SOIL DEGRADATION UNDER CONTRASTING CROPPING REGIMES FOLLOWING FOREST CLEARANCE IN NORTH EAST THAILAND

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by

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ABSTRACT

Soil degradation of Ultisols after clearance of dry Dipterocarp forest in North East Thailand is quantitatively assessed through measurements of changes in soil properties and soil quality indicators on a time series of study plots under sugarcane and cassava. Research plots with known times since forest clearance on similar Ultisols, were selected by a combination of participatory methods with farmers, collaboration with forestry and agricultural extension officers, information derived from soil maps and field survey, and interpretation of a time series of aerial photographs. Forest control plots were similarly selected for comparison.

Results show that soil degradation process are initiated under natural forest and surface effects appear to be related to canopy gaps, but no significant effect of frequency was found at 10-15cm soil depth. Soil degradation increases substantially in the first 20 years after forest clearance for cassava and for sugarcane production and, thereafter, approaches an equilibrium. Significant increases of bulk density under cassava and clay dispersion index under sugarcane indicate soil compaction and soil structure decline. Significant decreases in soil organic carbon, labile carbon and exchangeable cations were observed under both cropping regimes, whilst acidification was significant under sugarcane. Significant negative changes of relative soil quality indices (Δ RSQI < 0) over time were detected under cassava, but were greatest under sugarcane.

These findings suggest that the use of formerly forested Ultisols for the monoculture of sugarcane and, to a lesser extent, cassava is unsustainable because of the high risk of soil degradation and soil quality decline. Improper cultivation practices, such as burning, frequent ploughing and using chemical fertilizers without liming, enhanced the severity of soil degradation under sugarcane. The changes in soil quality demonstrated should help to develop early warning indicators and monitoring programmes to assess when and where soil degradation processes are active and at critical levels, thus improving sustainable soil management.

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Chapter 1

Introduction

Soils are fundamental to the well-being and productivity of both agriculture and natural ecosystems and because soil is in a large, but finite supply, the sustainable use of soils in agriculture and issues of soil quality and soil degradation are receiving increased attention as matters of global concern (Shainberg, 1999). The massive increase in global population, 1950 to 1998, which increased from 2500 million to 6000 million in the period (Young, 1998) is leading to an increase in food demand. In most of the world a major expansion in cropland area is no longer a feasible option, because most of potential cultivable land has already been brought under cultivation and the remaining land is located in ecologically-sensitive areas. Nevertheless, tropical forest continues to be cleared for agriculture expansion, such as for recent expansion of soybeans in Brazil (Mertens *et al.*, 2002).

In Thailand, population pressure is leading to deforestation, intensification of agriculture and, progressively, to soil and land degradation. From 1960 to 2002, the population increased from 26 million to 62 million (Local Administration Department, 2002), whilst the forest area decreased from 59 % to 25 % and agricultural land increased from 21 % to 41 % of the total area (Office of Agricultural Economics, 2002). Deforestation has been particularly severe in North East Thailand, the largest region of the country (about 33 percent of total area), where from 1961 to 1995 the natural forest area decreased from 52 % to 14 % (Limpinuntana *et al.*, 2000).

The soils most widely cleared for agriculture are acid, low fertility Ultisols (Soil Survey Staff 1999) that are particularly susceptible to soil degradation and cover 68.1 % of North East Thailand (Kheoruenromne, 1991). Most of these Ultisols were originally developed under forest cover prior to smallscale clearance for shifting cultivation on well drained sites, or for rice production in poorly drained valleys or depressions. Accelerated deforestation of Ultisols for commercial cropping of monocultures, including sugar cane, in recent decades is currently causing concern because of the perceived deterioration of soil quality through fertility decline and soil erosion (Vityakon, 1991; Ota *et al.*, 1992; Sriwongsa. 1994; Vityakon *et al.*, 2000a; Tangtrakarnpong and Vityakon, 2002).

This thesis addresses such concerns through a study of the progressive effects of differing cropping regimes on the properties of formerly forested Ultisols in this part of Thailand. Before outlining the objectives of the study, it is pertinent to review the characteristics of Ultisols in order to understand why this soil order is at a high risk of soil degradation and soil quality decline.

1.1 Soils of North East Thailand

Soils in North East Thailand include Ultisols, Alfisols, Inceptisols, Entisols, and

Oxisols, classified according to the United States Soil Taxonomy (Soil Survey Staff 1999), however, Ultisols are by far the most extensive, covering about 114,950.54 km^2 in this region (Kheoruenromne, 1991).

Ultisols are required to show a texture contrast between clay-depleted surface horizons and clay-enriched argillic or kandic horizons with a base saturation of less than 35 % (Soil Survey Staff, 1999). The prefix "Ulti" implies extreme leaching. In other soil classification systems, tropical Ultisols are approximately equivalent to Acrisols and some Nitisols in the FAO system (FAO-ISSS-ISRIC, 1998), Red-Yellow Podzolic soils in the 1938 Classification System in United States revised in 1949, Podzolico Vermelho-Amarelo in the Brazilian classification system and Sols ferrallitiques lessives or Sols ferrallitiques fortement de satures-appauris in French system (Van Wambeke, 1992, West *et al.*, 1997).

Ultisols are estimated to comprise about 11,054,000 km^2, which is 8.4 % of the global landmass not covered by ice-sheets. Approximately 80 % of Ultisols are in tropical regions and about 18% of the tropics are covered by these soils (Eswaran, 1993). The principal processes involved in the formation of Ultisols are clay mineral weathering leading to a dominance of kaolinite or other low activity clays, translocation of clay from the upper soil horizons to accumulate in an argillic or a kandic horizon, and leaching of basic cations from the profile (West *et al.*, 1997).

Ultisols are required to posses either an argillic or a kandic horizon that contains a considerable amount of silicate clay (West *et al.*, 1997). These soils are therefore found on parent materials that contain either appreciable quantities of phyllosilicates, or primary minerals that can weather to produce phyllosilicates. They occur under a range of climatic conditions (Wilding, 1999) between 40°N and 40°S latitude that must have, sometime during the year, evapotranspiration greater than precipitation when precipitation exceeds the water-retention capacity of the soil, and mean annual air temperatures above 6°C. Landscapes dominated by Ultisols have experienced geomorphic stability over relatively long periods of time. These environmental conditions are required to form the well-developed argillic horizons typical of Ultisols, and particularly, the strongly weathered kandic horizons found in some tropical Ultisols (Van Wambeke, 1992, West *et al.*, 1997).

The translocation of clay is a fundamental process in the formation of Ultisols and influences many soil physical properties, such as, limitation of infiltration rate, increase of run off and susceptibility to soil erosion. Clay eluviation results in sandy and loamy surface horizons with low organic matter content and weak structure that are subject to compaction and surface crusting. This can have a large impact on rooting and seedling emergence, but, more seriously, decreases the infiltration rate in surface horizons, increases runoff and accentuates the risk of erosion (West *et al.*, 1997). In this context, forest ecosystems on Ultisols in the tropics are at particular risk of accelerated soil erosion and deterioration of soil quality following removal of the protective forest canopy, particularly where the forest is replaced by agricultural monocultures cultivated as row crops on sloping ground.

A base saturation less than 35 % in the lower part of subsoil is another soil property that distinguishes the Ultisols from other soil orders. This characteristic, and other properties such as low pH, potentially high aluminum saturation and dominantly low activity clays associated with low cation exchange capacity, have a significant impact on the chemical properties of Ultisols (West *et al.*, 1997). The release of basic cations by weathering is equal to, or less than, the removal by leaching. Under natural forest vegetation mostly of the bases are commonly held in the vegetation biomass and the upper few centimetres of the soil by nutrient cycling. Thus, apart from the thin surface Ah horizons, Ultisols under forest normally have soil horizons that are acid and deficient in plant nutrients. Removal of the forest biomass by deforestation and disturbance or loss of the thin surface horizon are likely to lead to rapid soil fertility decline and aluminium toxicity in the absence of high inputs of fertilizer and lime. The sustainability of agricultural land use on such soils after forest clearance will depend heavily on the crops grown, the land husbandry methods, the availability of fertilizers and lime, regional and national agro-economic policies and local socio-cultural conditions.

The Ultisols of the North East Thailand were formed under a type of dry tropical forest found on low terraces, middle terraces, high terraces and along the foothills. They are classified into two sub-orders, Ustults and Aquults, and five prominent Great Groups, namely, Kandiaquults, Paleaquults, Kandiustults, Paleustults and Haplustults (Department of Land Development, 1999).

The Aquults are located mainly in the lowlands, whilst Ustults are dominant on the uplands. The dominant soil series include: Korat series (Kandiustults with marginally oxyaquic properties); Warin series (Kandiustults); Satuk series; and Yasothon series (Paleustults). All are quite superficially similar in general soil morphology and are often found as a soil toposequence. The Korat series is normally located on lower to middle slopes where deep subsoil drainage is affected by seasonal water logging. The Satuk series, found on middle slopes, has particularly deep argillic horizons. Well-drained Kandiustults of the Warin series occur on middle to upper slopes, whilst Paleustults with slightly more active clays (Yasothon series) occupy upper slopes. These soils only differ in their colour, drainage status and depth of their subsoil diagnostic horizons of clay increase. For purpose of land use and management, they have been grouped together as soil series group 35 in the Thai soil series grouping system (Department of Land Development, 1998). Furthermore, according to Soil Taxonomy 1975, these soil series were formerly classified in the same family, as fine-loamy, siliceous, Oxic Paleustults, before the recognition of the kandic horizon (Kheoruenromne, 1991; Department of Land Development, 1998). Overall, the dominant Ultisols in this region can be considered as low in fertility due to mainly small CEC, acidity of both A and Bt horizons and relatively small organic matter content, particularly the Kandiustults which, in addition, have a small CEC in subsoil. The Haplustults have sometimes been regarded as medium in soil fertility on the basis of their soil chemistry, but these soils have the more serious problem of a reduction in soil volume exploitable by roots because they are shallow-skeletal soils, often with petroplinthite close to the surface.

Although Ultisols have been considered as low productivity soils and the original concept for soils in this order was a group of soils that could not sustain continuous crop production without application of soil amendments (West *et al.*, 1997), they are used in Thailand, particularly, in the North East, for a variety of agricultural land uses, including intensive and extensive systems. Forest clearance from Kandiustults for sugarcane production has been particularly widespread in the Udon Thani province over the past 40 years and, particularly, since 1987, whilst forest clearance for cassava continues to expand in the Sakon Nakhon province. The evidence for land use changes on these soils in North East Thailand is discussed in more detail below (Section 1.2).

