there were a total loss about 35 percent of the C in loamy soils and about 46 percent of C in sandy soils (Thiessen *et al.*, 1982). Shrestha *et al.* (2007) reported that soils under natural forest have higher OC associated with all primary particles. Cultivated soils contained higher amounts of clay but less clay-associated OC than that of forest soils. Cultivation has more effect on macroaggregate than on microaggregate. Shrestha *et al*. (2007) studied soils under dominant land uses in the Middle Hills of Nepal, where land use change is progressing rapidly and the risks of soil degradation are high. The results showed that macroaggregates in the surface layers contained 14.9-24.8 and 5.5-20.7 g kg^{-1} OC while microaggregates contained 12.5-30.8 and 11.9-25.4 g kg^{-1} OC in cultivated and forest soils, respectively.

5. Effect of soil depth

Depth fractionations of OC can indicate the importance of preferential flow paths for C input that increases with soil depth (Bundt *et al*., 2001). In A horizons, OM is mainly derived from plant residues that are mixed into surface soils by tillage (von Lützow *et al*., 2006). In subsoils, C input occurs mainly through plant roots and leaching of dissolved OM. With the increasing depth there is less probability for any point in a soil to be located near a preferential flow path. Most soils store 37–39% of their total OC to 2 m in the 1 to 2 m depth section (Batjes, 1996). There should be a greater potential for OC preservation in the subsoil, where the OC saturation of mineral particles is small (Scharpenseel and Becker-Heidmann, 1989; Rumpel *et al*., 2002). Paul *et al*. (2001) suggested that, chemical interactions at depth were more important than physical processes in stabilization of OC, while physical processes (aggregation) had the strongest effect in the surface horizons. Kögel-Knabner *et al*. (2008) reported that the proportion of OC bound to minerals and stored in the clay fractions increased with depth and was generally higher in the subsoil than in the topsoil.

Major Upland Agricultural Soils in Northeast Thailand

Northeast Plateau is one of the six physiographic regions of Thailand (Moormann and Rojanasoonthon, 1972). The elevation, above mean sea level, of the plateau ranges between about 250 meters in the northwest and about 100 meters in the southeast (Department of Mineral Resources, 1987). Upland soils in Northeast Plateau, Thailand cover about 41% of the country upland field area (Office of Agricultural Economics, 2008). Upland soils in Northeast Plateau are mostly classified into Kandiustox Kandiustults, Paleustults, Haplustults, Haplustolls, Paleustalfs, Rhodustalfs, Haplustalfs, Dystrustepts and Ustifluvents (Soil Survey Division Staff, 2004) developed under oxidizing condition (Table 1). The red and yellow soils are commonly found in the upland portion of the area with undulating topography and soils of this region are generally sandy and well developed (Kheoruenromne, 1987).

Most of these soils are generally deep, highly leached and well-developed with low fertility status under tropical savanna climate (Kheoruenromne, 1987). Their clay fraction is relatively small and dominated by kaolinite (Yoothong, 1997). Other features of soils include laterite layer, plinthite layer and salt effect, low amount of nutrient, poor exchange properties and low to very low organic matter (Watana, 1998; Laosuwan, 2003; Panikorn, 2003; Wongpokhom, 2007). From the recent data on their general environmental condition and profile characteristic variability illustrate well that their parent materials and topographic difference play major roles in their genesis. Their profile differentiation varies according to stability of the landscape affected by surface transportation and erosion by water mainly.

Most of upland soils in this region are used for cultivating cassava, sugarcane and corn (Office of Agricultural Economics, 2008). These soil attributes have a profound impact on their agricultural productivity and year to year variability in yields of paddy and upland crops depending on rainfall (Polthanee, 2001). The yield of crops varies from low to moderate and is dependent on soil management (Yoothong, 1997).

Table 1 Upland soils in Northeast Plateau, Thailand (Modified from Soil Survey Division Staff, 2004).

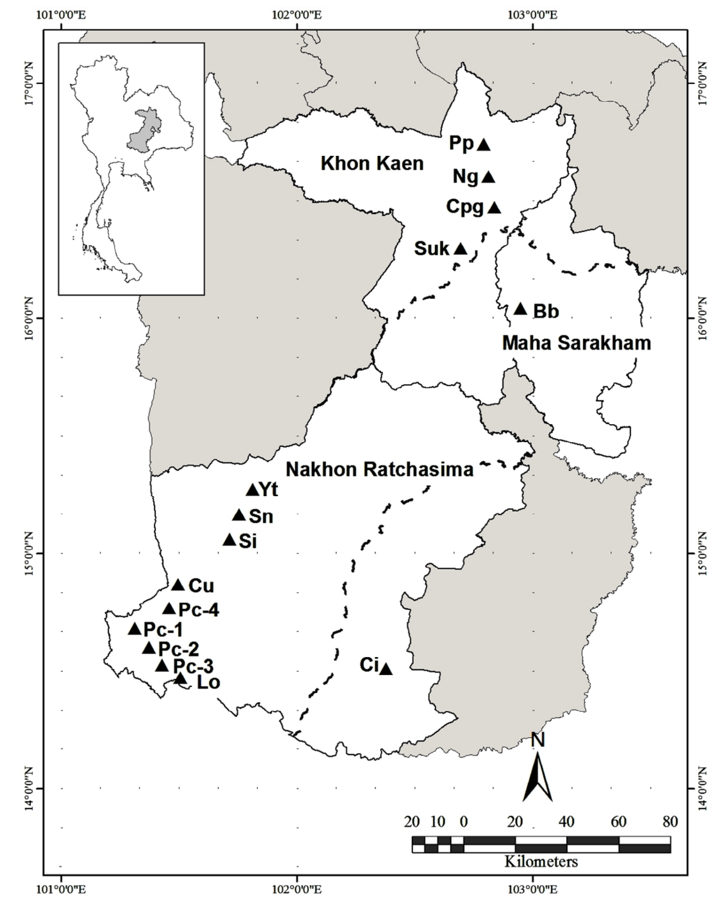
Suborder	Great group	Subgroup	Family	Series
Ustox	Kandiustox	Typic	vf, kao	Loei (Lo)
		Rhodic	vf, kao	Chok Chai (Ci) Pak Chong (Pc)
Ustults	Kandiustults	Typic	col, sili	Chum Phuang (Cpg)
			fl, sili	Warin (Wn)
		Rhodic (Oxyaquic)	fl, sili, iso	Korat (Kt)
	Paleustults	Typic	col, mixed, semiact	Huai Thalaeng (Ht)
			f, mixed, semiact	Sung Noen (Sn)
			fl, sili, subact	Satuek (Suk)
			fl, sili, semiact	Yasothon (Yt)
		Typic (Oxyaquic Plinthic)	lsk/c, kao, iso	Phon Phisai (Pp)
		Typic (Kandic)	f, kao, iso	Ban Chong (Bg)
	Haplustults	Plinthaquic	fl, mixed, subact	Khemarat (Kmr)
			lsk, mixed, semiact	Borabue (Bb)
		Petroferric	lsk/frag, mixed, subact	Sakon (Sk)
		Kanhaplic	lsk, mixed, iso	Phu Sana (Ps)
			fl, sili, iso	Lat Ya (Ly)
Ustolls	Haplustolls	Entic	lsk,carbonatic, iso	Takhli (Tk)
Ustalfs	Paleustalfs	Arenic	l, sili, semiact	Ban Phai (Bpi)
		Typic(Plinthic)	lsk, mixed, semiact	Sa Kaeo (Ska)
	Rhodustalfs	Typic	fl, mixed, semiact csk, kao	Sikhio (Si) Surin (Su)
	Haplustalfs	Typic	f, mixed, act	Chatturat (Ct)
			s, sili	Khambong (Kg)
		Arenic	s, sili	Nam Phong (Ng)
		Ultic	fsi, mixed, semiact	That Phanom: (Tp)
Ustepts	Dystrustepts	Typic	col, mixed, act	Chumphon Buri (Chp)
Fluvents	Ustifluvents	Typic	col, mixed, act,cal, iso	Tha Muang (Tm)
		Oxyaquic	col, mixed, superact, nona, iso	Chiang Mai (Cm)
Psamments	Ustipsamments	Typic	l, sili	Chan Thuek (Cu)
	Quartzipsamments	Ustic	s, sili, coated	Dan Khun Thot (Dk)

f =fine; vf=very fine; fl=fine-loamy; col=coarse-loamy; fsi = fine-silty; l = loamy; csk = clayey-skeletal; lsk = Loamy-Skeletal; s=sandy; sili=siliceous; kao=kaolinitic; subact = subactive; semiact=semiactive; act = Active

MATERIALS AND METHODS

Sampling Sites

Soil maps at scales of 1:100,000 and 1:50,000 and other maps (topographic map, geological map) were used as base maps to select the study area. Fifteen representative sites were selected in major upland agricultural areas which are well distributed in Nakhon Ratchasima, Maha Sarakham and Khon Kaen provinces. There are 12 soil series: Loei (Lo), Chok Chai (Ci), Pak Chong (Pc1, Pc2, Pc3, Pc4), Chum Phuang (Cpg), Sung Noen (Sn), Satuek (Suk), Yasothon (Yt), Phon Phisai (Pp), Borabue (Bb), Sikhio (Si), Nam Phong (Ng) and Chan Thuek (Cu) (Figure 1).



▲ Sampling site ☐ Province boundary --- Main river

Figure 1 Sampling locations for upland agricultural soils in Northeast Plateau, Thailand.

They cover approximately 26,849 km^2 (16.78 million rai) (Table 2). The classification and environmental setting of these soils are shown in Table 3. The study area is under tropical savanna climate (Aw) with an annual average rainfall of 1,000-1,400 mm and mean temperature of 25-38 ^{o}C (Meteorological Department of Thailand, 2006). The soils have ustic soil moisture regime and isohyperthermic temperature regime (Soil Survey Staff, 1993). All soils are deep (Table 3). Alfisols developed on metasedimentary rock, sandstone, calcareous sandstone and granite. Oxisols developed on limestone and basalt while Ultisols developed on sandstone, siltstone and other sedimentary rocks.

Land uses at the time of sampling were uncultivated lands, corn fields, tree with forage crops and cassava fields. (Figure 2 and Table 3). Historical management of tree with forage crops in this study indicates low soil management input whereas corn fields always have high surface input in every cropping.

Table 2 The areas of fifteen representative soils in Northeast Plateau, Thailand. (Modified from Soil Survey Division, 1986)

Soil name	Area		
	Million rai	km^2	%
Phon Phisai (Pp)	8.46	13,530	50.39
Num Phong (Ng)	2.10	3,359	12.51
Satuek (Suk)	1.79	2,860	10.65
Chum Phuang (Cpg)	1.37	2,188	8.15
Borabue (Bb)	0.96	1,537	5.72
Sung Noen (Sn)	0.52	834	3.11
Chok Chai (Ci)	0.45	713	2.66
Yasothon (Yt)	0.40	634	2.36
Loei (Lo)	0.35	560	2.09
Pak Chong (Pc)	0.21	344	1.28
Sikhio (Si)	0.15	242	0.90
Chan Thuek (Cu)	0.03	49	0.18
Total	16.78	26,849	100

Table 3 Pedological characterization of major upland agricultural soils in this study.

Subgroup	**Series**	**Site**	**Lat. Long.**	**Parent material**	**Physiographic position**	**Elevation (m MSL)**	**MAP (mm) MAT(˚C)**	**Slope (%)**	**Depth (m)**	**Land use**
Typic Kandiustox	Loei (Lo)	Nakhon Ratchasima	14.60' 101.39'	Limestone	Coalesing intermontane footslope	394	1,105 25.9	3	0-1.8+	Co
Rhodic Kandiustox	Chok Chai (Ci)	Nakhon Ratchasima	14.48' 102.22'	Basalt	Lava corrosion plain	266	1,097 27	1	0-2.0+	Cas
Rhodic Kandiustox	Pak Chong (Pc1)	Nakhon Ratchasima	14.65' 101.30'	Limestone	Karst corrosion plain	372	1,105 25.9	3	0-2.0+	Co
Rhodic Kandiustox	Pak Chong (Pc2)	Nakhon Ratchasima	14.65' 101.31'	Limestone	Karst corrosion plain	375	1,105 25.9	1	0-1.7+	Co
Rhodic Kandiustox	Pak Chong (Pc3)	Nakhon Ratchasima	14.63' 101.32'	Limestone	Karst corrosion footslope in limestone intermontane valley	418	1,105 25.9	3	0-1.7+	U
Typic Kandiustox	Pak Chong (Pc4)	Nakhon Ratchasima	14.68' 101.41'	Basalt	Corrosion footslope	320	1,105 25.9	4	0-1.7+	TF
Typic Kandiustult	Chum Phuang (Cpg)	Khon Kaen	16.47' 102.84'	Red sandstone	Upper backslope of residual low hill	178	1,242 27.4	3	0-1.3+	TF
Typic Kandiustult	Sung Noen (Sn)	Nakhon Ratchasima	15.05' 101.70'	Siltstone	Rise on siltstone corrosion plain	252	1,182 27.7	3	0-1.4+	Cas
Typic Haplustult	Satuek (Suk)	Khon Kaen	16.29' 102.69'	Sedimentary rocks	Lower part of high erosional terrace	167	1,379 27	3	0-2.1+	TF
Typic Kandiustult	Yasothon (Yt)	Nakhon Ratchasima	15.14' 101.73'	Red sandstone	Residual plain (Corrosion plain)	245	1,182 27.7	3	0-1.7+	Cas
Typic Plinthustult	Phon Phisai (Pp)	Khon Kaen	16.68' 102.80'	Metasedimentary rocks	Upper extended footslope	176	1,242 27.4	3	0-2.0+	Cas
Plinthic Haplustult	Borabue (Bb)	Maha Sarakham	16.04' 102.88'	Sandstone	Shoulder slope of low residual hill	215	1,257 27.4	7	0-0.8+	Cas
Typic Rhodustalfs	Sikhio (Si)	Nakhon Ratchasima	14.91' 101.68'	Calcareous sandstone	Corrosion plain (calcareous sandstone)	242	1,182 27.7	4	0-1.3+	Cas
Psammentic Haplustalf	Nam Phong (Ng)	Khon Kaen	16.67' 102.80'	Local alluvium and colluvium	Shoulder slope on dissected lower footslope	202	1,242 27.4	6	0-2.0+	Cas
Psammentic Haplustalf	Chan Thuek (Cu)	Nakhon Ratchasima	14.68' 101.45'	Granite	Upper midslope	333	1,105 25.9	5	0-2.0+	Cas

Lat = Latitude, Long = Longitude, MAP: mean annual precipitation; MAT: mean annual temperature

Co = Corn field, Cas = Cassava field, U = Uncultivated land, TF= Tree with for age crop

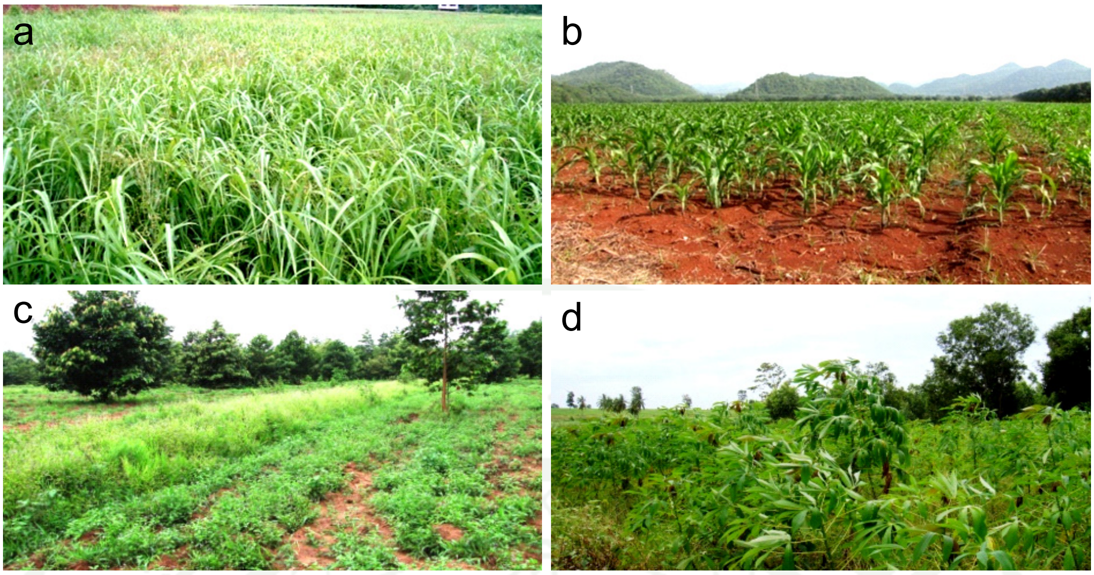


Figure 2 Present land uses of soils (a) uncultivated land, (b) corn field, (c) tree and forage crops, (d) cassava field.

Sample Preparation

These upland soils were sampled down to 2 meter depth. Analysis at the site included detailed profile description and sampling of soil from each genetic horizon by standard field study methods (Soil Survey Division Staff, 1993; Kheoruenromne, 2005). One hundred and sixteen soil samples, collected for the study, represent each genetic horizon of fifteen pedons. A part of samples were air-dried and gently crushed and then passed through 2000 and 1000 µm sieves. The resultant <2000 µm samples were used for general laboratory analysis. Fine earth soil samples (<2000 µm) were finely ground using ball mill and then passed through a 500 µm sieve for OC analysis. The clod samples were used for bulk density measurement. The core samples from topsoil were used for hydraulic conductivity measurement. For aggregate samples preparation, field-moist soils were gently broken to pass 8000, 2000, 1000 µm sieves. The resultant <8000 were used for aggregate size distribution (Elliott, 1986). The resultant of 1000-2000 µm was used for water aggregate stability (WAS) with the single sieve method (Kemper and Rosenau, 1986).

Laboratory Analyses

A summary of methods for physical, chemical, mineralogical, calculation and GIS analyses used in the study is shown in Table 4. The details of each method are in the Appendix B.

Table 4 Laboratory methods and analyses.

Analysis	Method	Reference	Sample[1/]
1. Physicochemical analysis			
1.1 Particle size analysis	Pipette method	Gee and Bauder, 1986	S
1.2 Hydraulic conductivity	Variable head method	Klute and Dirken, 1986	Core
1.3 Bulk density	Clod method	Blake and Hartge, 1986	Clod
1.4 Soil pH	1:1 soil:solution in H_2O, 1M KCl by pH meter	National Soil Survey Center, 1996	S
1.5 Organic carbon Organic matter	Walkley-Black method OC concentration x 1.724	Nelson and Sommers, 1996; Walkley and Black,1934	S
1.6 Total C	Dry Combustion by Auto CN analyzer	Elliott *et al*., 1991	S LMA SMA MiA SCf
1.7 Total N	Dry Combustion by Auto CN analyzer	Elliott *et al*., 1991	S LMA SMA MiA SCf
1.8 Available P	Bray II	Bray and Kurtz, 1945	S
1.9 Extractable bases (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+})	1 M NH_4OAc at pH 7.0 extraction and measured by AAS	Thomas, 1982a	S
1.10 Extractable acidity	Barium chloride-triethanolamine solution at pH 8.2	Thomas, 1982b	S
1.11 Cation exchange capacity by NH_4OAc pH 7.0	Saturating the exchange site and displacing by 1M NH_4OAc at pH 7.0	Chapman, 1965	S
1.12 Base saturation percentage	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	S
1.13 Extractable Fe, Al, Mn	Dithionite-Citrate-Bicarbonate (DCB) and measured by AAS	Mehra and Jackson, 1960	S
	Extraction in 0.2 M ammonium oxalate (pH 3.0) and measured by AAS	McKeague and Day, 1966	S
	Extraction in 0.1 M sodium pyrophosphate (pH 10.0) and measured by AAS	McKeague, 1967	S

Table 4 (Continued).

Analysis	Method	Reference	Sample$^{1/}$
2. Aggregation analysis			
2.1 Aggregate size distribution			
2.1.1 Macroaggregate (8000-250 µm)	Wet sieving of aggregate resultant of <8000 µm pass through 2000 and 250-µm sieves with sand correction	Elliott, 1986, Elliot *et al*., 1991	Agg1
2.1.2 Microaggregate (250-53 µm)	1) Wet sieving of aggregate resultant of <8000 µm pass through 250 and 53 -µm sieves with sand correction and	Elliott, 1986, Elliot *et al*., 1991	Agg1
	2) Isolate microaggregates contained within macroaggregates	Six *et al*., 2000b and Denef *et al*., 2001	LMA SMA
2.1.3 Silt and clay fraction (<53 µm)	1) Wet sieving of aggregate resultant of <8000 µm pass through 53 -µm sieves	Elliott, 1986, Elliot *et al*., 1991	Agg1
	2) Macroaggregates dispersed by ultrasonic dispersion (60 J ml^{-1})	Elliott, 1986, Elliot *et al*., 1991	LMA SMA
2.2 Water aggregate stability	Single sieve method by wet sieving	Kemper and Rosenau, 1986	Agg2
2.3 Mean weight diameter	By aggregate size distribution	Kemper and Rosenau, 1986	Agg1
3. Mineralogical analysis			
Mineral composition	By oriented clay and powder random X-ray diffraction (XRD) analysis (silt and clay fraction)	Brindley and Brown, 1980; Whittig and Allardice, 1986	Cl
4. Calculation			
4.1 Carbon stock in D1, D2, D3, D4	Expressed as Mg ha^{-1} for a specific depth by computed C concentration (kg Mg^{-1}) with bulk density, (Mg m^{-3})depth (m), area (10^{4}m^2 ha^{-1})	Veldkamp, 1994	
4.2 Carbon stock in 2 m depth	By summing up the C stock in each soil layer (D1, D2, D3, D4)	Batjes, 1996	
4.3 Carbon enrichment factors in aggregate	E_c = g C kg^{-1} fraction/ g C kg^{-1} whole soil	Christensen, 1996	
5. GIS analysis			
5.1 Carbon contour line	Inverse Distance Weighted Interpolation Method	Aguilar *et al*., 2005; Chaplot *et al*., 2006;	
5.2 The relationship between C_{seq} and spatial factors	Overlaying	ESRI, 1993	

$^{1/}$S = Soil samples (less than 2 mm), Cl = Clay samples, Core = Core samples, K = Kubiena samples, LMA = large macroaggregate (8000-2000 µm), SMA = Small macroaggregate (2000-250 µm), MiA = Microaggregate (250-53 µm), SCf = Silt and clay fraction (<53 µm), Agg1 = Aggregate size <8000 µm, Agg2 = Aggregate size 2000-1000 µm

Statistical Analyses

The data of samples from Ap (D1), Ap-0.6 m (D2), 0.6-1 m (D3) and 1-2 m (D4) layers were analyzed and the C_{seq} were computed for D1, D2, D3 and D4 to assure comparability. Simple and multiple linear correlation coefficients were calculated between variables. Multivariate stepwise regression analysis incorporating several soil properties was used to develop equation to predict total carbon. A two-way ANOVA (ANOVA-GLM procedure) was used to determine significant differences for soil and land use types with depth as the fixed main effects for some soil properties and OC sequestration. When significant differences were found, the Fisher probable least-squares differences (LSD) test at $P = 0.05$, 0.01 and 0.001 was used for mean comparisons between groups.

RESULTS AND DISCUSSION

Soil Characteristics

The typical appearance of major upland agricultural soils is shown in Figures 3 to 5. The summary of the field morphological characteristics of soils are given in Table 5. There are considerable differences in physicochemical soil properties among the soil profiles (Appendixes Table C1 to C3).

1. Synthesis on characteristics of major upland agricultural soils

The red and yellow soils are commonly found in major upland agricultural soils with undulating topography. Soils are generally well developed soils and sandy soils. They cover approximately 26,849 km^2 (16.78 million rai). The soils have ustic soil moisture regime and isohyperthermic temperature regime. They are Oxisols, Ultisols and Alfisols which Oxisols developed on limestone and basalt while Ultisols developed on sandstone, siltstone and sedimentary rock. Alfisols developed on metasedimentary rock, sandstone, calcareous sandstone and granite. Along with leaching, eluviation, illuviation and lessivage are major soil forming processes. Their evidence is the clay accumulation in the subsoils. In the oxidizing environment the dispersion of oxide solids must have been continuous to render the yellow and red colors in these soils (Buol *et al.*, 2003). Land uses at the time of sampling were uncultivated lands, corn fields, tree and forage crops and cassava fields.

All soils are deep, well drained with moderate to rapid permeability and moderate to slow runoff. The problem of lacking water should be more in Alfisols than in Oxisols and Ultisols. The bulk density (BD) values of these soils are low to high. The BD values of Oxisols are lower than that of Ultisols and Alfisols. Land use and cultivation also have effects on BD values in surface soils while subsoils are affected by clay and free iron oxide contents. The particle size distribution of these soils varies from clay to loamy sand and with 54-980 g kg^{-1}clay. The silt plus clay content (S+C) is dependent on type of parent rock; limestone > basalt > calcareous sandstone > siltstone > sedimentary rock > sandstone > granite > wash over local alluvium over mixed local alluvium and colluviums. Oxisol profiles do not show a textural change with depth and they have higher silt plus clay than do others and their color is generally more reddish than that of the sandier profiles.

The pH-H_2O of these soils is highest in Alfisols followed by Oxisols and Ultisols averaging 6.5, 5.6 and 5.0, respectively. Soil organic matter contents (SOM) of these soils are very low to moderately high. SOM of Oxisols is higher than that of Alfisols and Ultisols. The SOM normally has the effect on CEC and BD but for these upland agricultural soils the effect is not clear. Phosphorus in surface soils of Oxisols, Ultisols and Alfisols reflects their land use and management. Comparison of calcium in soils among various parent materials being calcareous sandstone >> limestone > basalt > siltstone > granite > sedimentary rock > sandstone > wash over local alluvium over mixed local alluvium and colluvium. The CEC values are very low to high. Oxisols have moderately low to high CEC followed by Alfisols that have very low to medium and Ultisols that have very low to low CEC. The CEC of these soils shows correlation with clay content and Fe_d.

Kaolinite is the most abundant mineral in the clay fraction of all samples. A greater amount of hematite is present in all depth of Oxisols and red Ultisols. Loei and Pak Chong 4 are Typic Kandiustox. Chok Chai and Pak Chong 1, 2 and 3 are Rhodic Kandiustox. Chum Phuang, Yasothon and Sung Noen are classified as Typic Kandiustult. Satuek, Borabue and Phon Phisai are Typic Haplustult, Plinthic Haplustult and Typic Plinthustult, respectively. Sikhio are Typic Rhodustalf while Nam Phong and Chan Thuek are Psammentic Haplustalf.

2. Field morphological properties

2.1 Oxisols

All Oxisols are very deep (>2m) and highly weathered. The profile development features are Ap-Bt-Bto for Oxisols developed on limestone (Lo, Pc1, Pc2, Pc3) and Ap-Bt-Bto-Bo for Oxisols developed on basalt (Ci, Pc4) (Figure 3). The relief of the site is undulating with slope of 1-4% and the mean annual precipitation is 1,105 mm (Table 3). Physiographic positions of these Oxisols include karst corrosion footslope in limestone intermontane valley, coalesing intermontane footslope, karst corrosion plain and corrosion footslope and lava corrosion plain (Table 3). The color of soil is dark reddish brown (2.5YR 2.5/4) to red (2.5YR 4/6) (Table 5).

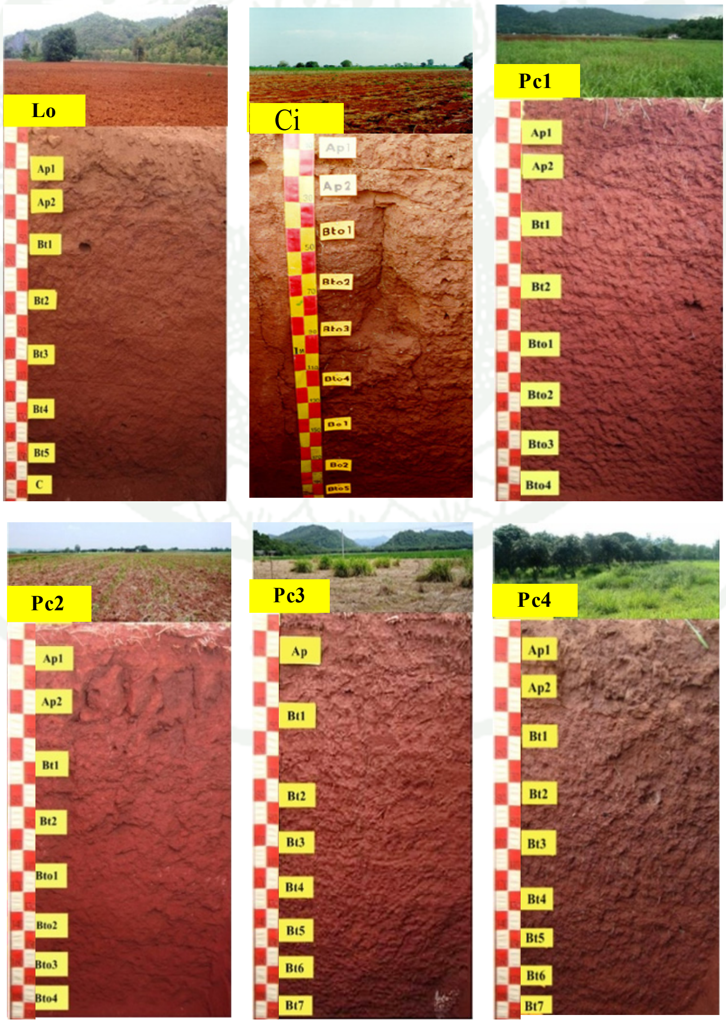


Figure 3 Representative upland Oxisols profiles in Northeast Thailand.

Field pH range is 4.5–8.0 in surface soils and ranging from 3.9-6.5 in subsoils. Oxisols developed on basalt (Pc4 and Ci) have field pH values in subsoils lower than do Oxisols developed on limestone do. Texture as influenced by their parent materials is clay throughout the profile except for silty clay and silty clay loam in Ap horizons of Lo and Pc4. Most Oxisols have a moderate to strong fine (5-10 mm) and medium (10-20 mm) subangular blocky to granular structure in topsoils and a semi-angular blocky structure to granular structure in subsoils. The few to common clay coatings on ped faces and pore walls are evident in the field. Except for Bo horizons of Oxisols developed on basalt do not have clay coating.

For Bt horizons, common to many ferri–argillan indicates prolonged leaching and oxidizing state of the solum (Kheoruenromne, 1987). There are few fine rock fragments and few to many vesicular and tubular pores occur in all horizons. Few clay balls and Fe-Mn oxide nodules exist in the subsoils. The presence of nodules in soils indicates the wetting and drying periods in their pedogenesis (Acquaye *et al*., 1992). Fine roots extend down to deeper than 180 cm.

2.2 Ultisols

The genetic horizons of Ultisols developed on sandstone include Ap-Bt-Crt (Cpg, Yt, Bb) on siltstone include Ap-Bt-Btc (Sn) and on sedimentary rock include Ap-Bt-Btc-Bv (Suk, Pp) (Figure 4). The relief of the site is undulating with slope of 3 - 7% and the mean annual precipitation range is 1,100-1,300 mm. Physiographic positions of Ultisols include siltstone corrosion plain, residual plain, upper extended footslope, upper backslope of residual low hill, lower part of high erosional terrace and shoulder slope of low residual hill (Table 3).

The color of Ultisols ranges from brown (7.5YR 4/4) to yellowish red (5YR 4/6) and reddish yellow (7.5YR 6/6) to red (2.5YR 4/6) in the lower horizons (Table 5). Field pH ranges are 4.0–6.5 in surface soils and 4.0 - 6.0 in subsoils. Texture ranges from loamy sand to sandy loam. Most Ultisols have weak to moderate and fine (5-10 mm) to medium (10-20 mm) subangular blocky and a semi-angular blocky structure in subsoils. Ulisols also have few variegated sands, few faint clay coats on ped faces and clay bridges among sand grains in subsoils. Clay coatings in the Bt and Btc horizons of these soils indicate their relatively well developed stage of soil formation (Buol *et al*., 2003). There are few to common vesicular and tubular pores in all horizons. Some subsoils have few strong clay balls (Yt), Fe oxide nodules (Sn) and silt pockets (Suk). The fine roots extend down to deeper than 130 cm (Table 5).

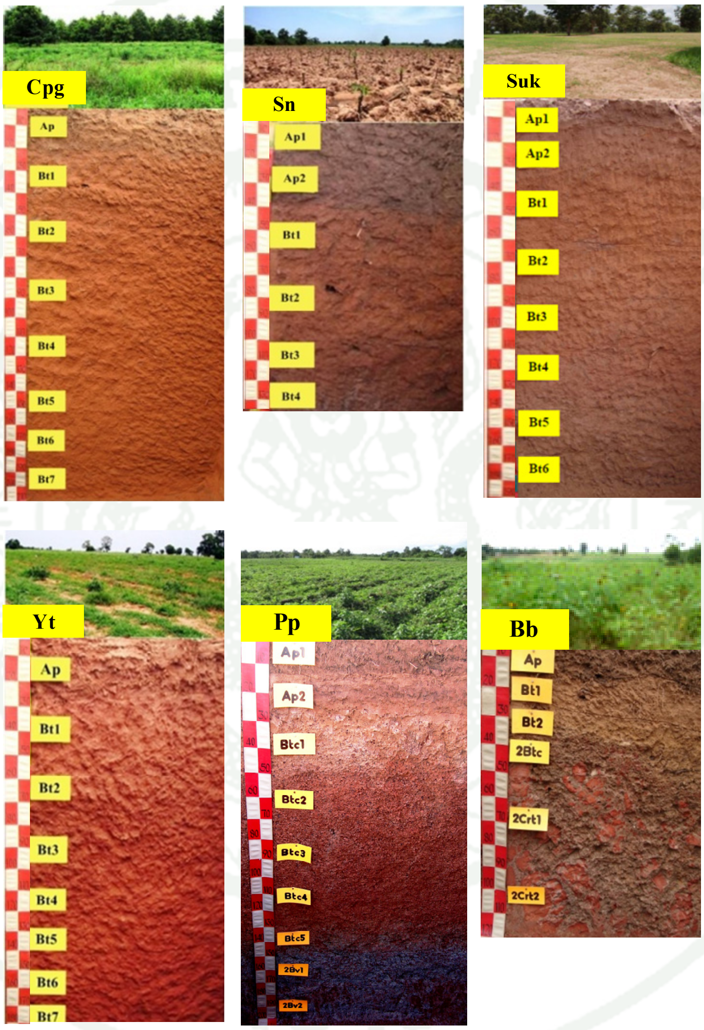


Figure 4 Representative upland Ultisol profiles in Northeast, Thailand.

2.3 Alfisols

An Alfisol (Si) developed on calcareous sandstone has Ap-Btk profile whereas Alfisol developed on wash over local alluvium over mixed local alluvium include Ap-E-Bt-C (Ng). The genetic horizons of Alfisol developed on granite include

Ap-AB-Bt-BCrt (Cu) (Figure 5). The relief of the site is undulating with slope of 4 - 6% and the mean annual precipitation range is 1,100-1,200 mm. Physiographic positions are corrosion plain, shoulder slope on dissected lower footslope and upper midslope (Table 3). The color of Si is yellowish red (5YR 5/6) to reddish brown (5YR 4/4). The color of Ng is brown (10YR 4/3) to reddish yellow (7.5YR 6/6) in topsoils and yellowish red (5YR 4/6) to red (2.5YR 4/8) in subsoils. The color of Cu is very dark gray (7.5YR 3/1) to dark gray (7.5YR 4/1) (Table 3). Field pH ranges are 7.0-8.0, 4.5–6.5 and 6.5–7.0 for Si, Ng and Cu, respectively. The Btk horizons of Si effervesce with HCl. Textures are sandy clay loam to clay for Si, loamy sand to sandy clay loam for Ng and loamy sand to slightly gravelly coarse sandy clay loam for Cu. Si has a moderate fine to medium subangular blocky structure and semi-angular blocky structure.

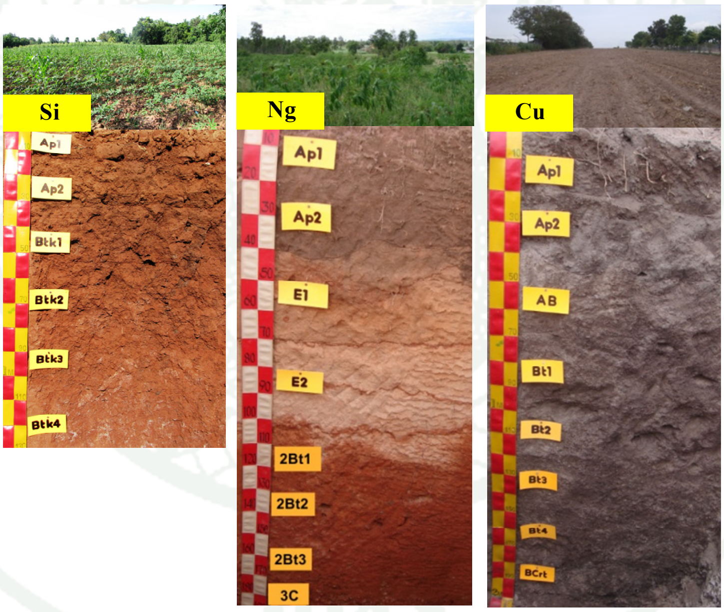


Figure 5 Representative upland Alfisol profiles in Northeast Thailand.

Table 5 Field morphology of major upland agricultural soils in Northeast Plateau, Thailand.

Soil series	Depth (cm)		Color Matrix	pH	Tex[1/]	Structure	Consistence	Coat	Others
Lo	0-20	Ap1	2.5YR 3/3	5.5	SC	2 fm sbk	SH, F, MS/MP	-	Common roots, few fine variegated sands
	35-55	Bt1	10R 3/4	7.0	C	2 fm sbk	H, F, MS/MP	Common clay coats	Very few roots, Fe-Mn oxide nodules
	85-110	Bt3	10R 3/4	4.5	C	2 fm sbk	SH, F, MS/MP	Common clay coats	Very few roots, few fine Fe-Mn oxide nodules
	140-165	Bt5	2.5YR 4/6	4.5	C	2 fm sbk	SH, F, MS/VP	Few clay coats	No root, common clay balls, few rock fragments few traces of charcoal fragments
Ci	0-10	Ap1	2.5YR 3/3	4.5	C	1-2 fm sbk	S, SF, MS/MP	-	Many roots, common narrow vertical cracks
	10-27	Ap2	2.5YR 2.5/4	5.0	C	3 fm se-abk	SH, SF, MS/MP	-	Common roots, clay balls, rounded rock fragments
	55-58	Bto2	2.5YR 2.5/4	5.5	C	3 fm sbk, c G	SH, SF, MS/MP	Few clay coats	Few roots, few clay balls, rounded rock fragments
	110-132	Bo1	2.5YR 2.5/3	5.5	C	2 fm sbk, 3 f G	SH, Fri, SS/MP	no clay coating	Very few roots, few clay balls
Pc1	0-18	Ap1	2.5YR 2.5/4	6.5	C	1-2 fm sbk, mf G	SH, Fri, SS/MP	Few clay coats	Many roots, few quartz fragments
	18-30	Ap2	2.5YR 2.5/5	7.0	C	1-2 fm sbk, mf G	SH, Fri, MS/MP	Few clay coats	Many roots, few quartz fragments
	30-58	Bt1	2.5YR 2.5/6	7.0	C	2 fm sbk	H, SF, MS/MP	Many clay coats	Few roots, few clay balls
	88-110	Bto1	2.5YR 3/6	7.0	C	2 fm sbk, mc G	H, F, S/P	Common clay coats	Very few roots, few clay balls
	138-175	Bto3	2.5YR 3/6	4.7	C	mf G	SH, Fri, SS/VP	Common clay coats	No root, few clay balls
Pc2	0-15	Ap1	2.5YR 2.5/4	8.0	C	2 fm sbk, G	SH, SF, SS/MP	Few clay coats	Common roots, very fine rock fragments
	15-35	Ap2	2.5YR 2.5/5	8.0	C	3 fm sbk	VH, SF, SS/MP	Few clay coats	Common roots, very fine rock fragments
	65-90	Bt2	10YR 3/4	7.0	C	3 fm se-abk	H, Fri, SS/MP	Few clay coats	Very few roots, few fine cracks
	120-148	Bto2	10YR 3/5	6.5	C	2 fm se-abk	H, Fri, SS/MP	Few clay coats	Very few roots, few fine Fe-oxide nodules
Pc3	0-28	Ap	2.5YR 2.5/4	5.4	C	2 fm sbk, G	SH, F, SS/MP	Common clay coats	Common roots,few rock fragments, clay balls
	28-50	Bt1	2.5YR 2.5/5	5.9	C	2 fm sbk, G	SH, F, SS/MP	Common clay coats	Very few roots,few rock fragments
	80-100	Bt3	2.5YR 2.5/6	5.0	C	2 fm sbk	SH, SF, SS/MP	Common clay coats	Very few roots,very few rock fragments
	123-147	Bt5	2.5YR 2.5/7	5.0	C	2 fm sbk	SH, SF, SS/MP	Common clay coats	Very few roots,very few rock fragments
Pc4	0-13/15	Ap1	5YR 3/2	7.0	SCL	3 fm sbk	VH, F, MS/MP	Few clay coats	Many roots, very few rock fragments, few cracks
	32-52	Bt1	5YR 3/3	5.4	C	3 fm sbk	VH, F, MS/MP	Common clay coats	Fine charcoal fragments, Mn-oxide nodules
	75-100	Bt3	2.5YR 2.5/3	4.5	C	3 fm se-abk	VH, F, MS/MP	Many ferri-argillan	Few roots, few clay balls
	120-143	Bt5	2.5YR 2.5/4	3.9	C	3 fm se-abk	H, F, MS/MP	Many ferri-argillan	Common reddish powder of iron oxides as patches
	170-200	Bt7	2.5YR 2.5/4	3.9	C	3 fm se-abk	VH, F, MS/MP	Common ferri-argillan	Few roots, few rock fragments

Table 5 (Continued).

Soil series	Depth (cm)		Color Matrix	pH	Tex[1/]	Structure	Consistence	Coat	Other
Cpg	0-20	Ap	5YR 4/6	5.0	SL	1-2 fm sbk	SH, Fri, SS/NP	-	Common roots, charcoal fragments
	20-45	Bt1	2.5YR 3/6	4.5	SL	1-2 fm sbk	SH, Fri, SS/NP	Few clay bridges	Few roots, few variegated sands
	75-100	Bt3	2.5YR 4/6	5.0	SL	1-2 fm SBK	SH, SF, SS/SP	Few clay bridges	Few roots, few variegated sands
	130-160	Bt5	2.5YR 4/6	5.5	SL	1-2 fm sbk	SH, Fri, SS/SP	Few clay bridges	Very few roots, few variegated sands
	185-210	Bt7	2.5YR 4/6	5.5	SL	1-2 fm sbk	SH, SF, SS/SP	Few clay bridges	Very few roots, few variegated sands
Sn	0-10	Ap1	7.5YR 4/4	6.5	L	1-2 fm sbk	SH, SF, SS/SP	-	Many roots, few variegated sands
	10-29	Ap2	7.5YR 4/5	6.0	FSL	1-2 fm sbk	SH, SF, SS/SP	-	Many roots, charcoal fragments
	55-81	Bt2	5YR 4/6	5.0	VFSCL	2 fm sbk	H, SF, SS/MP	Few clay coats	Common roots, few variegated sands
	110-135	Btc	10YR 5/4	6.0	SGSCL	3 fm sbk	VH, F, SS/MP	Few clay coats	Few roots, iron oxide nodules
Suk	0-10	Ap1	7.5 YR 4/3	5.0	SL	1-2 fm sbk	S, Fri, SS/SP	-	Many roots, few variegated sands
	10-25	Ap2	7.5 YR 6/4	4.0	SCL	2 fm sbk	SH, SF, SS/Sp	-	Common roots, few variegated sands
	55-80	Bt2	7.5 YR 6/6	4.5	SCL	3 fm se-abk	SH, SF, SS/Sp	-	Very few roots, silt pockets, few krotovina
	140-168	Bt5	10YR 6/6	4.5	SCL	2 fm se-abk	H,F, SS/MP	Common clay coats	Very few roots, few variegated sands
Yt	0-20	Ap	5YR 4/6	5.0	LS	2-3 fm sbk	SH, Fri, NS/NP	-	Many roots, few variegated sands
	20-41	Bt1	2.5YR 4/8	4.5	SL	2 mc abk	H, SF, NS/SP	Few clay bridges	Common roots, few variegated sands
	69-95	Bt3	2.5YR 4/6	4.0	SCL	2 fm sbk	H, SF, SS/MP	Few clay coats	Few roots, few variegated sands
	120-142	Bt5	2.5YR 4/6	4.0	SCL	2 fm sbk	SH, SF, SS/MP	Very few clay coats	Few roots, few variegated sands
	171-200	Bt7	2.5YR 4/6	4.0	SCL	2 fm sbk	SH, SF, SS/MP	Very few clay coats	No root, strong clay balls, distinct clay coats
Pp	0-20	Ap1	10YR 4/3	6.5	LS	1 fm sbk	S, VFri, NS/NP	-	Many roots , charcoal fragments
	35/40-68/70	E1	7.5YR 6/6	6.0	LS	1 fm sbk	S, VFri, NS/NP	-	Few roots, few variegated sands
	100-125	2Bt1	5YR 4/6	5.5	SL	3 fm semi-abk	H, F, SS/MP	Common ferri argillan coats	Very few roots, Fe-Mn oxides nodules
Bb	0-15	Ap	10YR 4/2, 90% 10YR 5/4, 10%	5.5	SL	2, 1 m sbk	SH, Fri, NS/NP	-	Many roots , variegated sands, charcoal fragments
	15-25/30	Bt1	7.5YR 6/6	5.0	SL	2, 1 m sbk	SH, Fri, SS/NP	Few clay bridges	Common roots, few variegated sands
	25-36	Bt2	7.5YR 6/6, 30% 7.5YR 5/8, 70%	4.5	SCL	2 fm sbk	H, SF, SS/MP	Common clay bridges few clay coats	Few roots, few variegated sands charcoal fragments
	80-115	2Crt2	7.5YR 7/2, 70% 7.5YR 5/8, 30%	5.0	VGSCL	weathered rock fragments	VH, F, MS/VP	Common clay bridges	Few roots, few variegated sands

Table 5 (Continued).

Soil series	Depth (cm)		Color Matrix	pH	Tex[1/]	Structure	Consistence	Coat	Other
Si	0-12	Ap1	5YR 5/6	8.0	SCL	2 fm sbk	H, F, MS/VP	-	Common roots, few variegated sands
	12-30	Ap2	5YR 4/4	7.0	SCL	2 fm sbk	H, F, MS/VP	Very few clay coats	Common roots, few variegated sands
	30-54	Btk1	5YR 4/5, 95% 5YR 8/2, 5%	8.0	C	3 mc se-abk	VH, F, VS/VP	Common clay coats	Few roots, very fine lime fragments, effervesce with HCl
	79-108	Btk3	2.5YR4/4, 80% 5YR8/2, 20%	8.0	C	3 mc se-abk	VH, F, VS/VP	Common clay coats some lime coat on pore walls	Trace of dead roots, lime fragments, Mn oxides nodules
Ng	0-20	Ap1	10YR4/3	6.5	LS	1 fm sbk	S, Vfri, NS/NP	-	Common roots, few charcoal fragments
	35/40-68/70	E1	7.5YR6/6	6.0	LS	2 fm sbk	S, Vfri, NS/NP	-	Very few traces of dead roots, variegated sands
	70-95/100	E2	7.5YR6/6	6.0	LS	1,2 fm sbk	SH, Fri, NS/NP	-	Very few traces of dead roots, variegated sands
	125-150	2Bt2	2.5YR4/8	4.5	SCL	3 fm se-sbk	H, F, SS/MP	Common ferri-argillan coats	Few traces roots, Fe-Mn oxide nodules Sands are more angular in subsoils
	175-202	3C	2.5YR4/6	4.5	VGSL	2 fm se-abk rock fragment	SH, SF, SS/SP	Few faint clay coat on pore walls	No root, many rock fragments
Cu	0-20	Ap1	7.5YR3/1	7.0	LS	1,2 fm sbk	SH, VFri, NS/NP	-	Many roots, few variegated sands
	45-70	AB	7.5YR4/1	7.0	CSL	2 fm sbk	SH, SF, SS/SP	Very few clay coats	Common roots, few variegated sands
	95-120	Bt2	5YR4/1	7.0	SGCSL	3 fm sbk	H, F, SS/SP	Very few clay coats	Common roots, variegated sands
	150-178	Bt4	5YR4/1	7.0	SGCSL	3 fm sbk	H, F, MS/SP	Very few clay coats	Few roots, common variegated sands
	178-200	BCrt	5YR4/1	6.5	SGCSCL	3 fm sbk	H, F, MS/SP	Very few clay coats	No roots, white spots of feldspar-kaolinite, large quartz grains

[1/] 1 = weak, 2= moderate, 3 = strong; f = fine, m = medium, c = coarse; abk = angular blocky structure, sbk =subangular blocky structure,
se-abk= semi-angular blocky structure, m = massive, g = granular structure, R = rock structure
dry SH = slightly hard, H = hard, moist Fri = friable, SF = slightly firm, F = firm, VF = very firm,
wet SS = slightly sticky, MS = moderately sticky, MP = moderately plastic, VP = very plastic

Ng has a weak fine and medium subangular blocky structure for topsoils and semi-angular blocky structure parting along rock fragments in subsoils. Cu has a moderate weak fine and medium subangular blocky structure. In subsoils, there are few Fe-Mn nodules, some lime coatings on pore wall (Si) and common ferri-argillan (Ng). Sand in Ng is more angular in subsoils. There are white spot of feldspar-kaolinite in subsoils of Cu. The fine roots extend down to deeper than 150 cm (Table 5).

3. Physical properties

3.1 Particle size distribution

All soils have clay accumulation in their subsoils due to clay illuviation. Texture of Oxisols is normally clay whereas Ultisols and Alfisols are clay to loamy sand (Figure 6). All of Oxisols contain low amounts of sand particles and very high clay contents (>350 g kg^{-1}) in all horizons. The silt plus clay content (S+C) of Oxisols increases in subsurface horizon especially in Bto and tends to be constant with depth (Figure 7). Oxisols have higher S+C than do other profiles. Most Ultisols are coarse textured due to the parent material (sandstone, sedimentary rock and siltstone). The S+C increases regularly from Ap, upper Bt horizons to a maximum in the upper part of the argillic horizon (Figure 7).

The silt plus clay content of Alfisols has an accumulation in Ap2, AB, Bt and Btk horizons, then decreases regularly with depth into the E, BCrt and C horizons (Figure 7). The S+C is dependent on type of parent rock; limestone > basalt > calcareous sandstone > siltstone > sedimentary rock > sandstone > granite > wash over local alluvium over mixed local alluvium and colluvium (Table 6). Differences in texture between individual soils are predominantly due to differences in soil parent materials although eluviation of clay from topsoils has played an important role in creating the sandier topsoils (Singh, 1991; Buol *et al*., 2003).

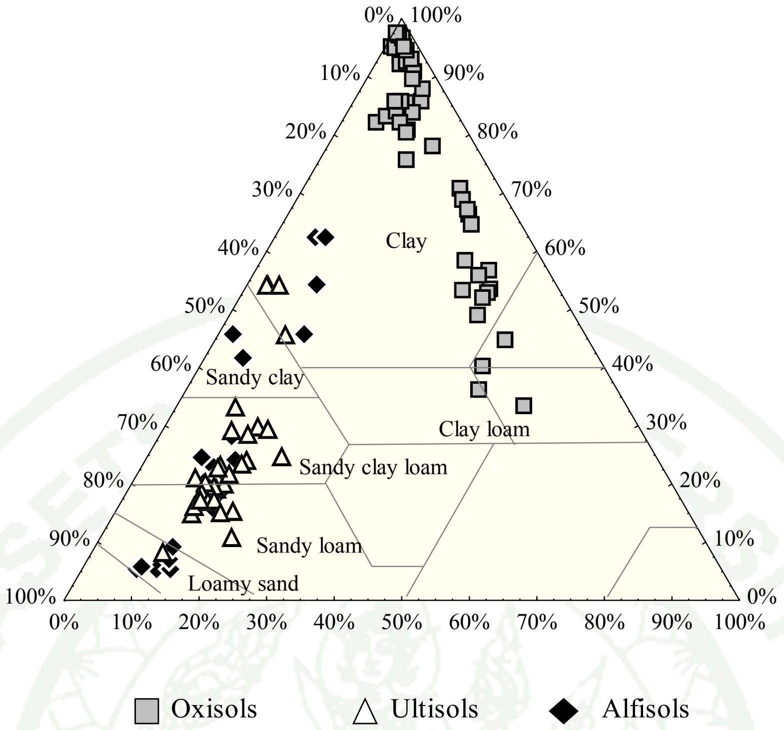


Figure 6 Textural classes of the 2 mm fraction of upland agricultural soil in Northeast Plateau, Thailand.

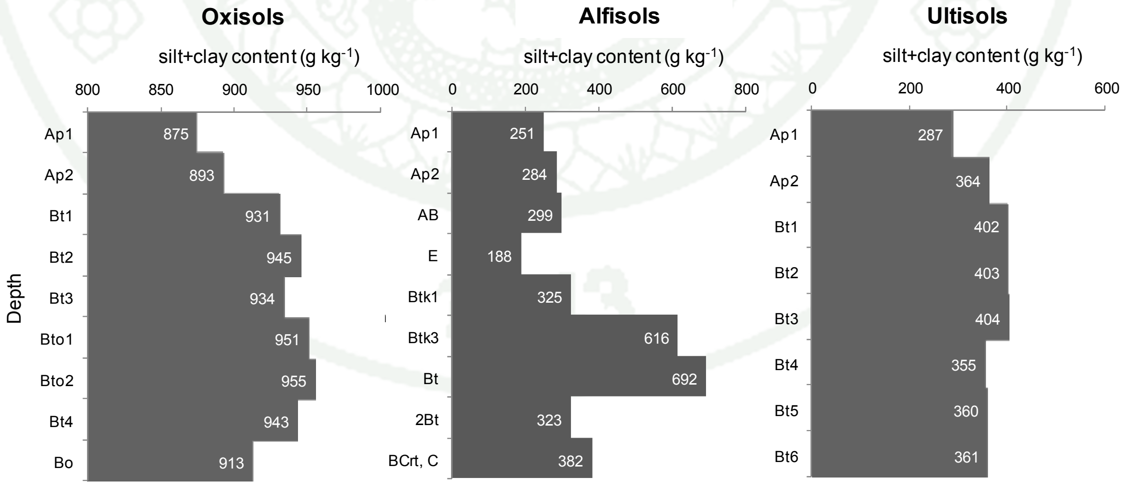


Figure 7 Silt plus clay content of major upland agricultural soils in Northeast Plateau, Thailand.

3.2 Hydraulic conductivity (Ksat)

Ksat values of Oxisols vary from moderately slow to moderate rapid (Appendix C1) in surface soil whereas vary from very slow to moderate in subsoils (Figure 8). Ksat values in surface soil of red Ultisols are lower than of Oxisols and they vary from slow to moderate (Figure 8). The Ksat values of Alfisols of surface soils and subsoils are higher than that of Oxisols and Ultisols ranging from moderately slow to rapid. Sandy textured soils normally have higher hydraulic conductivity than clayey textured soils. Therefore, the problem of lacking water in Alfisols should be more than in Oxisols and Ultisols.

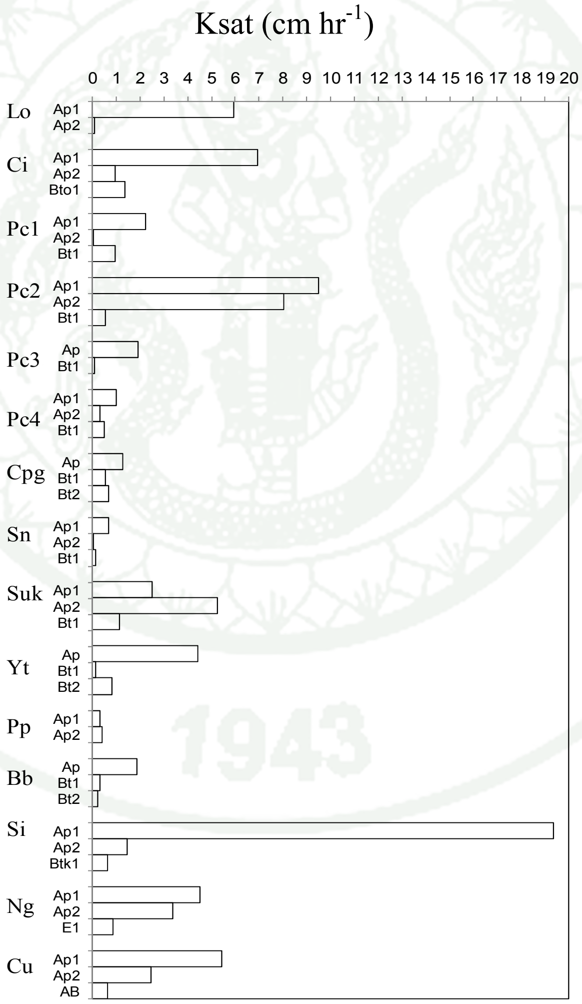


Figure 8 Ksat values of major upland agricultural soils in Northeast Plateau, Thailand.

3.3 Bulk density

The bulk density (BD) values of these soils are low to high (Appendix C1) ranging from 1.0-2.08 Mg m^{-3}. Most of profiles have lower BD values in subsoils than in surface soils reflecting an increase of clay content by illuviation (Schaetzl and Anderson, 2005) (Figure 9, Appendix Table C1). Land use and cultivation also have effects on BD values in surface soils (Pc3 and Pc4), which are higher than that in subsoils. The BD values of Oxisols are lower than that of Ultisols and Alfisols (Figure 9) responding to high porosity arising from the well structured condition of these soils (El-Swaify, 1980). The different BD values in these upland agricultural soils are attributed to the dominance of the difference of clay (R^2=0.57**) and free iron oxide contents (R^2=0.71**) (Figure 10).

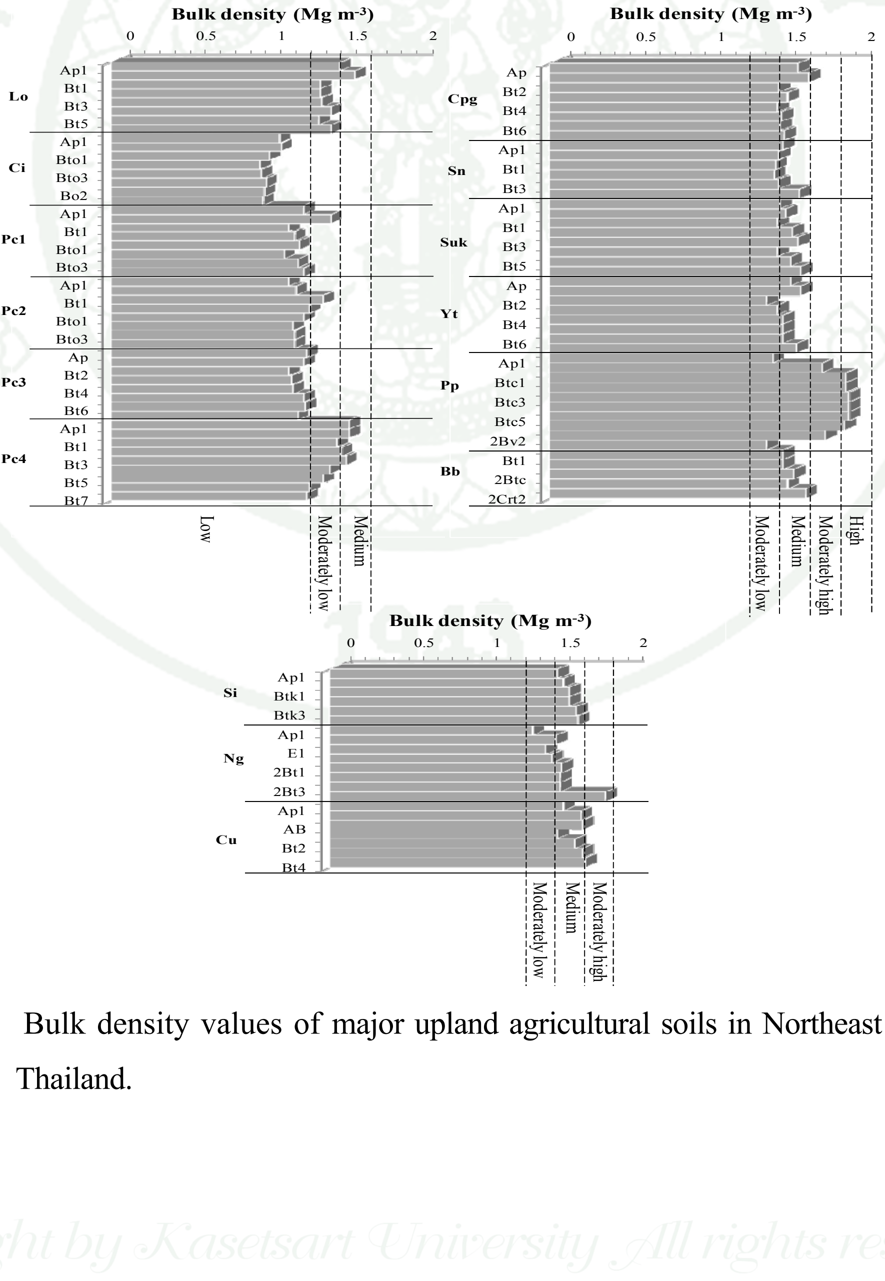


Figure 9 Bulk density values of major upland agricultural soils in Northeast Plateau, Thailand.

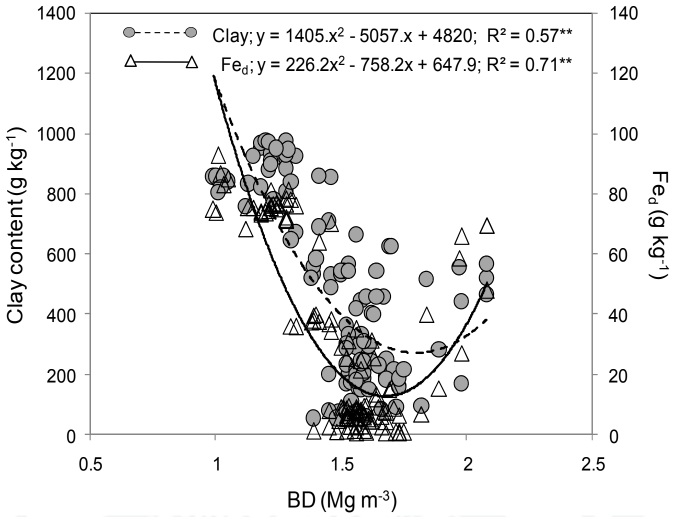


Figure 10 The relationships of bulk density with clay and free iron oxides for the major upland agricultural soils in Northeast Plateau, Thailand.

4. Chemical properties

Summary on chemical properties of these soils are given in Appendix Tables C2 and C3**.**

4.1 Soil pH

The pH-H_2O values of the soils range from extremely acid (3.9) to neutral (7.3). The pH-H_2O of these soils is highest in Alfisols followed by that in Oxisols and Ultisols averaging 6.5, 5.6 and 5.0, respectively (Figure 11). This is due to their parent materials (calcareous sandstone, granite and local alluvium) that contain high cations and that small amount of cations have been leached out from the profiles (Table 6). The pH ranges of Ultisols are narrower than that of the other soils because of the low variability of their parent materials. The lowest pH-H_2O value is in subsoils of Oxisols derived from weathered basalt (Table 7, Appendix Table C2). The pH-H_2O of Oxisols and Ultisols decreases with depth (Table 7). Though the soils developed on limestone, their subsoil pH values are also low being due to the leaching loss of cation and accumulation of H^+ by extreme weathering (Sposito, 2008). The pH-KCl values show the same trend but with values being about one unit less than that the pH-H_2O (Figure 11; Table 6), reflecting the predominance of acidic cations (Al^{3+} and H^+) at exchange sites and a net negative surface charge (Sanchez, 1976).

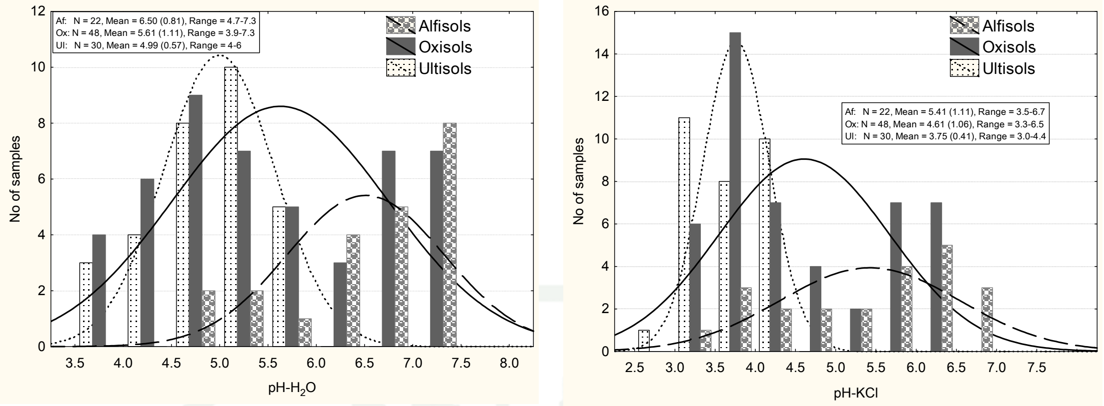


Figure 11 Histograms showing the variability of pH-H_2O and pH-KCl.

Table 6 Mean values of general properties for major upland agricultural soils on various parent materials in major upland agricultural soils in Northeast Plateau, Thailand.

	Limestone	Basalt	Sandstone	Sedimentary rock	Siltstone	Calcareous sandstone	Local alluvium[1/]	Granite
	(n=32)	(n=17)	(n=22)	(n=17)	(n=6)	(n=6)	(n=8)	(n=8)
Silt+Clay (g kg^{-1})	935	911	295	444	531	595	254	290
Sand (g kg^{-1})	65	89	705	556	469	406	746	710
BD (Mg m^{-3})	1.3	1.3	1.6	1.8	1.6	1.6	1.6	1.7
pH (H_2O)	6.1	4.7	5.0	5.6	5.1	7.0	5.7	6.9
pH (KCl)	5.0	3.8	3.8	4.1	3.6	6.2	4.2	6.1
OM (g kg^{-1})	8.3	8.8	3.6	3.3	4.5	8.1	2.0	6.6
TN (g kg^{-1})	0.70	0.64	0.44	0.35	0.37	0.65	0.34	0.50
Avail.P (mg kg^{-1})	8.5	3.0	3.5	1.0	0.67	3.7	2.1	89
Avail.K (mg kg^{-1})	40	137	52	115	108	78	25	39
Ca (cmol kg^{-1})	6.5	4.3	1.0	1.7	3.6	21	0.52	3.2
Mg (cmol kg^{-1})	1.3	1.8	0.65	1.4	1.8	1.0	0.35	0.51
K (cmol kg^{-1})	0.10	0.38	0.14	0.34	0.28	0.20	0.06	0.10
Na (cmol kg^{-1})	0.24	0.26	0.19	0.20	0.35	0.32	0.11	0.31
EA (cmol kg^{-1})	9.3	12	4.0	7.3	6.8	1.8	2.0	2.3
CEC (cmol kg^{-1})	12	9.8	4.3	7.8	6.9	11	1.8	4.7
Fe_d (g kg^{-1})	65	54	7.1	23	7.9	12	5.2	0.77
Al_d (g kg^{-1})	14	10	9.6	8	7.6	10	3.1	1.6
Mn_d (g kg^{-1})	0.47	0.49	0.06	0.61	0.10	0.26	0.03	0.12
Fe_o (g kg^{-1})	2.1	2.4	0.63	1.6	0.76	1.2	0.23	0.24
Al_o (g kg^{-1})	2.5	2.1	2.5	2.4	2.6	2.0	2.37	2.6
Mn_o (g kg^{-1})	0.12	0.20	0.02	0.10	0.06	0.20	0.01	0.10
Fe_p (g kg^{-1})	0.13	0.17	0.19	0.20	0.51	0.11	0.10	0.18
Al_p (g kg^{-1})	0.43	0.85	0.46	0.40	0.26	0.11	0.16	0.47
Mn_p (g kg^{-1})	0.07	0.07	0.02	0.02	0.03	0.05	0.01	0.04
Fe_o/Fe_d	0.03	0.04	0.09	0.07	0.10	0.09	0.04	0.30

[1/] Wash over local alluvium over mixed local alluvium and colluvium

Table 7 Mean values of some chemical properties for major upland agricultural soils on various soil types.

Horizons	pH	OM	Ca	CEC	Fe_d	Al_d	Mn_d	Fe_o	Al_o	Mn_o	Fe_p	Al_p	Mn_p
	H_2O	(g kg^{-1})	(cmol$_c$ kg^{-1})		(------------------------------g kg^{-1}								------------------------------------)
Oxisols													
Ap1	6.2	24	8.2	14	56	13	0.86	2.5	2.4	0.31	0.24	0.86	0.33
Ap2	6.4	12	7.9	11	56	12	0.57	2.5	2.3	0.30	0.27	0.65	0.11
Bt1	6.5	8.2	8.5	14	55	15	0.39	2.3	2.5	0.06	0.16	0.37	0.03
Bt2	6.0	6.1	7.3	13	59	14	0.33	2.3	2.5	0.08	0.12	0.44	0.02
Bt3	5.5	5.8	5.4	10	50	14	0.31	2.4	2.4	0.09	0.14	0.52	0.02
Bto1	5.8	6.2	5.1	9.8	78	8.5	0.41	2.0	2.1	0.08	0.12	0.69	0.02
Bto2	5.0	5.0	4.2	9.5	76	8.7	0.45	1.6	2.2	0.11	0.08	0.59	0.03
Bt4	4.9	4.9	4.9	11	53	16.	0.42	2.4	2.5	0.14	0.11	0.47	0.03
Bo	4.6	4.1	0.0	6.6	87	3.3	0.61	2.0	1.7	0.13	0.04	0.82	0.02
Ultisols													
Ap1	5.5	6.4	1.0	2.5	3.9	7.7	0.32	0.8	2.3	0.20	0.32	0.27	0.05
Ap2	5.1	4.9	2.2	3.7	4.1	5.8	0.54	1.2	3.2	0.34	0.62	0.14	0.05
Bt1	4.8	3.2	1.1	4.8	7.1	9.0	0.32	1.2	3.9	0.19	0.32	0.33	0.02
Bt2	5.0	2.3	0.9	5.0	7.1	9.5	0.29	0.9	3.2	0.16	0.23	0.37	0.01
Bt3	4.8	1.9	1.4	4.2	7.7	8.8	0.30	1.1	3.5	0.17	0.27	0.40	0.01
Bt4	5.1	2.2	0.4	3.3	6.5	9.0	0.37	0.9	3.2	0.21	0.25	0.45	0.01
Bt5	4.8	1.4	0.3	4.2	6.7	11	0.38	1.4	3.3	0.21	0.18	0.38	0.01
Bt6	4.9	1.2	0.9	2.7	7.3	11	0.25	0.9	2.4	0.13	0.16	0.34	0.01
Alfisols													
Ap1	6.6	9.4	3.8	4.4	3.7	4.6	0.10	0.6	2.3	0.08	0.18	0.17	0.05
Ap2	6.7	6.1	4.4	4.2	3.8	4.9	0.10	0.5	2.4	0.08	0.12	0.22	0.05
AB	7.1	5.8	2.8	4.0	0.7	1.6	0.09	0.1	2.6	0.07	0.18	0.50	0.10
E	6.6	0.7	0.2	0.5	1.1	2.4	0.02	0.1	2.3	0.01	0.12	0.15	0.01
Btk1	7.2	5.6	28	12	0.7	1.6	0.08	0.2	2.6	0.07	0.19	0.60	0.03
Btk3	7.2	9.1	27	13	13	11	0.26	1.3	2.3	0.19	0.11	0.11	0.05
Bt	6.9	5.3	2.9	5.3	15	9.7	0.31	1.0	1.6	0.23	0.08	0.08	0.03
2Bt	5.1	1.7	0.6	3.4	7.2	3.9	0.01	0.3	2.4	0.00	0.06	0.14	0.00
BCrt, C	5.5	3.2	2.0	3.2	8.4	2.8	0.24	0.5	2.7	0.19	0.15	0.30	0.02

4.2 Soil organic matter (SOM) and total nitrogen (TN)

Soil organic matter contents (SOM) of these upland agricultural soils are very low to moderately high ranging from 0.26-34.4 g kg^{-1}. SOM is highest in Oxisols (3.6-34 g kg^{-1}) followed by Alfisols (0.62-14 g kg^{-1}) and Ultisols (0.26-9 g kg^{-1}) (Figure 12). The SOM in these soils has a wide range whereas its range in Ultisols is narrower than in the other soils (Figure 12). The average SOM are highest in basalt derived soils (5.8 g kg^{-1}) and lowest in soils formed on wash over local alluvium over mixed local alluvium and colluvium (2.0 g kg^{-1}) (Table 4). The Ap horizon is fairly rich in SOM. Most profiles have a decrease of SOM with depth which is typical for tropical soils (Buol *et al*., 2003).

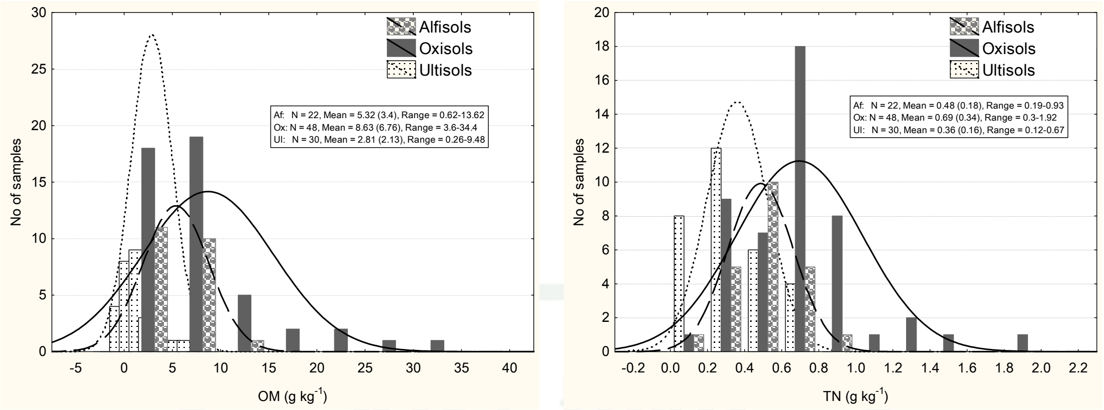


Figure 12 Histograms showing the variability of soil organic matter and total nitrogen.

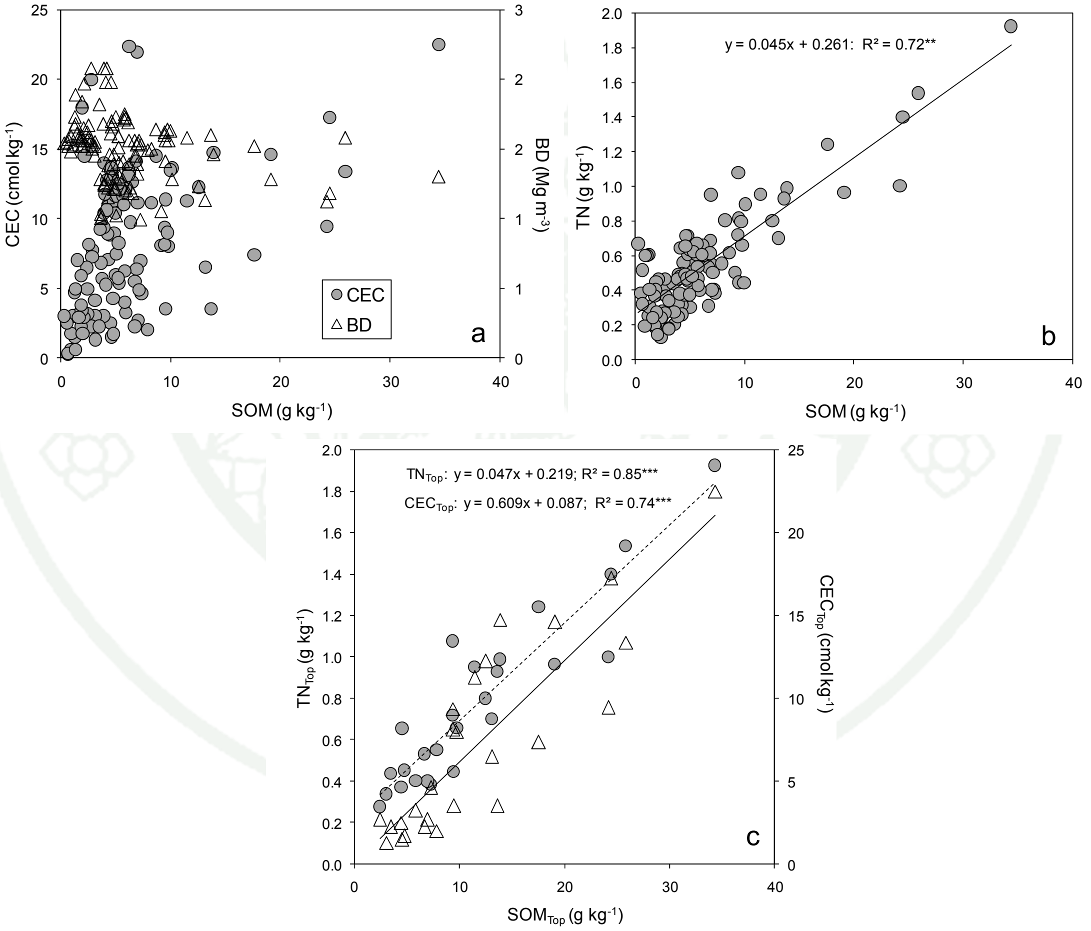


Figure 13 The relationships of organic matter with cation exchange capacity and bulk density (a), total nitrogen (b) of whole soil samples, and organic matter with total nitrogen and cation exchange capacity in surface soils (c) (**P<0.01, ***P<0.001).

The SOM normally have the effect on cation exchange capacity (CEC) and BD but for these major upland agricultural soils this effect is not clear (Figure 13a). Total nitrogen shows the same distribution trend with OM and they have a close relationship (R^2=0.72**) (Figure 13b). In surface soils, SOM has a positive relationship with CEC (R^2=0.74***) and TN (R^2=0.85***) (Figure 13c) reflecting that much of SOM is stored in surface soils.

4.3 Available phosphorus (Avail. P) and available potassium (Avail. K)

The available phosphorus (Avail. P) in these soils has a large range from very low to very high (1.8-627 mg kg $^{-1}$) in Ap horizon and very low to medium (0.11-12.67 mg kg $^{-1}$) in subsoils. It tends to decrease with depth. The Avail. P in surface soils of Oxisols, Ultisols and Alfisols (Figure 14) responds to land use and management. The highest values of Avail. P in surface soils of Chan Thuek (Cu) (627 mg kg^{-1}) (Appendix Table C2) indicate the effect from fertilizer application for new cropping. The subsurface horizons have lower amounts of Avail. P corresponding to their trend of SOM and low total P contents. The values of available potassium (Avail. K) of these soils have wide range (low to very high) (Figure 14) depending on application of fertilizer in Ap horizon and nature of parent material in subsoils. The soil weathered from basalt rocks (Pc4), siltstone (Sn) and metasedimentary rocks (Pp) have very high K concentration in subsoils (Table 6, Appendix Table C2).

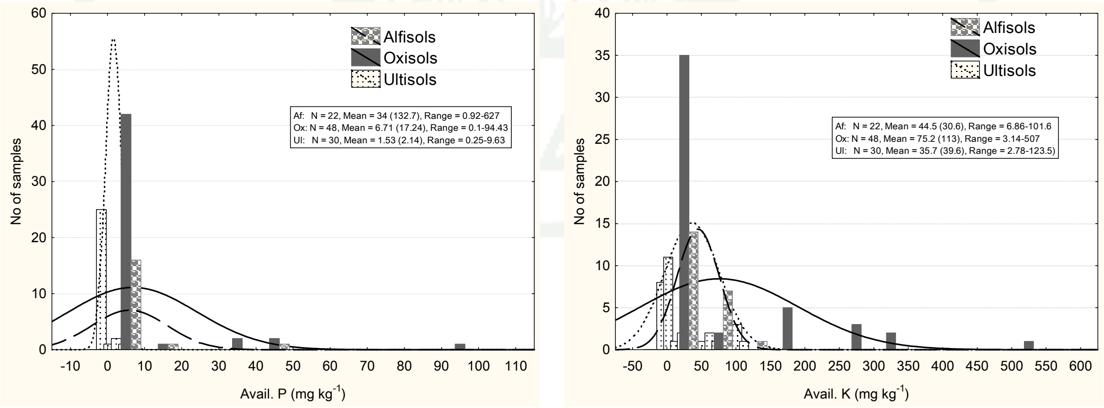


Figure 14 Histograms showing the variability of available phosphorus and potassium.

4.4 Exchangeable bases

The full data for exchangeable bases (Ca, Mg, K and Na) are given in (Appendix Table C2). Calcium concentration (Ca) is the major exchangeable base in these soils and ranges from 0.01-34 cmol kg^{-1}, averaging 7.0, 5.8 and 1.1 cmol kg^{-1} in Alfisols, Oxisols and Ultisols, respectively. Alfisols have wide range of Ca (Figure 15) due to the difference of their parent materials. Comparison of Ca in soils developed on various parent materials being calcareous sandstone >> limestone > basalt > siltstone > granite > sedimentary rock > sandstone > wash over local alluvium over mixed local alluvium and colluvium (Table 6). Magnesium (Mg), potassium (K) and sodium (Na) have low values ranging from 0-5.1, 0.01-1.3 and 0.03-0.71 cmol kg^{-1}, respectively. Mg and K of soil developed on weathered basalt are higher than that of soils on other parent materials (Table 6).

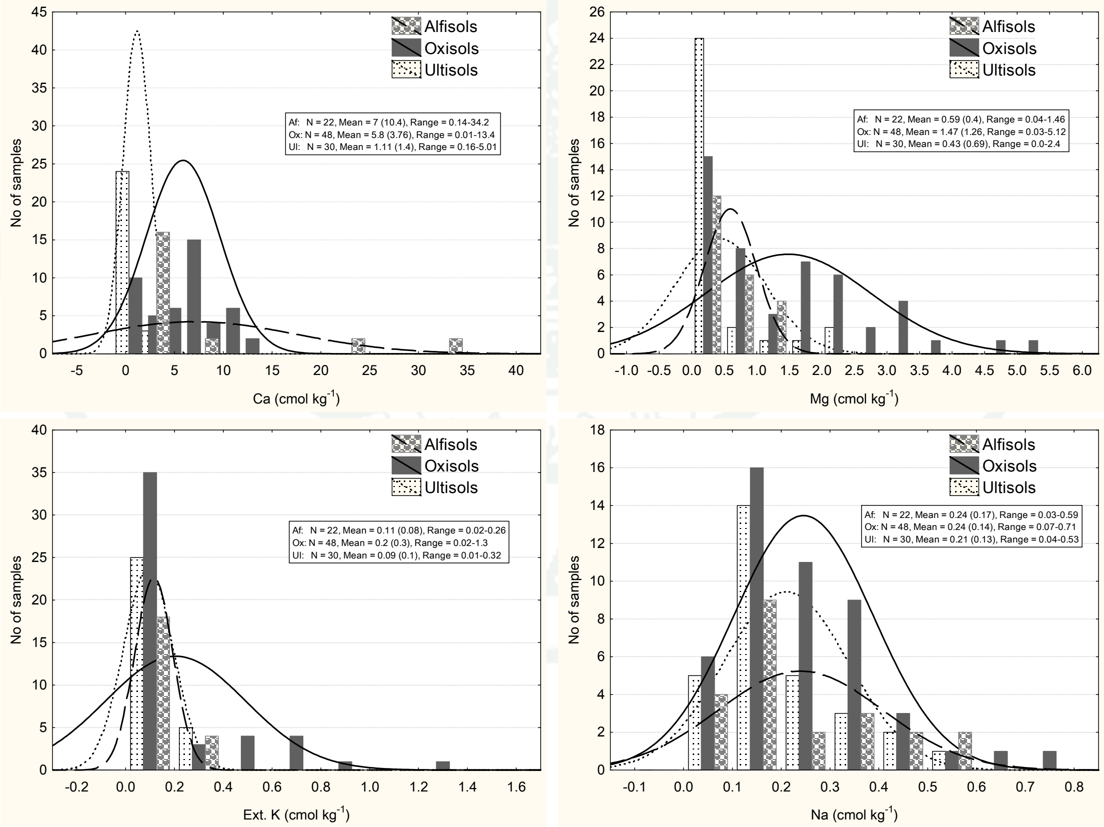
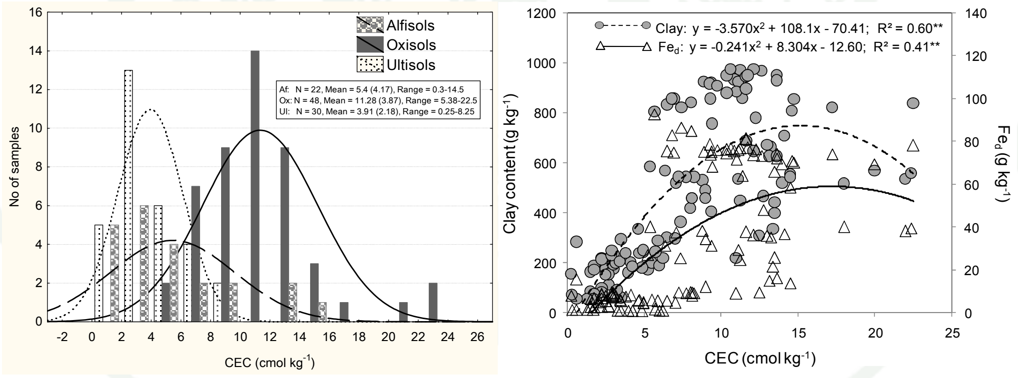


Figure 15 Histograms showing the variability of exchangeable bases.

4.5 Cation exchange capacity (CEC)

The CEC values range from very low to high from 0.25-22.5 cmol kg^{-1} in surface soil and from 1.3-22.5 and 0.25-22.4 cmol kg^{-1} in subsoils, respectively (Figure 16a). Oxisols have moderately low to high CEC (5.4-22.5 cmol kg^{-1}) reflecting their heavier texture followed by Alfisols very low to medium CEC (0.3-14.5 cmol kg^{-1}) and Ultisols very low to low CEC (0.25-8.25 cmol kg^{-1}). This is due to the dominance of kaolin and sesquioxides that generally have a low CEC (Brady and Weil, 2008). In addition, CEC shows polynomial correlation with clay content (R^2=0.6**) and Fe_d (R^2=0.41**) (Figure 16b). The CEC values in Bto and Bo horizons of Oxisols which have the dominance of sesquioxides are lower than that in the other horizons (Table 7). The CEC values of coarser textured soils (Alfisols) are related to clay concentration and their variations reflect the changes in clay concentration. The CEC values of soils developed on limestone and calcareous sandstone are higher than that of soils developed on the other parent materials (Table 6). SOM is mainly affected to CEC in these surface soils (Figure 16).



(a) (b)

Figure 16 Histograms showing the variability of cation exchange capacity (a) and relationships of cation exchange capacity with clay content and free iron oxide (**P<0.001).

4.6 Extractable acidity (EA)

Extractable acidity values (EA) of these soils range from very low to high (0.5 to 19.5 cmol kg^{-1}) (Figure 17). The average values are high (10.2 cmol kg^{-1}) for Oxisols, medium (4.4 cmol kg^{-1}) for Ultisols and low (2.0 cmol kg^{-1}) for Alfisols

(Figure 17). In addition, the comparison of EA in various parent material is basalt > limestone > sedimentary rock > siltstone > sandstone > granite > wash over local alluvium over mixed local alluvium and colluviums > calcareous sandstone (Table 6). This is due to its direct correlation with the leaching process and development of soils (Currie and Aber, 1997; Czepinska-Kaminska *et al.*, 2003). The EA concentrations of Ultisols and Oxisols are medium to high demonstrating the effectiveness of leaching of alkaline cations and the displacement of H^+ in the soils and indicating that they are moderately to highly developed soils (Brady and Weil, 2008).

4.7 Extractable iron, aluminum and manganese

In most profiles, crystalline Fe, Al and Mn oxides (Fe_d, Al_d, Mn_d) are increase with increasing depth (Appendix Table C4) reflecting their leaching condition and their trends are similar with that of the clay content (Buol *et al.*, 2003). The increase of redox concentration was reported to relate with a general increase in the amount of Fe_d (Hayes and Vepraskas, 2000). The Fe, Al and Mn for active or amorphous form (Fe_o, Al_o, Mn_o) and organic complex form (Fe_p, Al_p, Mn_p) decrease with increasing depth (Table 7). This normally indicates the amount of iron accumulated in the form of Fe humus complexes (Dahlgren *et al.*, 1997). The Fe extracted by pyrophosphate is probably associated with organic matter (Schuppli *et al.*, 1983). Extractable Fe_d, Al_d, Mn_d, Fe_o and Mn_o concentrations in Oxisols are higher than in Ultisols and Alfisols (Table 7). Except for Al_o and Fe_p in Ultisols that are higher than in Oxisols. All soils have the low Fe_o/Fe_d ratios and Oxisols have very low Fe_o/Fe_d ratio followed by Ultisols and Alfisols. Low values (< 0.1) of the Fe_o/Fe_d ratio indicate the maturity or crystallinity of free iron oxides for these soils (Fitzpatrick and Schwertmann, 1982).

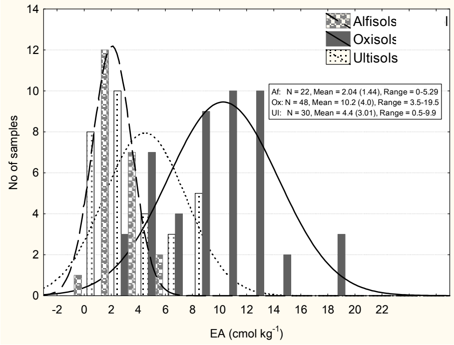


Figure 17 Histograms showing the variability of extractable acidity.

There is a trend of increasing Fe_d, Al_d and Mn_d values in the sequence of soils formed on limestone > basalt > sedimentary rock > calcareous sandstone > siltstone > sandstone > wash over local alluvium over mixed local alluvium and colluvium > granite (Table 6). There is a trend of increasing Fe_o, Al_o and Mn_o values in the sequence of soils formed on basalt > limestone > sedimentary rock > calcareous sandstone > siltstone > sandstone > granite > wash over local alluvium over mixed local alluvium and colluvium (Table 6). Ultisols developed on siltstone have the highest Fe_p value whereas basaltic Oxisols have the highest Al_p. The Fe_o/Fe_d in the sequence of soils increase in a sequence form granite > siltstone > calcareous sandstone > sandstone > sedimentary rock>wash over local alluvium over mixed local alluvium and colluviums > basalt > limestone (Table 6). These results indicate well that properties of iron oxides, such as crystallinity and Al substitution, have been related to pedogenic environments (leaching condition, parent material and stage of soil development) (Schwertmann, 1988; Buol *et al*., 2003)

5. Mineralogical characteristics

Mineralogical characteristics based X-ray diffraction analyses of clay and silt samples are shown in Appendix Table C4. Clay minerals are an indicator of the degree of soil development. In these upland agricultural soils, kaolinite is the most abundant mineral in the clay fraction of all samples. Hematite is the mineral in all red Oxisols and red Ultisols at all depths. Quartz concentration increases with depth and varies among these soils. Illite is one of the major minerals in Bb, Sn, Si, Cu and Pp and as a miner mineral (<5%) in Pc1, Pc2, Pc3, Pc4, Cpg, Suk, Yt, and it is absent in Lo, Ci and Ng. Smectite occurs in all horizons of Sn, Si, Cu, Lo, Pc1, Pc2, Cpg, Bb and Suk. Differences in mineralogy may also indicate the influence of parent materils. Quartz is the main mineral in all profiles in silt fraction of these upland soils (Appendix Table C4) as it is a ubiquitous and highly resistant mineral in soils (Stiles *et al*., 2003). High iron contents in red Oxisols are a cause for the presence of hematite in silt fraction. However, trace of kaolin is also present in silt fraction of red Oxisols. This condition indicates a continuous environment for the oxidation of iron compounds to form crystalline minerals and also indicates the highly developed status of soils (Suddhiprakarn *et al*., 1985). The inclusion of clay size minerals in the silt fraction is interpreted as a consequence of aggregation by iron oxides creating stable silt size aggregates (Schaefer, 2001).

6. Classification of major upland agricultural soils in Northeast Plateau, Thailand

Based on soil taxonomy (Soil Survey Staff, 2010), Lo, Ci, Pc1, Pc2, Pc3 and Pc4 are red Oxisols. Cpg, Sn, Suk, Yt, Pp and Bb are Ultisols whereas Si, Ng and Cu are Alfisols (Table 8). All soils have an ustic soil moisture regime. Soil moisture is dry ≥ 90 cumulative days. All soil temperature is ≥ 22 ^{o}C and means summer and winter differ ≤ 6 ^{o}C that are isohyperthermic.

Ustox have a kandic horizon within 150 cm of the mineral soil surface and apparent ECEC of 1.50 or more cmol$_c$ per kg^{-1} clay or a pH value (1M KCl) of less than 5.0 are Kandiustox. Lo and Pc4 are fine Typic Kandiustox. They do not have a petroferric contact, a lithic contact, or redox depletions with a moist colour value of 4 or more and chroma of 2 or less within 125 cm of the mineral soil surface and also do not have aquic conditions for some time in normal years. Ci, Pc1, Pc2, Pc3 are very-fine Rhodic kandiustox that are like Typic Kandiustox, but they have, in all horizons at a depth between 25 and 125 cm from the mineral soil surface, more than 50 percent colors that have a hue of 2.5YR or redder and a moist value, of 3 or less.

Cpg, Yt and Sn are Ustults that have a kandic horizon within 150 cm of the mineral soil surface and pH values (1M KCl) of less than 5.0 with low CEC (Typic kandiustults). Suk is a Typic Haplustult that does not have a petroferric contact, a lithic contact, kandic horizons and a hue of 2.5YR or redder and a moist value, of 3 or less in all subhorizons. Bb is a Plinthic Haplustult that has 5 percent or more (by volume) plinthite in one or more horizons within 150 cm of the mineral soil surface. Pp is an Ustult that have one or more horizons within 150 cm of the mineral soil surface.

Si is Typic Rhodustalf that has more than 50 percent colors hue of 2.5YR or redder; and value, moist, of 3 or less; and dry value no more than 1 unit higher than the moist value in all subhorizons. Ng and Cu are Psammentic Haplustalf that are the other Haplustalfs that have sandy particle-size class throughout the upper 75 cm of the argillic or throughout the entire argillic horizon if it is less than 75 cm thick.

Table 8 Classification of major upland agricultural soils (Soil Survey Staff, 2010).

Suborders	Great Groups	Subgroups	Family	Soil series
Ustox	Kandiustox	Typic Kandiustox	Fine, kaolinitic, isohyperthermic	Lo Pc4
		Rhodic Kandiustox	Very-fine, kaolinitic, isohyperthermic	Ci Pc1 Pc2 Pc3
Ustult	Kandiustult	Typic Kandiustult	Coarse-loamy, siliceous, isohyperthermic	Cpg
			Fine-loamy, kaolinitic, isohyperthermic	Yt
			Fine, mixed, isohyperthermic	Sn
	Haplustult	Typic Haplustult	Fine-loamy, siliceous, isohyperthermic	Suk
		Plinthic Haplustult	Loamy-skeletal, mixed, isohyperthermic	Bb
	Plinthustult	Typic Plinthustult	Clayey-skeletal, mixed, isohyperthermic	Pp
Ustalf	Rhodustalf	Typic Rhodustalf	Fine, mixed, isohyperthermic	Si
	Haplustalf	Psammentic Haplustalf	Loamy-skeletal, siliceous, isohyperthermic	Ng
			Loamy-skeletal, kaolinitic, isohyperthermic	Cu

Soil Aggregation

1. Synthesis on soil aggregation in major upland agricultural soils

The percentages of water aggregate stability (WAS) of subsoils are higher than of topsoils due to the effect of land use and management. The WAS in all soils are not clearly different with depth. The WAS of Oxisols are significantly higher than that of the other soils. Iron oxides act as the main cementing agent producing abundant stable soil aggregates in Oxisols. These reflect the better structure in Oxisols as compared to that of other soils. The WAS of Ultisols reflected by S+C and Fe_d in their profiles. The low %WAS of Btk horizons in Alfisols due to the effect of polyvalent cations (Ca^{2+}). There is a significant difference in the mean weight diameter (MWD) values of aggregates between Oxisols and other soils. The size of WAS is largest in Oxisols followed by Alfisols and Ultisols. The soil organic carbon concentration and land use are the key factors affecting WAS and MWD in surface soils. Whereas in subsoils, clay content and Fe oxides are the main factors that affect the differences of WAS and MWD in these soils.