1.2 Land use changes

Changes in the land use patterns of North East Thailand can be demonstrated by the study of the land use systems of Ban Kham Muang, Khon Kean, North East Thailand (Vityakon *et al.,* 2000a). These are representative of similar changes elsewhere in this region. Based on information from key-informant interviewing, these authors divided the changes of land use for agriculture into two phases as follows;

(i) Subsistence period, before 1967. Villagers mostly used land for subsistence purposes. After forest clearance, paddy fields were located in the lowlands, whilst other crops were usually cultivated on the uplands for subsistence. In some places forest remained on the uplands, or at the top of the slopes, and was used for raising buffaloes and cattle. Forest areas were also used for collecting natural foods, such as, wild animals, mushrooms, wild vegetables and fruits, medicinal herbs etc. Cotton was the most important field crop at this early period, but Kenaf was introduced around 1950. Cotton disappeared from the region around 1967. Toward the end of this phase, due to population increase, there was expansion of paddy fields by transforming the lower parts of the uplands marginal to lowland areas into paddy fields. These were called upper paddy fields. Crop production was based on indigenous knowledge. Natural fertilizers, such as, crop residues and manure were used as a source of plant nutrient inputs. Land preparation and transport was performed by animal traction and hand cultivation (Vityakon *et al.*, 2000a).

(ii) Subsistence-commercial period from 1968 to the present. Farming systems in the region have widely changed from full subsistence to a subsistence-commercial combination since 1968. Rice production was used not only for local consumption, but the surplus was offered for sale. Kenaf was produced for commercial purposes, but in 1971 cassava was introduced to this region and gradually replaced kenaf, as the production process was easier. Cassava became the main commercial crop and the growing area was rapidly expanded during 1973-1974. In 1987, commercial sugarcane was introduced in the Khon Kaen area, and a new sugar mill was established in Nam Phong district, about 25 km from Ban Kham Muang. Crop production technology has changed, with more chemical fertilizer replacing natural fertilizers, the number of buffalos and cattle have decreased because of the reduction of grazing areas and because machinery has often replaced animal and human power.

At the present, cassava and sugarcane are the predominant commercial crops on upland Kandiustults.

Recently, sugar mills shifted from Central Plain of Thailand to the North East region. There are currently thirteen sugar mills in the North East Thailand and three of them are in Udon Thani province. Since 1973 the natural forest area has progressively decreased due to forest clearance for the expansion of cassava and sugarcane production. Currently, the North East region is the largest area of cassava (534,359 hectare) and sugarcane (400,217 hectare) production in Thailand (Office of Agricultural Economics, 2002). In Udon Thani province in particular the sugarcane planting area increased from 21,185 hectares in 1974 to 80,613 hectares in 2002 (Office of the Cane and Sugar Board, 1974; Office of Agricultural Economics, 2002) and 52 % of the total area are concentrated in three districts, Si That, Kumpwapi and Chai Wan (24.18, 16.29 and 12 % respectively).

Economically, North East region is more suitable for sugarcane production than the Central Plain of Thailand, due to advantages in lower production costs, adequate labour supply and greater space for expansion of sugarcane production. However, because of adverse soil conditions, with sandy Ultisols on the undulating terrain, sugarcane production in North East region is at a higher risk of accelerated soil erosion and deterioration of soil quality than the Central Plain region, which is dominated by loamy to clayey Alfisols on the flat to slightly undulating terrain (Kheoruenromne, 1991). Moreover, sugarcane cropping requires intensive care with heavy machinery use and a large amount, 375 kg ha^{-1}, of chemical fertilizer when compared with 156 kg ha^{-1} of those in cassava cropping (Field crop research institute, 1999). It is predicted that the combination of these components, unfavourable environmental conditions and intensive upland cropping, will bring about severe soil degradation and threaten the sustainability of long-term crop production in North East Thailand.

A better understanding of soil degradation processes and monitoring of soil quality changes in this region of Thailand is therefore critical. The maintenance of soil quality, the prevention of soil degradation and the adoption of sustainable land management practice are essential for the future if land resources are to support the growing population in Thailand, that will increase up to 70 million in 2020 (Human Resources Planning Division, 2002). Similar problems affect many areas dominated by Ultisols in other parts of Southeast Asia and South America.

1.3 Project Aims and Objectives

The problems of agricultural land use in this region are particularly related to inherent soil properties, which tend to result in susceptibility to soil degradation processes after forest clearance. However, my own field investigations have shown that initial soil degradation processes, rainsplash, sheet and rill erosion, are often active under natural forest (Appendix I, proiles FA, FB and FC). The degree of degradation seems to increase substantially after forest clearance for cultivation, particularly on the 'uplands' where the degree of degradation is higher than that on the lowlands. There are few studies that have tried to evaluate soil property changes under different forms of land use following forest clearance in this region (Vityakon, 1991; Ota *et al.*, 1992; Vityakon *et al.*, 2000; Tangtrakarnpong and Vityakon, 2002). Most of them have employed a comparative assessment approach and have not systematically developed soil quality indicators for assessing soil degradation. Moreover, no attempt was made to assess further degradation of soil quality after forest clearance in these studies due to the lack of reliable temporal information.

If soil productivity in agricultural systems of North East Thailand is to be sustained, a better understanding of soil property changes over time is required. This needs the development of sound technique to define and monitor soil quality and soil degradation in this area and is the main subject of this thesis.

The purpose of the study reported here is to investigate whether different land use systems incorporating continuous cropping affect soil quality dynamics after forest clearance in upland Ultisols of North East Thailand. The main hypothesis to be tested is that utilization of upland Ultisols for field crop production (sugarcane and cassava) after forest clearance is leading to serious, long-term soil degradation and is an unsustainable form of land use. The results of the study should contribute to the continuing debate about the severity of soil degradation and the sustainability of sugarcane and cassava production as perceived by different interest groups within Thailand, which at present is not well informed by scientific assessment and monitoring. The results should also have wider application in the context of the use of Ultisols for continuous cropping elsewhere in the tropics.

The objectives of the study can be summarized as follows:

(i) to select appropriate soil quality indicators for assessing soil quality dynamics.

(ii) to examine the spatial variability of selected soil properties in relation to canopy cover under natural forest.

(iii) to assess soil property and soil quality changes over time after forest clearance under cassava and sugarcane cropping regimes by establishing a time series of sites with known land management on similar soils.

(iv) to use the results of objectives (i) to (iii) to test the hypothesis that the use of upland Ultisols in North East Thailand for continuous field crop production after forest clearance is leading to soil degradation and is unsustainable.

This thesis examines the progression of forest clearance on Ultisols in North East Thailand over the last 45 years and assesses the effects of cassava and sugarcane production on soil degradation over this period. This was accomplished through measurements of changes in soil properties on time series of study plots with known ages since forest clearance. The results are discussed in the context of the sustainability of these forms of agricultural land use. The assessment of soil quality is employed as a tool to measure the overall changes over time of soil attributes that had been selected as soil quality indicators. Soil attributes of upland Ultisols under natural forest (Dry Dipterocarp Forest) and the youngest cultivated soils are used as reference baselines for comparisons. The study includes the effect of canopy cover on the spatial variability of soil properties under these forests in order to establish the original properties of upland Ultisols and their variability. To assess spatial variability several individual study points were sampled within the study plots and analysed separately, instead of adopting a more conventional composite sampling approach. As a background to the research methods that are employed, it is first necessary to carefully define concepts of 'soil quality' and 'soil degradation', and their measurement in relation to sustainable land use (see Chapter 2).

Chapter 2

Concepts of Soil Degradation and Soil Quality and Their Potential Application to Changes in Ultisols Following Forest Clearance in North East Thailand

2.1 Soil degradation

Soil degradation has been defined in various ways. For instance, Blum (1997) defined soil degradation as a loss or a reduction of soil energy. All soil functions and soil uses are based on energy and soil degradation is equal to a loss or reduction of soil functions or soil uses. Soil degradation occurs when soil cannot perform one or several of its functions, so soil degradation is the loss of actual or potential productivity and utility. It implies a decline in soil's inherent capacity to produce economic commodities and perform environmental regulatory function (Lal, 1997a). Similarly, soil degradation has been defined as the temporary or permanent lowering of soils' productive capacity (Syers, 1997). Therefore, changes in soil properties that limit or reduce soil capacity to carry out functions may be defined as soil degradation.

Definition of soil degradation is not only difficult to understand but also proper assessment requires a complete understanding of soil degradation processes and how to measure such processes. The soil can degrade through agricultural degradative processes, namely, physical processes (e.g. soil structure decline, compaction and erosion), chemical processes (e.g. acidification, nutrient depletion and salinization) and biological processes (e.g. loss of soil biodiversity and soil organic carbon decline). The outcomes of these processes are reflected by changes in soil physical, chemical, and biological properties. Some guidelines to help in assessing soil degradation proposed by Hartemink (2003) are (i) clear signs of soil degradation that can be observed in the field such as rill and inter-rill erosion feature, sealing or slaking of soil surface, (ii) trends in soil properties such as organic matter decline, acidification, nutrient depletion, (iii) trends in crop yield. The last might be the best indicator of soil degradation in term of crop production. However, there are many factors that affect crop yield such as insect and disease damage, inadequate rainfall as well as crop variety.

It can be concluded that soil degradation evaluation can be operated by measuring soil property changes in relation to crop yield. Significant changes in soil properties should be related to significant changes in crop yield if other factors that influence crop yield could be in control. Control of growth factors of crops can be properly practiced in an experimental station but is not easy in a general farmer's field in a long-term investigation. Therefore, soil degradation observation and soil property change measurement should be the useful alternative ways of assessing long-term soil degradation in farmers' fields.

Numerous authors have studied changes in soil properties under various cropping systems. Changes of soil properties can be regarded as positive or negative. The negatively significant changes of certain soil properties indicate soil degradation. Changes of soil property data can be obtained by two sampling procedures: (i) Type I data, or chronosequential sampling, and (ii) Type II data, or biosequential sampling, or sampling from paired sites (Sanchez *et al.* 1985; Tan, 1996; Garside *et al.*, 1997 cited in Hartemink and Wood, 1998).

In the first procedure, soil data are continuously collected at the same site over time. A good example is the long term experiments at Rothamsted (Leigh and Johnston, 1994). The original level of soil properties is employed as the reference level for comparing with the level of the same soil properties that is taken later to investigate the trend of changes in such properties. It is more useful if trends are also traced under other land use system over the same time. This procedure is very useful and more reliable because the impact of land use and management practices on soil properties can be directly measured after specific periods of time. Previous soil samples can be stored and analysed together with the newly collected soil samples at the same time same condition but soil storage may affect some soil properties. Alternatively, previous analysed data can be compared, there after, with newly analysed data obtained from the same methods and laboratory condition (Hartemink, 2003). Several researchers have used this procedure for assessing changes in soil properties over time (Sanchez *et al.*, 1983; Morrison and Masilaca, 1989; Juo *et al.*, 1995; Azooz and Arshad, 1996; Alegre and Cassel, 1996; Lal, 1997b) However, there are some disadvantages in this procedure because it is costly and/or takes time to carry out data collection.

On the other hand, in the second procedure, soil data can be collected under adjacent different land use systems at the same time and then compared. Data collection can be obtained more quickly than the former procedure. The main assumption of this procedure is that the soils under the adjacent land use systems were originally identical. A decision is made based on the difference in magnitude of measured parameters between the 'interest' plots and the 'reference' plots. However, this procedure is inexpensive and saves time to carry out data collection. There are some disadvantages, for instance, actual original level of soil properties of the 'interest' plots can never be certained as the magnitude of changes in measured soil properties is relative to that of the 'reference' plots, which is also dynamic. Other confusing factors are differences in clay content, soil depth, or unknown history of land use. These limitations largely reduce the usefulness of this procedure. Therefore, comparative assessment, study site selection, data collection and data interpretation must be carefully undertaken. With intensive data collection, this procedure provides useful information for assessing soil property changes under various cropping systems and has been employed in numerous studies (Wood, 1985; Lal *et al.*, 1992; Whitbread *et a*l., 1996; Bramley et al., 1996; Ekanade, 1997; Mbagwu and Piccolo 1998; Westerhof *et al.*, 1999; Islam and Weil, 2000; McDonald *et al.*, 2002).

To compare these procedures, Hartemink (1998a) used Type I and Type II data collection procedures to investigate soil acidification of Hapluderts under sugarcane plantations in the Ramu Valley of Papua New Guinea. The results of the two procedures showed similar trends. Some researchers have modified Type II data collection procedures by collecting soil data under adjacent different land use systems with known periods of time since forest clearance (Koutika *et al.*, 1997; Jaiyeoba, 2003). This approach should be more effective for assessing soil property changes overtime and this type of procedures is employed in this thesis for assessing soil properties and soil quality changes over time after forest clearance by using change in several properties which relative permanent as well as dynamic.

Changes in soil properties that have been studied by using Type I and Type II data sampling procedures have been employed as individual indicators for evaluating soil physical, chemical and biological degradation in cultivated soils.

2.1.1 Soil physical properties

Most researchers have paid particular attention to physical degradative processes and soil erosion is considered to be a major cause of soil physical degradation under land use and management for crop cultivation in tropical regions. Lal *et al.* (1992) studied the effects of five cropping systems on soil erosion of Ultisols in southern Nigeria and reported that soil erosion was high under oil-palm (0.17 Mg ha^{-1}) and plantain systems (0.16 Mg ha^{-1}), and was negligible in the forested control (0.0004 Mg ha^{-1}). Similarly, McDonald *et al.* (2002) investigated the effects of different land use systems on surface runoff, soil erosion of Eutric and Chromic Cambisols (Tropepts) in Jamaica over a period of 5 years and found that the forest plots had soil erosion losses less than 0.5 Mg ha^{-1} per year, whereas agricultural plots caused a 7-fold increase in surface runoff and 21-fold increase in soil erosion.

Although soil erosion is a useful indicator for assessing soil physical degradation, the evaluation of soil susceptibility to runoff and water erosion in the field is often expensive or time-consuming (Barthes and Roose, 2002). Relevant indicators, such as, aggregate stability, clay dispersion, soil compaction that can be determined more simply would be useful alternative methods for evaluating soil susceptibility to run off and erosion. Soil structure decline can lead to soil crusting and surface sealing that inhibits water infiltration and consequently brings about run off and soil erosion. So measured soil structure or aggregate stability is a relevant indicator of soil susceptibility to runoff and erosion, particularly in tropical areas where intense rainfall is frequent (Barthes and Roose, 2002).

In crop cultivation, soil aggregates can be ruptured by cultivated practices. Whitbread *et al.* (1996) studied red brown earth soils from Duri, New South Wales, Australia and reported that the 2-4 mm aggregates from the cultivated site were 5.4 % less stable to wetting than those from the reference site. Aggregates and particle size < 0.125 mm increased by 8.3 % in the cultivated soil.

Also the methods of land preparation or cultivated technique can bring about soil aggregate degradation and/or a decline in aggregate size. Mbagwu and Piccolo (1998) found that forest soils (Entisols, Ultisols and Inceptisols) in Southern Nigeria had a higher percentage of macro-aggregates (> 0.25 mm) than in the cultivated soils and in the manual land preparation sites found a higher percentage of macro-aggregates (> 0.25 mm) than mechanical land preparation sites. The effects of different land use on Oxisol aggregation were also observed in the Cerrado savanna region in Brazil by Westerhof *et al.*(1999). They reported that in the topsoil of ploughed systems, a significantly lower amount of macro-aggregates (2– 0.194 mm) and a significantly higher amount of soil in the micro-aggregate size and primary particle fraction (< 0.076 mm) was observed when compared to pastures and the native Cerrado systems. In addition, the decreases of water stable aggregates (> 0.5 and 1.0 mm) at the depth of 0–10 cm over time of use were also found in the study of changes in soil properties related to traditional techniques of cultivation in the Nigerian semiarid Savannah (Jaiyeoba, 2003)

Aggregate stability is used to describe the ability of the soil to maintain its structure when exposed to different stress. As surface soils of Ultisols are very weakly structured, a measurement of aggregate stability may not be very meaningful. The assessment of dispersible clay is an alternative way to deal with this issue. Some researchers have employed clay dispersion index to assess the stability of soil aggregates and retported that clay dispersion index under natural forest or uncultivated soils were smaller than those under cultivated soils (Koutika *et al.*, 1997; Mbagwu and Piccolo, 1998; Westerhof *et al.*, 1999). Moreover, it was found that deforestation and the long-term cultivation of tropical soils could increase the clay dispersion due to the reduction of organic carbon (Mbagwu and Piccolo, 1998).

Such evidence from published research on a variety of soils with low activity clays from the humid and subhumid tropics shows that cultivated soils are more prone to surface sealing and erosion processes than uncultivated soils under forest.

Soil compaction is another soil attribute that indicates physical degradation of soils. Soil bulk density or soil porosity is a common soil parameter that many researchers have used to assess soil the compaction condition. In Fiji, Morrison and Masilaca (1989) found that soil bulk density markedly increased in the first year of the study of changes in the properties of an Oxisol following sugarcane cultivation over a period of 6 years (1978-1983). A soil bulk density increase of 48 % was also observed within 5 years after the secondary forest clearance for cultivation on Eutric and Chromic Cambisols (Tropepts) in Jamaica (McDonald *et al.*, 2002). In addition, increases in bulk density or decreases in porosity under cultivated soil when compared with the natural grassland or forest were reported on clayey Oxisols in the eastern Amazon basin (Koutika et al., 1997), on Fluvisols and Vertisols in Papua and New Guinea (Hartemink, 1998b) and on Typic Paleustults of Bangladesh (Islam and Weil, 2000).

This range of published research evidence indicates that cultivated soils are more compact than uncultivated soils under forest. Some research results show that the compaction in cultivated soils can be the result of land preparation, (Morrison and Masilaca, 1989), animal trampling (Koutika et al., 1997) or vehicular traffic (Hartemink, 1998b).

Infiltration rate has also been suggested as an appropriate method for assessing soil physical degradation due to the soil compaction process because soil infiltration is related to aggregate stability, soil bulk density and porosity. Alegre and Cassel (1996) evaluated the different land-clearing methods and post land-clearing management systems on Typic Paleudults at Yurimaguas, Peru. They reported that mechanical land clearing for crop production increased soil bulk density from 1.16 Mg m^{-3} before clearing to 1.42 Mg m^{-3} for the straight blade and 1.28 Mg m^{-3} for the shear-blade bulldozing and lowered the infiltration rate from 420 mm hr^{-1} to 35 and 95 mm hr^{-1} respectively. Also, Hartemink (1998b) demonstrated that the infiltration rate was negatively correlated with an increase in soil bulk density or the decrease of porosity.

However, infiltration rate in a soil could also be affected by other factors, such as soil pore sizes and uninterrupted pores, rather than soil bulk density or soil porosity *pe se.* In Canada, Azooz and Arshad (1996) found that even though bulk density was greater and total porosity lower for no-tillage soils than for tilled soils, water infiltration rates were significantly higher in no-tillage systems than those in conventional tillage system on Gray Luvisols. They suggested that greater infiltration rates measured in no-tillage system than in conventional tillage system probably resulted from the flow of water through macro pores.

Disagreement between these various findings indicates that water infiltration rate data seem to be too complicated for interpreting soil compaction.

2.1.2 Soil chemical properties

Most of the studies of soil chemical properties for assessing soil productivity have focused on nutrient availability and retention capacity. The main factors that influence nutrient availability are soil reaction and the existence of plant nutrient elements both in quantity and quality. Negative changes in these attributes can be expressed in terms of reduction of soil pH (or an increase in soil acidity), nutrient depletion and a decline in effective cation exchange capacity (ECEC) or cation exchange capacity (CEC).

Soil acidification is the result of the negative change in soil reaction that is expressed as the pH value. Improper land use and management often leads to soil acidification and a decrease of soil pH. A decrease of soil pH in continuous crop cultivation is commonly due either to ammonium fertilizer application or to loss of basic cations by leaching, erosion and crop removal. In North Queensland Australia, Wood (1985) reported that a decrease in soil pH in water of cultivated land rative to that of uncultivated land was observed and, in particular, a significant decrease was found at the depth of 20-30 cm under intensive sugarcane cultivation. In Fiji, a decrease of 0.7 pH unit was found in the topsoil horizons (0-12 cm) of an Oxisol under sugarcane cultivation over a period of 6 years (Morrison and Masilaca, 1989). The decreases in soil pH over time were also observed in continuous crop cultivation on Nigerian Oxic Paleustalf. The magnitude of changes over 8 years were 1.2 pH unit in the depth of 0-5 cm and 1.0 pH unit in the depth of 5-10 cm (Lal, 1997b). The similar trend of changes in soil pH was reported on alluvial soils under sugarcane in Papua and New Guinea (Hartemink, 1998a).

This range of published research results indicates that consecutive crop cultivation leads to soil acidification and a decrease of soil pH. Possible explanations include decline in soil pH buffering capacity associated with depletion of sources of basic cations and soil organic matter in cultivated soils. However, some authors claimed that it was due to the addition of ammonium fertilizer (Wood, 1985; Morrison and Masilaca, 1989; Hartemink, 1998a).

Nutrient depletion is an important attribute for assessing soil degradation in cropping systems because plant nutrients directly affect plant growth. Sanchez *et al.* (1983) reported that under crop production without fertilizer inputs, nutrient elements (N, P, K, Ca, Mg, S, Cu, Zn, Mn, B and Mo) significantly declined after burning in the first 8 years after clearing a fine loamy, isohyperthermic Typic Paleudult in the humid tropical rain forest environment of Peru. In North Queensland, Australia, decreases of exchangeable calcium and magnesium under sugarcane soils relative to uncultivated soils were observed in different soil types of the Herbert Valley (Wood, 1985). Similarly, a general decline in exchangeable calcium and magnesium with time was observed in Fiji where soil properties under sugarcane were monitored from 1978 to 1983 (Morrison and Masilaca, 1985). In contrast, Hartemink (1998a) found that between 1980s and 1990s, alluvial soils under sugarcane in Papua and New Guinea showed significant decreases in cation exchange capacity (CEC), total nitrogen, available phosphorus and exchangeable K, but the changes in exchangeable Ca and Mg were not significant.