Aggregate size distribution: LMA (2000-8000 µm) are more sensitive to land use and management. The other sizes of aggregate are affected by the difference type of the binding agents. In Oxisols, SMA (250-2000 µm) makes up the largest proportions. The high content of sesquioxide in Bo and Bto horizons provides the main binding agent for large size aggregates. MiA (53-250 µm) in red Ultisols (Cpg, Sn, Suk and Yt) makes up the largest proportions. Calcium concentrations have an effect on the formation of macroaggregate in Alfisols. In Ap horizon, the mass of LMA of uncultivated land are significantly higher than that of the other land uses.

The proportion of SCf (<53 µm) of Oxisols increases when separated from macroaggregates. In red Ultisols, the proportions of MiA increase when slaking macroaggregates. The hierarchical model of aggregation occurred in red Ultisols that microaggregates join together to form macroaggregates, and the bonds within microaggregates are stronger than the bonds between microaggregates.

2. Water aggregate stability (WAS)

Soil structure, the result of the process by which primary soil particles (sand, silt and clay) are aggregated with organic and amorphous materials controls aeration, water infiltration, water, gas, and solute transport, drainage, soil fertility and the ease of soil tillage (Dexter, 1988). Soil aggregate size distribution and stability are important indicators of soil physical quality and C_{seq}. Soil aggregations of these upland agricultural soils are summarized in the Appendix Table C5.

The percentages of water aggregate stability (WAS) of Oxisols, Ultisols and Alfisols range from 41-93, 20-84 and 32-84, respectively (Figure 18). The WAS of most Ap horizons are lower than that of subsoils (Figures 18, 21), this may due to the effect of land use and management especially soil tillage (Amezketa, 1999). Except for nevertheless some Ap horizons have higher WAS than do subsoils due to their high organic matter content. Oxisols contain higher percentage of WAS than do Alfisols and Ultisols averaging 77, 60 and 57%, respectively (Figure 18). This is commonly the case since Oxisols contain high silt plus clay and Fe content in their profiles.

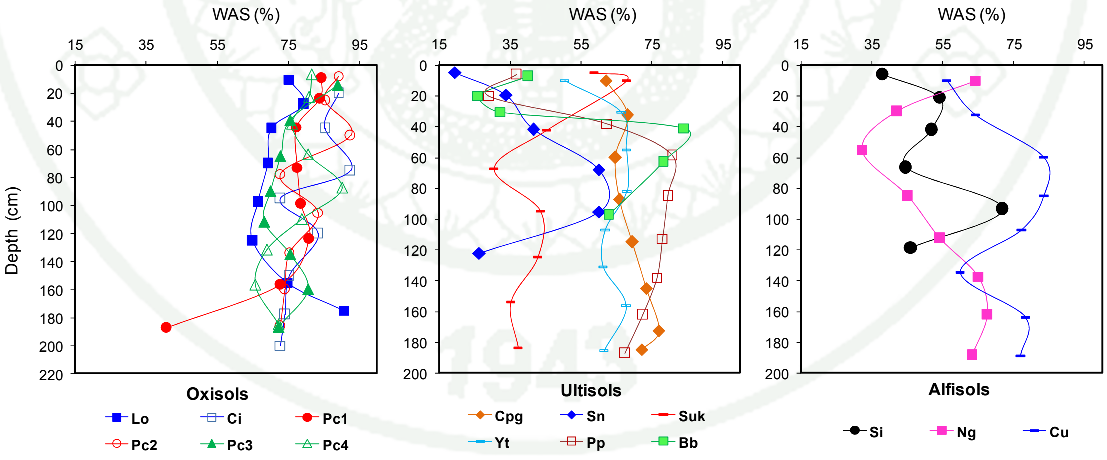


Figure 18 Water aggregate stability (WAS) distribution profiles of representative upland agricultural soils in Northeast Plateau, Thailand.

Iron oxides in Oxisols act as the main cementing agents producing abundant stable soil aggregates (Ben-Hur *et al*., 1985). These reflect the better structure and lower BD in Oxisols as compared to that of other soils. The percentages of WAS in all soils are not clearly different with depth , however Ap, AB, Bto and Bo horizons tend to have more %WAS than do the other horizons (Figure 19).

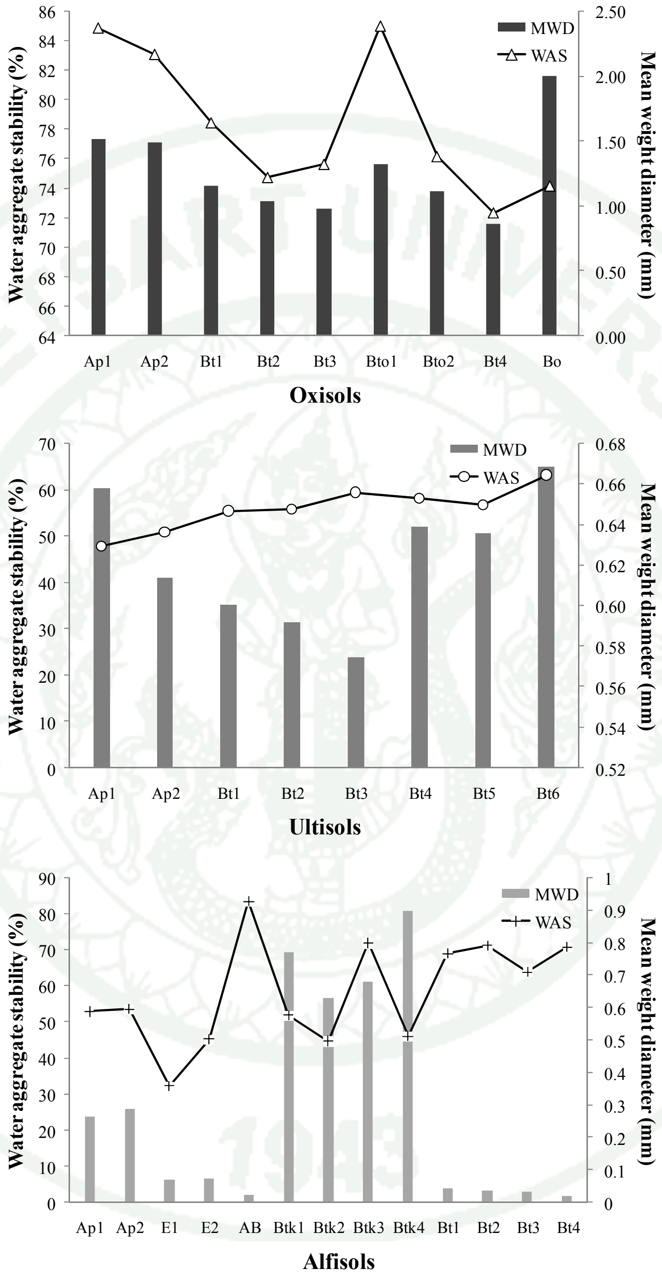


Figure 19 Water aggregate stability (%) and mean weight diameter (mm) at different soil horizons.

These results indicate OC, clay and sesquioxide contents as the key factors affecting %WAS (Figure 19). Mostly, subsoil aggregates of Ultisols are more stable than their topsoil aggregates. More stable aggregates in the subsoils of Ultisols are due to clay acting as a cementing material as is commonly the case when the soil contains > 20% clay (Ben-Hur *et al*., 1985). From these results, clay content and Fe oxides are the main effects on the differences of water aggregate-stability and MWD in subsoils horizons. The WAS of Ultisols has the same trend with that of silt plus clay and Fe_d in their profiles (Figure 19). Chappell *et al*. (1999) indicated that large differences in WAS between soil horizons of Ultisols were observed and statistically correlated with the clay content of bulk soil. In Alfisols, WAS values vary among their different horizons. The high values of WAS in middle horizons (Btk) in Alfisols (Figure 19) coincides with the high concentration of sum bases in these layers. This may be due to the effect of polyvalent cations such as Ca^{2+}, Fe^{3+} and Al^{3+} which are the main inorganic stabilizing agents (Amezketa, 1999).

The WAS have positive relationships with silt plus clay content ($R^2=0.30$, $P<0.001$) and iron oxide content ($R^2=0.32$, $P<0.001$) in these soils (Figure 20). Whereas, CEC and OC concentrations have weak relationships with WAS (Figure 20). Therefore, the difference of WAS among these soils can be induced by the difference of clay and iron oxide content. The aggregating role of OC could be less effective in soils that include large amounts of such clay and sesquioxides content (Tisdall and Oades, 1982).

3. Mean weight diameter (MWD)

Mean weight diameter are summarized in the Appendix Table C5. The size of WAS is largest in Oxisols, followed by that in Ultisols and Alfisols averaging 1.2, 0.42 and 0.23 mm, respectively (Figure 19, 21). There is a significant difference in the MWD values of aggregates between Oxisols and other soils (Figure 19, 21). Especially, these MWD in Bo horizons of red Oxisols are significantly higher than that of the other horizons (2.0 mm) (Figure 21). The size and stability of soil aggregates are related to clay mineral composition and content (Amezketa, 1999). The MWD distributions in their profiles show the same trend with WAS reflecting the predominance of OC and land use in surface soils. Figure 22 shows strong relationships of MWD with silt plus clay content ($R^2=0.43$, $P<0.001$) and bulk density ($R^2=0.49$, $P<0.001$).

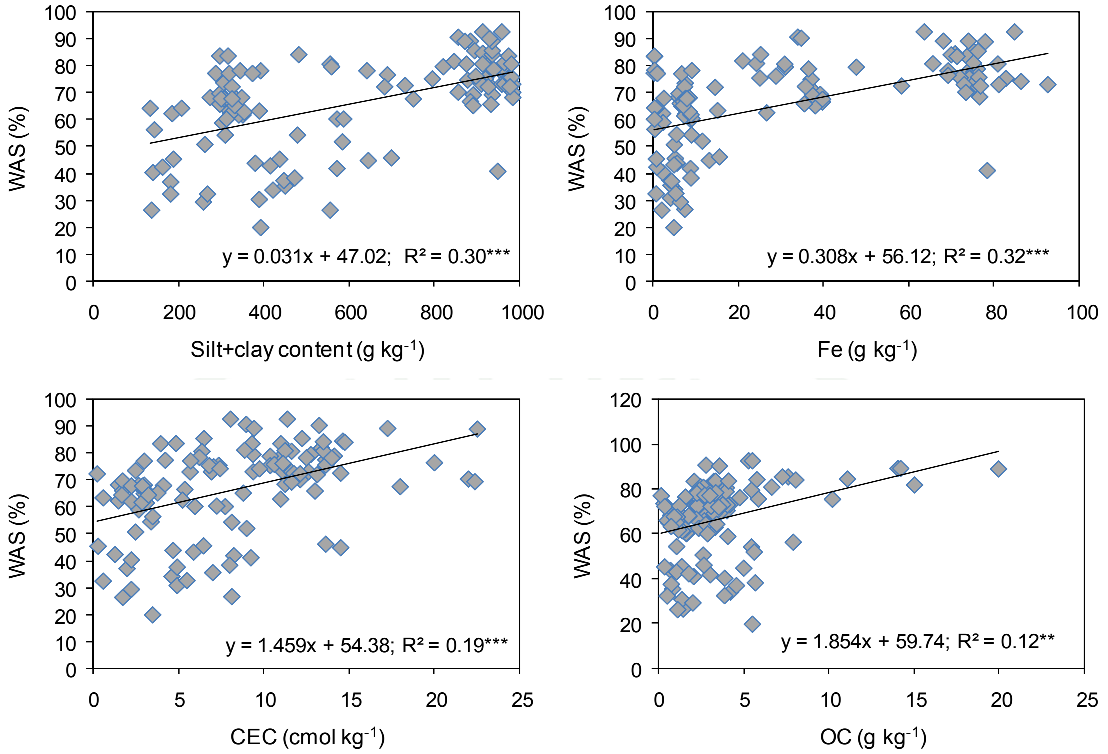


Figure 20 Relationships of water aggregate stability and some soil properties ***$P < 0.001$ and **$P < 0.01$.

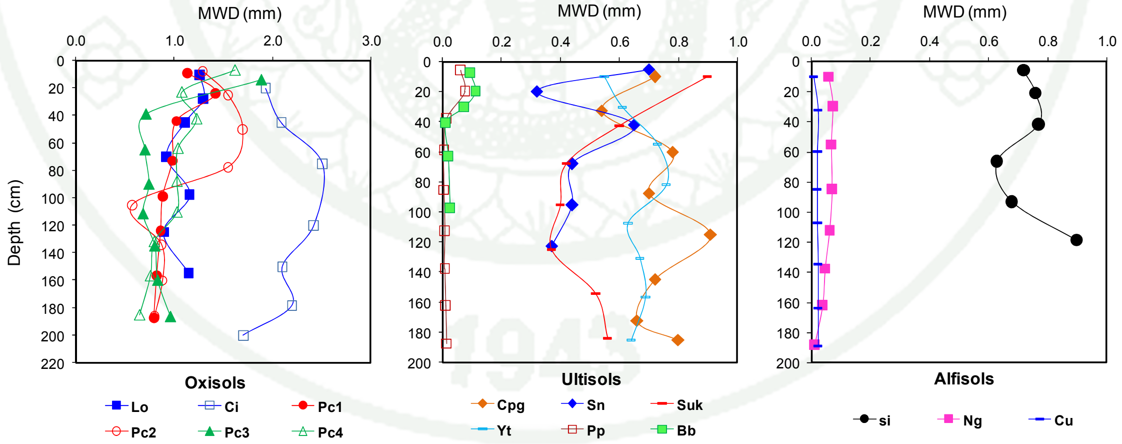


Figure 21 Mean weight diameter (MWD) distribution profiles of representative upland agricultural soils in Northeast Plateau, Thailand.

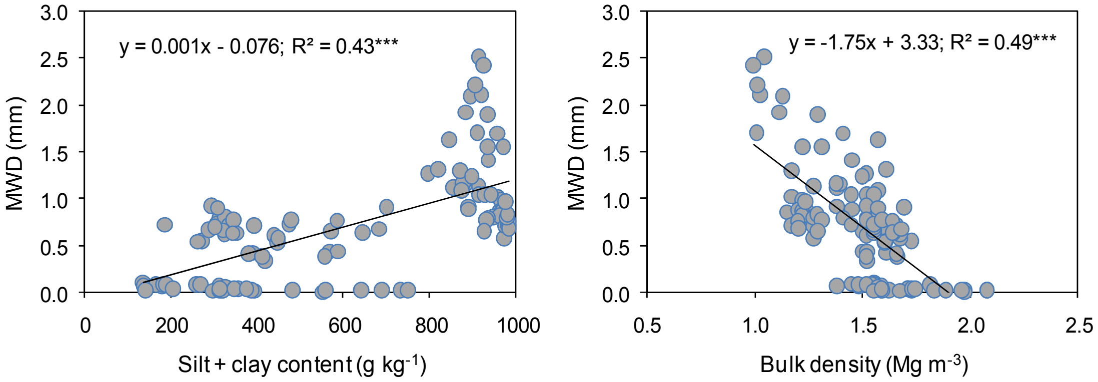
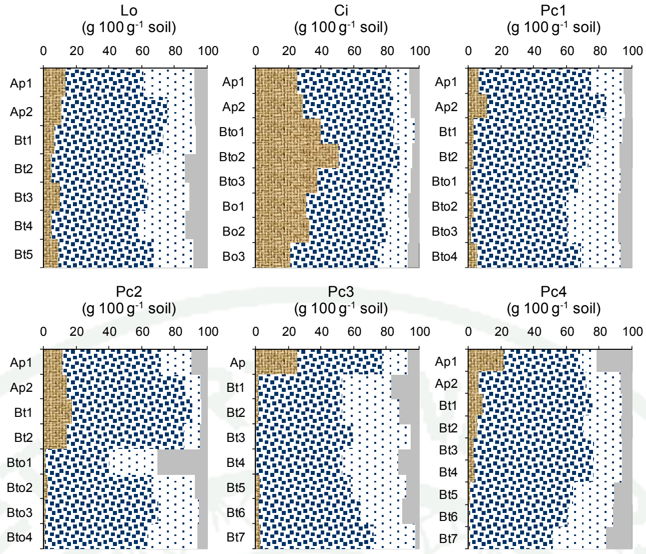


Figure 22 Relationships of mean weight diameter with some soil properties. ***P<0.001

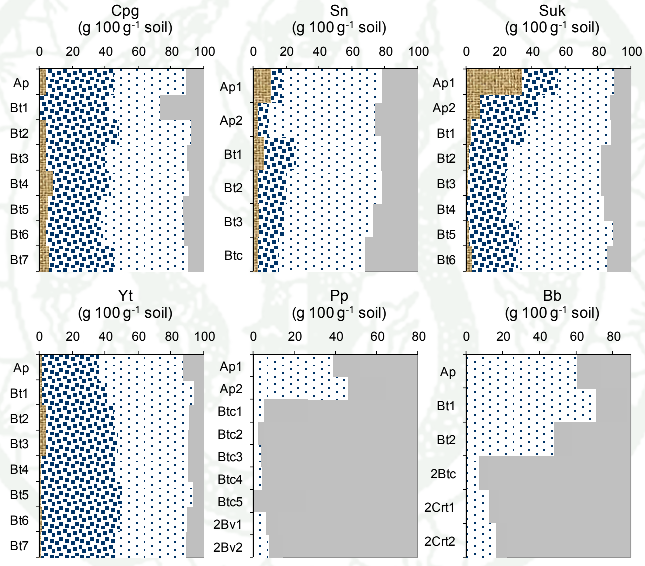
4. Aggregate size distribution

Bulk soils were separated into four aggregate size classes including silt and clay fraction (SCf: <53 µm), microaggregate (MiA: 53-250 µm), small macroaggregate (SMA: 250-2000 µm) and large macroaggregate (LMA: 2000-8000 µm). Aggregate size distributions are summarized in the Appendix Table C5.

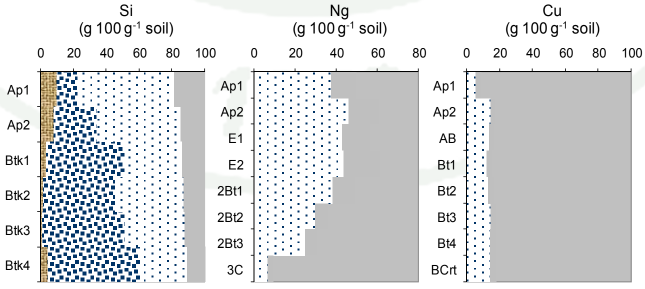
In Oxisols, all soils can be separated into four aggregate size classes. SMA (250-2000 µm) makes up the largest proportions ranging from 37-73 g 100 g^{-1} soils followed by MiA (53-250 µm) ranging from 6-35 g 100^{-1} g soils, LMA (2000-8000 µm) ranging from 0.35-70 g 100 g^{-1} soil and SCf (<53 µm) ranging from 3.3-31 g 100 g^{-1} soils (Figure 23). Figure 23 shows that SMA in Oxisols are constant with depth. A high content in stable macroaggregates has often been reported for clayey low activity clay tropical soils (Oades and Waters, 1991) but less frequently for coarse-textured ones (Spaccini *et al*., 2001) where it has been considered that macroaggregates could be less stable (Albrecht *et al*., 1998). For Bo and Bto horizons, the formation and stabilization of macroaggregates tend to be especially dependent on sesquioxide content that provides the main binding agent for aggregation (Six *et al*., 2000). The LMA tend to decrease with depth due to their more sensitivity to land use and management. These can be observed in Pc3 and Pc4 where land uses are uncultivated land (U) and tree with forage crop (TF). Jagadamma *et al*. (2009) showed that the soils under no-tillage management had significantly higher LMA (>2000 µm) as compared to that under plow tillage management.



Oxisols



Ultisols



Alfisols

▨ **LMA** ▨ **SMA** ⁚ **MiA** ■ **SCf**

Figure 23 Depth functions for silt and clay fraction (SCf: <53 µm), microaggregate (MiA: 53-250 µm), small macroaggregate (SMA: 250-2000 µm) and large macroaggregate (LMA, 2000-8000 µm) by weight (g per100 g soil).

The proportion of MiA (53-250 µm) accounts for 20 g 100 g^{-1} of dry soil weight in Oxisols and abundant in subsoils especially in Bt and Bto (Figure 23). The SC (<53 µm) in most of Oxisols also varies greatly and tends to increases with depth. Red Ultisols (Cpg, Sn, Suk and Yt) can be separated into four aggregate size classes but Pp and Bb can only be separated into LMA and SMA (Figure 23). MiA (53-250 µm) makes up the largest proportion ranging from 2.3-70 g 100 g^{-1} soils followed by SMA (250-2000 µm) ranging 6.6-49 g 100 g^{-1} soils, SCf (<53 µm) ranging 3.0-32 g 100 g^{-1} soils and LMA (2000-8000 µm) ranging 0.2-34 g 100 g^{-1} soils, respectively (Figure 23). From Figure 23 showed macroaggregate (LMA, SMA) tend to decrease with depth while SCf tend to increase with depth. These are correlated with the increasing depth of silt and clay content in Ultisols especially in Bt1, Bt2 horizons. For Alfisols, Ng and Cu samples can be separated into only MiA and SCf because their profiles have high sand content. In Si profile, Ap horizons contain a smaller size aggregate than that in the Btk horizons (Figure 23). This is due to calcium concentration effect on the formation of macroaggregate. The mass of LMA in Ap horizon of uncultivated land are significantly higher than that in the other land uses (P<0.05, Figure 24). Land use, agricultural practices and high concentration of OC in surface soils are the important effects on macroaggregation (Tisdall and Oades, 1982). The WAS values of uncultivated land are clearly higher than that of cassava field (P<0.05, Figure 24). There is no clear difference for SMA, MiA and SCf among different land uses (Figure 24). It is clear that land use and management have some effect on aggregate size distribution in Ap horizons whereas clay, sesquioxide and Ca concentration show some effect on aggregate size distribution in subsoils.

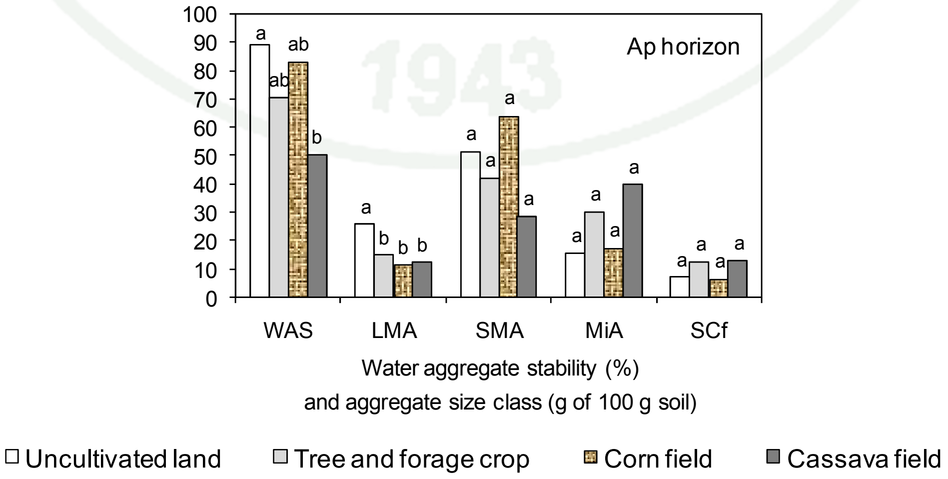


Figure 24 Aggregate size separation and water aggregate stability.

5. Particle-size composition of aggregate size class

Some Ultisols (Pp, Bb) and all of Alfisols were not included in this part because they could not be separated in four aggregate size classes. There is an increase of MiA (53-250 μm) separated from macroaggregates (>250 μm) in red Ultisols (Cpg, Sn, Suk, Yt) as compared to that of Oxisols (Table 9).

The proportion of SCf (<53 μm) increases from 9-15 g 100 g^{-1} soil in slaked samples to 21-70 g 100 g^{-1} soil in samples isolated from macroaggregate samples and this increase is greatest in Oxisols (Table 9). In red Ultisols, the mass of microaggregate increases with the separated of macroaggregate. There is a substantial decrease of macroaggregates with an increase of silt and clay particles in Oxisols. The clay (<2 μm) and silt (2–53 μm) particles are in aggregated form in all aggregate size classes of Oxisols and in microaggregate of Ultisols. The clay particle in bulk soils of Oxisols is related with clay particle in SMA and in MiA of red Ultisols (Figure 25).

Table 9 Aggregate mass distribution of soil samples and mass of SCf and MiA (<250 μm) disturbed from SMA and LMA aggregate (>250 μm) and particle size fraction within each aggregate size class.

Aggregate-size class	Mass of <250 μm*	Mass of aggregates	Mass of particle-size fractions		
(μm)	(g of wt MA)	(g 100g^{-1} soil)	<2 μm	2-53 μm	>53 μm
Oxisols (N=49)					
<53	49.8 ±1.4	8.5 ±0.7	6.8 ±1.2	1.7 ±0.4	
53-250	20.4 ±1.1	20.0 ±1.2	16.3 ±1.4	3.3 ±0.4	1.4 ±0.9
250-2000	-	57.2 ±1.9	44.7 ±0.5	9.1 ±0.3	4.1 ±1.7
>2000	-	12.1 ±2.2	8.9 ±0.2	2.1 ±0.2	1.2 ±0.8
Total, calculated	70.2 ±1.8	97.9 ±1.6	76.7 ±0.9	16.3 ±0.4	6.7 ±1.2
Ultisols (N=30)					
<53	7.6 ±0.6	14.7 ±1.3	10.1 ±0.6	4.6 ±0.3	
53-250	28.5 ±1.9	49.2 ±1.4	22.8 ±1.2	15.8 ±0.5	10.5 ±0.2
250-2000	-	30.6 ±2.2	7.0 ±2.1	3.9 ±1.2	20.7 ±0.4
>2000	-	4.5 ±1.1	1.0 ±1.6	0.6 ±0.6	2.9 ±0.2
Total, calculated	36.1 ±1.6	99.0 ±1.7	40.9 ±1.6	25.0 ±0.9	34.1 ±0.5

* Mass of SCf plus MiA (<250 μm) disturbed from LMA and SMA (>250 μm) (g weight from total coarse aggregates).

These are due to the aggregate hierarchy concept that macroaggregates (>250 µm) are collections of smaller microaggregates (<250 µm) held together with temporary and transient organic binding agents (Tisdall and Oades, 1982). These agents consist of plant roots, fungal hyphae, microbial or plant exudates, and humic material (Christensen, 2001). The arrangement of minerals, amorphous material, organic matter, and biota in aggregates of diameter <20, <53, 100-250, and >2000 µm is highly dependent on aggregate size (Vrdoljak and Sposito, 2002). The hierarchical model of aggregation proposes that microaggregates join together to form macroaggregates, and the bonds within microaggregates are stronger than the bonds between microaggregates.

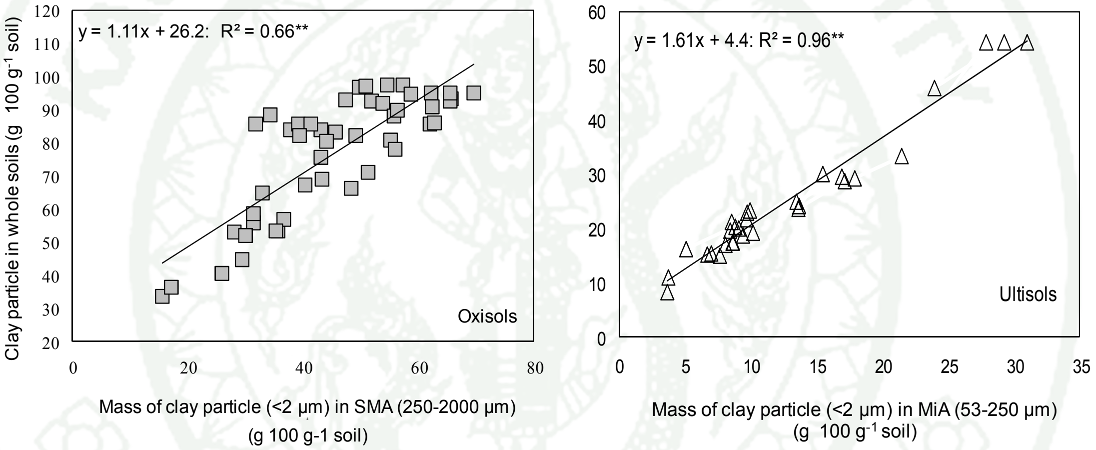


Figure 25 Relationship between clay particle in whole soils and mass of clay particle (<2 µm) in small macroaggregates (250-2000 µm) and microaggregates (53-250 µm) (** significant at *P*<0.01).

Depth Fractionation of Carbon Sequestration

The Ap (D1), base of Ap to 0.6 m (D2), 0.6 to 1 m (D3) and 1 to 2 m (D4) sections of the soil profiles were used to examine distribution of C and C_{seq} in the agricultural soils. Four depth sections help to quantify current depth fractionation of C concentration and C_{seq} in different soil and land use types and to examine the important mechanism and factors controlling sequestered C in each soil depth section from surface soil to the depth of 2 meters. Total carbon, organic carbon, inorganic carbon, carbon and nitrogen ratio and carbon sequestration in major upland agricultural soil are summarized in the Appendix Table C6. Total carbon, nitrogen and C/N ratios in different aggregate size classes are summarized in the Appendix Table C7.

1. Synthesis of depth fractionation of carbon sequestration in major upland agricultural soils

The results show that total carbon in these soils is mainly organic carbon. Soil organic carbon (OC) concentrations generally decrease with increasing soil depth. High decomposition rate of tends to lower the C/N ratio to near 10:1. The C/N ratio in these soils is affected by type of OM and land use. The uncultivated lands and corn fields have more N than do the cassava fields and tree with forage crops, respectively. The cassava fields have a wider range of C/N ratio than uncultivated lands, corn fields and tree and forage crops, respectively. The C_{seq} in these soils tends to significantly decrease from the surface soil (D1) (6.7-52 Mg C ha^{-1}) to the lower depth fractions. The extreme value of C stored in the D1 is in uncultivated lands (52 Mg C ha^{-1}). The C_{seq} in D2 section ranges from 3-37 Mg C ha^{-1}. The amount of C_{seq} in D3 section ranges from 2-28 Mg C ha^{-1}. The trend of C_{seq} in D4 section varies from 8-52 Mg C ha^{-1}. The sequestered C in D4 sections account for 51% of the C_{seq} in the first meter. Oxisols sequestered higher OC than Alfisols and Ultisols. The percentage of TC_{SCf} as compared to TC have a positive relationship with silt plus clay contents with depth especially in soil profiles that show a textural change with depth.

In surface soils, coarse aggregates (LMA, SMA) have a higher C/N ratio than do the fine aggregates (MiA, SC). The MiA (53-250 μm) and SC (<53 μm) in deep Bt and Bto horizons have large C/N ratio values effected to their low bulk density suggesting a physical protection from microorganism. Carbon content of macroaggregate in red Ultisols is 2.14 times greater than that of the microaggregate. Slaked microaggregate C in red Oxisols is in the Ap>Bt>Bto>Bo order but in red Ultisols it is higher in Bt than in Ap. Carbon associated with aggregate in Oxisols does not increase with increasing aggregate size classes. Macroaggregates of red Ultisols promote greater storage of C associated with microaggregates. A relationship between the carbon enrichment in microaggregate (<250 μm) and C in bulk soils of each genetic horizons indicates that stabilization of OC occurs in the fine aggregates of these soils.

2. Carbon concentration

2.1 Total carbon (TC)

The largest amount of TC and OC of all soil types are in D1 (Table 10). All profiles have a decrease of OC with depth which is typical for tropical soils (Buol *et al*., 2003). The TC of these soils are strongly correlated with OC (TC = 0.92OC + 1.26; R^2=+0.94***) (Figure 26) with values ranging from 1.1-20 g kg^{-1} (Table 10). Total carbon in Alfisols has a positive relationship with Ca reflecting the influence of calcareous sandstone and lime fragments present at the 0.3 m depth in their Btk horizons (R^2=+0.80**) (Figure 26).

2.2 Soil organic carbon (OC)

Soil organic carbon (OC) concentrations generally decrease with increasing soil depth (Table 10). Ap horizons of all soils have the highest OC, ranging from 7.8-20, 2.3-5.7 and 2.6-4.9 g kg^{-1} in Oxisols, Alfisols and Ultisols, respectively (Table 10). The concentrations of OC in all depths of Oxisols are significantly higher than that in Ultisols (P <0.05, Table 10). In D4 section, OC in Bv, Btc and C horizons declines and ranges between 0.5-3.3 g kg^{-1}.

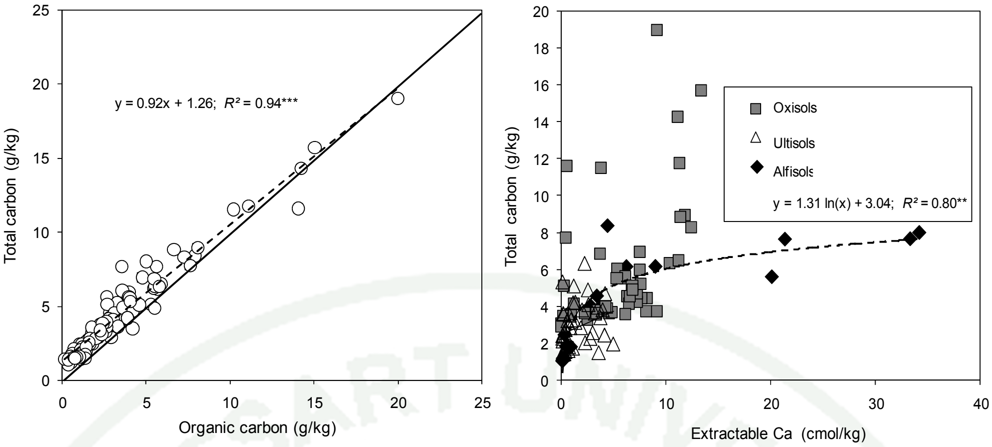


Figure 26 Relationships between organic carbon and extractable calcium with total carbon in whole soils.

2.3 Carbon and nitrogen ratio (C/N)

The ratio of C and N in these soils is higher in the Ap horizons and lower for subsoils horizons of their profiles, ranging from 5-14 in Ap horizons and 0.23-13 in subsoils (Figure 27). It tends to decrease with depth. High decomposition rate of soil in tropical savanna tends to lower the C/N ratio to near 10:1. Oxisols have C/N ratio in a range of 4-14, Ultisols in a range of 1-13 and Alfisols in the range of 1-9. The C/N ratio variability of Ultisols is higher than in other soils (Figure 27). It is due to the differences among their mineralization environments. There are no clear relationship between C/N ratio and other soil properties. The C/N values in Ap horizons do not differ among soil types although C concentration of Oxisols are significantly higher than of Ultisols and Alfisols as do in subsoils horizons (Figure 28). It is due to the highly decomposition rate of OM in tropical savanna climate. The C/N ratio in these soils is affected by type of OM and land use. Under reduced tillage systems, the limited level of soil disturbance modifies surface soil conditions, reducing microbial activity and, also, the rate of OM decomposition (Mielke *et al*., 1986).

Organic carbon and nitrogen in uncultivated soils are generally higher than in cultivated soils. Tree with forage crops, corn fields and cassava fields have a slight effect on OC, N and C/N ratio variation. Mean comparisons between land uses show that OC of uncultivated lands is quite higher than that of other land uses (*P*<0.05, LSD; Figure

29). The uncultivated lands and corn fields have more N than do the cassava fields and tree with forage crops, respectively. The cassava fields have a wider range of C/N than uncultivated lands, corn fields and tree and forage crops, respectively (Figure 29). In uncultivated soils, OC content are generally higher than that in cultivated soils and the C/N values of agricultural soils in tropical savanna climate also indicate the high rate of decomposition. Ashagrie *et al.* (2005) showed that the significant soil with land use interaction reflected a high initial C/N values and increased in the sandy soils.

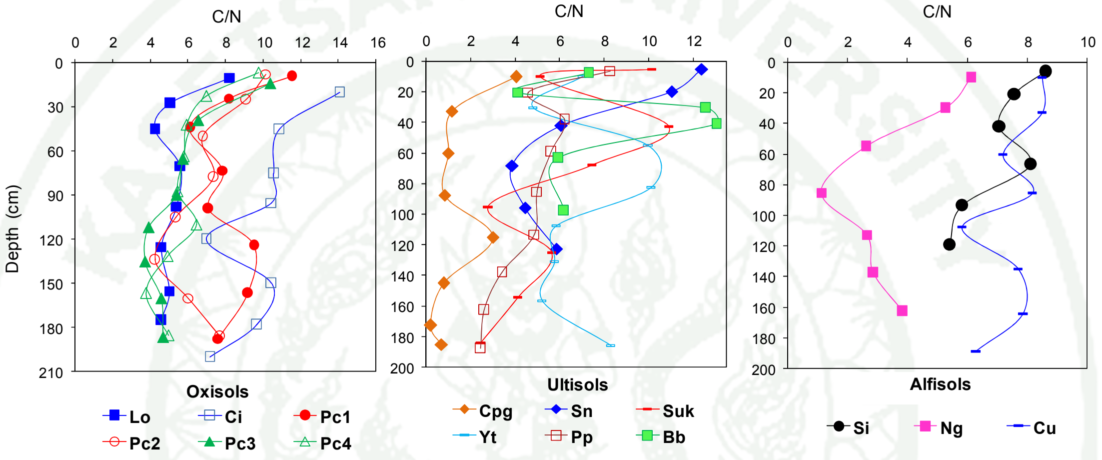


Figure 27 Carbon and nitrogen ratio (C/N) distribution profiles of representative upland agricultural soils in Northeast, Thailand.

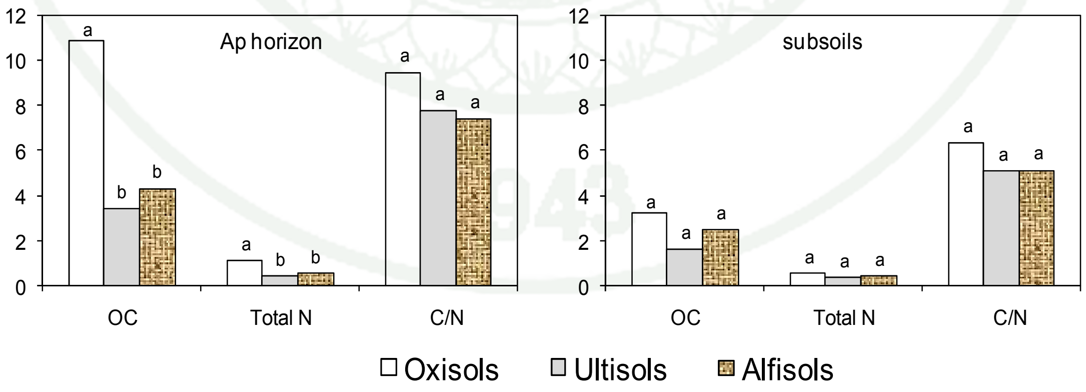


Figure 28 Mean values of organic carbon (OC), total nitrogen (TN) and ratio of carbon and nitrogen (C/N) in Ap and subsoils horizons of Oxisols, Ultisols and Alfisols. Mean values followed by the same letter in column are not statistically different at $P<0.05$; LSD.

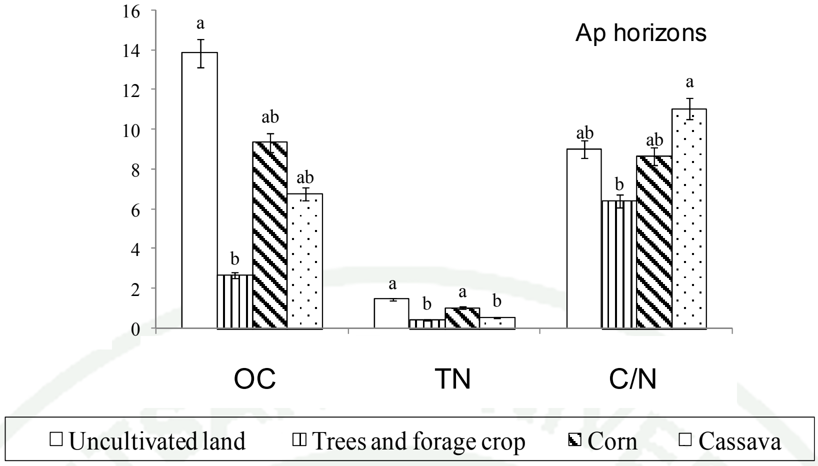


Figure 29 OC, N and C/N in Ap horizons of four land uses. Mean±SE followed by the same letter in column are not statistically different at *P*<0.05; LSD.

2.4 The total carbon in silt and clay fractions (TC_{SCf})

There should be a greater potential for OC preservation in the subsoil, where the OC saturation of mineral particles is small (Rumpel *et al*., 2002). The total carbon in silt and clay fractions (TC_{SCf}) in all profiles decreases with soil depth averaging 2.9, 2.5, 1.7 and 1.6 g kg^{-1} soil for D1, D2, D3 and D4 sections, respectively (Table 10). Ultisols have the percentage of TC_{SCf} as compared to TC increases with increasing depths and 59% of TC is in the 1-2 m depth sections (Table 10). For all soils, the percentages of TC_{SCf} as compared to TC are highest in D2 followed by D4, D3 and D1 (Table 10). This is due to the difference in silt plus clay content for D2 being greatly higher than for D1. The occlusion of C within silt and clay fractions is important throughout soil profiles especially in subsoil horizons (Moni *et al.,* 2010).

3. Depth fractionation of C_{seq}

The C_{seq} of these soils are closely related to OC and it tends to decrease with depth (Table 10). Large C_{seq} exists in the upper horizon (D1) ranging from 6.7-52 Mg C ha^{-1}. The extreme value of C stored in the D1 is in uncultivated lands (52 Mg C ha^{-1}) indicating important roles of land use and management on C_{seq} in surface soils (von Lützow *et al*., 2006). The C_{seq} in D2 section ranges from 3-37 Mg C ha^{-1}. The amount of C_{seq} in D3 section ranges from 2-28 Mg C ha^{-1}. The trend of C_{seq} in D4 section varies from 8-52 Mg C ha^{-1}. The C_{seq} in D4 sections are highest in Oxisols followed by that in

Alfisols and Ultisols (Table 10). More C is stored in D4 of Alfisols (28 Mg C ha^{-1}). This is due to the OC translocation into and within the mineral soils by leaching, leading to the formation of an E (elluvial)horizon, a zone of OM removal and a B (illuvial) horizon where a net accumulation of OC takes place (Rumpel *et al*., 2002). The C_{seq} in the middle layers (D2, D3) of Ultisols and Alfisols are higher than that in D1 whereas it is lower than that in D1 for Oxisols. This is due to land use and soil management in Oxisols under uncultivated lands and corn fields.

Table 10 Range and mean values of total carbon (TC), organic carbon (OC), total carbon in silt plus clay fractions (TC_{SCf}) and carbon sequestration (C_{seq}) in whole soils.

Horizon	Depth (m)	OC (g kg^{-1})			TC (g kg^{-1})			TC_{SCf} (g kg^{-1} soil)			TC_{SCf} (%) [1/]	C_{seq} (Mg C ha^{-1})		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean		Min	Max	Mean
All soils														
(n=116)	D1	2.3	20.0	7.3 A	3.0	20.0	7.4 A	0.3	7.2	2.9 A	40	7	52	21 AB
	D2	0.5	5.6	3.2 B	1.2	7.8	4.2 B	0.1	5.5	2.5 AB	58	3	37	18 AB
	D3	0.4	4.4	2.6 B	1.1	7.7	3.7 B	0.1	3.5	1.7 B	46	2	28	16 B
	D4	0.5	3.3	2.0 B	1.4	6.0	3.2 B	0.2	3.2	1.6 B	49	8	52	28 A
Oxisols														
Ap	D1	7.8	20.0	12.0 a	9.2	20.0	12.0 a	4.7	7.2	4.9 a	41	24	52	31 a
Bt, Bto	D2	3.0	5.3	4.4 a	4.1	6.5	5.4 a	2.1	5.5	4.0 a	74	14	26	22 a
Bt, Bto	D3	2.4	3.8	3.3 a	3.3	5.8	4.2 a	1.0	3.5	2.4 a	57	12	23	17 a
Bt, Bto, Bo	D4	2.3	3.3	2.7 a	2.9	5.1	3.9 a	1.2	3.2	2.4 a	61	24	44	34 a
Ultisols														
Ap	D1	2.6	4.9	3.3 b	3.3	4.8	3.9 b	0.5	1.3	0.9 b	23	8	15	10 b
Bt	D2	0.7	3.6	2.1 b	1.6	4.1	3.0 b	0.8	2.0	1.3 b	43	4	23	14 a
Bt, Btc	D3	0.5	4.4	1.9 b	1.5	4.1	2.7 b	0.6	2.4	1.5 a	56	3	28	13 a
Bt, Btc, Bv	D4	0.5	1.5	1.0 b	1.4	6.0	2.2 b	0.6	2.0	1.3 a	59	8	31	18 b
Alfisols														
Ap	D1	2.3	5.7	4.5 b	3.0	6.2	5.1 b	0.3	2.5	1.2 b	24	7	19	14 b
E, Bt,	D2	0.5	5.6	3.2 ab	1.2	7.8	4.4 ab	0.1	3.0	1.3 b	30	3	37	21 a
Btk, Bt	D3	0.4	4.3	2.7 ab	1.1	7.7	4.5 a	0.1	2.4	1.1 a	25	2	28	18 a
Btk, Bt, C	D4	0.5	3.3	2.0 ab	1.8	5.6	3.7 a	0.2	2.4	1.0 a	28	7	52	28 ab

[1/] The percentage of total carbon in silt plus clay fractions as compared to total carbon in whole soils. Differences between soil depths within all soils are indicated by different capital letters (A, B) and differences between soil types within one depth are indicated by small different letters (a, b); $P<0.05$ (Tukey's HSD test).

The C sequestered proportion of D1 in uncultivated lands is significantly higher than in corn fields, cassava fields and tree with forage crops averaging 43, 24, 14 and 9 Mg C ha^{-1}, respectively (Table 11). The largest amount of OC in uncultivated lands is in the surface soil (Post and Kwon, 2000) because of the high inputs from the litters and being less disturbed by cultivation management. The C_{seq} in middle sections (D2, D3) of cultivated soils (tree and forage crops, corn fields and cassava fields) have no difference among land uses ($P<0.05$) (Table 11). In D4 section, soils under corn fields have more C_{seq} than do soils under cassava fields and tree with forage crops, averaging 39, 23 and 11 Mg C ha^{-1} for corn fields, cassava fields and tree with forage crops, respectively (Table 11).

Table 11 Range and mean values of bulk density (BD), water aggregate stability (WAS), organic carbon (OC) and carbon sequestration (C_{seq}) with soil depths for land use types.

Depth	Land uses	OC (g kg^{-1})			C_{seq} (Mg C ha^{-1})		
		Min	Max	Mean	Min	Max	Mean
D1	Uncultivated	11.0	20.0	15.0 a	34.2	51.8	43.0 a
	Tree and forage	2.6	2.7	2.7 b	8.5	8.8	8.7 c
	Corn	5.7	11.0	8.5 b	18.8	26.2	23.9 b
	Cassava	2.3	11.0	4.8 b	6.7	24.3	13.5 bc
D2	Uncultivated	4.4	4.8	4.6 a	23.6	26.5	25.1 a
	Tree and forage	0.7	1.4	1.0 b	4.3	8.6	6.5 b
	Corn	3.0	4.8	3.8 a	14.4	26.0	21.5 ab
	Cassava	0.50	5.6	3.1 ab	3.0	36.8	18.7 ab
D3	Uncultivated	3.6	3.8	3.7 a	17.0	23.3	20.1 a
	Tree and forage	0.51	0.70	0.61 b	3.2	4.7	4.0 b
	Corn	2.4	3.6	3.2 a	11.7	22.1	17.8 ab
	Cassava	0.36	4.4	2.6 ab	2.2	28.4	16.0 ab
D4	Uncultivated	2.6	3.3	2.9 a	32.4	44.5	38.5 a
	Tree and forage	0.49	0.88	0.69 b	7.5	14.1	10.8 b
	Corn	2.3	3.1	2.8 a	27.6	52.1	38.7 a
	Cassava	0.94	2.4	1.5 b	15.6	30.6	22.7 ab

Significant differences between land uses within one depth fraction are indicated by different letters (a, b, c); $P<0.05$ (Tukey's HSD test).