A marked depletion of exchangeable potassium and magnesium under old sugar cane land compared with land recently utilized for sugar cane was observed by Bramley *et al.* (1996), but the results were not consistent across all study sites due to different soil types and control plot history. Ekanade (1997) also reported that continuous cultivation of Orthic Luvisols of hill-slopes in southwestern Nigeria led to significant depletion of plant nutrients (N, P, K, Ca, Mg) compared to adjacent forest soils.

These results from the literature suggest that in cultivation systems, nutrient elements are depleted as a consequence of leaching, erosion and crop removal where the rate of loss is greater than the rate of return into the soil. Consequently, decreases in nutrient elements that are easily leached, such as potassium, and those which are rarely included in the formulation of chemical fertilizers, such as calcium and magnesium, have been commonly observed in soils under continuous crop production.

2.1.3 Soil biological properties

It is well established that the amount and diversity of soil macro-organisms and micro-organisms are influenced by the soil environment and soil property, or soil environment dynamics indicate changes of soil organism populations and diversity and *vice versa*. Therefore, a measure of soil biological properties should be a useful indicator for assessing soil degradation. Some soil biological properties, such as, soil respiration (Parkin et al., 1996), soil enzyme activities and biodiversity (Dick *et al.*, 1996) and soil invertebrates (Blair *et al.*, 1996) have been suggested as indicators for assessing soil quality dynamics. However, as these attributes are quite multifaceted and results are difficult to interpret, few researchers have employed them as biological indicators for assessing soil degradation (Beyer *et al.*, 1991; Costantini *et al.*, 1996; Islam and Weil, 2000).

2.1.4 Soil organic matter

Separating soil function into chemical, physical, and biological processes is difficult, because these processes are dynamic and interactive in nature. There is rarely a one-to-one relationship between soil function and soil quality indicators (Schoenholtz *et al.*, 2000). A specific or given function is often governed by a number of soil properties or attributes, whilst any selected soil property or attribute may be relate to several soil functions. Soil organic matter is an excellent example of the latter, as it plays a role in many soil properties and functions.

Soil organic matter has long been considered as the key quality indicator of soil because it is a source and a sink of plant nutrients in soils and plays an important role in soil physical properties and influences many fundamental biological and chemical processes, for instance, maintaining soil tilt, aiding air and water infiltration and water retention, and promoting cation exchange capacity (Lawrence, 1996). Depletion of soil organic matter causes loss in water holding capacity, poor aggregation and acceleration of soil erosion, reduced soil biological activities and poor retention of nutrients. There are numerous researchers who have proposed and employed soil organic matter (SOM), or soil organic carbon (SOC), as a soil quality indicator. Moreover, it has been used in pedotransfer functions to calculate bulk density, water retention capacity, leaching potential, cation exchange capacity (CEC). Because of its influence on so many factors, Larson and Pierce (1991) suggested that soil organic matter is the single most important indicator of soil quality and productivity.

Therefore, soil property degradation can be expressed in terms of soil organic matter, or soil organic carbon, decline. Most researchers employ soil organic matter, and/or related parameters, such as soil organic carbon, labile carbon and microbial biomass carbon, as indicators for assessing soil degradation. Much of the reported research shows that a decline of soil organic carbon over time is commonly found in the topsoil horizons under continuous cultivation (e.g. Hartemink, 1998c; Islam and Weil, 2000; Blair, 2000; McDonald *et al.*, 2002; Jaiyeoba, 2003; etc.).

When natural vegetation is converted to cropland, organic carbon decreases markedly in the early stages, but approaches an equilibrium later on. Sanchez *et al.* (1983) reported that topsoil (0-15 cm) organic C decreased at a rate of 25% per year during the first year in a study of changes in soil properties on the first 8 years after clearing forest on a Typic Paleudult in Peru. Also, under sugarcane cultivation in

Fiji, a decrease of soil organic matter 27 % was observed in the topsoil horizons in the early months following sugarcane planting, the organic matter then stabilized at about two-thirds of the original level over a period of 6 years (Morrison and Masilaca, 1989). Similarly in Nigeria, Juo *et al.* (1995) monitored changes in soil chemical properties under various land use and management regimes for 13 years on a kaolinitic Alfisol. It was found that under continuous maize cropping, soil organic carbon at the depth of 0-15 cm decreased during the first 7 years, then reached a steady state.

Several researchers have found that the magnitude of organic matter decrease is greater due to improper cultivation practices. For example, Wood (1985) found a significant decrease of 53% in organic carbon content at the depth of 0-10 cm in the cultivated soil relative to uncultivated soil and claimed that burning sugarcane plots before harvesting was a major cause of this phenomenon. In addition, a decrease in soil organic matter content of 2.9 g kg^{-1} in the tillage plots compared with no-tillage plots was observed under 16 consecutive maize monoculture crops on a western Nigerian Oxic Paleustalf with a coarse-textured surface horizon (Lal, 1997). This information indiactes that intensive tillage also stimulates soil organic matter decomposition and decreases soil organic matter content in cultivated soils.

These results show that a decline of soil organic matter is commonly found, particularly in the topsoil horizons, when natural vegetation is converted to cropland, or when cultivated land is compared with uncultivated land. Management practices, such as burning cultivated plots and/or intensive tillage, stimulate soil organic matter decomposition leading to a decline of organic matter in cases of inadequate organic material inputs.

Changes in land use and agricultural practices also lead to changes in soil organic matter or organic carbon pools. Often these changes of soil organic carbon are gradual and subtle, and difficult to detect in the short to medium terms. Therefore, there is a need to develop analytical methods that can measure the active, passive and slow release pools of soil organic carbon. Fractionation of carbon on the basis of its lability should be a valuable technique that can detect the small, short term, medium-term and long- term changes in soil organic matter.

Lefroy, *et al.* (1993) studied on the changes in soil organic matter with cropping as measured by organic carbon fractions, using the different concentrations of potassium permanganate ($KMnO_4$) and found that changes in total carbon level were relatively insensitive as a sustainability measure. Labile carbon, using different strength $KMnO_4$, was shown to be a more sensitive indicator of change. $KMnO_4$ is a powerful oxidizing agent under neutral conditions, but it is relatively unstable and thus it cannot be use as a primary standard. This creates some problems in obtaining repeatable and quantitative results. To avoid these problems, the recommended procedures (Blair *et al.*, 1995) are rather complicated to follow.

Labile soil carbon pools, such as soil microbial carbon, have been suggested as more sensitive indices to monitor long- term trends in organic matter (Doran and Parkin, 1994; Larson and Pierce, 1994; Gregorich *et al.*, 1994). However, the fumigation extraction methods to determine microbial carbon are quite complex and time-consuming, which could limit their use in routine monitoring programs. On the other hand, a labile C fraction can be obtained by using water extraction from moist or air—dried soils (McGill *et al.*, 1986; Zsolnay and Gorlitz. 1994; DeLuca and Keenev, 1994: Harris and Safford, 1996). However, cold-water extraction provides very little carbon that is derived from microbial cells and there is poor correlation between the microbial biomass carbon and the amounts of soluble carbon extracted from moist soils (DeLuca and Keenev, 1994).

Sparling *et al.*(1998) studied the conditions to extract microbial biomass and suggested that a suitable combination was to air-dry soil at 20-25°C followed by a water extraction at 70°C for 18 hours to maximize the amount of microbial materials in a water extract of dry soil. The hot water extractable C content of the mineral soils was about 43% of the microbial carbon, which was similar to the 40-45% of microbial carbon obtained by fumigation extraction. Particularly for topsoil with organic carbon less than 10%, water-extractable C was more closely related to the microbial biomass carbon than the total C.

Ghani *et al.*(2002) evaluated the usefulness of the hot water-extraction carbon in detecting the impacts of subtle changes within the pastoral ecosystem and the impacts of long-term cropping, market gardening, pastoral agriculture and native vegetation, and found that there was strong positive correlation between microbial biomass-C (r^2 = 0.90), total carbohydrates and mineralisable N and micro-aggregate stability. These results indicated that hot water-extraction carbon is an integrated measurement that correlates with key biological and physical attributes of soils. In comparison to other methods, hot water-extraction of carbon is considerably easier, economic and less time consuming, does not require toxic fumigants, and the soil samples can conveniently be stored in an air-dry state at the room temperature until they are analyzed. Although this method requires further validation on other soils, it should be valuable method for soil quality monitoring according to Sparling *et al.*(1998) and Ghani *et al.*(2002).

Fractionation of carbon on the basis of its lability was therefore employed to detect the temporal changes of soil organic matter in the present study by using the hot water-extractable labile carbon method of Ghani *et al.* (2002) and by determining organic carbon by the wet combustion method of Walkley-Black titration (Nelson and Sommers, 1996).

2.2 Soil degradation in North East Thailand

2.2.1 Forest soils

There are three types of natural forest in North East Thailand: Dry Evergreen Forest, Mixed Deciduous Forest and Dry Dipterocarp Forest. The most extensive is Dry Dipterocarp Forest, which accounts for approximately 75% of the forest in this region (Ruangphanich, 1998). This forest has an open canopy and the trees shed their leaves in the hot dry season. Annual fires in the dry season are common and the impact of rainfall on dry surface soils at the beginning of the rainy season is often apparent, leading to soil erosion (Sakurai and Tanaka, 1998).

Most of the soils in this region are Ultisols derived from sandstone, shale or siltstone and are inherently low in nutrients (Ragland *et al.*, 1984), resulting in low fertility, under the natural forest. Vityakon, (1991), Ota *et al.* (1992), Tangtrakarnpong and Vityakon (2002) studied the properties of soils under natural forest in North East Thailand on Ultisols of the Yasothon series, Warin series and Korat series (Table 2.1), and found strongly to moderately acid soil reactions with the mean pH value is smaller in Yasothon series than Warin series and Korat series.

Table 2.1 Some soil properties indicating the fertility levels of some Ultisols under natural forest in North East Thailand.

Soil series	Unit	Yasothon	Warin					Korat			
			1(a)	2(a)	3(b)	4(b)	mean	1(a)	2(a)	3(c)	mean
Depth	Cm	0-18	0-26	0-25	0-20	0-20		0-12	0-24	0-15	
pHw		5.2	4.8	6.3	5.3	5.2	5.4	5.9	6.0	5.6	5.8
O.M.	%	1.15	0.67	1.23	1.32	1.27	1.12	1.68	1.23	0.95	1.28
BS	%	75	49	105	-	-	77	86	76	-	81
CEC	$cmol^{+}kg^{-1}$	2.17	1.88	1.99	8.85	8.53	5.3	4.20	2.15	8.9	5.0
Avail. P	$mg\ kg^{-1}$	3.62	1.81	3.92	4.33	3.33	3.34	5.69	1.44	10.6	5.91
Exch. K	$cmol^{+}kg^{-1}$	0.07	0.07	0.07	0.30	0.06	0.13	0.39	0.05	3.2	1.21

(a) Modified from Ota *et al.* (1992)
(b) Modified from Vityakon (1991)
(c) Modified from Tangtrakarnpong and Vityakon (2002)

Soil organic matter (OM) contents as well as base saturation percentage (BS) between Yasothon and Warin series are similar and tend to be smaller than those in Korat series. Cation exchange capacity (CEC) is also smaller in Yasothon series than Warin and Korat series. In contrast, available phosphorus values vary inconsistently, whereas exchangeable potassium levels tend to be higher in Korat series than those Yasothon and Warin series. The results suggest that that overall Ultisols under the natural forest are generally low in fertility, while in Korat series has better fertility than Yasothon and Warin series.