4. Carbon associated with aggregate size fractions

Two Ultisols (Pp, Bb) and all of Alfisols were not included in this part. Carbon, nitrogen and ratio of C/N in difference aggregate size classes are summarized in the Appendix Table C7. The C contents of the bulk soils decrease with depth from 2.38 to 14.08 g kg^{-1} in Oxisols and from 0.67-3.71 g kg^{-1} in red Ultisols (Table 12). The contribution of all aggregate sizes to the C storage in the mineral soil gradually decreases from the Ap to Bt.

Carbon and nitrogen ratio (C/N) of each aggregate size fraction ranges from 5-43 and 2-64 in Oxisols and red Ultisols, respectively. In surface soils, coarse aggregates (LMA, SMA) have a higher C/N ratio than do the fine aggregates (MiA, SC) contrasting with that of subsoil horizons (Figure 30). MiA (53-250 μm) and SC (<53 μm) in deep Bt and Bto horizons contain a large C/N value effected their low bulk density suggesting a physical protection from microorganism (Feller and Beare, 1997) (Figure 30).

In Oxisols, concentrations of C extracted from all aggregate size fractions are similar and do not increases with increasing aggregate size class (Table 12, Figure 31a). In all horizons, more than 26% of the total C is in the <250 μm fractions (MiA, SC) (Table 12, Figure 31a). In the Bo and Bto horizons, approximately 19% of the TC are in silt and clay particles (<53 μm) (Table 12, Figure 31a). In red Ultisols, the concentrations of C extracted from >250 μm (LMA, SMA) fractions are higher than from small aggregate (MiA, SC) (Figure 31b). The C content of >250 μm is 2.14 times greater as compared to that of <250 μm. Especially in Ap horizon, C in the >250 μm fractions are more than 40% of the TC (Table 12, Figure 31b).

However, C in bulk samples of Oxisols have positive correlation with C in SMA ($R^2=0.95^{**}$, $P<0.01$) whereas C in bulk samples of Ultisols are positively correlated with C in MiA ($R^2=0.65^{**}$, $P<0.01$) (Figure 32). The C associated with smaller aggregate (<250 μm) of red Ultisols tends to increase with the increase of larger aggregate (>250 μm). This result indicates that macroaggregates of red Ultisols promote greater storage of C associated with microaggregates. Sexstone *et al.* (1985) suggested that large aggregates represent microenvironments where the centers of the aggregates provide unfavourable conditions for microbial decomposition of OM.

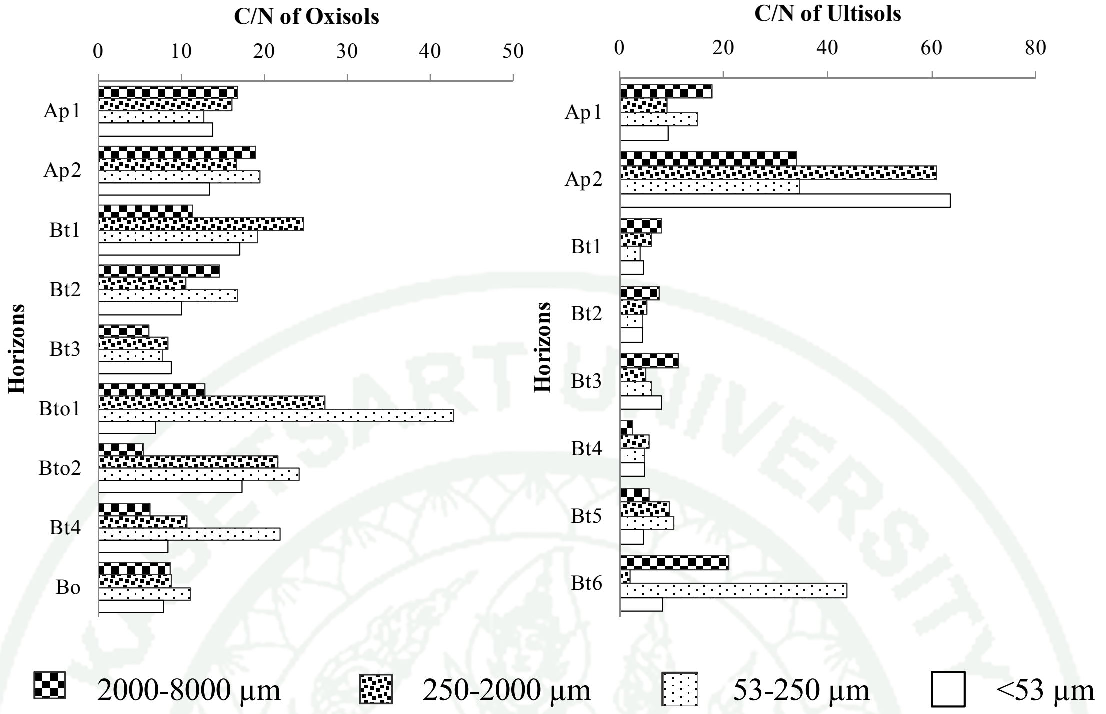


Figure 30 Carbon and nitrogen ratio (C/N) of aggregate size distribution in soil horizons of Oxisols and red Ultisols.

Table 12 Carbon concentrations in bulk soils and extracted from aggregate size fractions. mean (standard deviations)

Horizons	Depth (cm)	C in bulk soils (g kg^{-1})	C extracted from aggregates (g kg^{-1} soil)			
			8000-2000 μm	2000-250 μm	250-53 μm	<53 μm
Oxisols						
Ap1	0-14	14.08 (3.44)	1.36 (0.52)	1.27 (0.26)	1.04 (0.22)	1.16 (0.23)
Ap2	14-28	7.00 (1.00)	0.90 (0.16)	0.72 (0.09)	0.91 (0.41)	0.96 (0.43)
Bt1	28-50	4.73 (0.97)	0.69 (0.34)	0.53 (0.10)	0.55 (0.09)	0.58 (0.09)
Bt2	50-75	3.56 (0.64)	0.57 (0.19)	0.51 (0.06)	0.49 (0.08)	0.49 (0.08)
Bt3	75-100	3.33 (0.26)	0.53 (0.31)	0.42 (0.10)	0.44 (0.10)	0.48 (0.12)
Bto1	100-120	3.59 (1.54)	0.58 (0.02)	0.35 (0.01)	0.45 (0.09)	0.51 (0.18)
Bto2	120-140	2.90 (0.76)	0.33 (0.08)	0.38 (0.05)	0.45 (0.08)	0.43 (0.06)
Bt4	140-160	2.83 (0.50)	0.33 (0.06)	0.36 (0.06)	0.39 (0.05)	0.38 (0.02)
Bo	160-180	2.38 (0.45)	0.30 (0.03)	0.31 (0.04)	0.33 (0.03)	0.37 (0.04)
Red Ultisols						
Ap1	0-10	3.71 (1.37)	1.13 (0.70)	0.39 (0.19)	0.34 (0.10)	0.37 (0.08)
Ap2	10-20	2.82 (1.98)	0.69 (0.62)	0.50 (0.51)	0.34 (0.15)	0.26 (0.05)
Bt1	20-40	1.83 (1.01)	0.36 (0.06)	0.27 (0.10)	0.30 (0.07)	0.33 (0.09)
Bt2	40-60	1.35 (0.52)	0.38 (0.22)	0.22 (0.09)	0.19 (0.04)	0.22 (0.04)
Bt3	60-90	1.15 (0.64)	0.51 (0.40)	0.19 (0.07)	0.26 (0.13)	0.24 (0.11)
Bt4	90-120	1.25 (0.28)	0.20 (0.04)	0.16 (0.04)	0.17 (0.05)	0.25 (0.09)
Bt5	120-150	0.84 (0.54)	0.19 (0.02)	0.16 (0.06)	0.18 (0.03)	0.23 (0.06)
Bt6	150-180	0.69 (0.44)	0.27 (0.24)	0.13 (0.03)	0.14 (0.03)	0.21 (0.06)

(a)

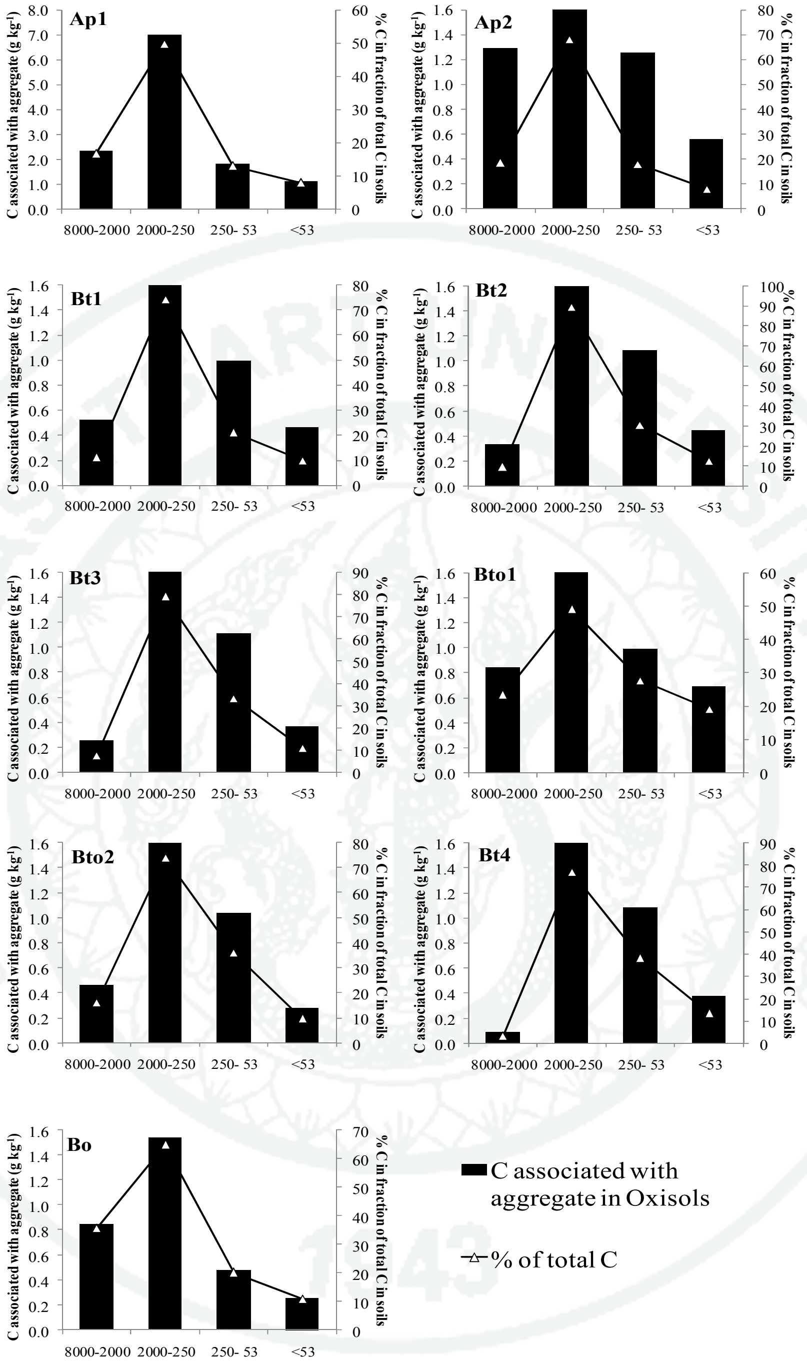


Figure 31 (a) Carbon associated with aggregate (g kg^{-1}) and carbon distribution (% of total C) in the aggregate size fractions separated from horizons of Oxisols.

(b) Carbon associated with aggregate (g kg^{-1}) and carbon distribution (% of total C) in the aggregate size fractions separated from horizons of red Ultisols.

(b)

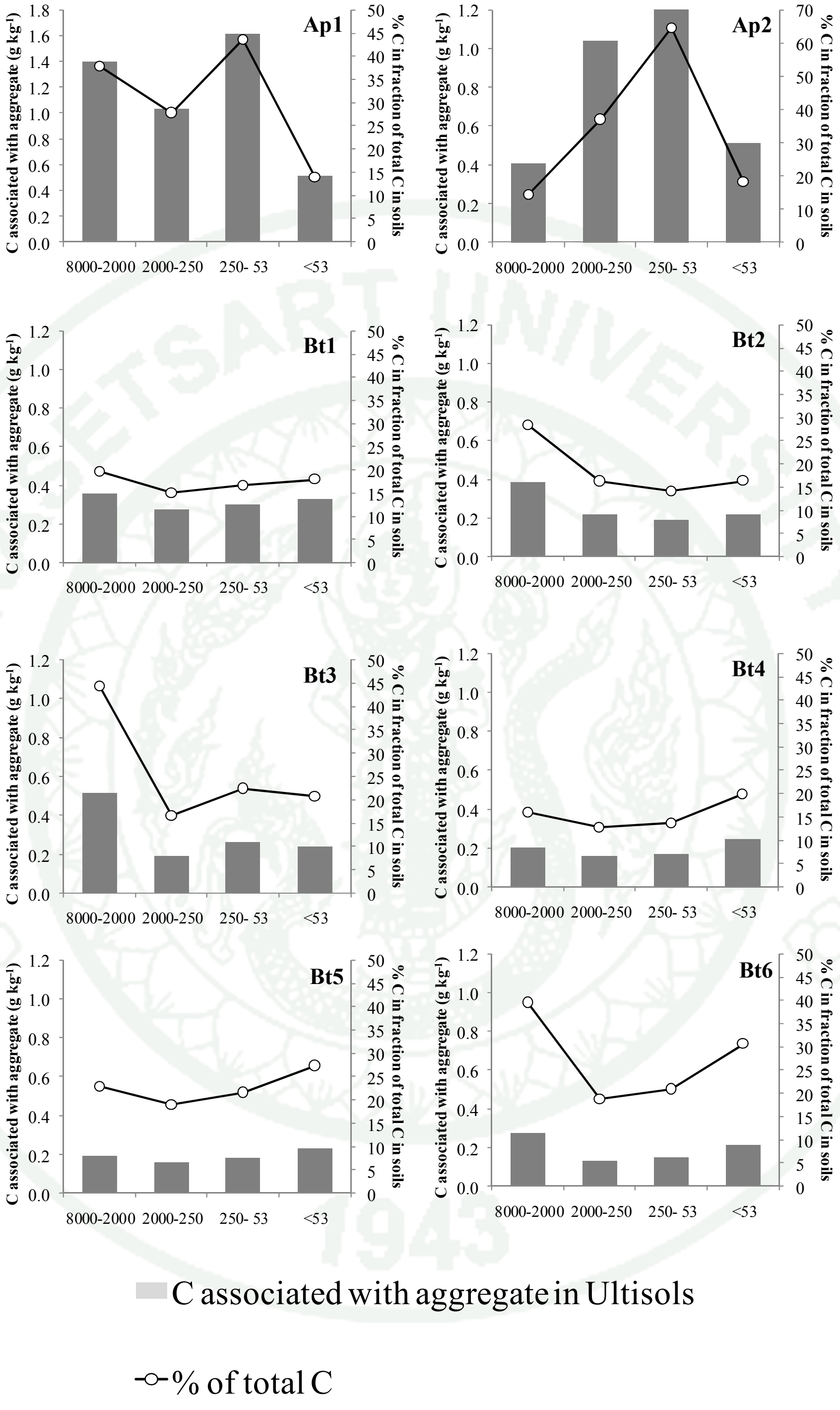


Figure 31 (Continued)

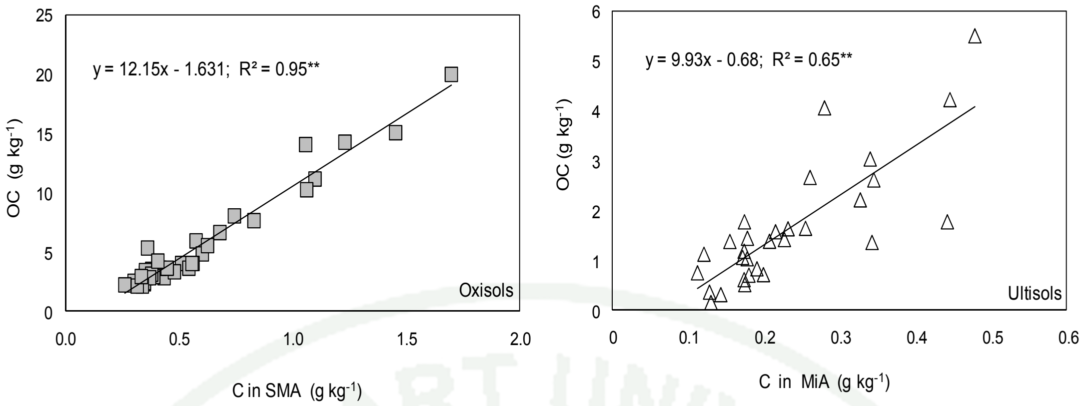


Figure 32 Relationship between the organic carbon in bulk soils and carbon associated with aggregate size 53-250 µm, 250-2000 µm (** significant at *P*<0.01).

However, Beare *et al.* (1994a) showed that the OC associated with macroaggregates was more easily mineralized than that in the microaggregate fractions. Carbon associated with aggregate in Oxisols does not increase with increasing aggregate size classes. Oxisols produce water stable aggregates but fail to produce an aggregate hierarchy because the main aggregate stabilizing agents are hydrous oxides of Al and Fe (Oades and Waters, 1991). Macroaggregate breakdown in Oxisols leads to a rapid release of the <20 µm particles generating 20–250 µm microaggregates (Blanco-Canqui and Lal, 2004).

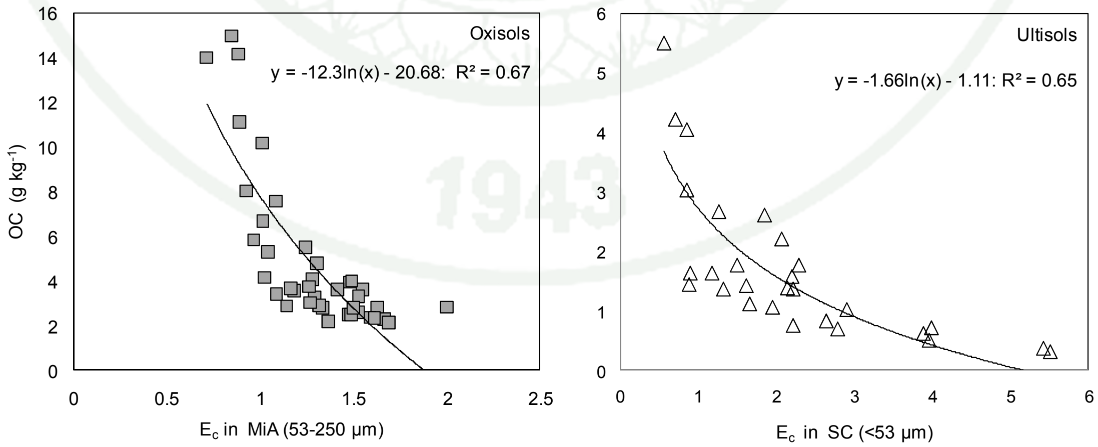


Figure 33 Relationship between the carbon enrichment factor in the aggregate size fraction <250 µm and the organic carbon of the bulk samples.

5. Carbon enrichment

To compare the carbon distributions in particle size fractions of top- and subsoil horizons carbon enrichment factors were used (Christensen, 1996, Kiem and Kögel-Knabner, 2003). The carbon enrichment factors (E_c = g C kg^{-1} fraction/g C kg^{-1} whole soil) of the 250-2000 μm fractions of both soils range between 0.9 and 1.9 (Table 13). Higher carbon enrichment ranging between 0.8 and 3.1 was calculated for the <53 μm fractions in both soils. The E_c in the <53 μm fractions of Oxisols and red Ultisols generally increases with depth, except for the Bt1 and Bt4 horizons of Oxisols (Table 13). The E_c of the 53-250 μm fractions in red Oxisols have a negative logarithmic relationship with C in bulk soils (Figure 33). Also the E_c of the <53 μm fractions in red Ultisols have a negative logarithmic relationship with C in bulk soils (Figure 33) suggesting that silt and clay fractions are enriched in stabilized carbon compounds. Organic carbon of the silt and clay fractions is mainly composed of microbial material (Baldock *et al*., 1992) and may be highly humified (Oades, 1988).

Table 13 Carbon enrichment factors (E_c = g C kg^{-1} aggregate/ g C kg^{-1} whole soil) of the aggregate size fraction isolated from horizons of Oxisols and red Ultisols.

	Horizons of Oxisols (cm)								
Aggregate-size class (μm)	Ap1 (0-14)	Ap2 (14-28)	Bt1 (28-50)	Bt2 (50-75)	Bt3 (75-100)	Bto1 (100-120)	Bto2 (120-140)	Bt4 (140-160)	Bo (160-180)
250-2000 μm	0.90	1.03	1.12	1.43	1.27	0.99	1.32	1.29	1.28
53-250 μm	0.74	1.30	1.17	1.38	1.31	1.25	1.55	1.39	1.37
<53 μm	0.82	1.38	1.22	1.37	1.43	1.41	1.48	1.33	1.57

	Horizons of red Ultisols (cm)							
Aggregate-size class (μm)	Ap1 (0-10)	Ap2 (10-20)	Bt1 (20-40)	Bt2 (40-60)	Bt3 (60-90)	Bt4 (90-120)	Bt5 (120-150)	Bt6 (150-180)
250-2000	1.06	1.79	1.49	1.62	1.65	1.26	1.89	1.87
53-250	0.92	1.19	1.66	1.41	2.23	1.36	2.15	2.09
<53	1.00	0.94	1.79	1.63	2.06	1.98	2.73	3.06

Factors Affecting Carbon Sequestration

The amount of C_{seq} in agricultural soils depends on local climatic and other site-specific conditions, as well as the type of land use and land management.

1. Synthesis of factors affecting carbon sequestration in major upland agricultural soils

The trend of C_{seq} in 2 m depth slightly increases with decreasing annual rainfall and increasing elevation. There are generally strong correlations between the C_{seq} and OC in the Ap horizons and the selected site variables (elevation and land use) and the other individual variables. The C_{seq} and OC have positive relationships with land use and elevation. While comparing the C_{seq} values of similar altitudes, their trend are affected by land use. The types of land use are arranged in order of elevation that is corn fields in higher elevation than cassava fields followed by tree and forage crops. Soil under the tree and forage crops has lower C_{seq} and OC than those under the other land uses followed by cassava, corn and uncultivated lands. This is due to the low soil management input on tree and forage crop area whereas corn fields always have high surface input in every cropping. The differences among soil parent materials have a slight effect on OC and C_{seq} of major upland agricultural soils in Northeast Plateau, Thailand. Especially, OC and C_{seq} in highly developed soils (Oxisols and Ultisols) are no different among parent materials. Whereas for younger developed soils (Alfisols), there are significant differences in C_{seq} and OC concentration among parent materials.

There are significant differences for depth fractions of C_{seq} interaction with soil types and land uses. The relative importance of C_{seq} on selected soil depth is controlled by the variation of silt plus clay contents, the amount of Fe-Al oxides, TC_{SCf}, WAS, MWD, ΔpH and CEC. The silt plus clay contents are found to be the best predictors of SOC content in these soils. Soil aggregations (WAS, MWD) are mainly differed by the difference of Fe and Al oxide concentrations. Uncultivated lands generally have higher C_{seq} in surface soil than do cultivated soils. Cultivated soils and their management have the important effect on C_{seq} in the D4 section, but C_{seq} in middle layers is not affected by any type of cultivation. There is no clear difference of BD and C/N ratio among land uses, soil types or soil depths. In soils and soil horizons with differing properties, various stabilization mechanisms are operative. The results indicate that land use and aggregation are the important factors for C_{seq} in the surface soils. The different stabilization processes of OC in subsoils (E, Bt, Bto, Bo, Btk, Btc, Bv and C horizons) are controlled by the interactions of pedogenesis processes including weathering of clay minerals, formation of iron oxides and hydroxides along with organomineral complexing and flow paths of C input from the surface soils.

The dynamics of C/N ratio in four aggregate size classes are not clearly different in three soil types but tending to decrease with increasing soils particle size (coarse texture) and increasing soil depth. The soil type interactions with soil aggregate have significant affect on C_{seq}. There is a linearly positive relationship of C in MiA (250-53 µm) and SCf (<53 µm) with C_{seq} and OC in these soils. This indicates that the soils aggregates (mainly MiA and SCf) are important physical protection in these upland agricultural soils in Northeast Plateau, Thailand.

2. Effect of soil forming factors

2.1 Climate, topography and vegetation

From this study, climates of all soils are quite similar (Table 2). However, the trend of C_{seq} in 2 m depth slightly increases with decreasing annual rainfall and increasing elevation (Figure 34). Nevertheless there is no clear relationship of annual rainfall and elevation with C_{seq} in 2 m depth. Paul *et al*. (1997), Trumbore (2000) and Jobbágy and Jackson (2000) suggested that climate, type of vegetation, land use and management were the best predictors of total OC in the top 20 cm of soil. Therefore, the associations between climate, elevation and vegetation types are important to OC and C_{seq} in these soils as illustrated by the Figures 34, 35, 36 and 37.

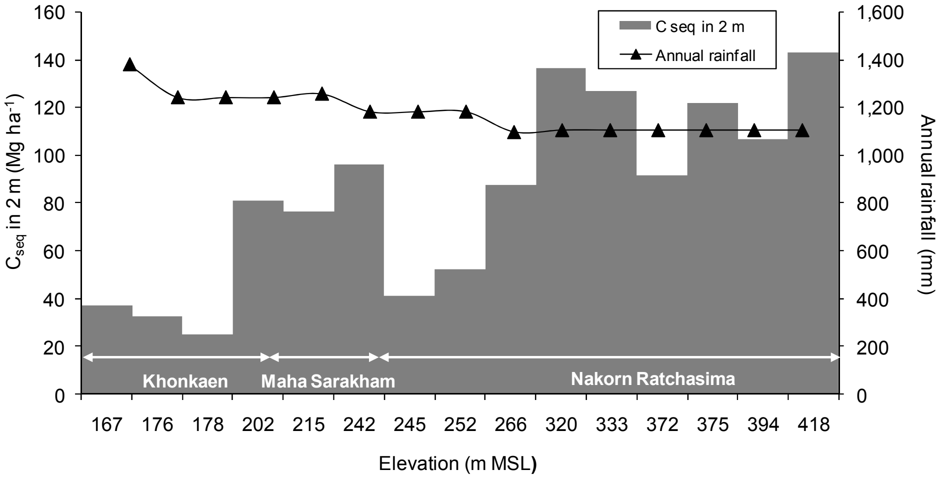


Figure 34 Carbon sequestration in 2 meter depth and annual rainfall in different elevation for major upland agricultural soils in Northeast Plateau, Thailand.

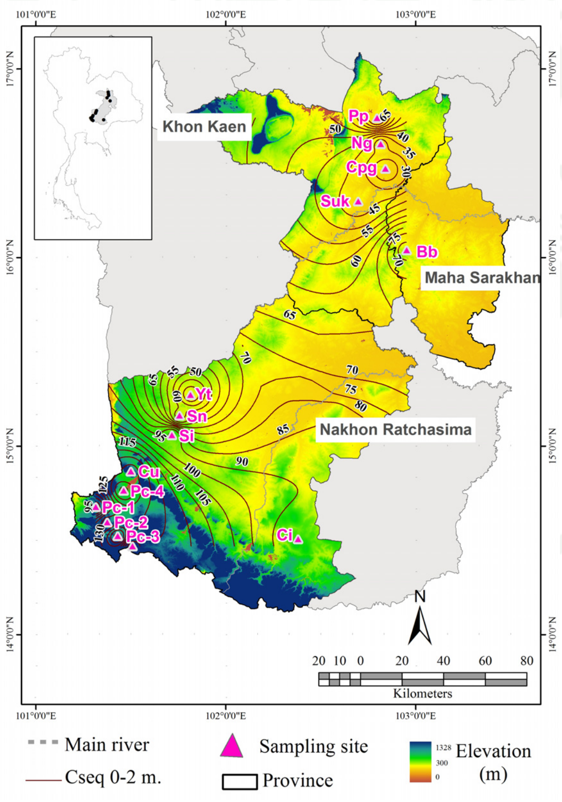


Figure 35 Contour lines of carbon sequestration in 2 meter depth with elevation of soil sampling sites.

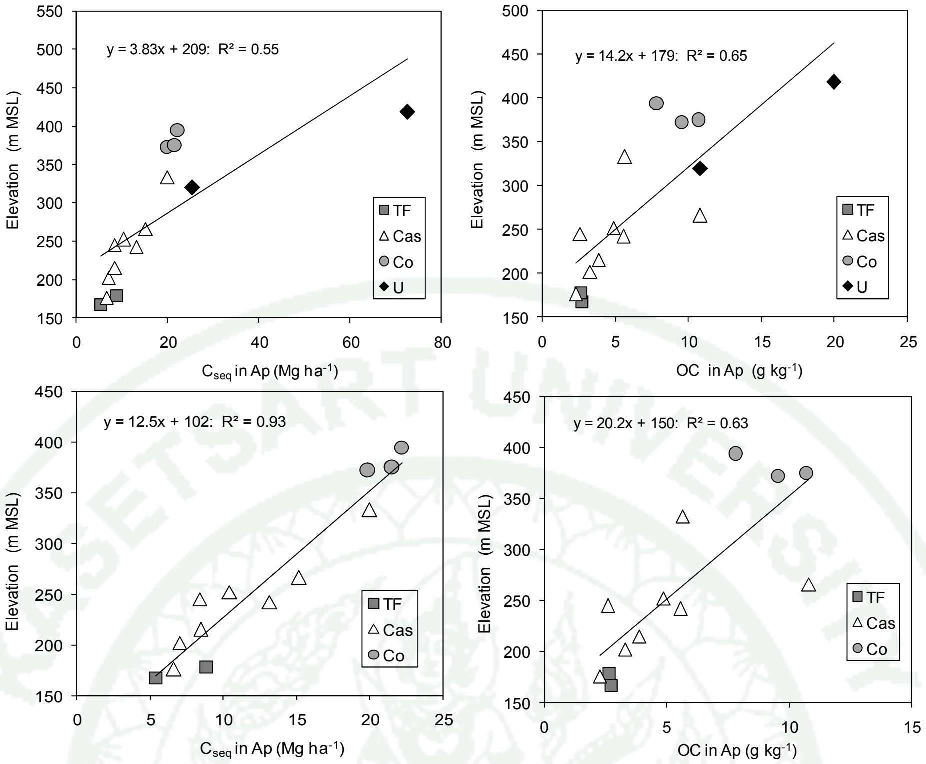


Figure 36 Scattering plot between elevation and carbon sequestration (C_{seq}) and organic carbon concentration (OC) in different land uses of upland agricultural soils.

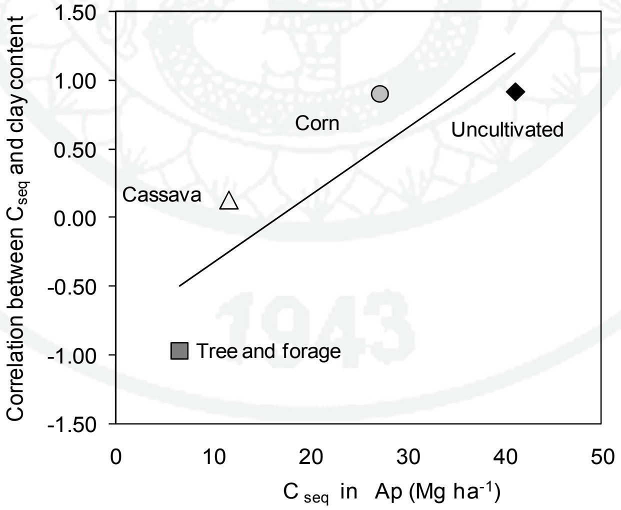


Figure 37 Correlation coefficients (Spearman rank) for the relationship between C_{seq} and clay in upland agricultural soils for different land use types.

Contours are one of several common methods used to denote elevation and depth on maps. GIS analysis results show contour line of C_{seq} in 2 meter depth with elevation of soil sampling sites (Figure 35). In these studies, C_{seq} increases with increasing altitudes was observed across contour lines of C in different altitudes (Figure 35). While comparing the C_{seq} values of similar altitudes, their trends are affected by land use. From data in Figure 36 it can be expected that C_{seq} and OC are consistently (i) highest under uncultivated lands especially in Ap horizons and (ii) they tend to increase with elevation. The types of land use arranged in order of descending elevation is corn fields occupying higher elevation than cassava fields followed by tree and forage crops (Figure 36). In addition, C_{seq} and OC have positive relationships with land use and elevation (R^2=0.93, R^2=0.63) (Figure 36). Physiographic position of karst corrosion plain and coalescing intermontanae footslope (370-400 m MSL), corrosion plain (170-330 m MSL), backslope of residual low hill and erosional terrace (160-180 m MSL) are managed as corn fields, cassava fields and tree and with forage crops, respectively.

Soils under the tree with forage crop have lower C_{seq} and OC than those under the other land uses followed by cassava fields, corn fields and uncultivated lands (Figure 36). This result is different from the findings of many studies that reported the high effect of higher C inputs and rooting depth of trees and grasses on significant sequestered C in soil profile (Lorenz and Lal, 2005). This is attributed to low soil management input on tree with forage crop areas whereas corn fields always have high surface input in every cropping.

There are generally strong correlations between the C_{seq} and OC in the Ap horizons and the selected site variables (elevation and land use) and the other individual variables. The C_{seq} in Ap horizons, which can be attributed to C_{seq} increases with increasing clay content (Figure 37). This result indicates that soils with higher clay content tend to have higher C stabilization. For cassava fields, the C_{seq} and clay relationship was not significant, and has a negative correlation with clay content in tree and forage crops, C_{seq}. These results suggest that additional OC and soil management have more important effects on contribute C_{seq} in surface soils than does soil texture. Trumbore (2000) also indicated that clay content was the best predictor of C_{seq} in deeper soil layers.

2.2 Parent material

Alfisols developed on metasedimentary rock, sandstone, calcareous sandstone and granite. Ultisols developed on sandstone, siltstone and sedimentary rock while Oxisols developed on limestone and basalt. Their parent materials have the main effect on the soil properties. The quantity and quality of OM stored can vary according to the type of parent materials. In Sierra Nevada Mountains, forest soils developed on basic parent materials accumulated more SOM than those on acid parent materials, presumably due to the difference in weathering rate, acidity, aggregate stability, and/or the amounts of clay-size minerals and poorly-crystalline phases of aluminum (Harradine and Jenny, 1958; Callesen *et al*., 2005).

The one-way ANOVA was used to describe the effect of parent material on soil C_{seq} and some soil properties. In Alfisols, parent materials have significant effects on SOC and C_{seq} (Table 14, $P<0.001$). There is a significant difference in C_{seq} and OC concentration between local colluviums and alluvium, granite, calcareous sandstone (Table 14). The C_{seq} and OC are largest in calcareous sandstone, followed by granite and local colluvium and alluvium. This may reflect the influence of silt plus clay content (silt+clay), calcium concentration (Ca) and free iron oxides (Fe_d) in calcareous sandstone (Table 14, $P<0.001$). However, WAS and MWD of calcareous sandstone are lowest reflecting their higher Ca. Granite soils have higher WAS and larger MWD than do other soils, that may positively affect their high C_{seq} and OC.

Oxisols formed on limestone and basalt parent materials. There are no differences of C_{seq} and OC in soils from on these parent materials due to their characteristic and process being similar (Table 14). Limestone and basalt have significant effects on the amorphous forms of inorganic Al (Al_o) ($P<0.01$), crystallinity of free iron oxides (Fe_o/Fe_d) ($P<0.05$) and mean weight diameter (MWD) ($P<0.05$) (Table 14, $P<0.001$). Fe_o/Fe_d and MWD values of soils derived from basalt are higher than that of soils derived from limestone. For MWD of Oxisols derived from highly weathered basalt with dominance of clay particles the high content of kaolinitic clay and sesquioxides can induce formation of microaggregates with strong stability. The amount of coarse microaggregates with a diameter of 0.01-1 mm in the soils sometime makes up 90 percent of the total content (Soil Survey Staff, 2010; Beinroth *et al*., 2000). Limestone soils have low values (<0.1) of the Fe_o/Fe_d ratio indicating their maturity or their well drained condition, and also indicating the dominance of crystalline iron oxides (hematite and goethite) (Blume and Schwertmann, 1969). Al_o in limestone is higher than in basalt and it has been related to pedogenic environments (leaching condition, parent material and stage of soil development) (Schwertmann, 1988, Buol *et al*., 2003)

Table 14 C_{seq}, OC and selected physicochemical properties of Alfisols, Oxisols and Ultisols developed on different parent material.

Alfisols[a]	C_{seq}	OC	Silt+clay	Ca	Fe_d	WAS	MWD
Calcareous	16.0 (5.0) a	4.7 (1.3) a	595 (99)a	20.7 (11.7)a	12.4 (2.8)a	51 (11)b	0.7 (0.1)b
Local alluvium	4.1 (1.9) b	1.1 (0.8) b	254 (95)b	0.5 (0.3) b	5.2 (5.1)b	54 (13)b	1.3 (1.2)b
Granite	15.8 (4.5) a	3.8 (1.7) a	290 (76)b	3.2 (0.6) b	0.8 (0.2)b	73 (11)a	2.8 (0.6)a
P^d	***	***	***	***	***	**	***
LSD[e]	*	*	*	*	*	*	*

Oxisols[b]	C_{seq}	OC	Fe_o/Fe_d	Al_o	MWD
Limestone	26.0 (10.1)	5.50 (4.6)	0.03 (0.12)	2.48 (0.17)	1.13 (0.40)
Basalt	26.5 (9.4)	5.48 (3.4)	0.56 (0.31)	2.08 (0.43)	1.69 (0.71)
P^d	0.91	0.98	*	**	*

Ultisols[c]	C_{seq}	OC	Silt+clay	Ca	Na	Fe_o	Al_o	MWD
Sandstone	8.3 (5.4)	2.1 (1.2)	295 (71) b	1.0 (1.0)b	0.1 (0.1)b	0.6 (0.3)b	2.5 (0.3)b	0.4 (0.3)b
Sedimentary	7.0 (3.3)	1.9 (0.9)	444 (158)ab	1.7 (1.3)b	0.2 (0.1)ab	1.6 (0.8)a	3.7 (1.7)a	1.3 (0.9)a
Siltstone	8.2 (2.0)	2.6 (1.6)	531 (84) a	3.6 (1.3)a	0.3 (0.1)a	0.8 (0.1)b	2.6 (0.2)b	0.2 (0.1)b
P^d	0.81	0.66	**	**	*	**	*	**
LSD[e]	ns	ns	*	*	*	*	*	*

Values are the mean (SD), Least significant difference (P=0.05)

C_{seq}=carbon sequestration (Mg ha^{-1}), OC=organic carbon (g kg^{-1}), Silt+clay=silt plus clay content (g kg^{-1}), Ca=calcium concentration (cmol kg^{-1}), Fe_d=free iron oxide (g kg^{-1}), Fe_o and Al_o = The amorphous forms of the inorganic Fe and Al (g kg^{-1}), Na=sodium concentration (cmol kg^{-1}), WAS = water aggregate stability (%), MWD=mean weight diameter (mm)

[a] Calcareous s.=calcareous sandstone (n=6),

Local allu & coll = local colluviums and alluvium (n=8), Granite (n=8)

[b] Limestone (n=31), Basalt (n=17)

[c] Sandstone (n=12), Sedimentary rock (n=8), Siltstone (n=4)

[d] *P* from one-way ANOVA, **, * < 0.01, 0.05, respectively

For Ultisols, there are no differences of C_{seq} and OC among parent materials whereas some soil characteristics (silt+clay, Ca, Na, Fe_o, Al_o and MWD) significantly differ among them (Table 14). The results show properties of iron oxides, such as crystallinity and Al substitution that have been related to pedogenic environments (leaching condition, parent material and stage of soil development) (Buol *et al*., 2003). Therefore, the difference among soil parent materials have a slight effect on OC and C_{seq} of major upland agricultural soils in Northeast plateau, Thailand. Especially, OC and C_{seq} in highly developed soils (Oxisols and Ultisols) are not different among parent materials. Whereas in younger soils (Alfisols), there are significant differences in C_{seq} and OC concentration among parent materials.

3. Factors affecting depth fractionation of SOC and C_{seq}

The analysis of variance (ANOVA) was used to describe the effect of soil type and land use on soil C_{seq} and some soil properties with depth. Soil type and land use have significant effects on SOC and C_{seq} at different depths in these soils (Table 15, $P<0.05$). Soil type and land use significantly affect WAS. However, BD and C/N are not affected by land use (Table 15).

Table 15 Two-way ANOVA for carbon sequestration, organic carbon and some properties in the soil types and land uses.

Source of variation	d.f.	C_{seq}	OC	BD	C/N	WAS
Soil type (A)	2	13.33*	22.53*	32.57*	0.53^{ns}	18.30*
Depth (B)	3	5.66*	18.38*	1.13^{ns}	0.25^{ns}	1.09^{ns}
A×B	6	3.37*	6.61*	0.58^{ns}	0.26^{ns}	1.37^{ns}
Error SS	48	493	143	2.67	386	816
Error MS	48	102	2.98	0.06	8.03	170
Source of variation	d.f.	C_{seq}	OC	BD	C/N	WAS
Land use (A)	3	20.14*	14.82*	2.38^{ns}	20.29^{ns}	10.00*
Depth (B)	3	13.25*	26.09*	0.02^{ns}	6.04^{ns}	0.32^{ns}
A×B	9	4.25*	3.93*	0.17^{ns}	2.72^{ns}	0.81^{ns}
Error SS	44	301	140	2.45	321	854
Error MS	44	68	3.12	0.06	7.30	194

C_{seq}=carbon sequestration; OC=organic carbon; BD=bulk density; C/N=carbon nitrogen ratio; AS=water aggregate stability**,** F-values for each variable are indicated; ns, not significant; *$P<0.05$

3.1 Effect of soil type

There is a considerable difference in physicochemical properties among soil type and soil depth, but with only little variation within the same soil type. Scatter plot of Oxisols and Ultisols with a trend line shows relationship of OC concentration with physical protection and organomineral complexes (Figure 38). Alfisols have no significant relationship between OC and soil properties. The OC concentration in Oxisols has a positive relationship with WAS (r = 0.56**). Organic carbon is considered an important aggregate binding agent and it may also be physically protected against decomposition within stable aggregates (Feller and Beare, 1997). In Oxisols, relationships between OC and aggregation are affected by the presence of sesquioxides (Barthès *et al.*, 2008). Organic carbon in Ultisols has a negative relationship with TC_{SCf} (r=0.52**; Figure 38). This result indicates that a greater proportion of C in Ultisols is bound to minerals and stored in the silt plus clay fractions.

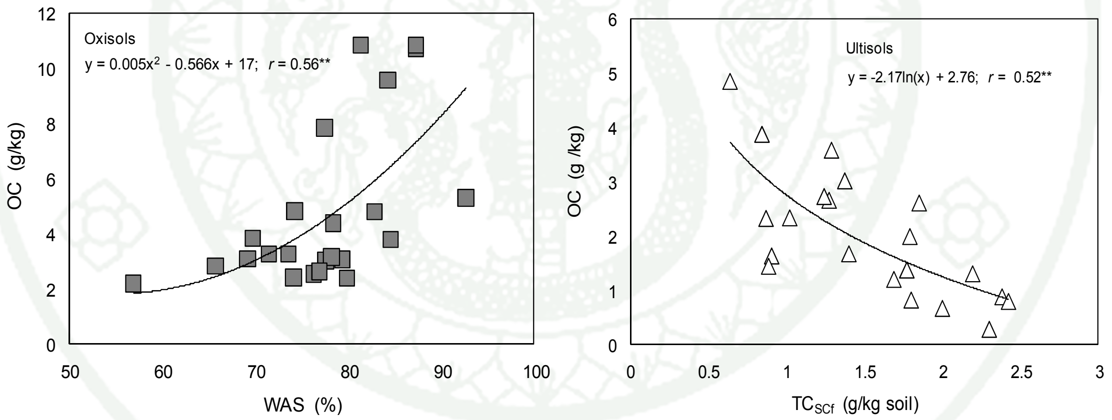


Figure 38 Effect of soil properties on organic carbon concentration of all soil depths.

3.2 Effect of soil depth

Ap horizons (D1)

The C_{seq} in all depth sections is positively related to OC (P<0.001; Figure 39). Carbon sequestration in D1 shows a clear effect on CEC (R^2=0.79***; Figure 40a). Especially in highly weathered soils, SOC in the broad sense can be responsible for a considerable part of nutrient stocks and CEC (Dick *et al.*, 2005). Crystalline Fe-oxides

(Fe_d) are closely related to C_{seq} in the D1 (R^2=0.75***), but not in the other soil depth sections (Figure 40b). The C_{seq} is positively correlated with silt plus clay contents (R^2=0.72***) (Figure 40c). This is similar to the eighty seven percent of the variation of OC in D1 that can be explained by silt plus clay contents (R^2=0.87***; Table 16). Silt plus clay contents were found the best parameters describing soil texture in the models for prediction of OC stocks (mass/area) over wide climatic gradient (Parton *et al*., 1987; Burke *et al*., 1989).

Most studies of textural effects on SOC are commonly restricted to surface layers, whereas strong spatial variability occurs due to management (Zinn *et al*., 2005b). Both WAS and MWD have weak effect on C_{seq} (R^2=0.68**, R^2=0.35*; Figure 40e, f). Results from stepwise multiple regression indicate that aggregate stability and MWD of D1 have positive relationships with Fe_o (amorphous Fe oxides) (R^2=0.62, Table 16). Barral *et al*. (1998) reported that concentrations of Fe-oxides and SOC were directly related to soil aggregate stability and in tropical soils, Fe-oxides become even more important (Six *et al*., 2002; Barthès *et al*., 2008).

In base of Ap to 0.6 meter depth section (D2)

The C_{seq} in D2 section is negatively correlated with TC_{SCf} (R^2=0.52**; Figure 40d) and positively related with CEC (R^2=0.33*) (Figure 40a). The silt plus clay contents have a positive relationship with SOC in D2 section that is the most predictive for SOC values (R^2=0.50, P<0.01; Table 16). The organomineral complexes are the main factors determining the amount of C_{seq} in these horizons since the proportion of OC bound to minerals and stored in the clay fractions increases with depth and has a close relationship with clay content (Kögel-Knabner *et al*., 2008). The crystalline Fe oxides (Fe_d-Fe_o) have positive relationship with WAS (R^2=0. 50**) and MWD (R^2=0.71**) in D2 depth section (Table 16). These results indicate that Fe-oxide are more important than SOC for MWD and WAS.

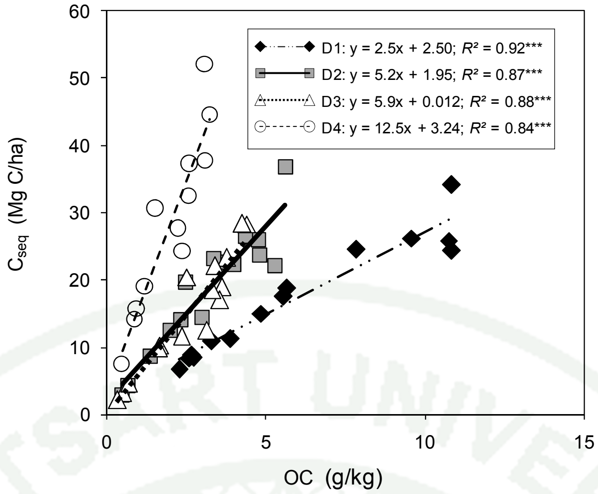


Figure 39 Linear relationships of carbon sequestration with organic carbon in various soil depths.

Table 16 Stepwise correlation equations for predicting soil organic carbon (OC), water aggregate stability (WAS) and mean weight diameter (MWD) of D1, D2, D3 and D4 from values of some soil properties.

Property	Depth		Correlation equation	*n*	R^2
OC	D1	=	1.3 + 0.01(silt + clay)	*n* = 14	$R^2 = 0.87$***
(g kg^{-1})	D2	=	0.84 + 0.004(silt + clay)	*n* = 15	$R^2 = 0.50$**
	D3	=	0.54 + 0.25(CEC)	*n* = 15	$R^2 = 0.54$**
	D4	=	1.82 + 0.002 (silt + clay) + 1.1(ΔpH)	*n* = 12	$R^2 = 0.62$**
WAS	D1	=	41 + 15.4 (Fe$_o$)	*n* = 14	$R^2 = 0.62$***
(%)	D2	=	54 + 0.39 (Fe$_d$-Fe$_o$)	*n* = 15	$R^2 = 0.50$**
	D3	=	73 + 4.2 (OC) - 4.9 (Al$_o$)	*n* = 15	$R^2 = 0.59$**
	D4		102 - 13.5(Al$_o$)	*n* = 12	$R^2 = 0.61$**
MWD	D1	=	0.27 + 0.46 Fe$_o$	*n* = 14	$R^2 = 0.62$***
(mm)	D2	=	0.44 + 0.016 (Fe$_d$-Fe$_o$)	*n* = 15	R^2= 0.71**
	D3	=	-	-	-
	D4	=	-	-	-

CEC=cation exchange capacity (cmol$_{(+)}$ kg^{-1}); Fe$_d$=iron oxide extracted by DCB (g kg^{-1}); Fe$_o$=iron oxide extracted by oxalate (g kg^{-1}); Fe$_d$-Fe$_o$=crystalline Fe-oxides; Al$_o$=Aluminum oxide extracted by oxalate (g kg^{-1}); ΔpH=pH$_{KCl}$ – pH$_{H2O}$; Silt + clay=silt plus clay contents (g kg^{-1}).