Some research has been undertaken on soil degradation under the natural forest in this region. Sriwongsa (1994) reported that soil loss under dry Dipterocarp forest was about 30-150 Mg ha^{-1} yr^{-1}, depending on the degree of slope. Also, Vityakon *et al.* (2000) measured soil erosion as affected by land management under differing land use types of undulating terrain of North East Thailand and reported that soil loss under dry Dipterocarp forest on the average slope of 2.8 %, was approximately 5-6 Mg $ha^{-1}yr^{-1}$.

2.2.2 Cultivated soils

After forest clearance in North East Thailand, rice has been grown on the lowlands where the relief ranges from slopes of 0-1°. Traditionally, farmers made ridges around each paddy plot for water storage purposes, consequently, soil erosion on paddy fields was limited. Sriwongsa (1994) reported that soil loss from paddy fields in this area was less than 10 Mg ha^{-1} yr^{-1}. Although the erosion problem was not serious, other degradation processes, such as, nutrient depletion, increased acidity and salinity have occurred in paddy fields (Ota *et al.*, 1992; Vityakon, 1991).

In contrast, soil degradation processes, such as soil erosion, nutrient depletion and acidity are major problems after forest clearance for sugarcane and cassava on Ultisols of the uplands. Soil erosion by water is considered to be the one of most important types of soil degradation in this region, particularly, on uplands where topography, soil properties, land use and management make land susceptible to erosion. Several reports dealing with soil erosion have been published.

Takahashi *et al.* (1983) compared soil erosion by water at Numphom, Chaiyapum, North East Thailand and found that soil loss from upland cultivation plots and forest plots were 107.0 and 4.7 m^3 ha^{-1}, respectively. Sriwongsa (1994) reported that soil loss from sugarcane and cassava plots varied from 10 Mg ha^{-1} $yr^{-1}$to more than 150 10 Mg ha^{-1} yr^{-1}, depending on the degree of the slope and cultivation practice. Also, Vityakon *et al.* (2000) compared soil loss by water erosion at Khon Kaen, North East Thailand and found that soil loss from upland cassava plots and sugarcane plots were 45 and 24 Mg ha^{-1} yr^{-1}, respectively.

There are a few research studies that have reported soil property changes in cultivated soils after forest clearance in this region. Ota *et al.* (1992) reported that the soil of cassava plots markedly decreased in organic matter content, exchangeable bases, available phosphorus, water-stable aggregates and soil porosity compared to those of adjacent natural forest soils on the same soil series of Ultisols. The decreases in some nutrients (N, P, K and Mg) were observed under cultivated soils relative to natural forest due to the effects of land use and soil management on sandy Ultisols this region (Vityakon, 1991). Similarly, the significant decreases in soil pH in water, organic carbon and microbial biomass carbon were also observed in the topsoils (0-15 cm) of Ultisols under sugarcane and cassava relative to dry Dipterocarp forest (Tangtrakarnpong and Vityakon, 2002).

Such evidence indicates that land use for crop production after forest clearance in this region is leading to soil degradation. However, there are limitations in these studies because most of them employed a comparative assessment (Type II data collection) and changes in individual soil properties approach that may provide some level of explanation of soil degradation, but does not reflect the quantitative changes of soil quality. Therefore, a more intensive and systematic research approach is needed to confirm these previous findings and to examine the progressive soil degradation and quantify soil quality changes after forest clearance in this region. The assessment of soil quality dynamics is an alternative method for assessing soil degradation.

2.3 Soil quality

Soil is a dynamic, living, natural body that acts in many key roles in terrestrial ecosystems (Doran and Parkin, 1994). The main functions or uses of soil have been summarised as follows; (i) sustains biomass production and biodiversity including preservation and enhancement of genetic pool because a large number of organisms live in and above the soil, (ii) acts as a protective medium by filtering, buffering and transforming compounds between atmosphere, groundwater and plant roots, (iii) supports socio-economic structure, cultural and aesthetic values and provides engineering foundations, (iv) preserves archaeological, geological and astronomical records (Blum and Santelises, 1994; Lal, 1997a; Blum, 1988). These functions are regarded as being defined by physical, chemical and biological soil properties and the combination of these properties determines soil quality (Lal, 1997a).

There are several definitions of soil quality that have been proposed by Larson and Pierce (1991), Pierce and Larson (1993), Doran and Parkin, (1994). A widely accepted definition of soil quality is "the capacity of a soil to function, within land use and ecosystem boundaries, to sustain biological productivity, maintain environmental quality, and promote plant, animal, and human health" proposed by Doran and Jones, (1996). This is a broad agreement with that of Karlen *et al.* (1997) who defined soil quality as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation". Soil quality thus depends to a large extent on the way that soil functions to benefit humans. In terms of food production, or mediation of contamination, soil quality means the extent to which a soil fulfils the role that humans have defined for it. Within agriculture, high soil quality equates with maintenance of high productivity without significant environmental or soil degradation (Singer and Ewing, 2000).

As the quality of a soil is determined by a combination of physical, chemical and biological properties, and these attributes differ among soils, so soils differ in their quality. Soil quality expresses both the inherent attributes of a soil and the ability of a soil to interact with applied input. Soil quality varies considerably over time and space, it is dynamic (Larson and Pierce, 1991). Soil quality can be maintained, improved or degraded through various land uses and management. Therefore, a negative change of soil quality indicates soil degradation.

2.3.1 Soil quality dynamics

In the evaluation of sustainable land management systems, there are two approaches, the comparative assessment approach and dynamic assessment approach. In the first approach, the performance of the system is determined in relation to alternatives. The characteristics and outputs of alternatives are compared at some time with respect to soil attributes. Then a decision is made based on the difference in magnitude of measured parameters that relate to sustainability of each system. This approach may appear reasonable, but it could not determine whether the system that produced the result was poorly designed, or operated in a way that was unstable and could not produce the desired output. As any soil system is dynamic, measures of sustainable management should also be dynamic (Larson and Pierce, 1994). The sustainability in a management system is assessed in term of its actual performance determined by measuring soil quality attributes over time.

The dynamics of soil quality, (or soil quality changes), can be divided into three main groups: random changes; cyclic changes; and trend changes (Arnold *et al.*, 1990 (*cited in* Larson and Pierce, 1991)). Random changes are short-term changes often brought on by weather fluctuations or by random human interventions. These changes are generally difficult to predict. Cyclic changes, are predictable changes, brought on by seasonal variations in weather, crop growth periods and/or ground water table fluctuations. Trend changes are the changes that show a definite tendency toward a certain general direction over years, such as decrease in nutrient status under a depletive management system, or by weathering of minerals. These changes are the most important in evaluating soil qualities for sustainability assessment. However, trends over short durations of time may be of the same magnitude as random or cyclic changes, so they are difficult to define (Larson and Pierce, 1991).

The aim of soil quality evaluation is to assess how the soil functions. The method to assess soil function can be undertaken by assuming that a soil is not good in quality unless it can perform the full potential function for a specific land use, or through adoption of a best management practice. For this condition, soil quality assessment requires measuring the current state of soil characteristics which are defined as an indicator and, then, comparing the result to base line or desired (threshold) values (Arshad and Martin, 2002). Some researchers have evaluated sustainable land use and management by employing soil quality dynamics as a tool (Karlen *et al.*, 1994; Wang and Gong, 1998; Islam and Weil, 2000; Brejda *et al.*, 2000; Essiet, 2001; Andrews *et al.*, 2002).

In these studies, soil sampling procedures and data collection are similar to those in section 2.1.1 and 2.1.2, but they used combinations of key properties as an indicator for comparison and interpretation, whereas those reviewed in the earlier section used single soil properties as indicators. So, the selection of key soil properties to be soil quality indicators and the combination of selected indicators into a soil quality index are important further steps to quantify overall changes of soil quality.

The term 'indicator' is used in various ways, according to the subject of concern and its context. Generally, indicators can be regarded as variables whose purpose is to measure change in a given phenomenon or process (Kumar, 1989(*cited in* Syers *et al.*, 1995)). A soil quality indicator is a measurable soil property that affects the capacity of a soil to perform a specific function (Karlen *et al.*, 1994).

Soil properties that have been proposed to be a minimum data set (MDS) of key soil quality indicators vary from author to author depending on the purposes of the studies (Larson and Pierce, 1991; Larson and Pierce, 1994; Doran and Parkin, 1994; Karlen *et al.*, 1994; Wang and Gong, 1998; Islam and Weil, 2000; Andrews *et al.*, 2002). These studies demonstrate that there have been a variety of possible techniques for selecting soil quality indicators. Effective selection of appropriate indicators depends on the ability of any approach to consider any soil property that has important roles in soil function.

2.3.2 Soil quality indicator selection

Although soil quality indicator selection can be done in various ways, most researchers have relied primarily on the minimum data set selected by expert opinion, as proposed by Larson and Pierce (1991), Larson and Pierce (1994), Doran and Parkin (1994) and Karlen *et al.* (1994). In this way, Wang and Gong (1998) selected 12 soil attributes to be soil indicators for assessing soil quality changes after eleven years of reclamation in subtropical China, namely: soil depth; texture; slope; organic matter; total N; available N; total P; available P; total K; available K; cation exchange capacity (CEC); and pH. These soil properties reflect the function of soils in relation to plant growth. However, the selection of soil variables to include in an index of soil quality could be simplified by statistical methods (Brejda *et al.*, 2000; Andrews *et al.*, 2002).

2.3.3 Indicator transformation and integration into soil quality index (SQI)

Once indicators are selected they have to be transformed into combinable scores and then integrated into a soil quality index. This procedure can be done in various ways, such as, mathematical scoring functions for quantifying soil quality dynamics (Karlen *et al.*, 1994), the weights of the indicators to quantify change in soil quality (Wang and Gong, 1998) and the fuzzy set approach (McBratney and Odeh, 1997; Kaufmann and Tobias, 2002). Moreover, Andrews *et al.* (2002) introduced linear and non-linear scoring method for scoring selected indicators and an additive index, a weighted additive index, and a decision support system for combining the indicators into soil quality indices.

This body of evidence in the research literature indicates that these types of scoring and combining methods are useful for forming a single soil quality index. However, some techniques are too complex and require an expert knowledge for operating. The linear scoring method and additive combining method are very simple and convenient, but there is a limitation as the results are highly dependent on the variance of each indicator (Andrews *et al.*, 2002). If this problem could be overcome by cautious data collecting and using more replication, the linear scoring and additive combining methods should be a useful tool and produce a valuable result for forming soil quality index.

2.3.4 Interpretation and application of soil quality index

Soil quality index (SQI) is a unitless number ranging from 0 to 1. The index outcome can be calculated as the magnitude of changes (ΔSQI) by comparing with the index of baseline or threshold levels (Larson and Pierce, 1994; Karlen *et al.*, 1994; Islam and Weil, 2000; Andrews *et al.*, 2002). The negative change of soil quality index ($\Delta SQI < 0$) indicates degrading soil quality, in contrast, the positive change of soil quality index ($\Delta SQI > 0$) indicates improving soil quality. The rate of change can be expressed in term of $\Delta SQI / \Delta t$, where Δt is the change over time. In a spatial dimensions approach, not only the changes in levels, but also the changes in the area of a soil quality can be obtained (Wang and Gong, 1998).

In addition, Wang and Gong (1998) introduced the concept of relative soil quality index (RSQI) that can calculate from the equation, $RSQI = (SQI / SQI_m)*100$, where SQI is soil quality index and SQI_m is the maximum value of SQI in comparison line. They suggested that RSQI could serve as a unified criterion for comparing soil quality between regions and $\Delta RSQI$ provided a standard for the assessment of soil quality dynamics.

It is apparent from this review that little quantitative information on soil quality dynamics in relation to soil degradation is available for North East Thailand. The current study was therefore designed to investigate soil property dynamics of Ultisols under sugar cane and cassava after forest clearance and employs the assessment of soil quality dynamics as a tool. This approach should produce valuable information and be a useful decision-making tool for government, consultants, farm advisors, resource conservationists, and other land managers to help to identify the most sustainable management practices for these soils.

Chapter 3

Methodology

3.1 Approaches and Procedures

The purpose of this study is to investigate whether different land use/cropping systems affect soil quality dynamics after forest clearance in upland soils of North East Thailand. The dynamic data can be obtained by two sampling procedures, Type I data and Type II data, as described in section 2.1. The first procedure is more useful and reliable than the latter, but the data collection can only be obtained by long-term experiments that are conducted on the same site for 10 years or more (Lal and Stewart, 1995b; Wang and Gong, 1998). The preferred duration of the experiment should be 25 years or more (Lal, 1995). The second procedure, using Type II data, is the alternative for researchers who have limited time but need to understand soil quality changes over a long time; this procedure was employed in this study. However, developing a methodology to accurately obtain previous knowledge of land use and assess soil variability within the sampling area is essential. Therefore, in this thesis, some standard techniques and methods have been modified to obtain useful information and data as described in the following sections.

3.1.1 Data collection

In this study, data collection procedures were conducted as follows: (i) select a time series of study plots on similar Ultisols in North East Thailand for sampling adjacent areas currently under forest and under cultivation for cassava and sugarcane with known times since forest clearance (see Section 3.2 below); (ii) select soil parameters to act as indicators of soil degradation processes (i.e. physical, chemical and biological processes) and of soil quality (see Section 3.4 below) (iii) measure the selected soil properties either in field and/or in the laboratory for analysis of changes in space and over time (see Section 3.5 below).

3.1.2 Data analysis

Field- and laboratory-measured soil properties were analysed to obtain any significant differences of mean values between study plots at the predetermined soil depths (see Section 3.3 below). Sensitive soil quality indicators were then selected by correlation analysis between significant changes of soil properties over time (see Section 3.6 below). Selected indicators were scored and combined into soil quality indices (SQI) and then relative soil quality indices (RSQI) were calculated and analysed to obtained any significant differences of RSQI mean between baseline and cultivated plots in the time series. Finally, changes of relative soil quality indices (Δ RSQI) were calculated, the negative change of RSQI (Δ RSQI < 0) indicated degrading soils, whereas the positive change of RSQI (Δ RSQI > 0) indicated improving soils (see Section 3.6 below).

3.2 The study sites

3.2.1 Study site selection

According to the purpose of the study, three main criteria were adopted for selecting study sites, namely: (i) land utilization types; (ii) the need to establish a time series of study plots with known ages since forest clearance; and (iii) the presence of similar upland Ultisols. Study plots were established on the lower to middle splope of Kandiustults under natural dry Dipterocarp forest, under cassava cropping systems, and under sugarcane plantations, as these are the major kinds of land use and soils on the uplands of North East Thailand, (established by my own field observations and key informants-interviews, and by reference to published information in Ruangphanich (1998) and Office of Agricultural Economics (2002). A time series of research sites was established and consisted of uncleared dry Dipterocarp forest adopted as the '0 year' baseline; cassava plots approximately 10-20 years and 20-30 years old; and sugarcane plots approximately 10-20 years, 30-40 years, and 40-50 years old. Methods used to establish this time series are described in Section 2.2.2 and included: (i) the interpretation of a time series of aerial photographs (scale 1: 50,000) and (ii) key informants interviews (plot owner farmers, farmer leaders, agricultural extension officers, and forestry officers). All of the cultivated plots selected were formerly under deciduous dry Dipterocarp forest. At each point in the time series, three replicate study plots have been investigated on the same Ultisol soil series, i.e. the Korat series, a Fine-loamy, siliceous, isohyperthemic (Oxyaquic) Kandiustults (Soil Survey Staff, 1999), on upland sites. Soil types were initially established by reference to detailed reconnaissance 1:100,000 scale soil maps of Sakon Nakhon and of Udon Thani Provinces (Department of Land Development, 1971; 1972) and were subsequently checked by soil variability assessments in the field (see Section 3.3)

3.2.2 Land use history of study plots

In this study a combination of semi-structured interviews (Sillitoe, 1998; Payton *et. al.*, 2003), published soil maps and time-series aerial photograph interpretation were employed to ascertain the historical pattern of land use changes and land management after forest clearance at the study sites.

Firstly, key informants (farmer leaders, agricultural extension and forest officers in the case of the Sakon Nakhon site, and farmer leaders, sugarcane research centre staff and sugar mill staff in the case of the Udon Thani site) were interviewed. In these interviews, a time series of black and white aerial photographs (scale 1: 50,000) in 1967, 1976 and 1996, and Detailed Reconnaissance Soil Maps of Sakon Nakhon and of Udon Thani Provinces, scale 1:100,000 were used. When any areas met the purposes, respondents could zone the selected areas on the acetate sheets that were put over both on the soil maps and the aerial photos. The study plots were finally selected on the basis of informed discussion and information gained.

Secondly, the farmers who owned the land on which the proposed study plots were located were asked to participate in the study. If they agreed, the appointments were made for interviewing. In these informal, semi-structured interviews, the interviewer asked questions to obtain the following information: time of natural forest clearance; former natural forest type; cropping systems; land preparation methods; crop varieties; cropping calendar; weed control methods; fertilizer and/or soil amendment applications; harvesting methods; crop yield changes; and farmers' perception of soil changes and/or soil degradation.

Finally, a group interview was held to discuss the general land use history of study sites and selected plots. The interviewer could use the information gained from participant mutual discussion in this step to contribute to and/or correct the data from the previous individual interviews.

The obtained information in this interview will be helpful in making a decision to accept or eject the study plots and also be useful in assessing changes in soil quality and productivity.

3.3 Soil variability assessment, soil description and soil sample collection

All study plots were first examined for soil variability using the soil toposequence or soil catena concept (Birkeland, 1999) as study tool, investigating and observing the soils to 120 cm depth at various points along the slope with an Edman soil auger. This information was employed to select 50 x 50 m plots with similar and relatively uniform Ultisols. Each selected study plot was divided into a grid pattern, consisting of 16 close-interval points at a spacing of 10 x 10 m and, then, seven randomised soil sampling points were selected by drawing lots (Gomez and Gomez, 1984). In addition to these seven sampling points, a modal profile pit was located near the centre of the plot to be representative of the main soil type.

Modal soil profile pits were described in detail according to Soil Survey Field Handbook (Hodgson, 1976; Kheoruenroam, 1984). Soil samples were collected from the main soil horizons described in these modal profile pits for standard soil analyses to confirm soil classification and at each of the seven random sampling points as described below.

As this study aims to examine the long-term soil degradation under crop production after forest clearance over the last 40 years, it was important to avoid short-term changes of soil properties that were affected by seasonal or annual disturbances at the soil surface. Soil samples were therefore collected from the random sampling points as triplicate cores from Ap horizons (or Ah/A horizons in forest plots) at 10-15 cm depth, and within subsurface horizons at approximately 40- 45 cm depth (n.b. usually on the upper Bt horizons). The triplicate cores were used to measure bulk density and were then bulked for other analyses. Canopy cover above each of the sampling points, and the modal profile pit within each of natural forest plots, was recorded by digital photography.

3.4 Soil property selection

Soil property selection depends on the purpose of the study. This study aims to evaluate soil degradation after forest clearance for crop production on upland Ultisols. So selected soil properties should relate to soil degradative processes likely to occur in these soils, namely, physical processes such as soil structure decline, soil compaction and soil erosion, chemical processes such as acidification and soil nutrient depletion, and biological processes such loss of soil biodiversity and soil organic carbon decline. This was accomplished by using an expert opinion approach (see Section 2.3.2) combining soil properties that could reflect these processes (see Section 2.1.1).

Soil organic carbon and labile carbon were used to indicate soil biological degradation and also soil organic matter status, which can reflect plant nutrient status, particularly, nitrogen, phosphorus and sulphur (Baldock and Nelson, 2000). Due to limitation of time nitrogen, phosphorus and sulphur were not determined directly in the present study. Effective cation exchange capacity and exchangeable Ca, Mg and K status were used to indicate soil chemical fertility and nutrient depletion. Soil reaction and acidity reflected soil acidification trends. Soil bulk density, infiltration rate and clay dispersion ratio were chosen to assess soil compaction and decline in structural stability associated with soil physical degradation processes.

In summary, the soil properties finally selected for assessing soil degradation in this study were: soil organic carbon (OC), labile carbon (LC), effective cation exchange capacity (ECEC), exchangeable calcium (Ca), magnesium (Mg) and potassium (K), soil reaction (pH in water and pH in KCl solution), exchangeable acidity, soil bulk density, clay dispersion ratio and infiltration rate.

Selected soil properties were measured either in field and/or in the laboratory. Sensitive properties were then selected by using statistical methods to act as soil quality deterioration indicators (see Section 3.6 data analysis)

3.5 Measurement and analysis of selected soil properties

There were two purposes for the analysis of soil samples in this study: (i) soil samples from the main horizons from modal profile pits were analysed to confirm soil classification and to assess soil degradation at the pedon scale; (ii) soil samples from seven study points in each plot were analysed to evaluate soil degradation at a plot scale.