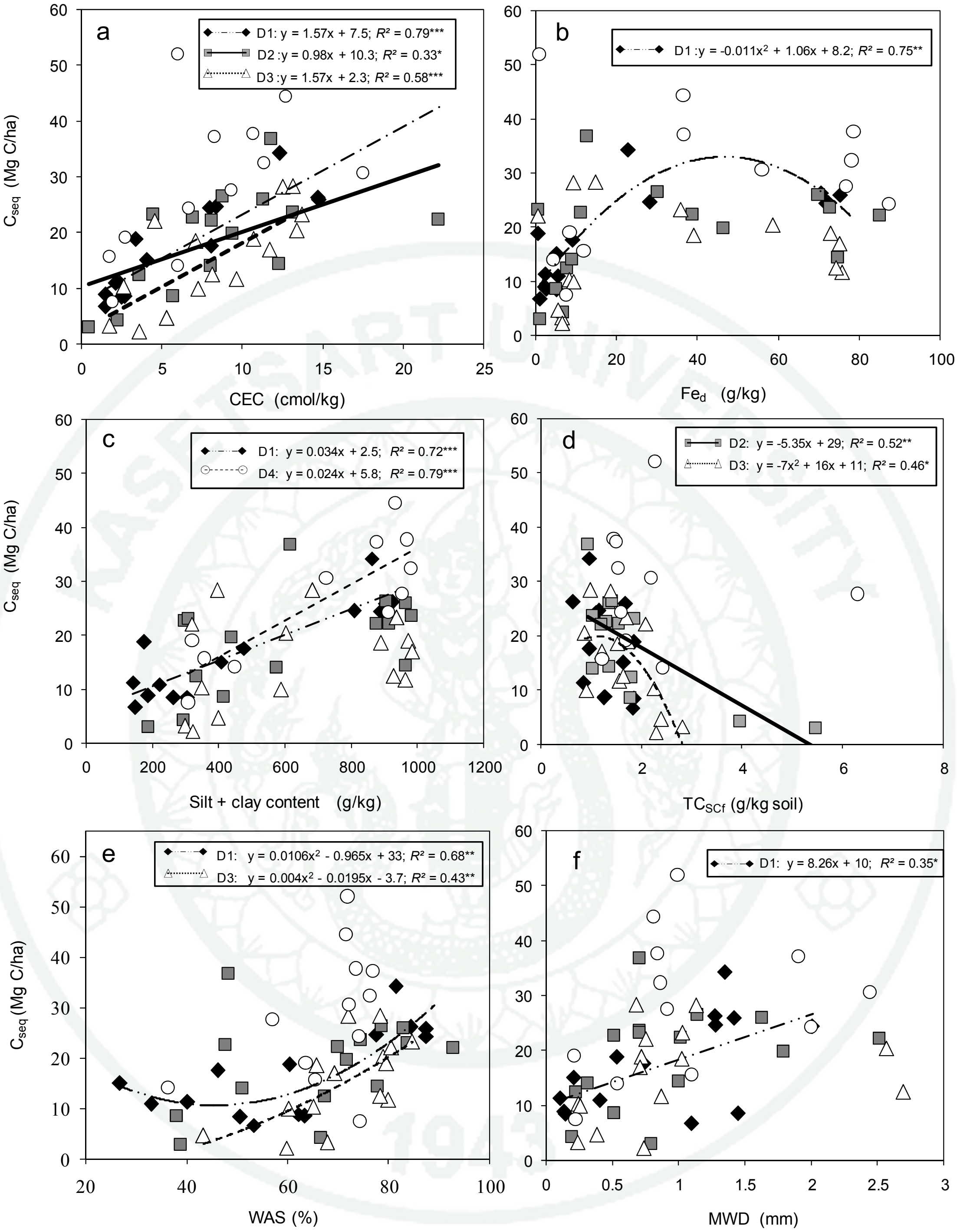


Figure 40 Relationships of carbon sequestration and some soil properties in various soil depths.

In 0.6 to 1 meter depth section (D3)

The C_{seq} in D3 section is affected by the similar soil properties as in the D2 section. In this section the C_{seq} tends to increase with increasing CEC and WAS (R^2=0.58*** and R^2=0.43**, respectively) (Figure 40a,e). The TC_{SCf} slightly affects C_{seq} in this sections (R^2=0.46*, Figure 40d). The OC is positively related with CEC (R^2=0.54**; Table 16). Aggregate stability in D3 section has a positive correlation with OC and a negative correlation with Al_o (R^2=0.59**; Table 16). These results indicate that the Fe oxides and the aggregate stability affect the sequestered OC due to Fe oxides binding both clay minerals and organic material forming mineral complexes promoting the formation of aggregates to sequester OC (Barthès *et al.*, 2008). The MWD has no correlation with SOC or other properties (Table 16) in this soil depth section.

In 1 to 2 meter depth section (D4)

The C_{seq} in the D4 section increases with the increasing C_{seq} in D1 (R^2=0.50*), D2 (R^2= 0.76**) and D3 (R^2= 0.61**) depth sections (Figure 41). The C_{seq} in the D4 section accounts for 51% of the C_{seq} in the first meter section (Table 10). The silt plus clay contents markedly affect C_{seq} (R^2=0.79***, Figure 40c) and SOC (Table 16) in this section. The WAS has a positive correlation with Al_o (R^2=0.61**; Table 16) whereas MWD in this D4 section has no correlation with SOC or other soil properties.

3.3 Effect of land use

There is no clear difference for BD and C/N values among different land uses (Table 17). The main factor land use (A) have the significant effect on WAS (P<0.05, Table 16). The WAS in the upper sections (0-0.6 m) is quite different among land uses but there is no clear difference in the lower sections (0.6-2 m) (P<0.05, Table 17). The C_{seq} and SOC are significantly different for land use (A), depth (B) and the interaction between land use (A) × soil depth (B) (P<0.05, Table 17).

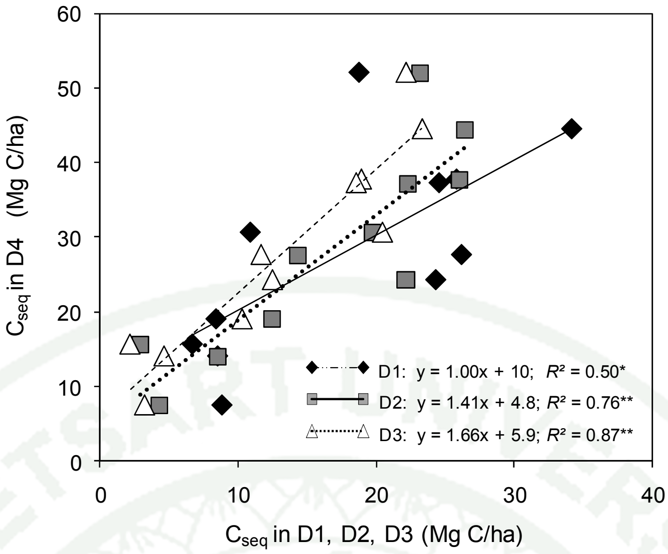


Figure 41 Linear relationships of carbon sequestration in D4 section and carbon sequestration in D1, D2 and D3 sections.

There is no difference for C_{seq} in D4 among most of cultivated and uncultivated lands (Table 17). This result relates to the relationship between the increasing of C_{seq} in D4 depth section with the increasing of C_{seq} in its upper horizons. Lorenz and Lal (2005) observed that the high surface input of OM favors the productions of dissolved OC that can be transported down to deeper soil horizons and thus contribute to the subsoil C storage. Soil under the tree and forage crops has significantly lower OC concentration in all depth sections than those under the other land uses ($P<0.05$; Table 17). This result is different from the findings of many studies that reported the high effect of higher C inputs and rooting depth of trees and grasses on significant sequestered OC in soil profile (Lorenz and Lal, 2005).

Table 17 Range and mean values of bulk density (BD), water aggregate stability (WAS), organic carbon (OC) and carbon sequestration (C_{seq}) with soil depths for land use types.

Depth	Land uses	BD (Mg m^{-3})			WAS (%)			OC (g kg^{-1})			C_{seq} (Mg C ha^{-1})		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
D1	Uncultivated	1.3	1.6	1.4 a	81	89	85 a	11.0	20.0	15.0 a	34.2	51.8	43.0 a
	Tree and forage	1.6	1.7	1.6 a	62	63	63 ab	2.6	2.7	2.7 b	8.5	8.8	8.7 c
	Corn	1.2	1.6	1.4 a	60	87	77 a	5.7	11.0	8.5 b	18.8	26.2	23.9 b
	Cassava	1.1	1.7	1.5 a	27	87	48 b	2.3	11.0	4.8 b	6.7	24.3	13.5 bc
D2	Uncultivated	1.2	1.5	1.4 a	74	78	76 ab	4.4	4.8	4.6 a	23.6	26.5	25.1 a
	Tree and forage	1.6	1.6	1.6 a	38	66	52 b	0.7	1.4	1.0 b	4.3	8.6	6.5 b
	Corn	1.2	1.4	1.3 a	70	84	78 a	3.0	4.8	3.8 a	14.4	26.0	21.5 ab
	Cassava	1.1	2.0	1.6 a	39	93	60 b	0.50	5.6	3.1 ab	3.0	36.8	18.7 ab
D3	Uncultivated	1.2	1.6	1.4 a	69	85	77 a	3.6	3.8	3.7 a	17.0	23.3	20.1 a
	Tree and forage	1.6	1.7	1.6 a	43	68	56 a	0.51	0.70	0.61 b	3.2	4.7	4.0 b
	Corn	1.2	1.4	1.3 a	66	80	76 a	2.4	3.6	3.2 a	11.7	22.1	17.8 ab
	Cassava	1.0	2.0	1.6 a	60	79	70 a	0.36	4.4	2.6 ab	2.2	28.4	16.0 ab
D4	Uncultivated	1.3	1.4	1.3 a	72	76	74 a	2.6	3.3	2.9 a	32.4	44.5	38.5 a
	Tree and forage	1.6	1.6	1.6 a	36	74	55 a	0.49	0.88	0.69 b	7.5	14.1	10.8 b
	Corn	1.2	1.4	1.3 a	57	77	70 a	2.3	3.1	2.8 a	27.6	52.1	38.7 a
	Cassava	1.0	2.0	1.6 a	26	74	59 a	0.94	2.4	1.5 b	15.6	30.6	22.7 ab

Significant differences between land uses within one depth are indicated by different letters (a, b, c); $P<0.05$ (Tukey's HSD test).

4. Effect of aggregation

Soil aggregate size distribution and stability are important indicators of soil physical quality, OC and C_{seq}. The analysis of variance (ANOVA) is used to describe the effect of the type of aggregate (LMA, SMA, MiA and SC_f), soil type and soil depth on soil C_{seq}, total carbon (TC), total nitrogen (TN), carbon and nitrogen ratio (C/N) and the amount of aggregate in these soils. The C_{seq} and TC are significantly different for the interaction between aggregate size class (A) × soil type (B) (Table 18, $^{*}P<0.05$, $^{***}P<0.001$), TC also significantly different among aggregate size classes. Aggregate size classes in different soil types (A×B) and different soil depth (A×C) significantly affect the amount of aggregate in these soils. From previous results soil type (B) soil depth (C) and their interaction (B×C) have significant effects on C_{seq}, total carbon (TC) and total nitrogen (TN) in these soils (Table 18). There is no clear difference for C/N values among different variation (Table 18).

Table 18 Analysis of variance for the amount of aggregate, C_{seq}, total carbon, total nitrogen and C/N in whole soils with difference aggregate size class, soil type and soil depth.

Source	C_{seq}	TC	TN	C/N	Aggregate		
					Amount[†]	WAS	MWD
Aggregate size class (A)	ns[§]	*	ns	ns	***	-	-
Soil type (B)	*	*	ns	ns	ns	***	***
Soil depth (C)	*	*	***	ns	ns	ns	ns
A×B	*	**	ns	ns	***	-	-
A×C	ns	ns	ns	ns	**	-	-
B×C	*	*	***	ns	ns	-	-
A×B×C	ns	ns	ns	ns	ns	-	-

* Significant at *P*<0.05, ***P*<0.01, ****P*<0.001. [§]ns = not significant

† Amount of soil present in aggregate, TC = Total carbon, TN = Total nitrogen, C/N = carbon and nitrogen ratio

Therefore, the types of aggregate have an effect on TC. The effects of soil type interaction with soil aggregate are significant affect on C_{seq} and TC. The amounts of aggregate tend to decrease with depth except in Oxisols that they are constant with depth (Table 19). The amounts of aggregate in Oxisols are higher than in Ultisols and Alfisols, reapectively. Most soils have the amount of macroaggregate (>250 μm) decreases with increasing depth whereas the amount of microaggregate (<250 μm) increases with increasing depth.

In all depths, Oxisols have the amount of macroaggregate higher than do the other soils and Ultisols have the amount of microaggregate higher than do the other soils. Alfisols have the amount of microaggregate averaging 26-47 g 100 g^{-1} soil (Table 19). Carbon concentrations tend to decrease with increasing depth in all soil types. Carbon in four aggregate size classes is not clearly different within in the same depth (Table 19). However in D1, Carbon in four aggregate size classes are highest and it tends to increase with increasing size of aggregate (D1: $C_{LMA}>C_{SMA}>C_{MiA}>C_{SCf}$). In D2, D3, and D4, carbon of Oxisols, Ultisols and Alfisols tends to increase with decreasing size of aggregate. Carbon in <250 μm (MiA, SCf) as compared with C in bulk soils increases with increasing depth. A conclusion can be made that carbon concentration have the association with <250 µm size aggregate that increases with soil depth (Table 19).

Table 19 The amount of aggregate, carbon, nitrogen concentrations, carbon and nitrogen ratio with different soil type, soil depth and aggregate size class.

		Amount [1/]			Carbon (g kg^{-1}soil)			Nitrogen (g kg^{-1}soil)			C/N		
		1	2	3 [2/]	1	2	3	1	2	3	1	2	3
Bulk soils	D1	97	97	47	12.0	3.9	5.1	1.21	0.47	0.58	10	8	9
	D2	98	90	42	5.4	3.0	4.4	0.66	0.38	0.48	8	8	9
	D3	97	82	36	4.2	2.7	4.5	0.52	0.38	0.45	8	7	10
	D4	99	85	26	3.9	2.2	3.7	0.47	0.37	0.39	8	6	9
Aggregate size													
8000-2000 µm	D1	17	8	-	1.36	1.13	-	0.095	0.072	-	14	16	-
2000-250 µm		58	27	-	1.27	0.29	-	0.094	0.037	-	14	8	-
250-53 µm		15	48	35	1.04	0.34	0.42	0.081	0.038	0.034	13	9	22
<53 µm		7	14	11	1.16	0.37	0.64	0.092	0.050	0.056	13	7	13
8000-2000 µm	D2	12	3	-	0.58	0.40	-	0.049	0.060	-	12	7	-
2000-250 µm		61	33	-	0.45	0.32	-	0.037	0.054	-	12	8	-
250-53 µm		18	40	31	0.65	0.28	0.40	0.043	0.063	0.052	16	6	9
<53 µm		7	14	11	0.68	0.29	0.48	0.052	0.062	0.060	13	5	11
8000-2000 µm	D3	10	3	-	0.37	0.42	-	0.051	0.069	-	7	6	-
2000-250 µm		55	29	-	0.38	0.19	-	0.044	0.052	-	9	4	-
250-53 µm		23	37	28	0.44	0.22	0.38	0.050	0.058	0.081	9	4	5
<53 µm		9	12	8	0.43	0.23	0.42	0.047	0.059	0.080	9	4	6
8000-2000 µm	D4	9	3	-	0.15	0.17	-	0.023	0.039	-	7	4	-
2000-250 µm		57	31	-	0.30	0.12	-	0.029	0.040	-	11	3	-
250-53 µm		24	37	19	0.30	0.14	0.46	0.028	0.036	0.068	11	4	7
<53 µm		9	14	6	0.33	0.19	0.47	0.028	0.053	0.056	12	4	7

[1/] The amount of aggregate (g 100 g^{-1} soil)

[2/] 1=Oxisols, 2=Ultisols, 3=Alfisols

The dynamics of C/N ratio are no clearly different in three soil types but tend to decrease with increasing soils particle size (coarse texture) and with increasing soil depth (Table 19). In Oxisols, C/N ratio of four aggregate size classes is quite similar averaging 7-14 but tends to increase with decreasing size of aggregate. For Ultisols, C/N ratio of four aggregate size classes ranges 3-16 and tends to increase with increasing aggregate size class. C/N ratios of Alfisols are ranging from 5-22 in MiA and SCf (Table 19).

There is a linearly positive relationship of C in MiA (250-53 µm) and SCf (<53 µm) with C_{seq} and OC in these soils (Figure 42; *P*<0.001), which indicates that these soil aggregates (mainly MiA and SCf) are important physical protection in major upland agricultural soils in Northeast Plateau, Thailand (Figure 42).

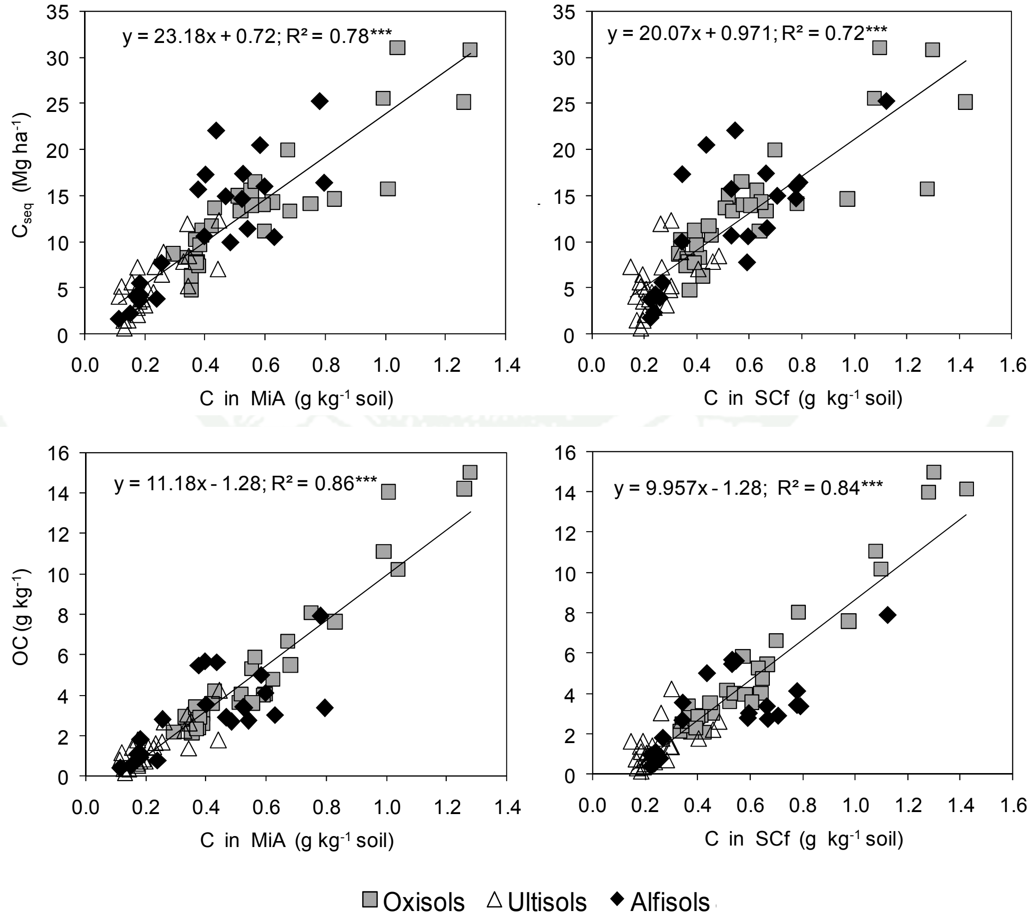


Figure 42 Linear relationships between carbon in microaggregate (MiA) and silt plus clay fractions (SCf) with carbon sequestration and carbon concentration in these soils.

CONCLUSIONS

The representatives of major upland agricultural soils in Northeast Plateau, Thailand are generally well developed and some are sandy. The red and yellow soils are commonly found in this area with undulating topography. Data on their general environmental condition and profile characteristic variability illustrate well that their parent materials and topographic difference play major roles in their genesis. The variation of physical and chemical properties of these soils with depth classically reflects the different nature of their parent materials and soil management.

In surface horizons, organic carbon, land use and management affect the aggregate size distribution, aggregate stability (WAS) and mean weight diameter (MWD) whereas clay and sesquioxide contents mainly affect that in subsoils. The size of WAS is largest in Oxisols followed by Alfisols and Ultisols. LMA (2000-8000 μm) are more sensitivity for land use and management. The other sizes of aggregate are affected by the difference type of the binding agent. The hierarchical model of aggregation occurred in red Ultisols that MiA join together to form macroaggregate (250-8000 μm) and the bonds within MiA are stronger than the bonds between MiA.

Most of total carbons in these soils are organic carbon. High decomposition rate of these soils tends to lower the C/N ratio to near 10:1. The C_{seq} in these soils tends to significantly decrease from the D1 to the lower depth fractions. The sequestered C in D4 section accounts for 51% of the C_{seq} in the first meter. Oxisols sequestered higher OC than Alfisols and Ultisols. In surface soils, coarse aggregates (LMA, SMA) have a higher C/N ratio than do the fine aggregates (MiA, SC) contrasting to that in in subsoil horizons. MiA (53-250 μm) and SC (<53 μm) in deep horizons contain a large C/N value effected their low bulk density suggesting a physical protection from microorganism. Carbon content of macroaggregate in red Ultisols is 2.14 times greater than that of the MiA. In Oxisols, C associated with aggregate does not increase with increasing aggregate size class except in Ap horizons. The intimate interactions occur between OC in bulk soil with C associated macroaggregate of Oxisols and C associated microaggregate in red Ultisols. These support an aggregate hierarchy in which microaggregate are bound together into macroaggregate by organic binding agents in Ultisols and in surface soils of

Oxisols. The C in SCf (<53 μm) increases with the increasing soil depth due to its close relationship with silt plus clay content. A relationship between the carbon enrichment in microaggregate (<250 μm) and C in bulk soils of each genetic horizons indicates that stabilization of OC occurs in the fine aggregates of these soils. In addition, there is a linearly positive relationship of C in MiA (250-53 μm) and SCf (<53 μm) with C_{seq} and OC in these soils, which indicates that soil aggregates (mainly MiA and SCf) are important physical protection in these soils.

Soil forming factor affecting mechanism of C_{seq} are positively correlated with elevation and slightly affected by annual rainfall. The trends of C_{seq} in similar altitudes are affected by land use. The C_{seq} in each land use is more affected by the difference of soil management than the effect from the type of land use. The differences among soil parent materials have a slight effect on OC and C_{seq}.

There are significant differences for depth fractions of C_{seq} interaction with soil types and land uses. The relative importance of C_{seq} on selected soil depth is controlled by the variation of silt plus clay content, the amount of Fe-Al oxides, %CSC_f, WAS, MWD, ΔpH and CEC. The silt plus clay contents are found to be the best predictors of SOC content in these soils. Soil aggregations (WAS, MWD) are mainly differed by the difference of Fe and Al oxides concentrations. Uncculticated lands generally have higher C_{seq} in surface soils than do cultivated soils. Cultivated soils and their management have the important effect on C_{seq} in the D4 section, but C_{seq} in middle layers have no clear difference in all cultivated soils. In soils and soil horizons with differing properties, various stabilization mechanisms are operative. This study reveals mechanisms for stabilization of the different OC fractions in different soils and their horizons. The results indicate that land use and aggregation are the important factors for C_{seq} in the surface soils. The different stabilization processes of OC in subsoils (E, Bt, Bto, Bo, Btk, Btc, Bv and C horizons) are controlled by the interactions of pedogenesis processes including weathering of clay minerals, formation of iron oxides and hydroxides along with organomineral complex and flow paths of C input from the surface soils.

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APPENDICES

Appendix A

Soil Profile Description

Loei series

I Information on the site

Profile symbol	: Lo
Soil name	: Loei
Classification	: Typic Kandiustox, Fine, kaolinitic, isohyperthermic
Date of examination	: July 28, 2009
Described by	: Irb Kheoruenromne, Kamolwan Laopoolkit, Worachart Wisawapipat, Wipawan Thaymuang, Khwunta Khawmee, Wittaya Jindaluang, Daojarus Ketrot, Boontarik Chimchart.
Location	: Approximately 30 m West of Pakchong-Khaoyai at Km 8 Ban Pongkasung, Tambon Nongnamdang, Amphoe Pakchong, Changwat Nakhon Ratchasima
Elevation	: Approximately 394 m (MSL)
Map sheet number	: Coordination : 47 758374^{E}, 1615986^{N}
Landform	
1. Physiographic position	: Coalesing intermontane footslope
2. Surrounding land form	: Undulating
3. Slope on which profile site	: 3% Aspect: 98 Azi
Land use	: Corn field, plrushed for new planting; neem banana,
Annual rainfall	: Approximately 1,200 mm
Mean temperature	: Approximately 26˚C
Climate	: Tropical Savanna
Others	: Agricultural and settlement

II General information on the soil

Parent material	: Mixed wash colluvium derived from weathered limestone and metasedimentary rocks
Drainage	: Well drained
Permeability	: Moderate
Runoff	: Moderate
Depth of ground water	: Deeper than 170 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap1	0-20	Dark reddish brown (2.5YR 3/3); sandy clay; moderate fine and medium subangular blocky structure; slightly hard dry, firm moist, moderately sticky and moderately plastic; very few very fine and few fine vesicular pores; common very fine and fine roots; few fine variegated sands and few traces of dead roots; strongly acid (field pH 5.5); clear, smooth boundary to Ap2.
Ap2	20-35	Dark reddish brown (2.5YR 3/4); clay; moderate fine and medium subangular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; few faint clay coats on pore walls and ped faces; very few very fine and common fine and few medium vesicular pores; few very fine and fine roots; few fine variegated sands and few clay balls and Fe-Mn oxides nodules; slightly acid (field pH 6.5); clear, smooth boundary to Bt1.

Bt1	35-55	Dusky red (10R 3/4); clay; moderate fine and medium subangular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; common faint clay coats on ped faces and pore walls; very few very fine and common fine vesicular pores and few fine tubular pores; very few very fine and fine roots; very few fine variegated sands and few fine Fe-Mn oxides nodules and few traces of dead roots; neutral (field pH 7.0); diffuse, smooth boundary to Bt2.
Bt2	55-85	Dusky red (10R 3/4); clay; moderate fine and medium subangular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; common faint clay coats on ped faces and pore walls; very few very fine and common fine vesicular pores and few fine tubular pores; practically no roots; very few fine variegated sands and few fine Fe-Mn oxides nodules; very strongly acid (field pH 5.0); gradual, smooth boundary to Bt3.
Bt3	85-110	Dusky red (10R 3/4); clay loam; moderate fine and medium subangular blocky structure; slightly hard dry, firm moist, moderately sticky and moderately plastic; common faint clay coats on ped faces and pore walls; very few very fine and common fine vesicular pores and few fine tubular pores; practically no roots; very few fine variegated sands and few fine Fe-Mn oxides nodules; very strongly acid (field pH 4.5); gradual, smooth boundary to Bt4.
Bt4	110-140	Red (2.5YR 4/6); clay loam; moderate fine and medium subangular blocky structure; slightly hard dry, firm moist, moderately sticky and moderately plastic; few faint clay coats on ped faces and pore walls; few very fine, fine and medium vesicular pores and few fine tubular pores; practically no roots; few rock (quartz) fragments and metasedimentary rock fragments and very few traces of dead roots; very strongly acid (field pH 4.5); gradual, smooth boundary to Bt5.
Bt5	140-165/170	Dark red (2.5YR 3/6); clay; moderate fine and medium subangular blocky structure; slightly hard dry, firm moist, moderately sticky and very plastic; few faint clay coats on ped faces and pore walls; few very fine, fine and medium vesicular pores and few fine tubular pores; practically no roots; few fine rock fragments and common clay balls and few traces of charcoal fragments; very strongly acid (field pH 4.5); abrupt, wavy boundary to C.
C	170-180^{+}	Red (2.5YR 4/6); very gravelly clay; moderate fine and medium subangular blocky structure parting partially along rock fragment surface; slightly hard dry, firm moist, moderately sticky and very plastic; few faint clay coats on ped faces and pore walls and rock fragment surface; few very fine and fine vesicular pores and few fine tubular pores; practically no roots; many rock fragments; very strongly acid (field pH 4.5).

Chok Chai series

I **Information on the site**

Profile symbol : Ci
Soil name : Chok Chai series
Classification : Rhodic Kandiustox; Very-fine, kaolinitic, isohyperthermic
Date of examination : January 24, 2003
Described by : Irb Kheoruenromne, Piboon Kanghae, Saowanuch Tawornpruek, Punyisa Trakoonyingcharoen, Suphicha Thanachit, Thanapol Srisupha-olarn and Wimolnan Kanket
Location : Cassava field, 800 m, east of Nong kakae-Nonghin Kone road (at Km 6.8), Ban Nong Hindat, Tambon Sawanphraya, Amphoe Khonburi, Changwat Nakhon Ratchasima
Elevation : Approximately 266 m (MSL)
Map sheet number : 5438 II Coordination : 48Q 0217709^{E}, 1605290^{N}

Landform
1. Physiographic position : Lava corrosion plain
2. Surrounding land form : Gently undulating
3. Slope on which profile site : 1% Aspect : West

Land use : Cassavafield, Kapook, Mango, and local weed (corn)
Annual rainfall : Approximately 1,300 mm
Mean temperature : Approximately 26^{o}C
Climate : Tropical savanna
Others : Agricultural

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 200 cm at time of sampling

III **Profile description**

Horizon	**Depth (cm)**	**Description**
Ap1	0-10	Dusky red (2.5YR 3/4); clay; strong fine and medium subangular blocky structure; soft dry, slightly firm moist, moderately sticky and moderately plastic; many very fine, fine and common medium vesicular pores; many very fine and fine roots; few traces of dead roots, common narrow vertical cracks through the horizons; very strongly acid (field pH 4.5); clear, smooth boundary to Ap2.
Ap2	10-27	Very dusky red (2.5YR 2.5/4); clay; strong fine and medium semi-angular blocky structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; many very fine, fine and common medium vesicular pores; common very fine and fine roots; common clay balls, few rounded and sub-rounded rock fragments, few narrow vertical cracks through the horizons; very strongly acid (field pH 5.0); clear, smooth boundary to Bto1
Bto1	27-55	Very dusky red (2.5YR 2.5/4); clay; strong fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, moderately 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; few very fine, fine and medium roots; few fine rounded and sub-rounded rock fragments; strongly acid (field pH 5.5); gradual, smooth boundary to Bto2.
Bto2	55-88	Very dusky red (2.5YR 2.5/4); clay; strong fine and medium subangular blocky partially parting to coarse granular structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; few faint clay coats on ped faces and pore walls; many very fine and fine vesicular and few fine simple tubular pores; few very fine, fine and medium roots; few very fine rounded and sub-rounded rock fragments, few clay balls, few accommodations of clay as hollow clay balls; strongly acid (field pH 5.5); clear, smooth boundary to Bto3.
Bto3	88-110	Very dusky red (2.5YR 2.5/3); clay; strong fine and medium subangular blocky partially parting to fine granular structure; slightly hard dry, friable moist, slightly sticky and moderately plastic; few faint very fine 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; few fine rounded rock fragments, few clay balls, few traces of dead roots; strongly acid (field pH 5.5); gradual, smooth boundary to Bo1.
Bo1	110-132	Very dusky red (2.5YR 2.5/3); clay; moderate fine and medium subangular blocky partially parting to strong fine granular structure; slightly hard dry, friable moist, slightly sticky and moderately plastic; practically no clay coatings; many very fine and few fine vesicular and few fine simple tubular pores; very few very fine and fine roots; few fine rounded rock embedded in the matrix, few clay balls; strongly acid (field pH 5.5); diffuse, smooth boundary to Bo2.
Bo2	132-160	Very dusky red (2.5YR 2.5/3); clay; moderate fine and medium subangular blocky partially parting to strong fine granular structure; slightly hard dry, friable moist, slightly sticky and moderately plastic; practically no clay coating; many very fine and few fine vesicular and simple tubular pores; practically no roots; few fine rounded rock fragments, few clay balls, few traces of burned roots; strongly acid (field pH 5.5); diffuse, smooth boundary to Bo3.
Bo3	160-200	Very dusky red (2.5YR 2.5/3); clay; moderate fine and medium subangular blocky partially parting to strong fine granular structure; slightly hard dry, friable moist, slightly sticky and moderately plastic; practically no clay coating; many very fine and few fine vesicular and simple tubular pores; practically no roots; few fine rounded rock fragments, few clay balls, few traces of burned roots; strongly acid (field pH 5.5).

Pak Chong 1 series

I **Information on the site**

Profile symbol : Pc 1
Soil name : Pak Chong
Classification : Rhodic Kandiustox; Very-fine, kaolinitic, isohyperthermic
Date of examination : April 11, 2009
Described by : Irb Kheoruenromne, Kamolwan Laopoolkit, Wipawan Thaymuang, Khwunta Khawmee, Wittaya Jindaluang, Daojarus Ketrot, Boontarik Chimchart, Worachart Wisawapipat.
Location : Ban Pang Asoke, Tambon Klangdong, Amphoe PakChong, Changwat Nakhon Ratchasima
Elevation : Approximately 372 m (MSL)
Map sheet number : 5238 II Coordination : 47 748683^{E}, 1621046^{N}

Landform
1. Physiographic position : Karst corrosion plain
2. Surrounding land form : Undulating
3. Slope on which profile site : 3% Aspect: 304 Azi
Land use : Corn based field crop system

Annual rainfall : Approximately 1,200 mm
Mean temperature : Approximately 26˚C
Climate : Tropical Savanna
Others : Agricultural and settlement

II **General information on the soil**

Parent material : Local alluvium and residuum derived from weathered 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**
Ap1	0-18	Dark reddish brown (2.5YR 2.5/4); clay; moderate weak fine and medium subangular blocky structure parting to medium and fine granular structure; slightly hard dry, friable moist, slightly sticky and moderately plastic; few faint clay coats on ped faces and pore walls; many very fine and fine vesicular pores;many fine and fine roots; few ants and worms, few quartz fragments and few traces of dead roots; neutral (field pH 7.0); clear, smooth boundary to Ap2.
Ap2	18-30	Dark reddish brown (2.5YR 2.5/4); clay; moderate weak fine and medium subangular blocky structure parting to medium and fine granular structure; slightly hard dry, friable moist, moderately sticky and moderately plastic; few faint clay coats on ped faces and pore walls; few very fine and common fine vesicular pores; many fine and fine roots; few ants and worms, few quartz fragments and few traces of dead roots; moderately alkaline (field pH 8.0); clear, smooth boundary to Bt1.

Bt1	30-58	Dark reddish brown (2.5YR 2.5/4); clay; moderate fine and medium subangular blocky structure; hard dry, slightly friable moist, moderately sticky and moderately plastic; many prominent clay coats on ped faces and pore walls; common very fine and few fine vesicular and few fine simple tubular pores; common very fine and fine roots; very few quartz fragment, few clay balls and very few traces of dead roots; moderately alkaline (field pH 8.0); gradual, smooth boundary to Bt2.
Bt2	58-88	Dark red (2.5YR 3/6); clay; moderate fine and medium subangular blocky structure; hard dry, slightly friable moist, moderately sticky and moderately plastic; many prominent clay coats on ped faces and pore walls; common very fine and few fine vesicular and few fine simple tubular pores; few very fine and fine roots; very few quartz fragment, few clay balls and very few traces of dead roots; moderately alkaline (field pH 8.0); clear, smooth boundary to Bto1.
Bto1	88-110	Dark red (2.5YR 3/6); clay; moderate fine and medium subangular blocky structure parting to medium and coarse granular structure; hard dry, friable moist, sticky and plastic; common disrict clay coats on pore walls and ped faces; many very fine and common fine vesicular and few fine simple tubular pores; very few very fine and fine roots; very few quartz fragment, few clay balls and very few traces of dead roots; moderately alkaline (field pH 8.0); gradual, smooth boundary to Bto2.
Bto2	110-138	Dark red (2.5YR 3/6); clay; moderate weak fine and medium subangular blocky structure parting to medium and fine granular structure; slightly hard dry, friable moist, slightly sticky and very plastic; common faint clay coats on ped faces and pore walls; common very fine and fine vesicular and fine simple tubular pores; practically no roots; very few quartz fragment, few fine clay balls; very strongly acid (field pH 4.0); clear, smooth boundary to Bto3.
Bto3	138-175	Dark red (2.5YR 3/6); clay; moderate weak fine and medium subangular blocky structure parting to medium and fine granular structure; slightly hard dry, friable moist, slightly sticky and very plastic; common faint clay coats on ped faces and pore walls; common very fine and fine vesicular and few simple tubular pores; practically no roots; very few quartz fragment, few fine clay balls; very strongly acid (field pH 4.5); gradual, smooth boundary to Bto4.
Bto4	175-200^+	Dark red (2.5YR 3/6); clay; moderate fine and medium subangular blocky structure parting to strong coarse and medium granular structure; hard dry, slightly friable moist, slightly sticky and very plastic; common faint clay coats on ped faces and pore walls; common very fine and fine vesicular and few simple tubular pores; practically no roots; very few quartz fragment, few fine clay balls; very strongly acid (field pH 4.5).

Pak Chong 2 series

I Information on the site

Profile symbol : Pc 2
Soil name : Pak Chong
Classification : Rhodic Kandiustox; Very-fine, kaolinitic, isohyperthermic
Date of examination : April 21, 2009
Described by : Irb Kheoruenromne, Kamolwan Laopoolkit, Wipawan Thaymuang, Khwunta Khawmee, Wittaya Jindaluang, Daojarus Ketrot, Boontarik Chimchart, Chalermraj Jitjaroenporn, Worachart Wisawapipat.
Location : D6 approximately 50 m Southeast of main road from front gate towards the mountain. Ban Pang Asoke, Tambon Klangdong, Amphoe Pak Chong, Changwat Nakhon Ratchasima
Elevation : Approximately 375 m (MSL)
Map sheet number : 5238 II Coordination : 47 749022^{E}, 1620694^{N}

Landform
1. Physiographic position : Karst corrosion plain
2. Surrounding land form : Flat
3. Slope on which profile site : 1% Aspect: 100 Azi
Land use : Corn left fallow at time of sampling

Annual rainfall : Approximately 1,300 mm
Mean temperature : Approximately 26˚C
Climate : Tropical Savanna
Others : Agricultural experimental and settlement building

II General information on the soil

Parent material : Mainly residuum derived from weathered 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
Ap1	0-15	Dark reddish brown (2.5YR 2.5/4); clay; moderate fine and medium subangular blocky structure parting partially to granular structure; slightly hard, slightly friable moist, slightly sticky and moderately plastic; few faint clay coats on ped faces and pore walls; common very fine and fine vesicular and few tubular pores; common very fine and fine roots; few fine rock fragment, clay balls, few fine Fe-oxide nodules and common traces of dead roots; moderately alkaline (field pH 8.0); clear, smooth boundary to Ap2.
Ap2	15-35	Dark reddish brown (2.5YR 2.5/4); clay; strong fine and medium subangular blocky structure; very hard dry, slightly friable moist, slightly sticky and moderately plastic; few distinct clay coats on ped faces and pore walls; few very fine and common fine vesicular and few tubular pores; common very fine and fine roots; very few fine rock fragment and few traces of dead roots; moderately alkaline (field pH 8.0); abrupt, smooth boundary to Bt1.

Bt1	35-65	Dark yellowish brown (10YR 3/4); clay; strong fine and medium semi-angular blocky structure; very hard dry, friable moist, moderately sticky and moderately plastic; many prominent clay coats on ped faces and pore walls; few very fine and common fine vesicular and few tubular pores; very few very fine and fine roots; very few fine rock fragments and very few trace of dead roots; moderately alkaline (field pH 8.0); gradual, smooth boundary to Bt2.
Bt2	65-90	Dark yellowish brown (10YR 3/4); clay; strong fine and medium semi-angular blocky structure; very hard dry, friable moist, moderately sticky and moderately plastic; many prominent clay coats on ped faces and pore walls; common very fine and few fine vesicular and few tubular pores; very few very fine and fine roots; very few fine rock fragments and few fine cracks and very few traces of dead roots; neutral (field pH 7.0); clear, smooth boundary to Bto1.
Bto1	90-120	Dark yellowish brown (10YR 3/4); clay; moderate fine and medium semi-angular partially parting to fine granular structure; hard dry, slightly firm moist, slightly sticky and moderately plastic; common distinct clay coats on ped faces and pore walls; common very fine and fine vesicular and few tubular pores; very few very fine and fine roots; very few fine rock fragments and very few trace of dead roots; slightly acid (field pH 6.5); clear, smooth boundary to Bto2.
Bto2	120-148	Dark yellowish brown (10YR 3/4); clay; moderate fine and medium semi-angular partially parting to fine granular structure; hard dry, friable moist, slightly sticky and moderately plastic; few faint clay coats on ped faces and pore walls; many very fine and few fine vesicular and few tubular pores; practically no roots; very few fine rock fragment and few fine Fe-oxide nodules and few clay balls; slightly acid (field pH 6.5); gradual, smooth boundary to Bto3.
Bto3	148-172	Dark yellowish brown (10YR 3/4); clay; moderate fine and medium semi-angular partially parting to fine granular structure; hard dry, friable moist, slightly sticky and moderately plastic; few faint clay coats on ped faces and pore walls; common very fine and fine vesicular and few tubular pores; practically no roots; very few rock fragments and very few clay balls and very few traces of dead roots; slightly acid (field pH 6.5); gradual, smooth boundary to Bto4.
Bto4	172-200^{+}	Dark yellowish brown (10YR 3/4); clay; moderate fine and medium semi-angular partially parting to fine granular structure; hard dry, friable moist, slightly sticky and moderately plastic; few faint clay coats on ped faces and pore walls; common very fine and fine vesicular and few tubular pores; practically no rootsf; very few rock fragments and very few clay balls; slightly acid (field pH 6.5).

Pak Chong 3 series

I **Information on the site**

Profile symbol	: Pc 3
Soil name	: Pak Chong
Classification	: Rhodic Kandiustox; Very-fine, kaolinitic, isohyperthermic
Date of examination	: April 21, 2009
Described by	: Irb Kheoruenromne, Kamolwan Laopoolkit, Wipawan Thaymuang, Khwunta Khawmee, Wittaya Jindaluang, Daojarus Ketrot, Boontarik Chimchart, Chalermraj Jitjaroenporn, Worachart Wisawapipat.
Location	: Approximately 80 m East in the intermontaince valley approximately 90 m South of corn silo. Ban Pang Asoke, Tambon Klangdong, Amphoe Pak Chong, Changwat Nakhon Ratchasima
Elevation	: Approximately 418 m (MSL)
Map sheet number	: 5238 II Coordination : $47\ 750263^{E}$, 1619049^{N}
Landform	
1. Physiographic position	: Karst corrosion footslope in limestone intermontane valley
2. Surrounding land form	: Slightly undulating
3. Slope on which profile site	: 3% Aspect: 142 Azi
Land use	: Left idle under grasses
Annual rainfall	: Approximately 1,300 mm
Mean temperature	: Approximately 26˚C
Climate	: Tropical Savanna
Others	: Corn and sorghum experimental fields and settlement building

II **General information on the soil**

Parent material	: Residuum derived from weathered 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	0-28	Dark reddish brown (2.5 YR 2.5/4); clay; moderate fine and medium subangular blocky structure partially parting to granular structure; slightly hard dry, firm moist, slightly and moderately plastic; common faint clay coats on ped faces and pore walls; common very fine and fine vesicular and few tubular pores; common very fine and fine roots; few fine rock fragments and clay balls and few traces of dead roots; neutral (field pH 7.0); abrupt, smooth boundary to Bt1.
Bt1	28-50	Dark reddish brown (2.5 YR 2.5/4); clay; moderate fine and medium subangular blocky structure partially parting to granular structure; slightly hard dry, firm moist, slightly sticky and moderately plastic; common distinct clay coats on ped faces and pore walls; common very fine and fine vesicular and tubular pores; common very fine and fine roots; very few very fine rock fragments and few traces of dead roots; moderately alkaline (field pH 8.0); gradual, smooth boundary to Bt2.

Bt2	50-80	Dark reddish brown (2.5 YR 2.5/4); clay; 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; common very fine and fine vesicular and few tubular pores; few very fine and fine roots; very few rounded rock fragments and very few traces of dead roots; moderately alkaline (field pH 8.0); clear, smooth boundary to Bt3.
Bt3	80-100	Dark reddish brown (2.5 YR 2.5/4); clay; 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; common very fine and fine vesicular and few tubular pores; very few very fine roots; very few rock fragments and big boulder running downward on the other side of profile in the soil pit and very few traces of dead roots; strongly acid (field pH 5.5); gradual, smooth boundary to Bt4.
Bt4	100-123	Dark reddish brown (2.5 YR 2.5/4); clay; moderate fine and medium subangular blocky structure; hard dry, firm moist, slightly sticky and moderately plastic; common faint clay coats on ped faces and pore walls; common very fine and fine vesicular and few tubular pores; very few very fine roots; very few rock fragments and few traces of dead roots; strongly acid (field pH 5.5); clear, smooth boundary to Bt5.
Bt5	123-147	Dark reddish brown (2.5 YR 2.5/4); clay; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; common faint clay coats on ped faces and pore walls; few very fine and common fine vesicular and few tubular pores; very few very fine roots; very few rock fragments; strongly acid (field pH 5.5); gradual, smooth boundary to Bt6.
Bt6	147-173	Dark reddish brown (2.5 YR 2.5/4); clay; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; common faint clay coats on ped faces and pore walls; few very fine and common fine vesicular and few tubular pores; very few very fine roots; very few rock fragments; strongly acid (field pH 5.5); gradual, smooth boundary to Bt7.
Bt7	173-200	Dark reddish brown (2.5 YR 2.5/4); clay; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; common faint clay coats on ped faces and pore walls; few very fine and common fine vesicular and few tubular pores; very few very fine roots; very few rock fragments; strongly acid (field pH 5.5).

Pak Chong 4 series

I Information on the site

Profile symbol : Pc 4
Soil name : Pak Chong
Classification : Typic Kandiustox; Fine, kaolinitic, isohyperthermic
Date of examination : April 22, 2009
Described by : Irb Kheoruenromne, Kamolwan Laopoolkit, Wipawan Thaymuang, Khwunta Khawmee, Wittaya Jindaluang, Daojarus Ketrot, Boontarik Chimchart, Chalermraj Jitjaroenporn, Worachart Wisawapipat.
Location : 20 m Southeaet of Pakchong Research Station main road approximately 800 m from the main office. Ban Pang, Tambon, Amphoe Pak Chong, Changwat Nakhon Ratchasima
Elevation : Approximately 320 m (MSL)
Map sheet number : 5238 II Coordination : 47 759709^{E}, 1624350^{N}

Landform
1. Physiographic position : Corrosion footslope (middle)
2. Surrounding land form : Undulating
3. Slope on which profile site : 4% Aspect: 279 Azi
Land use : Mango orchard-left idle under grasses
Annual rainfall : Approximately 1,300 mm
Mean temperature : Approximately 26˚C
Climate : Tropical Savanna
Others : Fruit tree experimental field/ mangoes mainly

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
Ap1	0-13/15	Dark reddish brown (5YR 3/2); clay; strong fine and medium subangular blocky structure; very hard dry; firm moist; moderately sticky and moderately plastic; few faint clay coats on ped faces and pore walls; few very fine and fine vesicular and tubular pores; many very fine and fine roots; very few very fine rock fragments and few fine surface cracks and common dead roots; neutral (field pH 7.0); gradual, smooth boundary to Ap2.
Ap2	15-32	Dark brown (7.5YR 3/2); clay; strong fine and medium subangular blocky structure; very hard dry; firm moist; moderately sticky and moderately plastic; few faint clay coats on ped faces and pore walls and few fine cracks; few very fine and common fine vesicular; many very fine and fine roots; few fine and very fine rock fragments and few fine vertical cracks and common dead roots; neutral (field pH 7.0); abrupt, smooth

		boundary to Bt1.
Bt1	32-52	Dark reddish brown (5YR 3/3); clay; strong fine and medium subangular blocky structure; very hard dry; firm moist; moderately sticky and moderately plastic; common distinct clay coats on ped faces and pore walls; few very fine and common fine vesicular and few tubular pores; few very fine and common fine roots; few fine rock fragments and Mn-oxide nodule and few traces of dead roots and fine charcoal fragments; neutral (field pH 7.0); gradual, smooth boundary to Bt2.
Bt2	52-75	Dark reddish brown (2.5YR 3/4); clay; strong fine and medium subangular blocky structure; very hard dry; firm moist; moderately sticky and moderately plastic; many prominent ferri-argillan coats on ped faces and pore walls; few very fine and common fine vesicular and tubular pores; few very fine and common fine roots; few fine rounded rock fragments and few traces of dead roots; moderately acid (field pH 6.0); gradual, smooth boundary to Bt3.
Bt3	75-100	Dark reddish brown (2.5YR 2.5/3); clay; strong fine and medium semi-angular blocky structure; very hard dry; firm moist; moderately sticky and moderately plastic; many prominent ferri-argillan coats on ped faces and pore walls; few very fine and common fine vesicular and tubular pores; few very fine and common fine roots; few fine clay blocks and very few very fine rock fragment and few traces of dead roots; very strongly acid (field pH 5.0); clear, smooth boundary to Bt4.
Bt4	100-120	Dark reddish brown (2.5YR 2.5/4); clay; strong fine and medium semi-angular blocky structure; hard dry; firm moist; moderately sticky and moderately plastic; many prominent ferri-argillan coats on ped faces and pore walls; few very fine and common fine vesicular and tubular pores; few very fine and fine roots; few fine rounded Mn-oxide nodules and few traces of dead roots; very strongly acid (field pH 4.5); clear, smooth boundary to Bt5.
Bt5	120-143	Dark reddish brown (2.5YR 2.5/4); clay; strong fine and medium semi-angular blocky structure; hard dry; firm moist; moderately sticky and moderately plastic; many prominent ferri-argillan coats on ped faces and pore walls; few very fine and fine vesicular and common tubular pores; few very fine and fine roots; common reddish powder of iron oxides as patches and few traces of dead roots; very strongly acid (field pH 4.0); gradual, smooth boundary to Bt6.
Bt6	143-170	Dark reddish brown (2.5YR 2.5/4); clay; strong fine and medium semi-angular blocky structure; hard dry; firm moist; sticky and plastic; common prominent ferri-argillan clay on ped faces and pore walls; few very fine and common fine vesicular and common fine tubular pores; few very fine and fine roots; few fine rock fragments and few traces of dead roots; very strongly acid (field pH 4.5); gradual, smooth boundary to Bt7.

Bt7	170-200	Dark reddish brown (2.5YR 2.5/4); clay; strong fine and medium semi-angular blocky structure; slightly hard dry; firm moist; slightly sticky and moderately plastic; common distinct ferri-argillan clay on ped faces and pore walls; few very fine and common fine vesicular and common tubular pores; few very fine and fine roots; few rock fragments and traces of dead roots; very strongly acid (field pH 4.5).

Chum Phuang series

I Information on the site

Profile symbol : Cpg
Soil name : Chum Phuang (Cpg)
Classification : Typic Kandiustult; Coarse-loamy, siliceous, isohyperthermic
Date of examination : July 17, 2009
Described by : Irb Kheoruenromne, Kamolwan Laopoolkit, Wipawan Thaymuang, Khwunta Khawmee, Wittaya Jindaluang, Daojarus Ketrot, Boontarik Chimchart, Chalermraj Jitjaroenporn, Worachart Wisawapipat.
Location : Approximately 500 m East behind the main office in LDD region 5. Tambon Nonsila, Amphoe Muang, Changwat Khonkaen
Elevation : Approximately 178 m (MSL)
Map sheet number : Coordination : 48 269471^{E}, 1822251^{N}

Landform
1. Physiographic position : Upper backslope of residual low hill
2. Surrounding land form : Undulating
3. Slope on which profile site : 3% Aspect: 98 Azi
Land use : Tree crop plot in experimental field

Annual rainfall : Approximately 1,200 mm
Mean temperature : Approximately 26˚C
Climate : Tropical Savanna
Others : Experimental and research activities of LDD

II General information on the soil

Parent material : Residuum and wash derived from weathered red sandstone
Drainage : Well drained
Permeability : Moderate
Runoff : Moderate
Depth of ground water : Deeper than 210 cm at time of sampling

III Profile description

Horizon	**Depth (cm)**	**Description**
Ap	0-20	Yellowish red (5YR 4/6); sandy loam; moderate weak fine and medium subangular blocky structure; slightly hard dry, friable moist, slightly sticky and non plastic; few very fine, few fine vesicular and few fine tubular pores; common very fine, fine and few medium roots; few fine variegated sands and few traces of dead roots and charcoal fragments; very strongly acid (field pH 5.0); clear, smooth boundary to Bt1.

Bt1	20-45	Dark red (2.5YR 3/6); sandy loam; moderate weak fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; few faint clay bridges among sand grains; few very fine, few fine vesicular and few fine tubular pores; few very fine and fine roots; few fine variegated sands and few traces of dead roots; very strongly acid (field pH 4.5); clear, smooth boundary to Bt2.
Bt2	45-75	Red (2.5YR 4/6); sandy loam; moderate weak fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; few faint clay bridges among sand grains; few very fine and common fine vesicular pores; few very fine and fine roots; few variegated sands and very few traces of dead roots and few fecal pellets; very strongly acid (field pH 5.0); clear, smooth boundary to Bt3.
Bt3	75-100	Red (2.5YR 4/6); sandy loam; moderate weak fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; few faint clay bridges among sand grains; very few very fine and common fine vesicular and few fine tubular pores; few very fine and fine roots; few variegated sands and few fine quartz fragments; very strongly acid (field pH 5.0); gradual, smooth boundary to Bt4.
Bt4	100-130	Red (2.5YR 4/6); coarse sandy loam; moderate weak fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; few faint clay bridges among sand grains; few very fine and common fine vesicular pores; few very fine and fine roots; few variegated sands and few fine quartz fragments and very few traces of dead roots; very strongly acid (field pH 5.0); gradual, smooth boundary to Bt5.
Bt5	130-160	Red (2.5YR 4/6); sandy loam; moderate weak fine and medium subangular blocky structure; slightly hard dry, friable moist, slightly sticky and slightly plastic; few faint clay bridges among sand grains; few very fine and common fine vesicular pores; very few very fine and fine roots; few variegated sands and few fine quartz fragments and very few traces of dead roots; strongly acid (field pH 5.5); gradual, smooth boundary to Bt6.
Bt6	160-185	Red (2.5YR 4/6); sandy loam; moderate weak fine and medium subangular blocky structure; slightly hard dry, friable moist, non sticky and slightly plastic; few faint clay bridges among sand grains; few very fine and common fine vesicular pores; very few very fine and fine roots; few variegated sands and few fine quartz fragments and very few traces of dead roots and fine charcoal fragments; strongly acid (field pH 5.5); gradual, smooth boundary to Bt7.
Bt7	185-210+	Red (2.5YR 4/6); sandy loam; moderate weak fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; few faint clay bridges among sand grains; few very fine and common fine vesicular pores; very few very fine and fine roots and few medium roots; few variegated sands and few fine quartz fragments; strongly acid (field pH 5.5).

Sung Noen series

I Information on the site

Profile symbol : Sn
Soil name : Sung Noen
Classification : Typic Kandiustult; Fine, mixed, isohyperthermic
Date of examination : May 5, 2009
Described by : Irb Kheoruenromne, Kamolwan Laopoolkit, Wipawan Thaymuang, Khwunta Khawmee, Wittaya Jindaluang, Daojarus Ketrot, Boontarik Chimchart, Chalermraj Jitjaroenporn, Worachart Wisawapipat.
Location : Approximately 50 m Southeast of Sikheiw-Dan Khuntot at Km 20.1 from Sikheiw. Ban Noanpradue, Tambon Noanpradue, Amphoe Dan Khuntut, Changwat Nakhon Ratchasima
Elevation : Approximately 252 m (MSL)
Map sheet number : Coordination : 47 790933^{E}, 1665921^{N}

Landform
1. Physiographic position : Rise on siltstone corrosion plain
2. Surrounding land form : Undulating
3. Slope on which profile site : 3% Aspect: 78 Azi
Land use : Cassava field, left fallow under glasses and cassava remnant

Annual rainfall : Approximately 1,200 mm
Mean temperature : Approximately 26˚C
Climate : Tropical Savanna
Others : Agricultural and settlement

II General information on the soil

Parent material : Residuum derived from weathered siltstone
Drainage : Well drained
Permeability : Moderate
Runoff : Moderate
Depth of ground water : Deeper than 135 cm at time of sampling

II Profile description

Horizon	Depth (cm)	Description
Ap1	0-10	Brown (7.5YR 4/4); loam; moderate weak fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; few very fine and fine vesicular and few fine tubular pores; many very fine, fine and common medium roots; few variegated sands and some charcoal fragments and traces of dead roots; slightly acid (field pH 6.5); clear, smooth boundary to Ap2.
Ap2	10-29	Brown (7.5YR 4/4); fine sandy loam; moderate weak fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; very few very fine and few fine tubular pores; many very fine, fine and common medium roots; few variegated sands and some charcoal fragments and traces of dead roots and some ant's holes; moderately acid (field pH 6.0); abrupt, smooth boundary to Bt1.

Bt1	29-55	Yellowish red (5YR 4/6); very fine sandy clay loam; moderate fine and medium semi-angular blocky structure; hard dry, slightly firm moist, slightly sticky and moderately plastic; few faint clay coats on ped faces and pore walls; few very fine and fine vesicular and few tubular pores; common very fine, fine and medium roots; few variegated sands and traces of dead roots; strongly acid (field pH 5.5); gradual,smooth boundary to Bt2.
Bt2	55-81	Yellowish red (5YR 4/6); very flagstones sandy clay loam; moderate fine and medium subangular blocky structure; hard dry, slightly firm moist, slightly sticky and moderately plastic; few faint clay coats on ped faces and pore walls; few very fine and fine vesicular and few tubular pores; common very fine, fine and medium roots; few variegated sands and traces of dead roots; very strongly acid (field pH 5.0); gradual, smooth boundary to Bt3.
Bt3	81-110	Yellowish red (5YR 4/6); very fine sandy clay loam; moderate fine and medium subangular blockly structure; hard dry, firm moist, slightly sticky and moderately plastic; few faint clay coats on ped faces and pore walls; very few very fine and few fine and medium vesicular and tubular pores; few very fine, fine and medium roots; few variegated sands and very few quartz fragments and large dead roots and few fines Fe and Mn oxides nodules; strongly acid (field pH 5.5); clear, smooth boundary to Btc.
Btc	110-135^{+}	Yellowish brown (10YR 5/4) 60% and yellowish red (5YR 4/6) 40%; slightly gravelly sandy clay loam; strong fine medium subangular blockly structure; very hard dry, firm moist, slightly sticky and moderately plastic; few distinct clay coats on pore walls mainly; few very fine and fine vesicular and tubular pores; few very fine and fine roots; few fine iron oxide nodules and few variegated sands; moderately acid (field pH 6.0).

Satuek series

I **Information on the site**

Profile symbol : Suk
Soil name : Satuek series
Classification : Typic Haplustult, fine-loamy, siliceous
Date of examination : July 7, 2007
Described by : Irb Kheoruenromne, Chutharmard Kaewmano, Natthapol Chittamart, Worachart Wisawapipat, Noppadon Prayunsuk, Wipawan Insomboon, Timtong Darunsontaya
Location : Ban Chotyai, Tambon Bantone, Amphoe Prayuen, Changwat Khonkaen.
Elevation : Approximately 167 m (MSL)
Map sheet number : 5559 IV Coordination: 48Q 253954 m E., 1803216 m N.

Landform
1. Physiographic position : Low part of high erosional terrace
2. Surrounding landform : Undulating

3. Slope on which profile site : 3%
Land us : Forage Crop field with some native trees
Annual rainfall : Approximately 1379 mm
Mean temperature : Approximately 27 ^{o}C
Climate : Tropical savanna
Others : Agricultural Eucalyptus and Mango

II **General information on the soil**

Parent material : Wash over residuum derived from clastic sedimentary rocks
Drainage : Well drained
Permeability : Moderate
Runoff : Moderate
Depth of ground water : More than 200 cm

III **Profile description**

Horizon	Depth (cm)	Description
Ap1	0-10	Mixed brown (7.5YR 4/3) 90 % and very dark gray (7.5YR 3/1) 10%; sandy loam; moderately weak fine and medium subangular blocky structure; soft dry, friable moist, slightly sticky and slightly plastic; few variegated sands; common very fine and fine vesicular pores; many very fine and fine roots; few traces of dead roots; very strongly acid (field pH 5.0); clear, smooth boundary to Ap2
Ap2	10-25/30	Light brown (7.5YR 6/4); sandy loam; moderately weak fine and medium subangular blocky structure; slightly 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; very few traces of dead roots; very strongly acid (field pH 4.5); clear, wavy boundary to Bt1
Bt1	30-55	Strong brown (7.5YR 5/8); sandy clay 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; few variegated sands and few faint krotovina; few very fine and fine vesicular pores; very few very fine and fine roots and common medium roots; few traces of dead roots; extremely acid (field pH 4.0); clear, smooth boundary to Bt2
Bt2	55-80	Mixed reddish yellow (7.5YR 6/6) 70% and reddish yellow (7.5YR 6/8) 30%; sandy clay 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; few variegated sands, few faint krotovina and few fine silt pockets; common very fine and few fine vesicular and few fine simple tubular pores; very few very fine and fine roots and few medium roots; few traces of dead roots; very strongly acid (field pH 4.5); clear, smooth boundary to Bt3
Bt3	80-110	Mixed reddish yellow (7.5YR 6/8) 85%, light brown (7.5YR 6/3) 10% and yellowish red (5YR 5/8) 2%; sandy clay loam; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; common faint clay bridges

		among sand grains and few faint clay coats on pore walls and ped faces; few variegated sands; common very fine and fine vesicular and few fine simple tubular pores; very few very fine and fine roots and very few medium roots; few traces of dead roots; very strongly acid (field pH 4.5); clear, smooth boundary to Bt4
Bt4	110-140	Mixed reddish yellow (7.5YR 6/6) 60%, yellowish red (5YR 5/6) 35% and pinkish gray (7.5YR 7/2) 5%; sandy clay loam; moderate fine and medium semi angular blocky structure; hard dry, firm moist, slightly sticky and moderately plastic; common faint clay bridges among sand grains and few faint clay coats on pore walls and ped faces; few variegated sands; common very fine and fine vesicular and few fine simple tubular pores; very few very fine and fine roots and very few medium roots; few traces of dead roots; very strongly acid (field pH 4.5); gradual, smooth boundary to Bt5
Bt5	140-168	Mixed brownish yellow (10YR 6/6) 88% and light brownish gray (10YR 6/2) 10%, few fine distinct brownish yellow (10YR 6/8) and few fine distinct reddish yellow (7.5YR 6/8) mottles; sandy clay loam; moderate fine and medium semi-angular blocky structure; hard dry, firm moist, slightly sticky and moderately plastic; common faint clay bridges among sand grains and common faint clay coats on pore walls and ped faces; few variegated sands; common very fine and fine vesicular and few fine simple tubular pores; very few very fine and fine roots and very few medium roots; few traces of dead roots; very strongly acid (field pH 4.5); gradual and smooth boundary to Bt6
Bt6	168-200+	Mixed brownish yellow (10YR 6/8) 89% and light gray (10YR 7/2) 10%; few fine strong brown (7.5YR 5/8) mottles; sandy clay loam; moderate fine and medium semi angular blocky structure; ; hard dry, firm moist, slightly sticky and moderately plastic; common faint clay bridges among sand grains and common faint clay coats on pore walls and ped faces; few variegated sands; common very fine and fine vesicular and few fine simple tubular pores; very few very fine and fine roots and very few medium roots; few traces of dead roots; very strongly acid (field pH 5.0)

Yasothon series

I Information on the site

Profile symbol : Yt
Soil name : Yasothon
Classification : Typic Kandiustult; Fine-loamy, kaolinitic, isohyperthermic
Date of examination : April 10, 2009
Described by : Irb Kheoruenromne, Somchai Anusonpornperm, Suphicha Thanachit, Chutharmard Kaewmano, Kamolwan Laopoolkit, Wipawan Thaymuang, Khwunta Khawmee, Wittaya Jindaluang, Daojarus Ketrot, Boontarik Chimchart.

Location	: Approximately 100 m East of Sikhiew-Dan Khunthod. Ban Kudmuang, Tambon Takian, Amphoe Dan Khunthod, Changwat Nakhon Ratchasima
Elevation	: Approximately 245 m (MSL)
Map sheet number	: Coordination : 47 793630^{E}, 1676161^{N}
Landform	
1. Physiographic position	: Residual plain (Corrosion plain)
2. Surrounding land form	: Undulating
3. Slope on which profile site	: 1% Aspect: 300 Azi
Land use	: Cassava field
Annual rainfall	: Approximately 1,200 mm
Mean temperature	: Approximately 27˚C
Climate	: Tropical Savanna
Others	: Agricultural and settlement

II **General information on the soil**

Parent material	: Residuum derived from weathered red 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	0-20	Yellowish red (5YR 4/6); loamy sand; moderate weak fine and medium subangular blocky structure; slightly hard dry, moist, non sticky and non plastic; few very fine, common fine vesicular pores; many very fine and fine roots; few variegated sands; very strongly acid (field pH 5.0); clear, smooth boundary to Bt1.
Bt1	20-41	Red (2.5YR 4/8); sandy loam; moderately medium and coarse subangular blocky structure; hard dry, slightly friable moist, non sticky and slightly plastic; few clay bridges among sand grains; few very fine, fine vesicular pores; common very fine and fine roots; few variegated sands; very strongly acid (field pH 4.5); gradual, smooth boundary to Bt2.
Bt2	41-69	Red (2.5YR 4/6); sandy loam; moderately fine and medium subangular blocky structure; hard dry, slightly friable moist, slightly sticky and moderately plastic; few faint clay coats on ped faces and clay bridges among sand grains; very few very fine, common fine vesicular pores; common very fine and fine roots; few variegated sands; very strongly acid (field pH 4.0); clear, smooth boundary to Bt3
Bt3	69-95	Red (2.5YR 4/6); sandy clay loam; moderately fine and medium subangular blocky structure; hard dry, slightly friable moist, slightly sticky and moderately plastic; few faint clay coats on pore walls and few clay bridges among sand grains; few very fine, common fine vesicular and few fine tubular pores; few very fine and fine roots; few variegated sands; very strongly acid (field pH 4.0); clear, smooth boundary to Bt4.

Bt4	95-120	Red (2.5YR 4/6); sandy clay loam; moderately fine and medium subangular blocky structure; slightly hard dry, slightly friable moist, slightly sticky and moderately plastic; very few faint clay coats on pore walls and few clay bridges among sand grains; common very fine and fine vesicular and very few fine simple tubular pores; few very fine and fine roots; few variegated sands; very strongly acid (field pH 4.0); gradual, smooth boundary to Bt5.
Bt5	120-142	Red (2.5YR 4/6); sandy clay loam; moderately fine and medium subangular blocky structure; slightly hard dry,slightly friable moist, slightly sticky and moderately plastic; very few faint clay coats on pore walls and few clay bridges among sand grains; common very fine and fine vesicular and very few fine simple tubular pores; very few very fine and fine roots; few variegated sands, some patchy areas of strong clay balls and distinct clay coats; very strongly acid (field pH 4.0); clear, smooth boundary to Bt6.
Bt6	142-171	Red (2.5YR 4/6); sandy clay loam; moderately fine and medium subangular blocky structure; slightly hard dry, slightly friable moist, slightly sticky and moderately plastic; very few faint clay coats on pore walls and few clay bridges among sand grains; common very fine and fine vesicular and very few fine simple tubular pores; practically no roots; few variegated sands, some patchy areas of strong clay balls and distinct clay coats; very strongly acid (field pH 4.0); gradual, smooth boundary to Bt7.
Bt7	171-200$^+$	Red (2.5YR 4/6); sandy clay loam; moderately fine and medium subangular blocky structure; slightly hard dry,slightly friable moist, slightly sticky and moderately plastic; very few faint clay coats on pore walls and few clay bridges among sand grains; common very fine and fine vesicular and very few fine simple tubular pores; practically no roots; few variegated sands; very strongly acid (field pH 4.0).

Phon Phisai series

I Information on the site

Profile symbol : Pp
Soil name : Phon Phisai (Pp)
Classification : Typic Plinthustult; Clayey-skeletal, mixed, isohyperthermic
Date of examination : July 17, 2009
Described by : Irb Kheoruenromne, Kamolwan Laopoolkit, Wipawan Thaymuang, Khwunta Khawmee, Wittaya Jindaluang, Daojarus Ketrot, Boontarik Chimchart, Chalermraj Jitjaroenporn, Worachart Wisawapipat.
Location : Approximately 50 m West of Road no.2 at Km 28 from Khon Kaen to Udon Thani. Tambon Muang Wan, Amphoe Nampong, Changwat Khonkaen
Elevation : Approximately 176 m (MSL)
Map sheet number : 5542I Coordination : 48 265826^E, 1846229^N

Landform
1. Physiographic position : Upper extended footslope
2. Surrounding land form : Undulating
3. Slope on which profile site : 3.5% Aspect: 270 Azi
Land use : Cassava field mixed with bean
Annual rainfall : Approximately 1,300 mm
Mean temperature : Approximately 26˚C
Climate : Tropical Savanna
Others : Agricultural and settlement

II General information on the soil

Parent material : Wash over residuum derived from weathered metasedimentary rocks
Drainage : Well drained
Permeability : Moderate
Runoff : Moderate
Depth of ground water : Deeper than 200 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap1	0-12	fine sandy loam; moderate weak fine and medium subangular blocky structure; slightly hard dry, friable moist, non sticky and non plastic; very few very fine and common fine vesicular pores; many very fine, fine and few medium roots; few fine variegated sands and few quartz fragments and few traces of dead roots and charcoal fragments; moderately acid (field pH 6.0); clear, smooth boundary to Ap2.
Ap2	12-28	Yellowish brown (10YR 5/4); fine 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 very fine and common fine vesicular pores; common very fine and fine roots; few variegated sands and few quartz fragments and few traces of dead roots and charcoal fragments and few Fe-Mn oxides nodules;

		strongly acid (field pH 5.5); clear, smooth boundary to Bto1.
Bto1	28-48	Strong brown (7.5YR 5/6); very gravelly sandy clay loam; moderate fine and medium subangular blocky structure; very hard dry, slightly friable moist, slightly sticky and slightly plastic; few faint clay coats on pore walls and nodules surface; very few very fine and few fine vesicular; very few very fine and fine roots; few variegated sands and many Fe-Mn oxides nodules and very few traces of dead roots; strongly acid (field pH 5.5); clear, smooth boundary to Bto2.
Bto2	48-70	Red (2.5YR 5/6); very gravelly sandy clay; moderate fine and medium subangular blocky structure parting along nodules surface; very hard dry, friable moist, moderately sticky and moderately plastic; common faint clay coats on pore walls and nodules surface; very few very fine and few fine vesicular; very few very fine and fine roots; many Fe oxides oncretions and nodules; moderately acid (field pH 6.0); gradual, smooth boundary to Bto3.
Bto3	70-100	Yellowish red (5YR 5/6); very gravelly sandy clay; moderate fine and medium subangular blocky structure parting along nodules surface; very hard dry, friable moist, moderately sticky and moderately plastic; common faint clay coats on pore walls and nodules surface; very few very fine and few fine vesicular; very few very fine and fine roots; many Fe oxides concretions and nodules; moderately acid (field pH 6.0); gradual, smooth boundary to Bto4.
Bto4	100-126	Reddish brown (5YR 5/4); very gravelly sandy clay; moderate fine and medium subangular blocky structure parting along nodules surface; very hard dry, friable moist, moderately sticky and moderately plastic; common faint clay coats on pore walls and nodules surface; very few very fine and few fine vesicular; practically no roots; many Fe oxides concretions and nodules; moderately acid (field pH 6.0); clear, smooth boundary to Bto5.
Bto5	126-150	Yellowish red (5YR 5/6), red (2.5YR 5/6) and light reddish gray (2.5YR 7/1); very gravelly sandy clay; moderate fine and medium subangular blocky structure parting along nodules surface; very hard dry, friable moist, very sticky and very plastic; common faint clay coats on pore walls and nodules surface and thick clay mass spotted layer; very few very fine and few fine vesicular and few fine tubular pores; practically no roots; many Fe oxides concretions and nodules and few fine cracks; very strongly acid (field pH 4.5); abrupt, smooth boundary to 2Bv1.
2Bv1	150-175	Light gray (10Y 7/1) 80% and reddish yellow (7.5 YR 6/8) 20%; very gravelly clay; strong fine and medium subangular blocky structure; very hard dry, very friable moist, very sticky and very plastic; common distinct clay coats on nodules surface; very few very fine and fine vesicular; practically no roots; common fine cracks; very

		strongly acid (field pH 4.5); gradual, smooth boundary to 2Bv2.
2Bv2	175-200^{+}	Light gray (10Y 7/1) 80% and reddish yellow (7.5 YR 6/8) 20%; very gravelly clay; strong fine and medium subangular blocky structure; very hard dry, very friable moist, very sticky and very plastic; common distinct clay coats on nodules surface; very few very fine and fine vesicular; practically no roots; many Fe-Mn nodules and concretion and common fine cracks; very strongly acid (field pH 4.5).

Borabue series

I Information on the site

Profile symbol : Bb
Soil name : Borabue
Classification : Plinthic Haplustult Loamy-skeletal, mixed, isohyperthermic
Date of examination : July 17, 2009
Described by : Irb Kheoruenromne, Kamolwan Laopoolkit, Wipawan Thaymuang, Khwunta Khawmee, Wittaya Jindaluang, Daojarus Ketrot, Boontarik Chimchart, Chalermraj Jitjaroenporn, Worachart Wisawapipat.
Location : Approximately 200 m North of Road 23 at Km Approximately 5 from Road No.2. Ban Nong Don, Amphoe Kutrang, Changwat Maha Sarakham
Elevation : Approximately 215 m (MSL)
Map sheet number : Coordination : 48 273198^{E}, 1774996^{N}

Landform
1. Physiographic position : Corrosion plain (calcareous sandstone)
2. Surrounding land form : Undulating
3. Slope on which profile site : 4% Aspect: 198 Azi
Land use : Plowed before planting cassava and corn

Annual rainfall : Approximately 1,200 mm
Mean temperature : Approximately 26˚C
Climate : Tropical Savanna
Others : Agricultural and settlement

II General information on the soil

Parent material : Residuum derived from weathered calcareous sandstone
Drainage : Well drained
Permeability : Moderate
Runoff : Moderate
Depth of ground water : Deeper than 130 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-15	Dark grayish brown (10YR 4/2) 90% and yellowish brown (10YR 5/4) 10%; sandy loam; moderate weak fine and medium subangular blocky structure; slightly hard dry, friable moist, non sticky and non plastic; few very fine and common fine vesicular pores; many very fine, fine and few medium roots; few fine variegated sands and common traces of dead roots and few fine

		charcoal fragments; strongly acid (field pH 5.5); clear, smooth boundary to Bt1.
Bt1	15-25/30	Reddish yellow (7.5 YR 6/6); 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 very fine and common fine vesicular pores; common very fine and fine roots; few fine variegated sands and few traces of dead roots and few fine charcoal fragments; very strongly acid (field pH 5.0); clear, wavy boundary to Bt2.
Bt2	25-36	Strong brown (7.5YR 5/8) 70% and reddish yellow (7.5YR 6/6) 30%; sandy clay loam; moderate fine and medium subangular blocky structure; hard dry, slightly firm moist, slightly sticky and moderately plastic; common faint clay bridges among sand grains and few faint clay coats on pore walls; few very fine and common fine vesicular and few fine simple tubular pores; few very fine and fine roots; very few fine variegated sands and few traces of dead roots and fine charcoal fragments; very strongly acid (field pH 4.5); abrupt, wavy boundary to 2Btc.
2Btc	36-46/60	Brown (7.5YR 5/4); strong brown (7.5YR 5/8) 10% mottles; gravelly sandy clay; moderate fine and medium subangular blocky structure partially parting along coarse fragments; hard dry, firm moist, moderately sticky and very plastic; common faint clay coats on ped faces and pore walls; few very fine and common fine vesicular and few fine simple tubular pores; few very fine and fine roots; very few fine variegated sands and few fine cracks and common sandstone fragments and few fine ferruginized rock fragments and few traces of dead roots; very strongly acid (field pH 4.5); abrupt, wavy boundary to 2Crt1.
2Crt1	60-80	Light brown (7.5YR 6/4); strong brown (7.5YR 5/8) 15% mottles; very gravelly sandy clay; strong fine and medium subangular blocky structure partially parting along weathered rock fragments; very hard dry, firm moist, moderately sticky and very plastic; common faint clay coats on ped faces and pore walls; few very fine and common fine vesicular and few fine simple tubular pores and few medium vesicular pores; few very fine and fine roots; few fine variegated sands and few traces of dead roots and many parts are weathered sandstone retaining rock structure; very strongly acid (field pH 4.5); gradual, smooth boundary to 2Crt2.
2Crt2	80-115^{+}	Pinkish gray (7.5YR 7/2); strong brown (7.5YR 5/8) 30% mottles; very gravelly sandy clay loam; strong fine and medium subangular blocky structure partially parting along weathered rock fragments; very hard dry, firm moist, moderately sticky and very plastic; common faint clay coats on ped faces and pore walls; few very fine and common fine vesicular and few fine simple tubular pores and few medium vesicular pores; few very fine and fine roots; few fine variegated sands and few traces of dead roots and many parts are weathered sandstone retaining rock structure; very strongly acid (field pH 5.0).

Sikhio series

I Information on the site

Profile symbol : Si
Soil name : Sikhio
Classification : Typic Rhodustalf; Fine, mixed, isohyperthermic
Date of examination : May 5, 2009
Described by : Irb Kheoruenromne, Somchai Anusonpornperm, Kamolwan Laopoolkit, Wipawan Thaymuang, Khwunta Khawmee, Wittaya Jindaluang, Daojarus Ketrot, Boontarik Chimchart, Chalermraj Jitjaroenporn, Worachart Wisawapipat.
Location : Approximately 4 m East of Sikhiu-Dan Khuntut at Km 5 from Mitraparb. Amphoe Sikhiu, Changwat Nakhon Ratchasima
Elevation : Approximately 242 m (MSL)
Map sheet number : Coordination : 47 788819^{E}, 1650348^{N}

Landform
1. Physiographic position : Corrosion plain (calcareous sandstone)
2. Surrounding land form : Undulating
3. Slope on which profile site : 4% Aspect: 198 Azi
Land use : Plowed before planting cassava and corn

Annual rainfall : Approximately 1,200 mm
Mean temperature : Approximately 26˚C
Climate : Tropical Savanna
Others : Agricultural and settlement

II General information on the soil

Parent material : Residuum derived from weathered calcareous sandstone
Drainage : Well drained
Permeability : Moderate
Runoff : Moderate
Depth of ground water : Deeper than 130 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap1	0-12	Yellowish red (5YR 5/6); sandy clay loam; moderate fine and medium subangular blockly structure ; hard dry, firm moist, moderately sticky and very plastic; many very few and common fine vesicular pores; common very fine and fine roots; few rock fragments and traces of dead roots; moderately alkaline (field pH 8.0); clear, smooth boundary to Ap2.
Ap2	12-30	Reddish brown (5YR 4/4); sandy clay loam; moderate fine and medium subangular blockly structure; hard dry, firm moist, moderately sticky and very plastic; very few faint clay coats on pore walls; common very few and fine vesicular pores and few fine tubular pores; common very fine and fine roots; few rock fragments and common traces of dead roots and few large pores; neutral (field pH 7.0); abrupt, smooth boundary to Btk1.

Btk1	30-54	Reddish brown (5YR 4/4) 95% and pinkish white (5YR 8/2) 5%; clay; strong medium and coarse semi-angular blocky structure; very hard dry, firm moist, very sticky and very plastic; common faint clay coats on pore walls and ped face; few very fine and common fine vesicular and few fine tubular pores; few very fine and fine roots; few rock fragment and very fine lime fragment and few traces of dead roots, effervesce with HCl; moderately alkaline (field pH 8.0); gradual, smooth boundary to Btk2.
Btk2	54-79	Reddish brown (5YR 4/4) 90% and pinkish white (5YR 8/2) 10%; clay; strong fine and medium subangular blocky structure; very hard dry, firm moist, very sticky and very plastic; common faint clay coats on pore walls and ped face; few very fine and common fine vesicular and few fine tubular pores; few very fine and fine roots; few rock fragment and very fine lime fragment and few fine dark Mn-oxides nodules and few traces of dead roots; moderately alkaline (field pH 8.0); clear, smooth boundary to Btk3.
Btk3	79-108	Reddish brown (2.5YR 4/4) 80% and pinkish white pink (5YR 8/2) 20%; clay; strong medium and coarse semi-angular blocky structure; very hard dry, firm moist, very sticky and very plastic; common faint clay coats on pore walls and ped face and some lime coats in pore walls; very few very fine and few fine vesicular and few tubular pores; few very fine and fine roots; lime fragments and few fine dark Mn-oxides nodules and few traces of dead roots; moderately alkaline (field pH 8.0); clear, smooth boundary to Btk4.
Btk4	108-130^{+}	Reddish brown (2.5YR 4/4) 70% and pink (5YR 8/5) 30%; clay; strong fine and medium semi-angular blocky structure; very hard dry, firm moist, very sticky and very plastic; common faint clay coats on pore walls and ped face and some lime coats in pore walls; very few very fine and few fine vesicular and few tubular pores; very few very fine and fine roots; lime fragments and few fine dark Mn-oxides nodules and few traces of dead roots; moderately alkaline (field pH 8.0).

Note: Btk1-4 effervesces with dilute HCl and increasing with depth.

Nam Phong series

I Information on the site

Profile symbol : Ng
Soil name : Nam Phong (Ng)
Classification : Psammentic Haplustalf; Loamy-skeletal, siliceous, isohyperthermic
Date of examination : July 18, 2009
Described by : Irb Kheoruenromne, Kamolwan Laopoolkit, Wipawan Thaymuang, Khwunta Khawmee, Wittaya Jindaluang, Daojarus Ketrot, Boontarik Chimchart, Chalermraj Jitjaroenporn, Worachart Wisawapipat.
Location : Approximately 45 m Northeast of Road from no.2 intersection to Ubolrat Dam at Km 350 m from the intersection. Ban Koon Yai Tambon, Amphoe Nampong Changwat Khonkaen
Elevation : Approximately 185 m (MSL)
Map sheet number : 5542I Coordination : 48 265394^{E}, 1844826^{N}

Landform
1. Physiographic position : Shoulder slope on dissected lower footslope
2. Surrounding land form : Undulating
3. Slope on which profile site : 6% Aspect: 76 Azi
Land use : Cassava field (not so healthy)
Annual rainfall : Approximately 1,300 mm
Mean temperature : Approximately 26˚C
Climate : Tropical Savanna
Others : Agricultural and settlement

II General information on the soil

Parent material : Wash over local alluvium over mixed local alluvium and colluvium
Drainage : Well drained
Permeability : Rapid
Runoff : Slow
Depth of ground water : Deeper than 202 cm at time of sampling

III Profile description

Horizon	**Depth (cm)**	**Description**
Ap1	0-20	Brown (10YR 4/3); loamy sand; weak fine and medium subangular blocky structure; soft dry, very friable moist, non sticky and non plastic; few very fine and common fine vesicular pores; many very fine, fine and few medium roots; few fine variegated sands and common traces of dead roots and few fine charcoal fragments; slightly acid (field pH 6.5); gradual, smooth boundary to Ap2.
Ap2	20-35/40	Brown (10YR 4/3); loamy sand; weak fine and medium subangular blocky structure; soft dry, friable moist, non sticky and non plastic; very few very fine and few fine vesicular pores; common very fine, fine and very few medium roots; few fine variegated sands and few traces of dead roots and few fine charcoal fragments; strongly acid (field pH 5.5); abrupt, wavy boundary to E1.

E1	40-68/70	Reddish yellow (7.5YR 6/6); loamy sand; weak fine and medium subangular blocky structure; soft dry, very friable moist, non sticky and non plastic; few very fine and common fine vesicular pores; few very fine, fine and medium roots; few faint variegated sands and quartz fragments and very few traces of dead roots and common fine charcoal fragments; moderately acid (field pH 6.0); abrupt, smooth boundary to E2.
E2	70-95/100	Reddish yellow (7.5YR 6/6); loamy sand; moderate weak fine and medium subangular blocky structure; slightly hard dry, friable moist, non sticky and non plastic; very few very fine, few fine and medium vesicular pores; few very fine and fine roots; very few faint variegated sands and few fine charcoal fragments; moderately acid (field pH 6.0); abrupt, wavy boundary to 2Bt1.
2Bt1	100-125	Yellowish red (5YR 4/6); sandy loam; strong fine and medium semi-angular blocky structure; hard dry, firm moist, slightly sticky and moderately plastic; common distinct patchy ferri-argillan coats on ped faces and pore walls; very few very fine and common fine and few medium vesicular pores; very few very fine and fine roots; few variegated sands and quartz fragments and soft Fe-oxide accumulation and few traces of dead roots and few fine Fe-Mn oxide nodules; strongly acid (field pH 5.5); clear, smooth boundary to 2Bt2.
2Bt2	125-150	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; common distinct patchy ferri-argillan coats on ped faces and pore walls; very few very fine and common fine and few medium vesicular pores; very few very fine and fine roots; few variegated sands and quartz fragments and soft Fe-oxide accumulation and very few traces of dead roots and very few fine Fe-Mn oxide nodules; very strongly acid (field pH 4.5); gradual, smooth boundary to 2Bt3.
2Bt3	150-175	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; common distinct patchy ferri-argillan coats on ped faces and pore walls; very few very fine and common fine and few medium vesicular pores; very few very fine and fine roots; few variegated sands and quartz fragments and soft Fe-oxide accumulation and very few fine Fe-Mn oxide nodules; very strongly acid (field pH 4.5); abrupt, smooth boundary to 3C.
3C	175-202^{+}	Red (2.5YR 4/6); very gravelly sandy loam; moderate fine and medium semi-angular blocky structure parting along rock fragments; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; few faint clay coats on pore walls; very few very fine and few fine vesicular pores; practically no roots; many rock fragments and few traces of dead roots; very strongly acid (field pH 4.5).

Chan Thuek series

I **Information on the site**

Profile symbol	: Cu
Soil name	: Chan Thuek (Cu)
Classification	: Psammentic Haplustalf; Loamy-skeletal, kaolinitic, isohyperthermic
Date of examination	: July 29, 2009
Described by	: Irb Kheoruenromne, Kamolwan Laopoolkit, Wipawan Thaymuang, Khwunta Khawmee, Wittaya Jindaluang, Daojarus Ketrot, Boontarik Chimchart, Chalermraj Jitjaroenporn, Worachart Wisawapipat.
Location	: Approximately 30 m East of Pakchong-Nong Sarai Road Ban Klongsai, Tambon Nong Sarai, Pakchong, Changwat Nakhon Ratchasima
Elevation	: Approximately 333 m (MSL)
Map sheet number	: Coordination : 47 764153^{E}, 1624570^{N}
Landform	
1. Physiographic position	: Upper midslope
2. Surrounding land form	: Undulating
3. Slope on which profile site	: 5% Aspect: 262 Azi
Land use	: Corn field plowing and soaked for new planting
Annual rainfall	: Approximately 1,300 mm
Mean temperature	: Approximately 26˚C
Climate	: Tropical Savanna
Others	: Agricultural and settlement

II **General information on the soil**

Parent material	: Residuum derived from weathered granite
Drainage	: Well drained
Permeability	: Moderate
Runoff	: Moderate
Depth of ground water	: Deeper than 200 cm at time of sampling

III **Profile description**

Horizon	Depth (cm)	Description
Ap1	0-20	Very dark gray (7.5YR 3/1); loamy sand; moderate weak fine and medium subangular blocky structure; slightly hard dry, very friable moist, non sticky and non plastic; few very fine, fine and medium vesicular pores; common very fine, fine and many medium roots; few fine variegated sands and few traces of dead roots; neutral (field pH 7.0); clear, smooth boundary to Ap2.
Ap2	20-45	Dark gray (7.5YR 4/1); loamy sand; moderate weak fine and medium semi-angular blocky structure; hard dry, friable moist, non sticky and non plastic; common very fine, fine and few medium vesicular pores; few very fine and fine roots; common fine variegated sands and few traces of dead roots; slightly alkaline (field pH 7.5); clear, wavy boundary to AB.
AB	45-70	Dark gray (7.5YR 4/1); 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 very fine and common fine and few medium vesicular pores; few very fine and few roots; few

		variegated sands and few traces of dead roots; neutral (field pH 7.0); clear, smooth boundary to Bt1.
Bt1	70-95	Dark gray (7.5YR 4/1); slightly gravelly coarse sandy loam; moderate fine and medium subangular blocky structure; hard dry, slightly firm moist, slightly sticky and slightly plastic; few faint clay coats on ped faces and pore walls; very few very fine and common fine and few medium vesicular pores; few very fine and fine roots; few variegated sands and few traces of dead roots; neutral (field pH 7.0); gradual, smooth boundary to Bt2.
Bt2	95-120	Dark gray (5YR 4/1); dark yellowish brown (10R 4/4) 7% sand grain; slightly gravelly coarse sandy loam; strong 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; very few very fine and common fine and few medium vesicular pores and few tubular pores; few very fine and fine roots; common variegated sands and few traces of dead roots; neutral (field pH 7.0); gradual, smooth boundary to Bt3.
Bt3	120-150	Dark gray (5YR 4/1) 45% and gray (5YR 5/1) 40%; dark yellowish brown (10R 4/4) 12% and pinkish white (2.5YR 8/2) 3% sand grain; coarse sandy clay loam; strong fine and medium subangular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; few faint clay coats on ped faces and pore walls; very few very fine and few fine and medium vesicular pores and few tubular pores; very few very fine and fine roots; common variegated sands and common white spots of feldspar-kaolinite mixture and few traces of dead roots and few black and dark spots of Mn-oxides and Fe-Mn oxides nodules; neutral (field pH 7.0); gradual, smooth boundary to Bt4.
Bt4	150-178	Dark gray (5YR 4/1) 28% and gray (5YR 5/1) 28%; strong brown (7.5YR 5/6) 20%, yellowish red (5YR 5/6) 20% and pinkish white (2.5YR 8/2) 4% sand grain; slightly gravelly coarse sandy loam; strong fine and medium subangular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; few faint clay coats on ped faces and pore walls; very few very fine and few fine and medium vesicular pores and few tubular pores; practically no roots; common variegated sands and common white spots of feldspar-kaolinite mixture and some increases of large quartz grains and few trace of dead roots and some weathered rock fragment; neutral (field pH 7.0); clear, smooth boundary to BCrt.
BCrt	178-200^{+}	Dark gray (5YR 4/1) 48%; strong brown (7.5YR 5/6) 30% and pinkish white (2.5YR 8/2) 7%; black (10YR 2/1) 15% Mn; slightly gravelly coarse sandy clay loam; strong fine and medium subangular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; few faint clay coats on ped faces and pore walls; few very fine, fine and medium vesicular pores and few tubular pores; practically no roots; common variegated sands and common white spots of feldspar-kaolinite mixture and some increases of large quartz grains and few trace of dead roots and some weathered rock fragment; slightly acid (field pH 6.5).

Appendix B

Methods of Laboratory Analyses

1. Physicochemical Analyses of Bulk soils

1.1 Particle Size Analysis

Particle size analysis was carried out to evaluate soil texture. A mass of 10 g air dried soil sample was pretreated to remove free soluble salt by washing in distilled water, centrifuging and decanting. For dispersion of soil, the soil was placed in a milk shake container and 10 mL of 5% sodium hexametaphosphate, a dispersing agent, was added. The volume of the contents was made up to about 200 mL with deionized water; the contents were stirred for 15 minutes on the milk shake mixer. The contents were then sieved through a 300-mesh (0.047 mm) sieve into a one litre cylinder and volume was made up to about 200 mL with deionized water. The sand grains that remained in the sieve were dried at 105°C overnight and were weighed. The suspension in the cylinder was stirred well with an agitator in an up-down motion for 30 seconds. The pipette method was used as a direct sampling procedure. Twenty five milliliters of suspension was pipetted from a depth of 10 cm for clay at appropriate times based on Stoke's Law (i.e. at 25°C for <0.002 mm sized fraction sampling time at 10 cm depth is 6 hr). Suspensions were dried at 105°C and weighed (Gee and Bauder, 1986). The amount of sand, silt and clay were calculated. The percentage of clay (<2 μm), silt (0.002 to 0.05 mm) and sand (0.05 to <2 mm) were plotted on ternary plots, and soils were classified using soil textural triangle classes (Soil Survey Staff, 2006).

1.2 Hydraulic Conductivity (K_{sat})

A saturated undisturbed soil (core sample) was installed in a cylinder and supplied with water to the bottom of the sample. During the water flow in the standpipe, measured the time for the water level to fall from H_1 to H_2. Calculation of the hydraulic conductivity was from the equation:

$$K_{sat} = (aL/At)\ \log_e (H_1/H_2)$$

Where Ksat= hydraulic conductivity value, a = the cross sectional area of the standpipe, L= the soil sample length, A= cross section area of the sample, t= time, H_1 = height of initial water and H_2= height of final water (Klute and Dirksen, 1986)

1.3 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 2-3 cm, diameter) 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 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).

1.4 Soil pH

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

1.5 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 sulfate (Nelson and Sommers, 1996). A weight of 1.0 g of soil (<0.5 mm) was placed in a 250 mL Erlenmeyer flask. Five mL of 1 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 took on a greenish cast and then changed to dark green. The flask was allowed to stand with occasional swirling for 30 minutes. Then 30 mL of deionized water was added to the flask, swirled gently then 3-4 drops of o-phenanthroline indicator were added and the solution was titrated with 1 M $FeSO_4$ until the color changed to a red end point.

1.6 Available Phosphorus

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

1.7 Available Potassium

A soil sample weighing 10 g was placed in an Erlenmeyer flask and approximately 50 mL 1 M 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. K contents in the leachate were determined by atomic absorption spectrophotometry.

1.8 Base Saturation Percentage (BSP)

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).

1.9 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 (Thomas, 1982a). A soil sample weighing 10 g for clayey and 25 g for sandy soil was placed in an Erlenmeyer flask and approximately 50 mL 1 M 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. Calcium, Mg, K and Na contents in the leachate were determined by atomic absorption spectrophotometry.

1.10 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, 1987b). It includes all acidity generated by replacement of the hydrogen and aluminum ions from permanent and pH-dependent exchange sites. A soil sample weighing 4 g was placed in an Erlenmeyer flask and 100 mL of buffer solution at 8.2 (0.5 M $BaCl_2$ H_2O and 2 N triethanolamine) were added. The contents were topped by rubber bung, shaken for 30 min, left to stand overnight and shaken 30 min then left for 2 hours. Taken 50 mL of the content by using the pipette controller, placed to new Erlenmeyer flask. The extracts were added 3 drops of mixed indicator (bromocresol green and methyl red in 95% ethyl alcohol). 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 buffer solution was titrated with 0.2 M HCl as the blank in the same condition as extract samples. The amount of HCl consumed was used to calculate the extractable acidity expressed as cmol H^+ kg^{-1}.

1.11 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 (Chapman, 1965; National Soil Survey Center, 1996). The 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 for clayey and 25 g for sandy soils was placed in an Erlenmeyer flask, to which 50 mL of 1M NH_4OAc at 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 1M 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 a Kjeldahl flask to which 25 mL of 50% NaOH were added. 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 0.01M 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 by sum) 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).

1.12 Base Saturation

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).

1.13 Extractable Fe, Al, Mn

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 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 spectrophotometer (AAS), standard solutions of these elements were prepared in a matrix of extracting solution (Mehra and Jackson, 1960).

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).

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 (National Soil Survey Center, 1996). 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.