As there are several methods to determine the levels of each soil property, selecting one of the methods depends on (a) the laboratory equipment available, (b) the type of soil to be analysed (c) the degree of accuracy to be needed, and (d) the number of samples to be analysed for any one group of experiments. From these criteria, the methods for soil sample analysis in the study were selected as described below.

3.5.1 Soil organic matter (SOM)

Carbon is the major element contained in soil organic matter, about 48-58 % of the total weight. As the determination of soil organic matter is difficult to quantify, organic carbon is typically measured instead of organic matter and then organic matter can be estimated through multiplying organic carbon value by a factor. The factor of 1.724 was used based on the assumption that the organic matter consists of 58 % organic carbon (Nelson and Sommers, 1982). The organic carbon can be assessed for various purposes such as, a part of soil profile analytical data for a soil survey, an indicator of soil quality, or to monitor the changes in soil quality due to management.

There are many variations of methods for assessing soil carbon content that have been summarized by Myers (1995). The wet combustion (Walkley-Black) method is widely used for measuring organic carbon. This organic carbon is decomposed soil organic matter. It does not include relatively fresh plant residues, roots, charcoal, or carbonate carbon. In the present research, an amount (100-500 mg) of 0.5 mm air-dried soil was oxidized by heat of reaction with potassium dichromate and then measured by ferrous sulphate titration (Nelson and Sommers, 1996).

The hot-water extractable carbon was measured according to the method described by Ghani *et al.* (2002). Soil samples (3 g oven dry weight) were weighed into 50 ml polypropylene centrifuge tubes, 30 ml of distilled water was added and the tubes shaken, capped and then left them for 16 hrs in a hot-water bath at 80°C. At the end of the extraction period, each tube was shaken for 10 seconds to ensure that HWC released from the soil organic matter was fully suspended in the extraction medium. Then the tubes were centrifuged for 20 minutes at 3500 rpm. The supernatant was filtered through a 0.45 μm cellulose nitrate filter. Total carbon (inorganic and organic C) in hot water extracts was determined using a Shimadzu TOC 5050A instrument.

3.5.2 Soil reaction

Soil pH influences chemical reactions, nutrient availability and is a key chemical indicator because it is routinely, easily, and inexpensively measured and therefore appears in most soil quality assessments.

Generally, soil pH is determined by concentration of active hydrogen ion (H^+) in soil solution. In order to measure pH in soil solution, a glass electrode, a reference electrode and a pH meter which a millivoltmeter is usually employed (Rowell, 1994). The difference among laboratories are the detail of soil: water or soil: solution ratio, containing solution, method and time of mixing and shaking, time of standing before reading, etc., (McLean, 1982; Rowell, 1994; Pushparajah and Myers, 1994).

In this study, soil pH has been measured following MAFF (1986). A suspension of 10 g soil and 25 ml distilled water was made and the pH was read after shaking on orbital shaker set at 275 revs per minute for 15 minutes and standing for 2 hours. For pH in M KCl, the same procedure was followed except that 25 ml M KCl was used instead of 25 ml distilled water. The first value was recorded as pH in water and the later value was recorded as pH in M KCl. In addition, soil pH in each horizon of modal soil profiles was also measured by colorimetric method with soil pH test kits (Kheoruenroam, 1984) in field investigation.

3.5.3 Cation exchange capacity (CEC)

The major soil exchangeable cations are basic cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) and acid cations (Al^{3+}, H^+). These positive charged ions are retained in the soil by interacting with negative charged particles in the soil. The negative charges in the soil are derived from isomorphous substitution within the structures of layer silicate minerals, broken bonds at mineral edges and external surfaces, dissociation of acidic functional group in organic compounds, and the preferential adsorption of certain ions on the particle surface (Rhoades, 1982). The negative charges show the potential ability of the soil in retaining the ions of opposite charges that can be indirectly expressed in term of cation exchange capacity.

Cation exchange capacity (CEC) is a measure of the quantity of readily exchangeable cations neutralizing negative charge in the soil (Rhoades, 1982). Methods of CEC determination are based on measuring the amount of the index cation that has be used to replace the original cations in the soil. Several methods have been employed for determining CEC in various soil conditions. For instance, the method of Polemio and Rhoades, (1977) is particularly suited to arid land soils and to those which markedly contain carbonates, gypsum, and zeolites, whereas, the method of Gillman (1979) is recommended for determining the CEC of acid soils in the tropics (Rhoades, 1982).

However, the ammonium acetate method (buffered at pH 7) is widely used to estimate CEC for soil classification purposes (Pushparajah and Myers, 1994). Therefore, in this study the ammonium acetate method was used to determine the CEC in soil profiles in order to confirm classification. The procedure can be summarized as follows: (i) soil samples were extracted and leached with ammonium acetate (buffered at pH 7) in leaching columns (ii) the retained soils in the leaching column were washed with ethanol (iii) the soils were subsequently leached in the leaching column with potassium chloride (iv) CEC values were determined from the amount of NH_4^+ in the leachate as measured by an auto-analyser.

3.5.4 Effective cation exchange capacity (ECEC)

In this study the conventional ammonium acetate method for CEC determination was not used for assessing soil degradation for the plot scale soil samples. As high aluminum saturation and the pH variable charges are often prominent properties of acid tropical Ultisols, these attributes could be the sources of error in CEC determination if the ammonium acetate (pH 7) method was applied. Because the replacing power of exchangeable Al and its hydroxy forms is stronger than that of NH_4^+, the replacement processes may not be complete. This error would result in an underestimate of CEC (Rhoades, 1982). For these reasons the effective cation exchange capacity (ECEC), that gives the CEC of the soil near its natural pH (Anderson and Ingram, 1993), was used in this study. ECEC was calculated by summation of exchangeable basic cations and exchangeable acidity (Pushparajah and Myers, 1994).

Exchangeable basic cations were determined by the ammonium acetate extraction method using the centrifuge procedure, as described by Thomas (1982). Exchangeable Ca and Mg in the supernatant were measured by atomic absorption spectrophotometry, whilst K and Na were measured by flame photometry.

Exchangeable acidity in this study was measured by successive leaching of the soil with M KCl and then titratration with 0.1M NaOH (Thomas, 1982).

3.5.5 Soil bulk density (Db)

Some soil physical properties are static in time, some are dynamic over time. Some are resistant to change, whilst some are easily changed through management practices. If changed, some properties will easily recover, but some are irreversible. These characteristics will determine whether a property or process is useful for assessing soil quality and monitoring the maintenance of soil quality over time.

Soil bulk density varies among soils of different textures, structures and organic matter content, but within a given soil series it can be used to monitor degree of soil compaction and/or structural collapse. The bulk density of soil is a dynamic property, which varies with soil conditions and can be easily changed by land use and management. It is a widely used to serve as an indicator of soil compaction or relative restrictions to root growth (Table 3.1).

There are various methods for measuring soil bulk density such as rubber balloon, sand replacement, clod, radiation and core sampling methods (Campbell and enshall, 1991). The most usual and simple method is the 'core sampling method' that has been selected for this study. The core samplers have been inexpensively made by cutting a 5.15 cm length of a stainless steel pipe with a diameter of 7.27 cm. These have been driven vertically into the soil at the specified sampling depths to collect three replicate soil cores to measure soil bulk density at each study point, both on surface soil horizons and sub- surface horizons and of each horizon in modal soil profiles.

Table 3.1 Estimated soil bulk density thresholds for root restricting compacted condition as determined by soil texture class (Arshad *et al.*, 1996).

Soil texture class	Minimum bulk density for root restriction ($Mg\ m^{-3}$)
Coarse, medium, and fine sands and loamy sands	1.80
Very fine sand, loamy fine sand	1.77
Sandy loams	1.75
Loams, sandy clay loam	1.70
Clay loam	1.65
Sandy clay	1.60
Silt, silt loam	1.55
Silty clay loam	1.50
Silty clay	1.45
Clay	1.40

3.5.6 Infiltration rate

A clay increase between surface and subsoil horizons in the form of either an argillic or kandic horizon is one of the criteria for classifying Ultisols (West and Beinroth, 2000). This morphology of the Ultisols influences many soil physical properties, such as, limitation of infiltration rate and increase of run off. In addition, sandy and loamy surface horizons with low organic matter content and weak structure are subject to compaction and surface crusting, which can have a large impact on infiltration.

There are two common methods assessing infiltration: sprinkler and flooded or ponded infiltration (Lowery *et al.*, 1996). The first method is not simple to undertake because water has to be sprayed on the soil surface to simulate rainfall. The later method, where water is flooded on the soil surface and water intake rate is obtained, is much simpler. Flooded infiltration can be undertaken with either a single- or double- ring infiltrometer. In this study, the double- ring infiltrometer method (Pushparajah and Myers, 1994) was selected to measure water infiltration rates at each study point. The double – ring infiltrometer was operated on un-pre-wetted soil at each study point. Infiltration readings were made every minute for the first 10 minutes, every 5 minutes between 10 and 30 minutes, and every 60 minutes between 60 and 180 minutes. Water in the inner ring was occasionally refilled when the level had dropped to about 10 cm. Infiltration rate was calculated by Philip equation;

$$F = at^{0.5} + bt$$

Where (F) is cumulative depth (cm), (t) is time (second), (a) and (b) are constants (Landon, 1984).

3.5.7 Clay dispersion index

Aggregate stability is used to describe the ability of the soil to maintain its structure when exposed to different stress. As surface soils of Ultisols are very weakly structured, a measurement of aggregate stability may not be very meaningful. The assessment of dispersible clay is an alternative way to deal with this issue. The clay dispersion index (DC) is the ratio of water dispersible clay to total clay. This can be express in simple equation as follows;

$$DC = (\text{water dispersible clay})*100 / (\text{total clay})$$

Where total clay is the clay fraction obtained from standard particle size analysis, but water dispersible clay is the clay fraction obtained from particle size analysis by sedimentation in distilled water without the pre-treatment and subsequent dispersion steps (Mbagwu and Piccolo, 1998).

Some researchers have employed clay dispersion index to assess the stability of soil aggregates (Koutika *et al.*, 1997; Mbagwu and Piccolo, 1998; Westerhof *et al.*, 1999). The principle procedure to obtain water dispersible clay can be summarized as follows: (i) A soil sample is shaken with distilled water on a reciprocal shaker; (ii) soil suspension is transferred to 1 litre graduated cylinder and distilled water is added to make the volume up to 1 litre mark; (iii) the soil suspension in the cylinder is agitated and then allowed to settle waiting for appropriate time to measure clay fraction at a certain depth from water surface by hydrometer or by the pipette method.

In this study, the procedure of Mbagwu and Piccolo (1998) was employed with some modifications. The procedure was operated as follows: (i) ten grams of < 2 mm soil was put in 1 litre glass bottle and 200 ml of distilled water added and left to stand overnight; (ii) the soil suspension in the bottle was shaken on a end-over-end shaker for 2 hours at 20 rpm and then transferred to 1 litre graduated cylinder and distilled water added to make the volume up to 1 litre mark; (iii) the soil suspension in the cylinder was agitated and then allowed to settle for 8 hours and 10 minutes and then soil suspension was sampled at a depth of 10 cm with 25 ml Andreason pipette; (iv) the pipette sample was placed into a pre-weighed 50 ml beaker and dried in an oven at 105 °C for 24 hours and then reweighed to determine the water dispersible clay mass in the beaker.