2. Mineralogical Analysis

X-Ray Diffraction (XRD) for Clay and Silt Fraction Samples. The clay fraction for mineralogical analysis was separated by using a sedimentation procedure. Pre-treatments of the 2 mm soil to remove organic carbon were by using H_2O_2 (Gee and Bauder, 1986). The clay fraction for mineralogical analysis was separated using the same method with particle size analysis in above procedure to obtain 10 g of clay fraction. 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 free excess salt. The Dithionite-Citrate-Bicarbonate method (DCB) was used to remove iron. The dialysis method was used to remove salt from the clay fraction. The DI water overriding the dialysis tube was replaced several times until the conductivity of the water was equal to that of the DI water.

X-ray diffraction analysis was used to identify and to make semiquantitative measurements of the crystalline mineral components of the clay fraction. The clay fraction from sedimentation was pretreated using 4 treatments. The clay after Mg^{2+} and K^+ saturation were placed on ceramic plates, washed with ≈10% glycerol on the Mg^{2+} saturation plates for the glycerol treatment, and heated to 550 ^{o}C for the K^+ saturation plate for heat treatment (Brindley and Brown, 1980). Minerals were determined for all horizons by X-ray diffraction (XRD) analysis using a monochromatised CuKα radiation with a Philips PW-3020 diffractometer (Cu Kα, 50kV, 20mA). Clay fractions were scanned respectively from 4 to 45° 2θ, using a step size of 0.02° 2θ and a scan speed of 0.04° 2θ sec^{-1}. Silt was prepare as a random powder for some horizons and analyzed using a Philips X'Pert diffractometer (Co Kα, 50kV, 20mA), scanned from 4 to 65° 2θ.

Relative proportions of various minerals were calculated by comparing the XRD peak intensity with the intensity for standard minerals (Brindley and Brown, 1980).

3. Analysis of Aggregation

3.1 Wet Aggregate Stability

Aggregate stability was determined following the principle that unstable aggregates will break down more easily than stable aggregates when dry aggregates are immersed to water. For this study, the wet sieving method described by Kemper and Rosenau (1986) was used to determine aggregate stability. Aggregates of 1 to 2 mm size have been found by these and other workers (Seybold and Herrick 2001; Ruiz-Vera and Wu 2006) to be best suited to the screen size and sieving speed employed in this procedure.

Four grams of 1 to 2-mm air-dried soil aggregates in a sieve were slowly pre-moistened with distilled water to prevent slaking of the aggregates, then the filled sieve was placed into a can filled with distilled water. To determine aggregate stability, the sieve (60 mesh) was immersed for 5 minutes then the sieve was lowered and raised for 3 minutes with a stroke of 1.3 cm, at about 34 strokes/min. Unstable aggregates slaked and/or dispersed and resultant fine materials passed through the sieve and were collected in the water-filled can underneath the sieve. After this fixed time, the liquid was removed and water containing 2 g L^{-1} sodium hexametaphosphate was added to the can for soils with pH > 7 or 2 g L^{-1} NaOH for soils with pH < 7 and the remaining soil was wet sieved to disperse remaining aggregates and separate the sand fraction from the silt and clay fractions. The aggregates that remained stable after 3 minutes of sieving were gently rubbed across the screen with a rubber tipped rod so that all aggregates were destroyed and the fine residue on the sieve was washed into the collecting can. Sand grains and plant roots remained on the sieve so that the mass of aggregates could be calculated by difference. After drying the suspensions with the disaggregated material from the aggregates, the weight of both stable and unstable aggregates were determined. Dividing the weight of stable aggregates by the total aggregate weight gives an index of aggregate stability. Statistical analysis of data was limited to regression analysis and utilised Statview software (StatSoft Inc. 2003).

3.2 Aggregate size distribution in <8000 μm

Aggregate separations were done by wet sieving of aggregate resultant of <8000 μm. There was rapidly immersed in water (slaked treatment). The <8000 μm air dried gently crushed and then passed through 2000, 250 and 53-μm sieves. A 100-g subsample was used to separate four aggregate fractions by a wet-sieving method adopted from Elliott (1986). First, the soil was submerged for 5 minutes in deionised water to allow slaking. Then, the soil was successively passed through a series of three sieves to separate four fractions. Aggregate fractions were oven dried (50°C), weighed and stored in glass jars at room temperature (21°C). Sand correction was performed in each aggregate-size class because sand was not considered part of those aggregate (Elliot *et al*., 1991). Aggregate size classes were expressed as:

a) Large macroaggregates = LMA (2000-8000 µm)

b) Small macroaggregates = SMA (250–2000 µm)

c) Microaggregates = MiA (53–250 µm)

d) Silt and clay fraction = SCf (<53 µm)

Microaggregates contained within stable macroaggregates (>2000 and 250- to 2000-µm) were mechanically isolated according to the methodology described by Six *et al*. (2000) and Denef *et al*. (2004). Briefly, a 10-g macroaggregate subsample was immersed in deionized water on top of a 250-µm mesh screen inside a cylinder. Macroaggregates were shaken together with 50 glass beads (4-mm diameter) until complete macroaggregate disruption was observed. Once the macroaggregates were broken up, microaggregates and other <250-µm material passed through the mesh screen with the help of a continuous water flow until a 53-µm sieve. The material retained on the 53-µm sieve was wet sieved to ensure that the isolated microaggregates were water stable (Six *et al*., 2000).

3.3 Silt and Clay Fractions

Firstly, a moist soil sample (<8000 µm; equivalent to 50 g air dried soil) was submersed in distilled water for 5 minutes on top of a sieve (250 and 53 µm aperture) and the sieve was moved 50 times by a wet-sieving method adopted from Elliott (1986). Secondly, the macroaggregates (>250 µm) of all samples were dispersed by ultrasonic dispersion using an energy input of 60 J ml^{-1}. Thereafter the fractions >53 mm were removed by wet sieving. Finally, all silt and clay fraction (<53 µm) were dried (50 ˚C), weighed and analyzed for total C content.

3.4 Particle Size Composition of Aggregate Size Classes and Isolated 53-250 µm and <53 µm Fraction from >250 µm

The resultant of all aggregate size fractions were used for separate particle size distribution; clay particle (<2 µm), silt particle (2-53 µm) and sand particle (>53 µm); was further dispersed by ultrasonification (10 minutes) to disrupt persisting microaggregates and then fractionated by sedimentation. A capillary-rewetted was used for isolated microcroaggregate (53-250 μm) and silt and clay fraction (<53 μm) from macroaggregate (>250 μm).

The 100 g air-dried >250 μm were capillary-rewetted before immersion in water (rewetted treatment). Dried-soils were placed on filter paper that was slowly moistened until a water content of 1.05 times field capacity was reached. The volumetric water content of the soil at field capacity was determined for all individual samples. A higher amount of disruptive energy occurs upon slaking because rapid wetting of dry soil leads to an entrapment of air and a buildup of air pressure within the aggregates (Kemper *et al*., 1985). Aggregates of lower stability disrupt because they cannot withstand this pressure. In contrast, soil rewetted to 1.05 times field capacity is at maximum. Rewetted aggregate >250 μm submerged for 5 min on a 250 μm sieve and separate in to <53 and 53-250 μm by a wet-sieving method. The 53-250 μm and <53 μm fractions were oven-dried and weighed.

3.5 Mean Weight Diameter

An approximation of the median size of the aggregates was calculated as:

Mean weight diameter (MWD): An approximation of the median size of the water- stable aggregates was calculated as:

$$\text{MWD (mm)} = \sum_{i=1}^{n} \overline{\chi}_i \times \omega_i \qquad (2)$$

where is $\overline{\chi}$ the mean diameter of each size fractions, and ω_i is the proportional weight of the corresponding size fractions (Kemper and Rosenau, 1986).

where MWD is the mean weight diameter in μm, *a* the fraction 8000-2000 μm in wt.%, *b* the fraction 250–2000 μm in wt.%, *c* the fraction 250– 53 μm in wt.% and *d* the fraction < 53 μm in wt.%.

3.6 Water aggregate stability

Water aggregate stability (WAS) was measured with the single sieve method (Kemper and Rosenau, 1986). Unstable aggregates will break down more easily than destable aggregates when immersed in to water. Aggregates of 1 to 2 μm size have been found by these and other workers (Seybold and Herrick, 2001; Ruiz-Vera and Wu, 2006) to be best suited to the screen size and sieving speed employed in this procedure. After drying the suspensions with the disaggregated material from the aggregates, the weight of both stable and unstable aggregates were determined.

Water aggregate stability (WAS): Water aggregate stability was measured with the single sieve method (Kemper and Rosenau, 1986). After drying the suspensions with the disaggregated material from the aggregates, the weight of both stable and unstable aggregates were determined using the equation;

$$\text{WAS (\%)} = \frac{\text{Retained soil material - Sand}}{\text{Soil sample - Sand}} \times 100 \qquad (1)$$

4. Carbon Analyses and the Computation of Carbon Pools

Total C in bulk soils and four fractions were determined by a dry combustion method using a TruSpec CN soil and sediment Analyzer (Truespec Leco CNS). Carbon stocks (Mg C ha^{-1}) were calculated from total C concentration (g C kg^{-1} soil) and bulk density (ρ_d) (Mg m^{-3}) for all depth sections (D). Carbon stocks were corrected for specific differences in bulk density of each horizon (Veldkamp, 1994).

$$\text{C pool layer (Mg ha}^{-1}\text{)} = \text{C layer (kg Mg}^{-1}\text{)} \times \rho_d \text{ layer (Mg m}^{-3}\text{)} \times \text{D (m)} \times 10^{-3}\text{Mg kg}^{-1} \times 10^{4}\text{m}^{2}\text{ ha}^{-1} \qquad (3)$$

All aggregate fractions were oven dried at 50 ˚C. Total carbon and nitrogen in aggregate size were measured by a dry combustion method using a TruSpec CN soil and sediment analyzer (Truespec Leco CNS).

Appendix C

Results of Laboratory Analyses

Appendix Table C1 Physical properties of major upland agricultural soil in Northeast Plateau, Thailand.

Horizon	Depth	Sand	Silt	Clay	Textural class	Bulk density	Ksat
	(cm)		(g kg^{-1})			(Mg m^{-3})	(cm hr^{-1})
Loei (Lo): *Typic Kandiustox*							
Ap1	0-20	205	433	362	Clay loam	1.52	5.92
Ap2	20-35	179	419	403	Clay loam	1.62	0.08
Bt1	35-55	142	325	533	Silty clay	1.39	
Bt2	55-85	106	335	558	Clay	1.39	
Bt3	85-110	114	303	583	Clay	1.40	
Bt4	110-140	107	364	529	Clay	1.46	
Bt5	140-165/170	119	361	519	Clay	1.38	
C	170-180+	143	368	489	Clay	1.46	
Chok Chai (Ci): *Rhodic Kandiustox*							
Ap1	0-10	115	129	756	Clay	1.12	nd
Ap2	10-27	106	62	832	Clay	1.13	nd
Bto1	27-55	88	73	840	Clay	1.05	
Bto2	55-88	73	71	856	Clay	0.99	
Bto3	88-110	72	72	856	Clay	1.00	
Bo1	110-132	81	63	856	Clay	1.03	
Bo2	132-160	91	89	820	Clay	1.02	
Bo3	160-200	90	106	804	Clay	1.01	
Pak Chong (Pc1): *Rhodic Kandiustox*							
Ap1	0-18	87	105	808	Clay	1.28	2.21
Ap2	18-30	65	81	854	Clay	1.46	0.009
Bt1	30-58	40	10	950	Clay	1.18	0.96
Bt2	58-88	36	31	933	Clay	1.22	
Bto1	88-110	35	16	949	Clay	1.25	
Bto2	110-138	36	40	924	Clay	1.15	
Bto3	138-175	42	38	920	Clay	1.24	
Bto4	175-200+	50	34	916	Clay	1.28	
Pak Chong (Pc2): *Rhodic Kandiustox*							
Ap1	0-15	127	52	821	Clay	1.18	9.48
Ap2	15-35	64	157	779	Clay	1.23	8.04
Bt1	35-65	41	101	858	Clay	1.41	0.54
Bt2	65-90	30	45	925	Clay	1.32	
Bto1	90-120	25	91	883	Clay	1.28	
Bto2	120-148	29	92	879	Clay	1.21	
Bto3	148-172	27	64	908	Clay	1.22	
Bto4	172-200+	35	69	896	Clay	1.22	
Pak Chong (Pc3): *Rhodic Kandiustox*							
Ap	0-28	64	98	838	Clay	1.30	1.9
Bt1	28-50	21	50	929	Clay	1.28	0.052
Bt2	50-80	16	18	967	Clay	1.18	
Bt3	80-100	16	9	975	Clay	1.20	
Bt4	100-123	18	12	971	Clay	1.21	
Bt5	123-147	19	6	975	Clay	1.28	
Bt6	147-173	20	35	945	Clay	1.29	
Bt7	173-200+	21	29	949	Clay	1.24	

Appendix Table C1 (Continued).

Horizon	Depth (cm)	Sand	Silt	Clay	Textural class	Bulk density (Mg m^{-3})	Ksat (cm hr^{-1})
		(g kg^{-1})					
Pak Chong (Pc4): *Typic Kandiustox*							
Ap1	0-13/15	152	515	333	Sandy clay loam	1.58	0.98
Ap2	15-32	124	430	446	Sandy clay	1.58	0.31
Bt1	32-52	102	364	533	Clay	1.50	0.49
Bt2	52-75	87	346	567	Clay	1.53	
Bt3	75-100	69	269	662	Clay	1.56	
Bt4	100-120	59	233	708	Clay	1.45	
Bt5	120-143	66	247	688	Clay	1.41	
Bt6	143-170	66	263	671	Clay	1.32	
Bt7	170-200+	74	280	646	Clay	1.30	
Chum Phuang (Cpg): *Typic Kandiustults*							
Ap	0-20	813	104	83	Loamy Sand	1.66	1.28
Bt1	20-45	726	112	162	Sandy loam	1.73	0.51
Bt2	45-75	689	107	203	Sandy clay loam	1.53	0.67
Bt3	75-100	702	111	187	Sandy loam	1.59	
Bt4	100-130	702	127	170	Sandy loam	1.52	
Bt5	130-160	690	135	174	Sandy loam	1.55	
Bt6	160-185	710	115	174	Sandy loam	1.54	
Bt7	185-210+	673	173	154	Sandy loam	1.57	
Sung Noen (Sn): *Typic Kandiustults*							
Ap1	0-10	606	102	292	Sandy clay loam	1.56	0.68
Ap2	10-29	579	88	333	Sandy clay loam	1.53	0.043
Bt1	29-55	427	31	542	Clay	1.51	0.095
Bt2	55-81	429	29	542	Clay	1.50	
Bt3	81-110	411	47	542	Clay	1.53	
Btc	110-135+	444	98	458	Clay	1.67	
Satuek (Suk): *Typic Haplustult*							
Ap1	0-10	696	194	110	Sandy loam	1.54	2.48
Ap2	10-25/30	693	155	152	Sandy loam	1.58	5.26
Bt1	30-55	563	138	300	Sandy clay loam	1.52	1.14
Bt2	55-80	609	151	241	Sandy clay loam	1.62	
Bt3	80-110	618	146	236	Sandy clay loam	1.66	
Bt4	110-140	585	128	287	Sandy clay loam	1.52	
Bt5	140-168	549	155	295	Sandy clay loam	1.61	
Bt6	168-200+	554	198	249	Sandy clay loam	1.68	
Yasothon(Yt): *Typic Kandiustults*							
Ap	0-20	736	114	150	Sandy loam	1.61	4.41
Bt1	20-41	678	131	192	Sandy loam	1.68	0.13
Bt2	41-69	663	137	200	Sandy loam	1.45	0.82
Bt3	69-95	652	115	233	Sandy clay loam	1.52	
Bt4	95-120	647	136	217	Sandy clay loam	1.56	
Bt5	120-142	680	124	196	Sandy clay loam	1.56	
Bt6	142-171	699	89	212	Sandy clay loam	1.56	
Bt7	171-200+	658	113	229	Sandy clay loam	1.65	

Appendix Table C1 (Continued).

Horizon	Depth	Sand	Silt	Clay	Textural class	Bulk density	Ksat
	(cm)		(g kg^{-1})			(Mg m^{-3})	(cm hr^{-1})
Phon Phisai (Pp): *Typic Plinthustult*							
Ap1	0-12	818	107	75	Loamy Sand	1.49	0.29
Ap2	12-28	741	164	96	Sandy loam	1.82	0.39
Btc1	28-48	678	152	170	Sandy loam	1.98	
Btc2	48-70	446	114	441	Clay	1.98	
Btc3	70-100	440	95	465	Clay	2.08	
Btc4	100-126	357	124	519	Clay	2.08	
Btc5	126-150	308	125	567	Clay	2.08	
2Bv1	150-175	269	177	554	Clay	1.97	
2Bv2	175-200+	248	236	516	Clay	1.84	
Borabue (Bb): *Plinthaquic Haplustults*							
Ap	0-15	860	62	79	Loamy Sand	1.45	1.85
Bt1	15-25/30	862	63	74	Loamy Sand	1.56	0.32
Bt2	30-36	729	71	199	Sandy loam	1.56	0.22
2Btc	36-46/60	516	86	398	Sandy clay	1.63	
2Crt1	60-80	605	87	308	Sandy clay loam	1.59	
2Crt2	80-115+	645	139	216	Sandy clay loam	1.71	
Sikhio (Si): *Typic Rhodustalfs*							
Ap1	0-12	527	56	417	Sandy clay	1.56	19.35
Ap2	12-30	520	22	458	Sandy clay	1.60	1.42
Btk1	30-54	415	127	458	Clay	1.64	0.63
Btk2	54-79	354	104	542	Clay	1.64	
Btk3	79-108	316	59	625	Clay	1.69	
Btk4	108-130+	301	74	625	Clay	1.70	
Nam Phong (Ng): *Psammentic Haplustalf*							
Ap1	0-20	865	81	54	Loamy Sand	1.39	4.52
Ap2	20-35/40	836	110	54	Loamy Sand	1.55	3.39
E1	40-68/70	816	130	54	Loamy Sand	1.48	0.85
E2	70-95/100	809	120	71	Sandy loam	1.52	
2Bt1	100-125	690	106	204	Sandy clay loam	1.59	
2Bt2	125-150	667	96	237	Sandy clay loam	1.58	
2Bt3	150-175	674	81	246	Sandy clay loam	1.58	
3C	175-202+	611	107	282	Sandy clay loam	1.89	
Chan Thuek (Cu): *Psammentic Haplustalf*s							
Ap1	0-20	856	86	58	Loamy Sand	1.60	5.43
Ap2	20-45	792	116	91	Loamy Sand	1.72	2.44
AB	45-70	701	141	158	Sandy loam	1.73	0.60
Bt1	70-95	684	137	179	Sandy loam	1.56	
Bt2	95-120	680	138	183	Sandy loam	1.68	
Bt3	120-150	685	128	187	Sandy loam	1.73	
Bt4	150-178	653	130	216	Sandy clay loam	1.75	
BCrt	178-200+	626	132	242	Sandy clay loam	1.59	

Appendix Table C2 Chemical properties of major Upland agricultural soils in Northeast Plateau, Thailand.

Horizon	Depth	pH (1:1)		OM	Avail. P	Avail. K	Extractable Bases				EA	CEC	BS
		H_2O	KCl				Ca	Mg	Na	K			
	(cm)			(g kg^{-1})	(----------mg kg^{-1}-----------	-)	(---------------------------------	-------cmol kg^{-1}-------	------------	------------	------------	---------)	(%)
Loei (Lo):													
Ap1	0-20	6.7	6.5	17.6	40.0	81.7	3.8	0.7	0.21	0.25	9.0	7.4	35.3
Ap2	20-35	7.3	6.5	9.4	1.7	19.1	3.7	0.5	0.05	0.22	6.0	9.4	42.7
Bt1	35-55	7.3	5.9	6.9	1.1	16.6	5.3	0.6	0.04	0.15	7.0	22.0	46.4
Bt2	55-85	7.2	5.8	6.2	1.1	23.8	6.8	0.3	0.06	0.13	11.0	22.4	39.9
Bt3	85-110	7.1	5.6	5.3	0.8	31.9	4.3	0.4	0.08	0.21	14.0	5.4	26.0
Bt4	110-140	6.9	5.3	4.4	0.5	47.6	2.3	0.3	0.12	0.10	15.0	8.8	15.6
Bt5	140-165/170	6.2	5.0	4.3	0.5	45.8	1.0	0.3	0.12	0.37	13.0	7.1	11.8
C	170-180+	6.0	4.7	4.8	1.5	19.8	1.2	0.6	0.05	0.07	11.0	9.0	15.3
Chok Chai (Ci):													
Ap1	0-10	4.3	3.5	24.2	18.0	17.6	0.49	0.03	0.22	0.61	18.5	9.4	6.8
Ap2	10-27	4.5	3.6	13.1	4.4	6.5	0.40	0.35	0.08	0.71	19.0	6.5	7.5
Bto1	27-55	4.7	3.7	9.1	1.2	4.3	0.30	0.26	0.05	0.15	19.5	8.1	3.8
Bto2	55-88	4.5	3.6	7.2	0.8	3.1	0.14	0.15	0.04	0.21	13.0	6.9	4.0
Bto3	88-110	4.5	3.8	3.6	0.8	3.8	0.03	0.14	0.05	0.13	14.0	9.3	2.4
Bo1	110-132	4.7	3.7	3.6	0.5	4.7	0.02	0.12	0.06	0.09	14.0	6.8	2.0
Bo2	132-160	4.4	3.7	5.0	0.5	3.3	0.01	0.07	0.04	0.13	10.0	7.4	2.4
Bo3	160-200	4.6	3.8	3.7	0.5	3.5	0.01	0.06	0.04	0.11	14.0	5.7	1.5
Pak Chong (Pc1):													
Ap1	0-18	6.5	5.6	19.1	41.9	71.9	11.3	1.38	0.18	0.49	4.2	14.6	76.0
Ap2	18-30	7.0	5.8	13.9	30.3	26.4	11.8	1.60	0.07	0.18	3.7	14.8	78.6
Bt1	30-58	7.0	6.2	6.1	0.8	18.4	8.2	1.05	0.05	0.29	3.5	13.6	73.4
Bt2	58-88	6.8	6.3	4.2	0.4	17.1	9.1	0.95	0.04	0.52	4.0	10.9	72.8
Bto1	88-110	7.0	6.3	3.9	0.6	11.3	8.1	0.58	0.03	0.31	5.0	10.4	64.5
Bto2	110-138	4.8	3.7	4.3	0.4	8.8	4.6	0.36	0.02	0.17	11.1	8.9	31.5
Bto3	138-175	4.7	3.7	3.9	0.3	10.5	3.5	0.49	0.03	0.43	11.9	9.4	27.1
Bto4	175-200+	4.4	3.6	3.6	0.3	7.3	2.5	0.36	0.02	0.42	12.1	9.3	21.3

Appendix Table C2 (Continued).

Horizon	Depth	pH (1:1)		OM	Avail. P	Avail. K	Extractable Bases				EA	CEC	BS
		H_2O	KCl				Ca	Mg	Na	K			
	(cm)			(g kg^{-1})	(--------mg kg^{-1}--------)		(-----------------------------------cmol kg^{-1}-------------------------------)						(%)
Pak Chong (Pc2):													
Ap1	0-15	7.2	6.4	24.5	97.4	288.3	11.1	2.1	0.74	0.26	4.46	17.3	76.0
Ap2	15-35	7.3	6.1	12.5	42.6	42.6	12.4	1.9	0.11	0.34	4.70	12.3	75.8
Bt1	35-65	7.1	6.0	9.5	0.8	25.7	10.3	0.9	0.07	0.35	5.45	11.4	68.2
Bt2	65-90	6.0	4.5	6.9	0.4	17.0	6.1	0.9	0.04	0.13	8.91	11.1	44.6
Bto1	90-120	5.6	4.3	5.6	0.4	15.3	7.0	2.5	0.04	0.14	9.41	11.0	50.6
Bto2	120-148	5.3	4.2	4.9	0.3	13.3	6.3	3.0	0.03	0.19	8.66	10.4	52.3
Bto3	148-172	5.5	4.6	6.3	0.4	10.9	7.7	1.6	0.03	0.36	7.43	9.8	56.6
Bto4	172-200+	5.6	4.4	4.9	0.3	14.1	7.2	1.6	0.04	0.10	7.67	11.6	54.0
Pak Chong (Pc3):													
Ap	0-28	5.4	4.3	34.4	5.83	276.4	9.1	2.4	0.71	0.09	14.8	22.5	45.4
Bt1	28-50	5.9	5.1	10.1	0.25	18.0	11.2	1.7	0.05	0.23	9.6	13.6	57.9
Bt2	50-80	5.3	4.3	6.5	0.32	19.8	7.2	1.3	0.05	0.41	11.6	12.6	43.6
Bt3	80-100	5.0	3.8	5.8	0.11	12.4	6.5	2.1	0.03	0.21	12.6	12.1	41.1
Bt4	100-123	5.0	3.7	4.8	0.11	14.4	4.8	3.3	0.04	0.31	13.5	11.3	38.5
Bt5	123-147	5.0	3.6	4.1	0.11	23.8	3.4	2.6	0.06	0.11	13.0	10.6	32.0
Bt6	147-173	5.1	4.1	5.0	0.11	17.8	4.4	0.9	0.05	0.12	11.0	11.6	32.8
Bt7	173-200+	5.1	3.9	3.9	0.11	17.3	6.1	1.6	0.04	0.10	12.2	11.8	39.0
Pak Chong (Pc4):													
Ap1	0-13/15	7.0	5.7	25.9	8.7	507.1	13.3	2.4	1.30	0.38	4.6	13.4	79.1
Ap2	15-32	6.1	4.8	11.5	8.7	310.8	11.3	1.8	0.79	0.16	6.1	11.3	69.8
Bt1	32-52	5.4	4.0	8.2	3.1	337.4	7.5	2.1	0.86	0.16	8.8	11.1	54.7
Bt2	52-75	4.7	3.6	6.9	1.3	281.9	7.5	3.0	0.72	0.33	8.8	6.4	56.8
Bt3	75-100	4.5	3.5	6.2	1.2	188.9	5.4	4.7	0.48	0.24	11.3	13.3	48.9
Bt4	100-120	4.0	3.3	6.8	0.5	156.6	6.1	3.4	0.40	0.18	11.8	14.1	46.2
Bt5	120-143	3.9	3.3	5.6	0.4	171.7	7.6	3.9	0.44	0.32	11.5	11.6	51.4
Bt6	143-170	3.9	3.4	4.6	0.5	161.9	6.8	5.1	0.41	0.23	11.3	13.0	52.6
Bt7	170-200+	3.9	3.5	5.3	0.4	167.0	6.5	2.7	0.43	0.22	9.3	12.1	51.4

Appendix Table C2 (Continued).

Horizon	Depth	pH (1:1)		OM	Avail. P	Avail. K	Extractable Bases				EA	CEC	BS
		H_2O	KCl				Ca	Mg	Na	K			
	(cm)			(g kg^{-1})	(--------mg kg^{-1}--------)		(------------------------------------cmol kg^{-1}--------------------------------)						(%)
Chum Phuang (Cpg):													
Ap	0-20	5.7	4.0	4.6	4.6	11.0	0.23	0.17	0.03	0.11	2.0	1.50	21.3
Bt1	20-45	5.1	3.6	1.2	9.6	9.1	0.19	0.10	0.02	0.14	3.0	1.50	13.0
Bt2	45-75	5.4	4.3	1.1	1.8	3.8	0.78	0.26	0.01	0.26	1.5	3.00	46.6
Bt3	75-100	5.4	4.4	0.9	1.2	10.0	0.73	0.32	0.03	0.09	3.5	1.75	25.1
Bt4	100-130	5.3	4.3	1.9	0.9	5.2	0.29	0.18	0.01	0.50	0.5	1.75	66.2
Bt5	130-160	5.2	4.3	0.5	0.8	2.8	0.18	0.20	0.01	0.32	3.5	2.50	16.9
Bt6	160-185	5.2	4.0	0.3	0.8	5.9	0.34	0.14	0.02	0.28	1.5	3.00	34.2
Bt7	185-210+	5.1	4.0	0.6	0.9	4.3	0.22	0.45	0.01	0.18	1.5	0.25	36.4
Sung Noen (Sn):													
Ap1	0-10	5.9	4.1	9.5	2.71	111.2	2.60	0.95	0.28	0.15	3.3	3.50	54.7
Ap2	10-29	5.5	4.3	7.3	0.98	72.6	4.23	0.97	0.19	0.21	5.3	4.63	51.5
Bt1	29-55	4.8	3.4	5.2	0.41	79.5	2.03	1.78	0.20	0.22	9.9	8.25	30.0
Bt2	55-81	4.9	3.4	2.8	0.25	118.1	1.93	1.49	0.30	0.53	9.2	7.75	31.5
Bt3	81-110	4.8	3.2	2.8	0.26	123.5	4.18	2.40	0.32	0.49	7.9	7.25	48.3
Btc	110-135+	5.2	3.5	2.5	0.25	119.1	5.01	2.37	0.30	0.34	5.3	8.13	60.3
Satuek (Suk):													
Ap1	0-10	5.4	3.7	7.0	5.3	34.1	0.17	0.01	0.087	0.118	6.0	2.70	6.0
Ap2	10-25/30	4.6	4.2	2.4	0.5	9.4	0.17	0.00	0.024	0.332	7.0	2.68	7.0
Bt1	30-55	5.0	4.1	2.3	0.6	15.4	1.16	0.04	0.039	0.082	9.7	6.48	12.0
Bt2	55-80	5.6	4.1	2.4	0.5	11.9	0.22	0.04	0.030	0.039	9.0	4.93	3.6
Bt3	80-110	4.9	3.8	1.2	0.5	12.8	0.28	0.04	0.033	0.198	4.0	4.69	12.1
Bt4	110-140	6.0	3.4	1.8	0.3	13.8	0.39	0.04	0.035	0.191	10.0	5.90	6.2
Bt5	140-168	4.8	3.3	1.4	0.4	13.8	0.44	0.05	0.035	0.162	7.8	7.02	8.0
Bt6	168-200+	5.7	3.2	1.3	0.7	14.7	3.62	0.05	0.038	0.078	4.9	4.93	43.6

Appendix Table C2 (Continued).

Horizon	Depth	pH (1:1)		OM	Avail. P	Avail. K	Extractable Bases				EA	CEC	BS
		H_2O	KCl				Ca	Mg	Na	K			
	(cm)			(g kg^{-1})	(--------mg kg^{-1}--------)		(------------------------------------cmol kg^{-1}------------------------------)						(%)
Yasothon(Yt):													
Ap	0-20	5.0	4.1	4.5	6.1	80.2	0.99	0.38	0.21	0.21	0.74	2.5	70.7
Bt1	20-41	4.2	3.3	3.8	1.5	66.9	0.86	0.10	0.17	0.06	1.73	3.0	40.7
Bt2	41-69	4.0	3.6	3.1	0.7	31.6	0.66	0.07	0.08	0.19	2.23	4.1	31.0
Bt3	69-95	4.0	3.4	3.1	1.0	17.0	0.28	0.10	0.04	0.13	2.97	3.0	15.6
Bt4	95-120	4.0	3.4	2.7	0.9	17.5	0.46	0.06	0.04	0.19	1.73	2.3	30.2
Bt5	120-142	4.4	3.7	2.4	0.6	16.9	0.30	0.03	0.04	0.16	2.48	3.1	17.6
Bt6	142-171	4.3	3.5	1.8	0.6	17.5	0.22	0.08	0.04	0.16	2.48	2.3	16.8
Bt7	171-200+	4.2	3.0	2.0	0.4	20.9	0.16	0.16	0.05	0.13	2.97	2.9	14.4
Phon Phisai (Pp):													
Ap1	0-12	6.6	5.7	7.9	2.6	34.3	1.25	0.44	0.09	0.13	2.0	2.0	48.8
Ap2	12-28	6.0	4.6	3.5	1.1	19.8	0.91	0.49	0.05	0.13	1.5	2.3	51.3
Btc1	28-48	6.2	4.6	4.1	1.4	61.7	1.39	0.65	0.16	0.25	3.5	5.3	41.2
Btc2	48-70	6.5	4.9	4.5	0.7	353.9	3.55	3.71	1.13	0.20	7.5	13.5	53.4
Btc3	70-100	6.5	5.0	4.1	0.5	515.0	4.00	3.95	1.51	0.40	7.0	12.8	58.5
Btc4	100-126	6.6	5.1	3.9	0.3	472.8	3.79	4.50	1.44	0.54	8.0	14.0	56.2
Btc5	126-150	5.1	3.5	2.7	0.3	226.0	3.05	4.99	0.59	0.18	13.0	20.0	40.4
2Bv1	150-175	4.8	3.3	2.1	0.5	84.5	2.83	3.85	0.22	0.18	14.5	14.5	32.8
2Bv2	175-200+	4.7	3.2	1.9	0.6	71.4	2.33	3.50	0.18	0.14	16.5	18.0	27.2
Borabue (Bb):													
Ap	0-15	5.4	4.6	6.7	15.0	36.5	1.39	0.34	0.10	0.08	2.5	2.3	43.3
Bt1	15-25/30	5.6	4.1	1.9	1.6	21.8	0.55	0.18	0.07	0.10	2.5	1.8	26.5
Bt2	30-36	4.9	3.5	6.7	1.6	63.1	1.18	1.05	0.19	0.12	7.5	5.5	25.3
2Btc	36-46/60	4.9	3.4	9.9	1.9	164.5	2.28	2.56	0.43	0.18	14.5	13.5	26.7
2Crt1	60-80	4.9	3.4	5.2	1.9	154.7	2.65	2.42	0.42	0.17	11.5	12.5	33.0
2Crt2	80-115+	5.4	3.5	5.7	2.0	150.9	3.27	2.33	0.42	0.37	9.5	11.0	40.2

Appendix Table C2 (Continued).

Horizon	Depth	pH (1:1)		OM	Avail. P	Avail. K	Extractable Bases				EA	CEC	BS
		H_2O	KCl				Ca	Mg	Na	K			
	(cm)			(g kg^{-1})	(--------mg kg^{-1}--------)		(-----------------------------------cmol kg^{-1}------------------------------)						(%)
Sikhio (Si):													
Ap1	0-12	6.2	4.9	9.8	3.9	83.8	6.2	0.94	0.21	0.59	2.6	8.0	75.2
Ap2	12-30	6.8	5.8	9.4	3.2	61.1	9.0	0.49	0.16	0.42	5.3	8.1	65.7
Btk1	30-54	7.1	6.4	9.7	2.6	65.8	21.4	0.83	0.17	0.27	0.7	9.0	97.2
Btk2	54-79	7.3	6.6	8.6	4.0	68.2	34.2	1.07	0.17	0.36	0.7	14.5	98.2
Btk3	79-108	7.2	6.7	6.1	4.3	87.4	33.3	1.46	0.22	0.10	0.7	13.1	98.2
Btk4	108-130+	7.2	6.6	4.6	4.4	101.6	20.1	1.18	0.26	0.18	1.0	13.6	95.6
Nam Phong (Ng):													
Ap1	0-20	6.7	5.2	4.8	5.0	18.6	0.66	0.18	0.05	0.17	1.0	1.7	51.5
Ap2	20-35/40	6.0	4.5	3.1	4.2	13.0	0.35	0.08	0.03	0.06	1.0	1.3	34.2
E1	40-68/70	6.6	4.7	0.9	1.6	6.9	0.19	0.04	0.02	0.03	1.0	0.6	21.9
E2	70-95/100	6.5	4.5	0.6	1.4	7.5	0.14	0.04	0.02	0.05	0.0	0.3	100.0
2Bt1	100-125	5.4	3.6	1.8	1.2	67.7	0.65	0.21	0.17	0.11	2.5	3.4	31.3
2Bt2	125-150	5.2	3.6	1.8	1.2	48.2	0.51	0.42	0.12	0.12	3.0	3.8	28.1
2Bt3	150-175	4.7	3.5	1.6	1.1	21.7	0.70	0.72	0.06	0.19	3.0	2.9	35.8
3C	175-202+	4.8	3.6	1.3	0.9	16.2	0.95	1.13	0.04	0.12	4.5	0.6	33.2
Chan Thuek (Cu):													
Ap1	0-20	7.0	6.5	13.6	626.8	98.6	4.4	0.6	0.25	0.11	2.0	3.5	73.0
Ap2	20-45	7.3	6.3	5.9	45.3	46.3	3.7	0.4	0.12	0.58	1.0	3.3	82.8
AB	45-70	7.1	6.2	5.8	12.7	21.6	2.8	0.4	0.06	0.45	1.0	4.0	78.8
Bt1	70-95	7.1	6.0	7.1	4.3	21.2	3.4	0.3	0.05	0.37	2.0	4.9	67.4
Bt2	95-120	7.1	6.0	4.7	3.9	42.1	2.6	0.4	0.11	0.13	1.5	4.2	68.6
Bt3	120-150	7.0	5.9	5.0	4.7	46.3	2.9	0.5	0.12	0.39	2.5	6.0	61.1
Bt4	150-178	6.4	6.4	5.8	5.7	19.5	2.8	0.6	0.05	0.24	4.0	6.2	48.3
BCrt	178-200+	6.2	5.5	5.2	5.4	16.4	3.0	0.9	0.04	0.19	4.0	5.7	50.6

Appendix Table C3 Extractable Fe, Al and Mn contents by dithionite (Fe_d, Al_d, Mn_d), oxalate (Fe_o, Al_o, Mn_o) and Na-pyrophosphate (Fe_p, Al_p, Mn_p), and ratio of Fe_o/Fe_d of the whole soil samples in major upland soils.

Horizon	**Fe_d**	**Fe_o**	**Fe_p**	**Fe_o/Fe_d**	**Al_d**	**Al_o**	**Alp**	**Mn_d**	**Mn_o**	**Mn_p**
	(----------g kg^{-1}----------)									
Loei (Lo):										
Ap1	25.3	1.31	0.30	0.05	18.49	2.49	0.86	0.308	0.201	0.153
Ap2	31.3	1.87	0.60	0.06	16.30	2.20	0.49	0.147	0.059	0.034
Bt1	38.0	2.10	0.38	0.06	20.35	2.98	0.36	0.108	0.009	0.005
Bt2	39.4	2.25	0.27	0.06	19.73	2.71	0.50	0.112	0.004	0.001
Bt3	39.9	1.72	0.13	0.04	19.00	2.44	0.67	0.118	0.005	0.002
Bt4	38.3	1.38	0.12	0.04	16.65	2.86	0.61	0.112	0.007	0.001
Bt5	37.3	1.13	0.07	0.03	20.36	2.62	0.68	0.135	0.008	0.004
C	34.2	1.22	0.10	0.04	15.23	2.39	0.45	0.215	0.089	0.031
Chok Chai (Ci):										
Ap1	68.2	2.90	0.25	0.04	3.34	1.74	1.99	0.984	0.549	0.224
Ap2	75.3	2.80	0.24	0.04	3.29	1.75	1.64	1.081	0.641	0.202
Bto1	84.9	2.20	0.20	0.03	3.44	1.65	1.43	0.550	0.106	0.032
Bto2	74.7	2.20	0.10	0.03	3.18	1.72	1.39	0.506	0.071	0.016
Bto3	73.7	1.90	0.05	0.03	3.36	1.70	1.13	0.536	0.093	0.017
Bo1	82.9	2.00	0.05	0.02	3.46	1.71	0.99	0.540	0.079	0.013
Bo2	86.4	2.00	0.04	0.02	3.19	1.63	0.78	0.597	0.119	0.013
Bo3	92.6	2.10	0.03	0.02	3.22	1.62	0.68	0.678	0.180	0.023
Pak Chong (Pc1):										
Ap1	71.0	3.78	0.09	0.05	13.22	2.42	0.26	0.538	0.202	0.164
Ap2	70.0	2.92	0.07	0.04	12.67	2.07	0.25	0.490	0.168	0.104
Bt1	73.8	2.25	0.06	0.03	10.50	2.08	0.22	0.293	0.017	0.005
Bt2	75.4	2.09	0.06	0.03	12.02	2.47	0.22	0.283	0.013	0.005
Bto1	76.2	2.13	0.10	0.03	12.82	2.39	0.25	0.287	0.009	0.003
Bto2	75.3	2.06	0.08	0.03	13.82	2.39	0.41	0.275	0.009	0.005
Bto3	75.0	1.81	0.09	0.02	11.79	2.56	0.40	0.276	0.011	0.007
Bto4	78.5	1.72	0.10	0.02	9.32	2.41	0.44	0.299	0.012	0.008
Pak Chong (Pc2):										
Ap1	74.1	2.21	0.10	0.03	14.37	2.39	0.34	0.726	0.369	0.206
Ap2	76.3	1.97	0.08	0.03	8.00	2.71	0.28	0.690	0.364	0.102
Bt1	63.7	1.98	0.08	0.03	12.71	2.09	0.36	0.301	0.076	0.018
Bt2	75.8	1.72	0.10	0.02	7.81	2.38	0.52	0.351	0.056	0.021
Bto1	71.4	1.67	0.07	0.02	9.11	2.30	0.39	0.400	0.129	0.035
Bto2	74.3	1.16	0.07	0.02	8.21	2.35	0.33	0.436	0.143	0.039
Bto3	76.0	1.04	0.08	0.01	9.47	2.64	0.22	0.539	0.213	0.054
Bto4	81.2	1.05	0.10	0.01	10.94	2.31	0.25	0.549	0.209	0.052
Pak Chong (Pc3):										
Ap	78.0	2.71	0.31	0.03	10.94	2.69	0.70	1.961	0.000	0.956
Bt1	72.1	3.03	0.09	0.04	9.62	2.67	0.43	0.942	0.000	0.080
Bt2	73.1	2.71	0.08	0.04	14.48	2.34	0.49	0.672	0.242	0.046
Bt3	73.5	2.86	0.08	0.04	10.40	2.36	0.45	0.583	0.156	0.020
Bt4	76.7	2.78	0.08	0.04	12.95	2.63	0.50	0.646	0.173	0.019
Bt5	76.5	2.80	0.07	0.04	14.04	2.30	0.52	0.702	0.209	0.027
Bt6	81.0	3.04	0.08	0.04	17.21	2.58	0.45	0.851	0.289	0.045
Bt7	76.9	3.45	0.11	0.04	20.60	2.58	0.47	0.818	0.295	0.041

Appendix Table C3 (Continued).

Horizon	Fe_d	Fe_o	Fe_p	Fe_o/Fe_d	Al_d	Al_o	Alp	Mn_d	Mn_o	Mn_p
	(---				g kg^{-1}					---)
Pak Chong (Pc4):										
Ap1	21.3	2.17	0.39	0.10	19.01	2.37	0.98	0.669	0.525	0.247
Ap2	24.5	2.77	0.38	0.11	18.04	2.61	0.57	0.436	0.273	0.111
Bt1	29.1	2.02	0.20	0.07	21.76	2.64	0.50	0.317	0.186	0.063
Bt2	31.1	2.61	0.10	0.08	16.28	2.66	0.49	0.233	0.097	0.031
Bt3	35.0	2.66	0.20	0.08	12.81	2.46	0.43	0.235	0.097	0.028
Bt4	36.7	2.78	0.23	0.08	16.07	2.13	0.40	0.233	0.082	0.039
Bt5	37.6	2.87	0.27	0.08	14.00	2.46	0.36	0.271	0.105	0.046
Bt6	35.7	1.96	0.09	0.05	13.02	2.38	0.34	0.283	0.122	0.052
Bt7	36.0	2.26	0.03	0.06	14.88	2.74	0.34	0.177	0.113	0.048
Chum Phuang (Cpg):										
Ap	2.6	0.36	0.05	0.14	16.26	2.28	0.45	0.081	0.058	0.031
Bt1	6.3	0.57	0.02	0.09	14.46	2.26	0.41	0.156	0.111	0.042
Bt2	7.1	0.51	0.00	0.07	18.77	2.11	0.25	0.078	0.030	0.011
Bt3	6.7	0.39	0.01	0.06	14.82	2.23	0.23	0.069	0.020	0.005
Bt4	6.4	0.36	0.02	0.06	16.94	2.37	0.23	0.065	0.018	0.005
Bt5	7.9	0.43	0.02	0.05	18.27	2.04	0.24	0.066	0.018	0.005
Bt6	7.0	0.33	0.01	0.05	20.36	2.10	0.22	0.072	0.017	0.005
Bt7	7.7	0.33	0.03	0.04	21.16	2.16	0.22	0.067	0.017	0.006
Sung Noen (Sn):										
Ap1	5.2	0.59	0.55	0.11	7.34	2.45	0.14	0.123	0.094	0.063
Ap2	5.4	0.53	0.51	0.10	7.56	2.09	0.14	0.122	0.090	0.069
Bt1	9.1	0.88	0.77	0.10	8.35	2.82	0.43	0.059	0.018	0.014
Bt2	9.0	0.76	0.57	0.08	8.32	2.48	0.37	0.056	0.016	0.010
Bt3	9.4	0.78	0.45	0.08	7.41	2.79	0.30	0.082	0.040	0.016
Btc	7.8	0.89	0.39	0.11	7.22	2.50	0.19	0.140	0.104	0.035
Satuek (Suk)										
Ap1	2.7	1.68	0.42	0.62	4.20	2.12	nd	0.961	0.592	1.000
Ap2	2.9	1.93	0.73	0.67	3.96	4.24	nd	0.962	0.589	0.980
Bt1	5.6	2.61	1.20	0.47	9.94	7.72	nd	0.985	0.598	1.000
Bt2	4.4	1.76	0.66	0.40	7.36	5.66	nd	0.951	0.599	0.969
Bt3	5.9	2.44	0.46	0.41	9.04	6.70	nd	1.000	0.588	0.992
Bt4	5.3	1.87	0.51	0.36	5.54	5.04	nd	0.966	0.593	0.958
Bt5	4.5	3.29	0.39	0.73	8.48	5.68	nd	0.996	0.598	0.962
Bt6	4.2	2.54	0.34	0.61	5.64	3.35	nd	0.969	0.578	0.988
Yasothon(Yt):										
Ap	5.3	0.39	0.26	0.07	3.08	2.43	0.21	0.097	0.048	0.046
Bt1	7.4	0.65	0.17	0.09	3.32	2.69	0.16	0.068	0.020	0.015
Bt2	7.9	0.48	0.11	0.06	3.64	2.36	0.47	0.058	0.011	0.009
Bt3	8.8	0.60	0.16	0.07	3.75	2.30	0.67	0.063	0.013	0.008
Bt4	8.0	0.51	0.21	0.06	4.51	2.29	0.67	0.066	0.014	0.009
Bt5	7.7	0.53	0.14	0.07	5.00	2.29	0.52	0.072	0.018	0.008
Bt6	8.3	0.47	0.28	0.06	4.48	2.39	0.52	0.065	0.011	0.007
Bt7	9.2	0.59	0.15	0.06	4.15	2.04	0.41	0.076	0.017	0.008

Appendix Table C3 (Continued).

Horizon	Fe_d	Fe_o	Fe_p	Fe_o/Fe_d	Al_d	Al_o	Alp	Mn_d	Mn_o	Mn_p
	(--------	--------	--------	--------	--------g kg^{-1}	--------	--------	--------	--------	--------)
Phon Phisai (Pp):										
Ap1	4.7	0.46	0.18	0.10	9.62	2.20	0.39	0.087	0.060	0.034
Ap2	6.7	0.47	0.28	0.07	9.55	2.12	0.22	0.090	0.060	0.025
Btc1	26.9	0.98	0.20	0.04	9.06	2.78	0.33	0.183	0.087	0.017
Btc2	65.8	1.45	0.45	0.02	8.42	2.12	0.34	1.048	0.619	0.019
Btc3	47.9	1.07	0.37	0.02	9.10	2.80	0.32	0.273	0.153	0.014
Btc4	69.3	1.11	0.20	0.02	7.07	2.72	0.21	0.326	0.155	0.013
Btc5	69.3	1.27	0.19	0.02	8.33	2.11	0.39	0.036	0.009	0.004
2Bv1	58.5	1.47	0.08	0.03	10.26	2.69	0.57	0.008	0.000	0.003
2Bv2	40.0	0.88	0.07	0.02	12.05	2.09	0.68	0.007	0.000	0.004
Borabue (Bb):										
Ap	2.6	0.48	0.19	0.19	7.25	2.62	0.28	0.018	0.009	0.011
Bt1	2.4	0.46	0.22	0.19	7.79	3.21	0.23	0.008	0.000	0.003
Bt2	5.7	1.49	0.46	0.26	7.11	2.01	0.53	0.008	0.000	0.005
2Btc	25.5	1.44	0.93	0.06	7.51	2.61	0.86	0.011	0.001	0.005
2Crt1	9.4	1.25	0.33	0.13	8.50	3.29	0.56	0.016	0.001	0.005
2Crt2	8.8	1.05	0.33	0.12	8.22	2.77	1.24	0.014	0.000	0.003
Sikhio (Si):										
Ap1	9.2	1.53	0.20	0.17	9.82	2.06	0.13	0.195	0.164	0.068
Ap2	9.3	1.03	0.08	0.11	10.75	1.98	0.16	0.203	0.175	0.071
Btk1	11.9	1.40	0.11	0.12	11.56	2.60	0.12	0.246	0.183	0.050
Btk2	13.5	1.11	0.12	0.08	10.29	2.02	0.10	0.270	0.199	0.045
Btk3	14.8	1.04	0.08	0.07	9.64	1.35	0.06	0.320	0.233	0.036
Btk4	15.9	0.90	0.08	0.06	9.84	1.94	0.09	0.299	0.235	0.031
Nam Phong (Ng):										
Ap1	1.2	0.15	0.17	0.13	2.38	2.02	0.21	0.046	0.034	0.033
Ap2	1.2	0.24	0.15	0.19	2.49	2.59	0.25	0.052	0.039	0.030
E1	1.1	0.16	0.11	0.15	2.54	2.01	0.17	0.024	0.017	0.011
E2	1.1	0.13	0.13	0.11	2.35	2.50	0.13	0.006	0.001	0.004
2Bt1	5.8	0.29	0.08	0.05	3.67	2.00	0.15	0.010	0.000	0.003
2Bt2	7.4	0.25	0.01	0.03	3.96	2.61	0.15	0.011	0.000	0.004
2Bt3	8.3	0.23	0.08	0.03	3.95	2.56	0.12	0.013	0.001	0.003
3C	15.4	0.41	0.09	0.03	3.31	2.67	0.14	0.054	0.025	0.008
Chan Thuek (Cu):										
Ap1	0.8	0.20	0.17	0.25	1.47	2.69	0.17	0.049	0.040	0.042
Ap2	0.7	0.15	0.12	0.20	1.51	2.66	0.26	0.053	0.040	0.034
AB	0.7	0.14	0.18	0.20	1.64	2.63	0.51	0.087	0.066	0.056
Bt1	0.6	0.22	0.18	0.34	1.42	2.56	0.51	0.068	0.052	0.055
Bt2	0.6	0.18	0.22	0.31	1.42	2.10	0.68	0.034	0.026	0.025
Bt3	0.7	0.23	0.15	0.34	1.44	2.66	0.59	0.026	0.021	0.018
Bt4	0.8	0.28	0.21	0.37	1.96	3.20	0.62	0.199	0.189	0.033
BCrt	1.3	0.50	0.22	0.37	2.24	2.65	0.45	0.432	0.345	0.035

Appendix Table C4 Minerals in clay and silt fractions of major upland agricultural soils.

Horizon	Depth	Clay fraction							Silt fraction		
	(cm)	Kao	Hem	Int	Sme	HIV	Qtz	Ill	Qtz	Kao	Hem
Loei (Lo):*Typic Kandiustox*											
Ap1	0-20	xxxx	x	Tr.	x	x	-	-	xxxx	Tr.	-
Ap2	20-35	xxxx	x	Tr.	x	x	-	-	xxxx	Tr.	-
Bt1	35-55	xxxx	x	Tr.	x	x	Tr.	-	xxxx	Tr.	-
Chok Chai (Ci): *Rhodic Kandiustox*											
Ap2	10-27	xxxx	x	-	-	-	-	-	xxxx	Tr.	Tr.
Bto2	55-88	xxxx	x	-	-	-	Tr.	-	xxxx	Tr.	Tr.
Bo1	110-132	xxxx	x	-	-	-	Tr.	-	xxxx	Tr.	Tr.
Pak Chong (Pc1): *Rhodic Kandiustox*											
Ap1	0-18	xxxx	x	Tr.	Tr.	Tr.	-	Tr.	xx	Tr.	Tr.
Ap2	18-30	xxxx	x	x	x	x	-	Tr.	xxxx	Tr.	Tr.
Bt1	30-58	xxxx	x	Tr.	x	Tr.	-	Tr.	xxxx	Tr.	Tr.
Pak Chong (Pc2): *Rhodic Kandiustox*											
Ap1	0-15	xxxx	x	-	x	-	-	Tr.	xxx	Tr.	Tr.
Ap2	15-35	xxxx	x	-	x	-	-	Tr.	xxxx	Tr.	Tr.
Bt1	35-65	xxxx	x	Tr.	x	-	-	Tr.	xxxx	Tr.	Tr.
Pak Chong (Pc3): *Rhodic Kandiustox*											
Ap	0-28	xxxx	x	-	-	x	-	Tr.	xxxx	Tr.	Tr.
Bt1	28-50	xxxx	x	-	-	x	-	Tr.	xxxx	Tr.	Tr.
Bt2	50-80	xxxx	x	-	-	x	Tr.	Tr.	xxxx	Tr.	Tr.
Pak Chong (Pc4): *Rhodic Kandiustox*											
Ap1	0-13/15	xxxx	x	-	-	-	Tr.	Tr.	xxxx	Tr.	Tr.
Ap2	15-32	xxxx	x	-	-	-	Tr.	Tr.	xxxx	Tr.	Tr.
Bt1	32-52	xxxx	x	-	-	-	Tr.	Tr.	xxxx	Tr.	Tr.
Chum Phuang (Cpg): *Typic Kandiustult*											
Ap	0-20	xxxx	x	-	x	-	Tr.	Tr.	xxxx	-	-
Bt1	20-45	xxxx	x	-	x	-	Tr.	Tr.	xxxx	-	-
Bt2	45-75	xxxx	x	-	Tr.	-	Tr.	Tr.	xxxx	-	-
Sung Noen (Sn): *Typic Kandiustult*											
Ap1	0-10	xxx	-	x	xx	-	-	xx	xxxx	-	-
Ap2	10-29	xxx	-	x	xx	-	-	xx	xxxx	-	-
Bt1	29-55	xxx	-	x	xx	-	-	xx	xxxx	-	-
Satuek (Suk): *Typic Paleustults*											
Ap1	0-10	xxxx	-	-	Tr.	x	x	Tr.	xxxx	-	-
Ap2	10-25/30	xxxx	-	-	Tr.	x	Tr.	Tr.	xxxx	-	-
Bt1	30-55	xxxx	-	-	Tr.	x	Tr.	Tr.	xxxx	-	-
Yasothon(Yt): *Typic Kandiustult*											
Ap	0-20	xxxx	Tr.	-	-	-	x	Tr.	xxxx	Tr.	-
Bt1	20-41	xxxx	Tr.	-	-	-	x	Tr.	xxxx	Tr.	-
Bt2	41-69	xxxx	Tr.	-	-	-	x	Tr.	xxxx	Tr.	-
Phon Phisai (Pp): *Typic Plinthustult*											
Ap1	0-12	xxx	-	-	-	-	x	x	xxxx	-	-
Btc1	28-48	xxx	-	-	-	-	x	x	xxxx	-	-
2Bv1	150-175	xxx	-	-	-	-	Tr.	x	xxxx	-	-
Borabue (Bb): *Plinthic Haplustult*											
Ap	0-15	xx	-	x	xx	-	-	xx	xxxx	-	-
Bt1	15-25/30	xx	-	x	x	-	-	xxxx	xxxx	-	-
Bt2	30-36	xxxx	-	Tr.	x	-	-	xx	xxxx	-	-

Appendix Table C4 (Continued).

Horizon	Depth	Clay fraction							Silt fraction		
	(cm)	Kao	Hem	Int	Sme	HIV	Qtz	Ill	Qtz	Kao	Hem
Sikhio (Si): *Typic Rhodustalf*											
Ap1	0-12	xx	-	x	xx	-	-	xx	xxxx	-	-
Ap2	12-30	xx	-	x	xx	-	-	xx	xxxx	-	-
Btk1	30-54	xx	-	x	xx	-	-	xx	xxxx	-	-
Nam Phong (Ng): *Psammentic Haplustalf*											
Ap1	0-20	xx	-	-	-	-	xx	-	xxxx	-	-
Ap2	20-35/40	xx	-	-	-	-	xx	-	xxxx	-	-
E1	40-68/70	xx	-	-	-	-	xx	-	xxxx	-	-
Chan Thuek (Cu): *Psammentic Haplustalf*											
Ap1	0-20	xxxx	-	x	xx	-	-	x	xxxx	-	-
Ap2	20-45	xxxx	-	Tr.	x	-	-	x	xxxx	-	-
AB	45-70	xxxx	-	Tr.	x	-	-	Tr.	xxxx	-	-

Minerals : Kao = kaolinite,Hem = hematite, Int = interstratified of 1.0 and 1.4 nm clay, Sme = smectite, HIV = hydroxyl Al interlayered vermiculite, Qtz = quartz and Ill = illite

: xxxx = >60%, xxx = 40-60%, xx = 20-40%, x = 5-20%, Tr. = <5%

Appendix Table C5 Water aggregate stability (WAS), mean weight diameter (MWD) and aggregate size distribution.

Horizon	**Depth** (cm)	**WAS** (%)	**MWD** (mm)	**LMA**[1/]	**SMA**[1/]	**MiA**[1/]	**SCf**[1/]
				(--------------------g 100 g^{-1} soil--------------------)			
Loei (Lo):							
Ap1	0-20	75.43	1.26	13.45	47.50	30.65	8.41
Ap2	20-35	79.52	1.30	10.97	64.41	16.96	7.65
Bt1	35-55	70.30	1.11	6.68	66.44	19.64	7.23
Bt2	55-85	69.30	0.92	4.94	56.31	24.80	13.95
Bt3	85-110	66.45	1.16	10.36	53.82	24.68	11.14
Bt4	110-140	65.04	0.89	4.94	53.06	28.67	13.33
Bt5	140-165/170	74.92	1.15	9.30	57.83	24.32	8.55
C	170-180+	90.73	nd	69.60	nd	9.71	5.67
Chok Chai (Ci):							
Ap1	0-10	89.23	1.93	25.38	57.00	11.53	6.08
Ap2	10-27	85.45	2.09	28.97	55.03	10.83	5.17
Bto1	27-55	92.68	2.51	39.75	45.01	12.33	2.91
Bto2	55-88	72.98	nd	50.85	37.27	7.63	4.25
Bto3	88-110	83.51	2.42	37.75	45.95	11.23	5.07
Bo1	110-132	75.33	2.10	30.63	48.38	14.06	6.92
Bo2	132-160	74.16	2.20	32.87	47.99	12.78	6.35
Bo3	160-200	72.95	1.70	21.05	54.84	16.68	7.44
Pak Chong (Pc1):							
Ap1	0-18	84.50	1.13	6.50	68.51	19.56	5.43
Ap2	18-30	84.08	1.42	11.62	72.68	11.15	4.55
Bt1	30-58	77.50	1.02	3.43	73.34	17.28	5.94
Bt2	58-88	77.71	0.98	3.04	70.58	18.71	7.68
Bto1	88-110	78.81	0.88	2.01	65.55	25.14	7.31
Bto2	110-138	81.05	0.86	3.59	56.18	31.81	8.42
Bto3	138-175	72.99	0.82	2.16	58.60	30.58	8.66
Bto4	175-200+	40.86	0.79	5.10	63.63	24.22	7.05
Pak Chong (Pc2):							
Ap1	0-15	89.23	1.29	11.67	59.94	18.34	10.06
Ap2	15-35	85.45	1.55	14.47	71.98	9.12	4.43
Bt1	35-65	92.68	1.70	17.38	73.26	5.72	3.64
Bt2	65-90	72.98	1.55	14.66	70.91	9.45	4.98
Bto1	90-120	83.51	0.57	1.54	38.94	28.76	30.76
Bto2	120-148	75.33	0.87	2.30	63.48	26.73	7.49
Bto3	148-172	74.16	0.88	1.25	68.74	24.91	5.09
Bto4	172-200+	72.95	0.80	0.98	62.98	29.61	6.42
Pak Chong (Pc3):							
Ap	0-28	88.99	1.89	25.67	51.52	15.77	7.04
Bt1	28-50	75.54	0.71	1.70	51.13	30.00	17.17
Bt2	50-80	73.00	0.70	1.35	51.56	34.73	12.36
Bt3	80-100	70.08	0.74	0.55	58.90	35.07	5.48
Bt4	100-123	68.37	0.68	0.66	52.44	33.99	12.92
Bt5	123-147	75.75	0.80	2.31	56.03	33.41	8.26
Bt6	147-173	80.68	0.83	1.74	62.16	25.39	10.72
Bt7	173-200+	72.42	0.96	2.76	69.15	25.80	2.29

Appendix Table C5 (Continued).

Horizon	Depth (cm)	WAS (%)	MWD (mm)	LMA[1/]	SMA[1/]	MiA[1/]	SCf[1/]
				(--------------------g 100 g^{-1} soil--------------------)			
Pak Chong (Pc4):							
Ap1	0-13/15	81.83	1.62	21.53	46.73	10.28	21.46
Ap2	15-32	80.88	1.08	6.05	66.30	20.43	7.21
Bt1	32-52	76.15	1.23	8.85	67.09	17.67	6.39
Bt2	52-75	80.63	1.04	5.46	64.65	23.08	6.82
Bt3	75-100	90.32	1.03	3.62	73.27	16.67	6.44
Bt4	100-120	78.86	1.03	3.74	72.67	17.49	6.10
Bt5	120-143	69.14	0.80	1.08	62.92	25.11	10.90
Bt6	143-170	65.82	0.76	0.7	60.1	27.5	11.6
Bt7	170-200+	72.27	0.65	0.35	51.02	33.01	15.63
Chum Phuang (Cpg):							
Ap	0-20	62.14	0.72	3.72	41.64	43.48	11.16
Bt1	20-45	68.18	0.54	0.31	41.83	31.14	26.73
Bt2	45-75	64.78	0.78	4.19	44.56	43.32	7.93
Bt3	75-100	65.91	0.70	4.41	35.34	50.13	10.12
Bt4	100-130	69.57	0.91	8.91	34.76	47.31	9.02
Bt5	130-160	73.49	0.72	5.52	32.13	49.24	13.11
Bt6	160-185	77.01	0.66	3.90	34.39	49.53	12.18
Bt7	185-210+	72.22	0.80	5.65	39.45	45.19	9.71
Sung Noen (Sn):							
Ap1	0-10	19.54	0.70	10.62	6.57	61.24	21.57
Ap2	10-29	33.89	0.32	2.84	6.75	64.43	25.98
Bt1	29-55	41.65	0.65	6.96	19.16	51.46	22.42
Bt2	55-81	60.04	0.44	2.93	17.75	57.22	22.11
Bt3	81-110	60.22	0.44	3.60	15.17	53.99	27.24
Btc	110-135+	26.33	0.37	2.77	12.51	52.29	32.42
Satuek (Suk)							
Ap1	0-10	58.80	nd	34.12	21.78	33.57	10.54
Ap2	10-25/30	67.90	0.90	8.92	34.58	43.76	12.74
Bt1	30-55	45.34	0.60	2.86	33.65	51.51	11.99
Bt2	55-80	30.50	0.42	1.24	24.07	56.62	18.07
Bt3	80-110	43.63	0.40	0.91	23.19	57.60	18.30
Bt4	110-140	42.96	0.37	0.19	23.85	59.64	16.32
Bt5	140-168	35.33	0.52	2.02	29.67	57.28	11.02
Bt6	168-200+	37.39	0.56	3.21	28.26	54.00	14.53
Yasothon(Yt):							
Ap	0-20	50.50	0.55	1.35	35.42	50.83	12.40
Bt1	20-41	66.51	0.61	1.82	38.97	52.82	6.38
Bt2	41-69	67.84	0.73	3.70	41.77	45.28	9.25
Bt3	69-95	68.06	0.76	4.08	43.68	42.52	9.72
Bt4	95-120	61.93	0.63	1.21	44.78	44.43	9.57
Bt5	120-142	61.33	0.67	0.91	49.41	42.83	6.86
Bt6	142-171	67.76	0.69	1.77	47.38	40.15	10.70
Bt7	171-200+	61.66	0.64	1.20	45.20	42.33	11.28

Appendix Table C5 (Continued).

Horizon	Depth	WAS	MWD	LMA[1/]	SMA[1/]	MiA[1/]	SCf[1/]
	(cm)	(%)	(mm)	(--------------------g 100 g^{-1} soil--------------------)			
Phon Phisai (Pp):							
Ap1	0-12	36.85	0.062	nd	nd	38.6	13.0
Ap2	12-28	29.07	0.075	nd	nd	46.21	17.94
Btc1	28-48	62.43	0.013	nd	nd	4.99	21.60
Btc2	48-70	80.76	0.004	nd	nd	2.35	2.85
Btc3	70-100	79.47	0.006	nd	nd	3.51	3.14
Btc4	100-126	78.14	0.007	nd	nd	4.24	4.03
Btc5	126-150	76.44	0.007	nd	nd	nd	25.51
2Bv1	150-175	72.47	0.011	nd	nd	6.36	5.58
2Bv2	175-200+	67.46	0.014	nd	nd	7.82	6.29
Borabue (Bb):							
Ap	0-15	40.12	0.095	nd	nd	60.57	12.99
Bt1	15-25/30	26.06	0.111	nd	nd	70.37	16.99
Bt2	30-36	32.34	0.075	nd	nd	47.45	10.10
2Btc	36-46/60	84.22	0.012	nd	nd	7.15	4.61
2Crt1	60-80	78.24	0.020	nd	nd	12.10	5.52
2Crt2	80-115+	62.79	0.026	nd	nd	16.44	5.64
Sikhio (Si):							
Ap1	0-12	38.08	0.72	9.45	13.34	58.67	18.55
Ap2	12-30	54.15	0.76	7.52	26.57	51.21	14.69
Btk1	30-54	51.83	0.77	3.48	47.54	35.04	13.94
Btk2	54-79	44.64	0.63	1.58	43.44	41.98	12.99
Btk3	79-108	71.95	0.68	1.21	50.04	36.29	12.46
Btk4	108-130+	45.97	0.90	4.33	56.32	28.12	11.22
Nam Phong (Ng):							
Ap1	0-20	64.32	0.060	nd	nd	37.18	12.56
Ap2	20-35/40	42.10	0.074	nd	nd	45.96	14.78
E1	40-68/70	32.15	0.068	nd	nd	42.74	13.55
E2	70-95/100	45.19	0.070	nd	nd	43.38	17.82
2Bt1	100-125	54.30	0.061	nd	nd	38.24	11.08
2Bt2	125-150	65.08	0.047	nd	nd	29.78	6.50
2Bt3	150-175	67.67	0.039	nd	nd	24.52	5.70
3C	175-202+	63.27	0.011	nd	nd	6.72	2.63
Chan Thuek (Cu):							
Ap1	0-20	56.24	0.009	nd	nd	5.16	3.45
Ap2	20-45	64.30	0.023	nd	nd	14.48	3.03
AB	45-70	83.53	0.021	nd	nd	13.34	2.80
Bt1	70-95	83.60	0.019	nd	nd	11.91	3.45
Bt2	95-120	77.29	0.021	nd	nd	13.07	3.19
Bt3	120-150	60.01	0.023	nd	nd	14.37	3.61
Bt4	150-178	78.38	0.022	nd	nd	13.86	3.72
BCrt	178-200+	77.09	0.022	nd	nd	13.89	4.16

nd = not detected

[1/] LMA = large macroaggregate, SMA = small macroaggregate, MiA = microaggregate, SCf = silt and clay fractions

Appendix Table C6 Total, organic, inorganic carbon, ratio of OC/N and carbon sequestration in major upland agricultural soils.

Horizon	**Depth**	**OC**	**TC**	**IC**	**TN**	**OC/N**	**C$_{seq}$**
	(cm)	(----------------------------	g kg^{-1}	----------------------	)		(Mg C kg^{-1})
Loei (Lo):							
Ap1	0-20	10.20	11.52	1.32	1.24	8	31.01
Ap2	20-35	5.46	6.85	1.39	1.08	5	13.27
Bt1	35-55	4.01	5.54	1.53	0.95	4	11.15
Bt2	55-85	3.59	4.90	1.31	0.64	6	14.97
Bt3	85-110	3.05	4.00	0.95	0.57	5	10.68
Bt4	110-140	2.55	3.65	1.10	0.56	5	11.17
Bt5	140-165/170	2.47	3.56	1.09	0.49	5	10.23
C	170-180+	2.78	4.13	1.35	0.61	5	4.06
Chok Chai (Ci):							
Ap1	0-10	14.04	11.60	-	1.00	14	15.72
Ap2	10-27	7.60	7.74	0.14	0.70	11	14.60
Bto1	27-55	5.28	5.12	-	0.50	11	15.52
Bto2	55-88	4.18	3.50	-	0.40	10	13.64
Bto3	88-110	2.09	3.06	0.97	0.30	7	6.26
Bo1	110-132	2.09	2.93	0.84	0.20	10	4.73
Bo2	132-160	2.90	2.91	0.01	0.30	10	8.28
Bo3	160-200	2.15	2.91	0.76	0.30	7	8.67
Pak Chong (Pc1):							
Ap1	0-18	11.08	11.76	0.68	0.96	12	25.53
Ap2	18-30	8.05	8.96	0.91	0.99	8	14.10
Bt1	30-58	3.54	4.44	0.90	0.58	6	11.70
Bt2	58-88	2.46	3.73	1.27	0.31	8	9.00
Bto1	88-110	2.26	3.72	1.46	0.32	7	6.22
Bto2	110-138	2.46	3.62	1.16	0.26	9	7.92
Bto3	138-175	2.26	3.77	1.51	0.25	9	10.37
Bto4	175-200+	2.06	3.27	1.21	0.27	8	6.59
Pak Chong (Pc2):							
Ap1	0-15	14.19	14.30	0.11	1.40	10	25.12
Ap2	15-35	7.26	8.30	1.04	0.80	9	17.86
Bt1	35-65	5.50	6.34	0.84	0.81	7	23.27
Bt2	65-90	4.03	5.50	1.47	0.55	7	13.30
Bto1	90-120	3.24	5.05	1.81	0.61	5	12.44
Bto2	120-148	2.84	4.56	1.72	0.67	4	9.62
Bto3	148-172	3.63	4.44	0.81	0.60	6	10.63
Bto4	172-200+	2.84	4.22	1.38	0.37	8	9.70
Pak Chong (Pc3):							
Ap	0-28	19.94	19.00		1.92	10	72.58
Bt1	28-50	5.85	6.50	0.65	0.90	7	16.47
Bt2	50-80	3.76	4.70	0.94	0.66	6	13.31
Bt3	80-100	3.37	4.15	0.78	0.62	5	8.09
Bt4	100-123	2.78	3.69	0.91	0.71	4	7.74
Bt5	123-147	2.38	3.62	1.24	0.64	4	7.31
Bt6	147-173	2.88	3.91	1.03	0.63	5	9.66
Bt7	173-200+	2.29	3.56	1.27	0.49	5	7.67

Appendix Table C6 (Continued).

Horizon	**Depth**	**OC**	**TC**	**IC**	**TN**	**OC/N**	**C_{seq}**
	(cm)	(--------------------------g kg^{-1}			------------------------)		(Mg C kg^{-1})
Pak Chong (Pc4):							
Ap1	0-13/15	15.01	15.70	0.69	1.54	10	30.83
Ap2	15-32	6.64	8.83	2.19	0.95	7	19.93
Bt1	32-52	4.76	6.94	2.18	0.80	6	14.28
Bt2	52-75	3.97	5.97	2.00	0.69	6	13.97
Bt3	75-100	3.57	6.04	2.47	0.66	5	13.92
Bt4	100-120	3.96	5.65	1.69	0.61	6	11.48
Bt5	120-143	3.27	5.23	1.96	0.67	5	10.60
Bt6	143-170	2.68	5.13	2.45	0.71	4	9.55
Bt7	170-200+	3.08	4.54	1.46	0.62	5	12.01
Chum Phuang (Cpg):							
Ap	0-20	2.66	3.61	0.95	0.65	4	8.83
Bt1	20-45	0.71	2.12	1.41	0.60	1	3.07
Bt2	45-75	0.61	1.81	1.20	0.60	1	2.80
Bt3	75-100	0.51	1.60	1.09	0.60	1	2.03
Bt4	100-130	1.12	1.47	0.35	0.37	3	5.11
Bt5	130-160	0.31	1.45	1.14	0.38	1	1.44
Bt6	160-185	0.15	1.43	1.28	0.67	0	0.58
Bt7	185-210+	0.36	1.40	1.04	0.51	1	1.41
Sung Noen (Sn):							
Ap1	0-10	5.50	4.89	-	0.44	12	8.58
Ap2	10-29	4.22	4.69	0.47	0.38	11	12.27
Bt1	29-55	3.03	3.80	0.77	0.50	6	11.90
Bt2	55-81	1.64	2.84	1.20	0.42	4	6.40
Bt3	81-110	1.63	2.44	0.81	0.37	4	7.23
Btc	110-135+	1.44	1.96	0.52	0.25	6	6.01
Satuek (Suk)							
Ap1	0-10	4.05	5.32	1.27	0.40	10	6.24
Ap2	10-25/30	1.41	2.27	0.86	0.28	5	4.47
Bt1	30-55	1.36	1.73	0.37	0.12	11	5.15
Bt2	55-80	1.38	1.48	0.11	0.18	7	5.57
Bt3	80-110	0.70	1.56	0.86	0.25	3	3.48
Bt4	110-140	1.05	1.60	0.55	0.19	6	4.81
Bt5	140-168	0.83	1.55	0.73	0.20	4	3.73
Bt6	168-200+	0.75	1.49	0.75	0.30	2	4.02
Yasothon(Yt):							
Ap	0-20	2.61	3.27	0.66	0.37	7	8.40
Bt1	20-41	2.21	3.52	1.31	0.46	5	7.80
Bt2	41-69	1.77	3.22	1.45	0.18	10	7.19
Bt3	69-95	1.77	3.57	1.80	0.17	10	7.00
Bt4	95-120	1.57	2.74	1.17	0.27	6	6.12
Bt5	120-142	1.38	2.59	1.21	0.24	6	4.74
Bt6	142-171	1.03	2.44	1.41	0.20	5	4.66
Bt7	171-200+	1.18	2.41	1.23	0.14	8	5.65

Appendix Table C6 (Continued).

Horizon	Depth	OC	TC	IC	TN	OC/N	C_{seq}
	(cm)	(--------------------------g kg^{-1}			------------------------)		(Mg C kg^{-1})
Phon Phisai (Pp):							
Ap1	0-12	4.57	5.10	0.53	0.55	8	8.17
Ap2	12-28	2.01	2.84	0.83	0.44	5	5.85
Btc1	28-48	2.35	3.13	0.78	0.38	6	9.31
Btc2	48-70	2.63	3.95	1.32	0.47	6	11.46
Btc3	70-100	2.40	3.81	1.41	0.48	5	14.98
Btc4	100-126	2.25	3.38	1.13	0.46	5	12.17
Btc5	126-150	1.58	2.57	0.99	0.46	3	7.89
2Bv1	150-175	1.22	2.26	1.04	0.46	3	6.01
2Bv2	175-200+	1.10	2.03	0.93	0.45	2	5.06
Borabue (Bb):							
Ap	0-15	3.88	4.22	0.34	0.53	7	8.44
Bt1	15-25/30	1.12	1.91	0.79	0.27	4	2.62
Bt2	30-36	3.87	4.19	0.32	0.31	13	6.64
2Btc	36-46/60	5.77	6.32	0.55	0.44	13	22.57
2Crt1	60-80	3.02	4.09	1.07	0.51	6	16.33
2Crt2	80-115+	3.31	3.63	0.32	0.53	6	19.81
Sikhio (Si):							
Ap1	0-12	5.67	6.18	0.51	0.66	9	10.61
Ap2	12-30	5.45	6.19	0.74	0.72	8	15.70
Btk1	30-54	5.61	7.67	2.06	0.79	7	22.08
Btk2	54-79	5.00	8.03	3.03	0.62	8	20.50
Btk3	79-108	3.53	7.69	4.16	0.60	6	17.30
Btk4	108-130+	2.66	5.63	2.97	0.49	5	9.95
Nam Phong (Ng):							
Ap1	0-20	2.77	3.56	0.79	0.45	6	7.70
Ap2	20-35/40	1.78	2.48	0.70	0.34	5	5.52
E1	40-68/70	0.50	1.20	0.70	0.19	3	2.22
E2	70-95/100	0.36	1.06	0.70	0.32	1	1.64
2Bt1	100-125	1.06	1.78	0.72	0.40	3	4.21
2Bt2	125-150	1.04	1.86	0.82	0.36	3	4.11
2Bt3	150-175	0.92	1.79	0.87	0.24	4	3.63
3C	175-202+	0.75	1.83	1.08	0.40	2	3.83
Chan Thuek (Cu):							
Ap1	0-20	7.90	8.40	0.50	0.93	9	25.28
Ap2	20-45	3.41	3.96	0.55	0.40	9	14.66
AB	45-70	3.35	4.03	0.68	0.46	7	17.39
Bt1	70-95	4.11	4.59	0.48	0.50	8	16.03
Bt2	95-120	2.72	3.39	0.67	0.47	6	11.42
Bt3	120-150	2.88	3.61	0.73	0.37	8	14.95
Bt4	150-178	3.35	4.06	0.71	0.43	8	16.42
BCrt	178-200+	3.01	3.68	0.67	0.48	6	10.53

OC = organic carbon, TC = total carbon, IC = inorganic carbon (from calculated), TN = total nitrogen, OC/N = carbon and nitrogen ratio, C_{seq} = carbon sequestration

Appendix Table C7 Carbon, nitrogen and ratio of C/N in four aggregate size classes.

Horizon	Total carbon				Total nitrogen				C/N				E_c			
	LMA	SMA	MiA	SCf	LMA	SMA	MiA	SCf	LMA	SMA	MiA	SCf	LMA	SMA	MiA	SCf
	(-----------g kg^{-1} soil------------)				(--------------g kg^{-1} soil---------------)											
Loei (Lo):																
Ap1	0.81	1.06	1.04	1.10	0.072	0.083	0.075	0.118	11.20	12.89	13.89	9.33	0.079	0.104	0.102	0.108
Ap2	0.90	0.62	0.68	0.66	0.041	0.045	0.075	0.072	21.80	14.01	9.15	9.22	0.165	0.114	0.125	0.122
Bt1	0.55	0.56	0.60	0.64	0.050	0.042	0.037	0.047	11.06	13.29	16.17	13.76	0.138	0.140	0.149	0.160
Bt2	0.42	0.45	0.51	0.52	0.098	0.065	0.104	0.095	4.32	6.91	4.89	5.52	0.118	0.125	0.142	0.146
Bt3	0.32	0.38	0.39	0.46	0.067	0.089	0.067	0.089	4.76	4.28	5.77	5.15	0.104	0.124	0.128	0.150
Bt4	0.32	0.34	0.39	0.39	0.046	0.059	0.062	0.057	6.95	5.67	6.26	6.90	0.125	0.132	0.153	0.155
Bt5	0.32	0.30	0.37	0.34	0.039	0.030	0.084	0.067	8.15	10.26	4.41	5.09	0.130	0.123	0.149	0.138
C	nd	0.37	0.42	0.43	nd	0.056	0.086	0.080	nd	6.69	4.84	5.36	nd	0.134	0.150	0.155
Chok Chai (Ci):																
Ap1	0.91	1.06	1.01	1.28	0.068	0.082	0.075	0.050	13.42	12.99	13.42	25.68	0.065	0.075	0.072	0.091
Ap2	0.74	0.83	0.83	0.97	0.025	0.029	0.086	0.125	30.07	28.32	9.67	7.79	0.098	0.110	0.109	0.128
Bto1	0.58	0.36	0.55	0.63	0.045	0.114	0.049	0.092	12.95	3.16	11.21	6.86	0.110	0.068	0.105	0.119
Bto2	0.39	0.41	0.43	0.51	0.077	0.071	0.084	0.090	5.04	5.71	5.10	5.65	0.092	0.097	0.103	0.122
Bto3	0.27	0.34	0.35	0.42	0.046	0.047	0.031	0.052	5.93	7.16	11.51	8.14	0.132	0.162	0.170	0.203
Bo1	0.27	0.32	0.35	0.37	0.037	0.033	0.048	0.053	7.51	9.75	7.32	7.11	0.132	0.152	0.170	0.179
Bo2	0.33	0.34	0.33	0.41	0.062	0.039	0.043	0.052	5.44	8.55	7.65	7.88	0.115	0.116	0.114	0.142
Bo3	0.29	0.26	0.29	0.33	0.022	0.031	0.016	0.039	13.37	8.34	18.44	8.57	0.136	0.122	0.137	0.155
Pak Chong (Pc1):																
Ap1	1.15	1.10	0.99	1.08	0.116	0.084	0.086	0.077	9.92	13.08	11.58	14.06	0.104	0.099	0.090	0.097
Ap2	0.83	0.75	0.75	0.78	0.111	0.058	0.056	0.057	7.48	12.80	13.44	13.71	0.103	0.093	0.093	0.097
Bt1	0.37	0.38	0.42	0.45	0.001	0.007	0.016	0.017	364.83	52.63	25.78	25.55	0.105	0.108	0.119	0.126
Bt2	nd	nd	0.36	0.40	nd	nd	0.012	0.002	nd	nd	31.32	162.87	nd	nd	0.148	0.163
Bto1	nd	0.35	0.38	0.38	nd	0.008	0.017	0.00014	nd	44.02	22.84	2728.36	nd	0.154	0.167	0.169
Bto2	nd	0.31	nd	0.39	nd	0.005	nd	0.005	nd	60.13	nd	79.02	nd	0.127	nd	0.157
Bto3	nd	nd	nd	0.34	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0.152
Bto4	nd	0.320	nd	nd	nd	nd	0.010	nd	nd	nd	nd	nd	nd	0.156	nd	nd

Appendix Table C7 (Continued).

Horizon	Total carbon				Total nitrogen				C/N				E_c			
	LMA	SMA	MiA	SCf	LMA	SMA	MiA	SCf	LMA	SMA	MiA	SCf	LMA	SMA	MiA	SCf
	(-----------g kg^{-1} soil------------)				(--------------g kg^{-1} soil---------------)											
Pak Chong (Pc2):																
Ap1	1.299	1.232	1.261	1.423	0.109	0.128	0.096	0.124	11.93	9.65	13.07	11.47	0.092	0.087	0.089	0.100
Ap2	nd	nd	1.629	1.706	nd	nd	0.028	0.071	nd	nd	57.63	24.17	nd	nd	0.224	0.235
Bt1	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Bt2	0.509	0.510	0.518	0.538	0.037	0.037	0.030	0.055	13.64	13.63	17.17	9.70	0.126	0.127	0.128	0.134
Bto1	nd	0.354	0.421	nd	nd	0.010	0.004	nd	nd	34.66	94.58	nd	nd	0.109	0.130	nd
Bto2	nd	0.435	0.464	0.490	nd	0.035	0.019	0.013	nd	12.48	24.15	38.27	nd	0.153	0.164	0.172
Bto3	nd	0.415	0.424	0.425	nd	0.018	0.008	0.007	nd	22.52	56.03	61.54	nd	0.114	0.117	0.117
Bto4	nd	nd	0.569	nd	nd	nd	0.033	nd	nd	nd	17.47	nd	nd	nd	0.200	nd
Pak Chong (Pc3):																
Ap	2.100	1.701	0.668	0.767	0.049	0.046	0.062	0.076	42.65	37.29	10.73	10.03	0.105	0.085	0.033	0.038
Bt1	0.650	0.577	0.565	0.571	0.090	0.033	0.029	0.039	7.26	17.43	19.66	14.74	0.111	0.099	0.097	0.098
Bt2	nd	nd	0.477	0.394	0.079	0.019	nd	nd	nd	nd	nd	nd	nd	nd	0.127	0.105
Bt3	0.379	0.351	0.367	0.365	0.086	0.054	0.077	0.032	4.43	6.44	4.76	11.48	0.113	0.104	0.109	0.108
Bt4	0.425	0.358	0.373	0.369	0.071	0.053	0.087	0.043	5.96	6.73	4.30	8.60	0.153	0.129	0.134	0.133
Bt5	0.297	0.347	0.378	0.361	0.055	0.039	0.044	0.040	5.44	8.90	8.69	9.11	0.125	0.146	0.159	0.152
Bt6	0.248	0.389	0.381	0.399	0.063	0.044	0.023	0.033	3.93	8.95	16.46	12.02	0.086	0.135	0.132	0.139
Bt7	0.356	0.339	0.369	0.393	0.049	0.014	0.031	0.044	7.24	23.44	12.09	8.88	0.155	0.148	0.161	0.171
Pak Chong (Pc4):																
Ap1	1.878	1.456	1.281	1.298	0.158	0.138	0.090	0.104	11.91	10.56	14.22	12.48	0.125	0.097	0.085	0.086
Ap2	1.114	0.682	0.674	0.698	0.067	0.058	0.091	0.057	16.69	11.71	7.37	12.29	0.168	0.103	0.102	0.105
Bt1	1.175	0.604	0.624	0.647	0.074	0.039	0.041	0.045	15.83	15.61	15.13	14.34	0.247	0.127	0.131	0.136
Bt2	0.785	0.564	0.591	0.580	0.030	0.049	0.043	0.039	25.88	11.41	13.77	14.91	0.198	0.142	0.149	0.146
Bt3	0.886	0.543	0.555	0.605	0.098	0.037	0.044	0.061	9.06	14.54	12.73	9.95	0.248	0.152	0.156	0.169
Bt4	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Bt5	nd	0.480	0.500	nd	nd	0.044	0.005	nd	nd	10.96	100.93	nd	nd	0.147	0.153	nd
Bt6	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

Appendix Table C7 (Continued).

Horizon	Total carbon				Total nitrogen				C/N				E_c			
	LMA	SMA	MiA	SCf	LMA	SMA	MiA	SCf	LMA	SMA	MiA	SCf	LMA	SMA	MiA	SCf
	(-----------g kg^{-1} soil------------)				(--------------g kg^{-1} soil---------------)											
Chum Phuang (Cpg):																
Ap	2.126	0.251	0.261	0.339	0.118	0.058	0.078	0.092	18.06	4.31	3.35	3.70	0.799	0.094	0.098	0.127
Bt1	0.290	0.169	0.200	0.284	0.166	0.057	0.079	0.142	1.74	2.98	2.52	2.00	0.408	0.237	0.281	0.399
Bt2	0.217	0.165	0.174	0.238	0.079	0.091	0.093	0.076	2.73	1.81	1.86	3.14	0.356	0.271	0.285	0.390
Bt3	0.164	0.143	0.175	0.202	0.087	0.062	0.074	0.088	1.89	2.32	2.35	2.30	0.321	0.280	0.343	0.396
Bt4	0.169	0.122	0.121	0.186	0.087	0.074	0.049	0.070	1.96	1.65	2.48	2.64	0.151	0.109	0.108	0.166
Bt5	0.163	0.092	0.143	0.171	0.068	0.046	0.054	0.077	2.40	1.99	2.65	2.22	0.527	0.296	0.462	0.552
Bt6	0.109	0.104	0.130	0.186	0.037	0.050	0.058	0.086	2.93	2.08	2.26	2.17	0.728	0.694	0.868	1.241
Bt7	0.187	0.129	0.128	0.195	0.099	0.059	0.056	0.109	1.89	2.17	2.30	1.79	0.521	0.358	0.357	0.543
Sung Noen (Sn):																
Ap1	0.917	nd	0.479	0.308	0.030	nd	0.013	0.023	30.30	nd	35.81	13.47	0.167	nd	0.087	0.056
Ap2	1.127	0.863	0.446	0.302	0.005	0.013	0.008	0.003	213.87	64.07	56.31	117.82	0.267	0.205	0.106	0.071
Bt1	0.396	0.410	0.341	0.262	0.065	0.088	0.081	0.042	6.11	4.63	4.20	6.29	0.131	0.135	0.112	0.086
Bt2	0.639	0.297	0.255	0.193	0.036	0.036	0.065	0.037	17.70	8.33	3.92	5.29	0.389	0.181	0.156	0.118
Bt3	1.077	0.253	0.232	0.148	0.033	0.045	0.021	0.008	33.02	5.64	11.31	18.99	0.660	0.155	0.142	0.091
Btc	nd	0.219	0.178	0.128	nd	0.027	0.020	0.020	nd	8.14	9.00	6.35	nd	0.152	0.124	0.089
Satuek (Suk)																
Ap1	0.491	0.313	0.280	0.349	0.037	0.022	0.029	0.029	13.40	14.37	9.66	11.91	0.121	0.077	0.069	0.086
Ap2	0.248	0.146	0.227	0.228	0.018	0.021	0.017	0.024	13.61	6.81	13.14	9.42	0.176	0.103	0.161	0.161
Bt1	0.337	0.232	0.343	0.302	0.095	0.110	0.162	0.111	3.57	2.11	2.12	2.71	0.249	0.171	0.253	0.223
Bt2	0.501	0.128	0.155	0.183	0.130	0.077	0.079	0.089	3.86	1.67	1.96	2.06	0.365	0.093	0.113	0.133
Bt3	0.300	0.122	0.180	0.196	0.110	0.076	0.104	0.102	2.73	1.61	1.73	1.92	0.429	0.175	0.258	0.280
Bt4	0.228	0.148	0.172	0.207	0.072	0.087	0.083	0.095	3.17	1.70	2.07	2.18	0.217	0.141	0.163	0.196
Bt5	0.202	0.194	0.191	0.219	0.095	0.106	0.072	0.063	2.12	1.83	2.67	3.48	0.244	0.234	0.231	0.264
Bt6	0.164	0.156	0.112	0.166	0.073	0.082	0.041	0.109	2.25	1.91	2.72	1.53	0.220	0.208	0.151	0.222

Appendix Table C7 (Continued).

Horizon	Total carbon				Total nitrogen				C/N				E_c			
	LMA	SMA	MiA	SCf	LMA	SMA	MiA	SCf	LMA	SMA	MiA	SCf	LMA	SMA	MiA	SCf
	(-----------g kg^{-1} soil------------)				(--------------g kg^{-1} soil---------------)											
Yasothon(Yt):																
Ap	0.967	0.609	0.345	0.483	0.102	0.069	0.030	0.055	9.52	8.77	11.62	8.75	0.371	0.233	0.132	0.185
Bt1	0.410	0.281	0.327	0.460	0.020	0.019	0.044	0.058	20.61	14.96	7.49	7.93	0.185	0.127	0.148	0.208
Bt2	0.174	0.287	0.174	0.266	0.028	0.032	0.018	0.037	6.32	9.08	9.59	7.11	0.099	0.162	0.099	0.150
Bt3	0.504	0.244	0.442	0.405	0.067	0.023	0.050	0.043	7.48	10.73	8.93	9.45	0.285	0.138	0.250	0.229
Bt4	nd	0.202	0.216	0.347	nd	0.015	0.021	0.035	nd	13.57	10.24	9.83	nd	0.129	0.137	0.221
Bt5	0.209	0.191	0.208	0.297	0.016	0.008	0.008	0.035	12.91	24.78	26.24	8.48	0.151	0.138	0.150	0.215
Bt6	0.201	nd	0.178	0.300	0.003	nd	0.020	0.011	78.28	nd	9.12	27.54	0.195	nd	0.173	0.291
Bt7	0.706	nd	0.174	nd	0.002	nd	0.001	nd	405.75	nd	202.41		0.598	nd	0.148	nd
Phon Phisai (Pp):																
Ap1	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ap2	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Btc1	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Btc2	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Btc3	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Btc4	nd	nd	0.338	0.391	nd	nd	0.088	0.091	nd	nd	3.8	4.31	nd	nd	0.150	0.174
Btc5	nd	nd	0.308	0.331	nd	nd	0.094	0.070	nd	nd	3.3	4.71	nd	nd	0.195	0.210
2Bv1	nd	nd	0.217	0.249	nd	nd	0.047	0.078	nd	nd	4.6	3.21	nd	nd	0.178	0.204
2Bv2	nd	nd	0.177	0.269	nd	nd	0.046	0.104	nd	nd	3.9	2.58	nd	nd	0.161	0.244
Borabue (Bb):																
Ap	nd	nd	0.255	0.327	nd	nd	0.059	0.058	nd	nd	4.3	5.61	nd	nd	0.066	0.084
Bt1	nd	nd	0.136	0.152	nd	nd	0.031	0.053	nd	nd	4.4	2.87	nd	nd	0.121	0.135
Bt2	nd	nd	0.377	0.274	nd	nd	0.061	0.044	nd	nd	6.2	6.24	nd	nd	0.097	0.071
2Btc	nd	nd	0.328	1.039	nd	nd	0.050	0.183	nd	nd	6.5	5.68	nd	nd	0.057	0.180
2Crt1	nd	nd	0.446	0.415	nd	nd	0.076	0.065	nd	nd	5.8	6.41	nd	nd	0.148	0.138
2Crt2	nd	nd	0.272	nd	nd	nd	0.071	nd	nd	nd	3.8	nd	nd	nd	0.082	nd

Appendix Table C7 (Continued).

Horizon	Total carbon				Total nitrogen				C/N				E_c			
	LMA	SMA	MiA	SCf	LMA	SMA	MiA	SCf	LMA	SMA	MiA	SCf	LMA	SMA	MiA	SCf
	(-----------g kg^{-1} soil------------)				(--------------g kg^{-1} soil---------------)											
Sikhio (Si):																
Ap1	0.913	0.667	0.398	0.532	0.070	0.034	0.027	0.029	12.99	19.70	14.67	18.08	0.161	0.118	0.070	0.094
Ap2	0.791	0.690	0.377	0.531	0.037	0.049	0.026	0.035	21.51	14.07	14.51	15.36	0.145	0.127	0.069	0.098
Btk1	1.582	0.818	0.437	0.546	0.041	0.046	0.029	0.017	38.42	17.75	15.06	32.09	0.282	0.146	0.078	0.097
Btk2	4.316	0.850	0.583	0.436	0.141	0.141	0.124	0.096	30.65	6.04	4.70	4.53	0.863	0.170	0.117	0.087
Btk3	0.980	0.580	0.401	0.344	0.092	0.128	0.086	0.074	10.67	4.52	4.66	4.63	0.278	0.164	0.114	0.097
Btk4	0.538	0.520	0.484	0.343	0.139	0.118	0.143	0.085	3.87	4.41	3.39	4.04	0.202	0.196	0.182	0.129
Nam Phong (Ng):																
Ap1	nd	nd	0.255	0.591	nd	nd	0.049	0.065	nd	nd	5.23	9.05	nd	nd	0.092	0.213
Ap2	nd	nd	0.183	0.268	nd	nd	0.066	0.062	nd	nd	2.76	4.35	nd	nd	0.103	0.151
E1	nd	nd	0.151	0.236	nd	nd	0.033	0.040	nd	nd	4.62	5.91	nd	nd	0.303	0.472
E2	nd	nd	0.113	0.223	nd	nd	0.039	0.048	nd	nd	2.93	4.65	nd	nd	0.315	0.619
2Bt1	nd	nd	0.185	0.242	nd	nd	0.080	0.069	nd	nd	2.33	3.51	nd	nd	0.175	0.228
2Bt2	nd	nd	0.170	0.238	nd	nd	0.072	0.090	nd	nd	2.38	2.64	nd	nd	0.164	0.228
2Bt3	nd	nd	0.182	0.223	nd	nd	0.046	0.092	nd	nd	3.94	2.43	nd	nd	0.198	0.242
3C	nd	nd	0.239	0.258	nd	nd	0.099	0.002	nd	nd	2.41	141.08	nd	nd	0.319	0.344
Chan Thuek (Cu):																
Ap1	nd	nd	0.781	1.124	nd	nd	0.011	0.095	nd	nd	72.54	11.88	nd	nd	0.099	0.142
Ap2	nd	nd	0.523	0.779	nd	nd	0.024	0.048	nd	nd	22.07	16.34	nd	nd	0.153	0.228
AB	nd	nd	0.526	0.664	nd	nd	0.031	0.071	nd	nd	16.94	9.39	nd	nd	0.157	0.198
Bt1	nd	nd	0.597	0.779	nd	nd	0.056	0.086	nd	nd	10.74	9.04	nd	nd	0.145	0.190
Bt2	nd	nd	0.541	0.668	nd	nd	0.062	0.101	nd	nd	8.71	6.59	nd	nd	0.199	0.246
Bt3	nd	nd	0.468	0.707	nd	nd	0.046	0.058	nd	nd	10.22	12.09	nd	nd	0.163	0.245
Bt4	nd	nd	0.795	0.791	nd	nd	0.064	0.074	nd	nd	12.43	10.63	nd	nd	0.237	0.236
BCrt	nd	nd	0.630	0.595	nd	nd	0.064	0.056	nd	nd	9.83	10.57	nd	nd	0.209	0.198

nd = not detected, LMA = large macroaggregate, SMA = small macroaggregate, MiA = microaggregate, SCf = silt and clay fraction
E_c = carbon enrichment factors (E_c = g C kg^{-1} fraction/g C kg^{-1} whole soil)

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