Total clay mass was obtained from particle size analysis in soil profiles as described in section 3.5.8

3.5.8 Particle size analysis

The standard method, reviewed by Rowell (1994), was used to determine the particle size distribution of soil horizons from the modal profiles in this study. The following stages were involved: (i) soil sample pretreatment with hydrogen peroxide to remove organic matter; (ii) dispersion of remaining mineral soil by shaking in the presence of sodium hexametaphosphate; and (iii) sand fraction separation by sieving and silt and clay separation by sedimentation and pipette sampling employing the principle of Stoke's Law. The sand was subdivided using the United States Department of Agriculture size fractions (Landon, 1984).

3.6 Data analysis

3.6.1 Forest canopy gap analysis

Forest canopy structure influences a wide range of soil biophysical and ecological processes (Ingleby *et al.*, 1998; Jenssen *et al.*, 2002; Clinton, 2003). Numerous techniques (Ingleby *et al.*, 1998; Sabol *et al.*, 2002; Jenssen *et al.*, 2002; Bellow and Nair, 2003) have been developed to measure canopy structure, such as leaf area and openness (i.e. gaps). Hemispherical (fisheye lens) canopy photography is one of optical method that was employed by several researchers for measuring leaf area or canopy gaps in the forests (e.g. Ingleby *et al.*, 1998; Myers *et al.*, 2000; Macfarlane *et al.*, 2000).

Recently, Frazer *et al.* (2001) assessed the technical differences between digital and conventional film fisheye lens photography for the analysis of forest canopy structure and gap light transmission. The results suggested that the hemispherical (fisheye) photography of the consumer-grade digital cameras should be a useful material for the analysis of forest canopy structure due to the shortage and high cost of conventional film-based hemispherical photography systems. In addition, Archibold and Ripley (2004) claimed that digital imagery analysis provided a rapid assessment of canopy structure. This may be useful for long-term monitoring of stand responses to different management techniques.

Hemispherical photographs generally provide a 180° field of view and produce a projection of a hemisphere on a plane. The resulting circular image, therefore, shows a complete view of all sky directions, with the zenith in the center of the image and the horizons at the edges (Jonckheere *et al.*, 2003). Moreover, the fisheye lens commonly produces an optical distorted image. These attributes of a hemispherical photograph may be unsuitable and unnecessary to the approach of this study. As each study plot covers an area of 50 x 50 m, consisting of 7 study points, each of which covers an area of 1 x 1 m each, the canopy structure that relates to the study points should be recorded exactly above each point.

Due to the small size of each study point in this study, an ordinary digital camera without fisheye lens was employed to take an individual canopy photograph directly above each study point in forest plots by being set on the stand upward to the sky at the high of 80 cm from ground levels and heading toward the North. The canopy photographs were saved in JPEG formats and were imported into the ArcView GIS 3.2® for spatial analysis and calculation of canopy gap areas.

3.6.2 Field and laboratory data analysis

The results of soil variable data were analysed by using Minitab® and Microsoft excel®, following the procedures described below.

Sensitive indicator selection

Soil variables of the study plots in a time series of the same horizons in each study site were first tested for normality by the Kolmogorov-Smirnov procedures and for homogeneity of variance by Bartlett's procedures (Gordon and Gordon, 1994; Neter *et al.*, 1985). The data then analysed by using one-way analysis of variance (ANOVA) in order to obtain an indication of any significant differences ($P < 0.05$). For skewed data, normalisation was attempted by transformation with common logarithms. Where transformations failed to normalise the data, non-parametric procedures were used to obtain an indication of any significant differences ($P < 0.05$). The comparisons of means in parametric statistics were operated by Dunett's multiple comparison and those of medians in non-parametric statistics were operated by Mood's median test (Ott and Longnecker, 2001; Mood, 1954). The simple linear correlation with time since forest clearance was tested to reflect the temporal changes of soil variables. Soil variables that significantly changed both in magnitude and over time were selected as sensitive indicator for assessing soil quality dynamics.

Soil property changes

Assessing soil property changes over the periods of time investigated can be simply be done by calculating the difference of each of the measured soil properties between the control plots (F plots in case of cassava and S1 in case of sugarcane) and the cultivated plots (C1 and C2 plots in case of cassava and S2 and S3 in case of sugarcane) at various times after forest clearance. The magnitude of changes (Δ) can be calculated as follows: $\Delta_{.}$= mean or median value of soil properties in the cultivated plots – those of control plots.

The means and medians of each of the soil properties measured have been obtained from two replications for C1 and S3 three replications for F, C2, S1 and S2. The results are present in Chapter 5.

Scoring and combining soil quality index

A linear scoring method and additive combining method, as described by Andrews *et al.* (2002), were used to transform selected indicators into soil quality indices (SQI) in each profile, or at each study point, and then calculated relative soil quality index (RSQI) by using the equation as described by Wang and Gong (1998) in each profile or at each study point. The RSQIs between study plots in a time series of the same horizons in each study site were compared by using one-way analysis of variance in order to obtain an indication of any significant differences ($p < 0.05$). For skewed data, normalisation was attempted by transformation with common logarithms. Where transformations failed to normalise the data, non-parametric procedures were used to obtain an indication of any significant differences ($p < 0.05$). The magnitude of RSQI changes (Δ RSQI) was calculated by the following equation; Δ RSQI = RSQI(c) – RSQI (b), where RSQI(c) is relative soil quality index of cultivated soil and RSQI (b) is relative soil quality index of baseline soil. The negative change of RSQI (Δ RSQI < 0) indicated degraded soils whereas the positive change of RSQI (Δ RSQI > 0) indicated improved soils.

RSOI classification and distribution

To obtain spatial changes of RSQI, the RSQI at each study point of the study plots was imported into ArcView GIS 3.2® for spatial analysis and then RSQI areas were classified by modifying the criteria of Wang and Gong (1998) as follows;

Classes	RSQI Value
I	90 – 100
II	80 – 90
III	70 – 80
IV	60 – 70
V	50 – 60
VI	40 – 50
VII	30 – 40
VIII	< 30

Distributions of RSQI classes in the study plots were employed to indicate degraded or improved soils.

Chapter 4

Soil Characteristics, Variability and Land Use History of the Study Plots

4.1 Site characteristics

North East Thailand lies between latitudes 14°10'and 18°10'N, and between longitudes 101°30'and 105°40' E and consists largely of the undulating Korat plateau. It is separated by hill ranges from northern and central parts of Thailand to the west and from Cambodia to the south, and by the Mekhong river from Laos to the north and the east.The Korat plateau can be divided into the Korat basin to the south of the Phuphan range and the Sakon Nakhon basin to the north (Figure 4.1). In this study, there are two principal research sites, both of which are in the Sakon Nakhon Basin, one located in Sakon Nakhon province and the other is in neighbouring Udon Thani province (Figure 4.2).

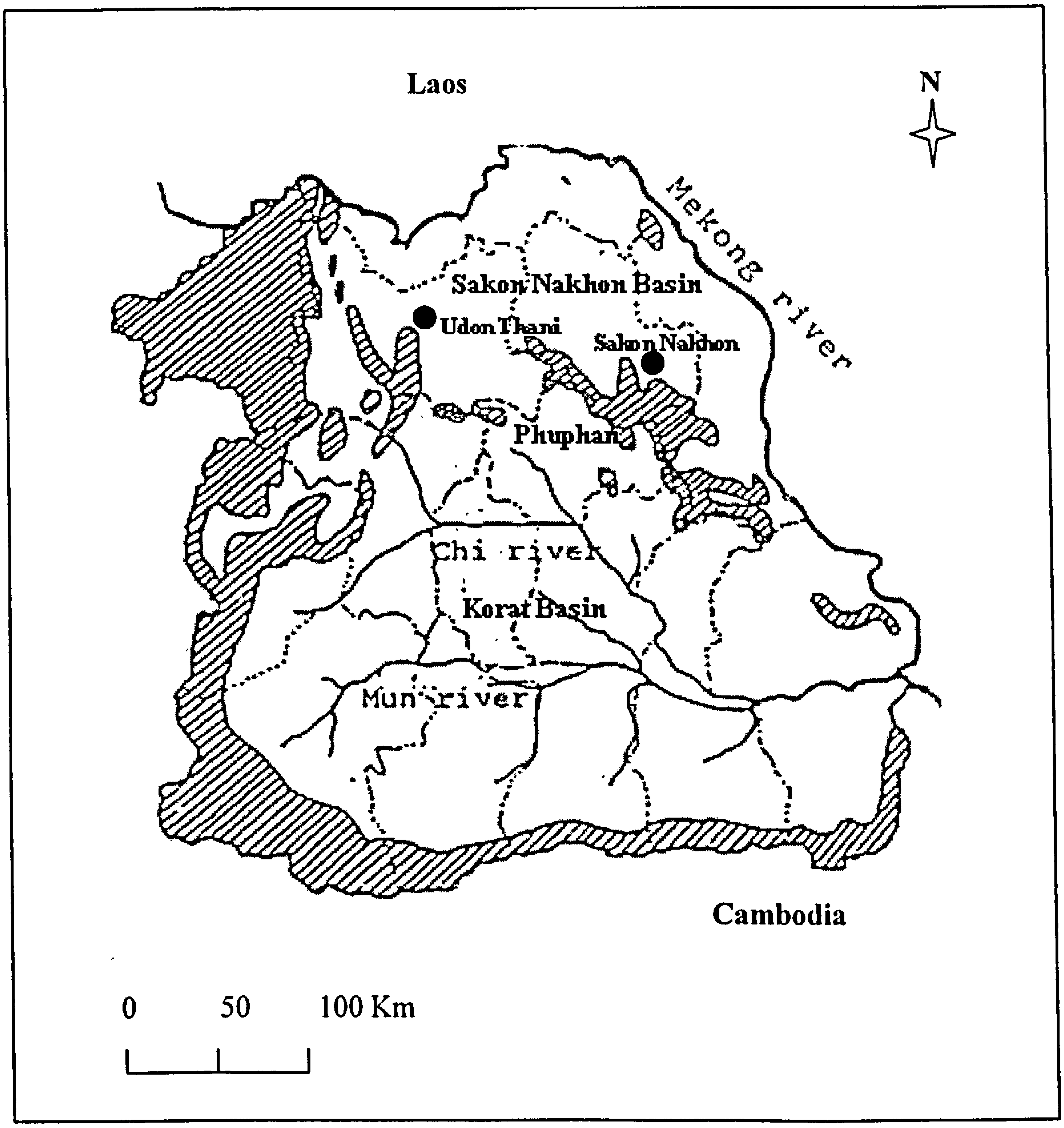


Figure 4.1 Topography of North East Thailand.

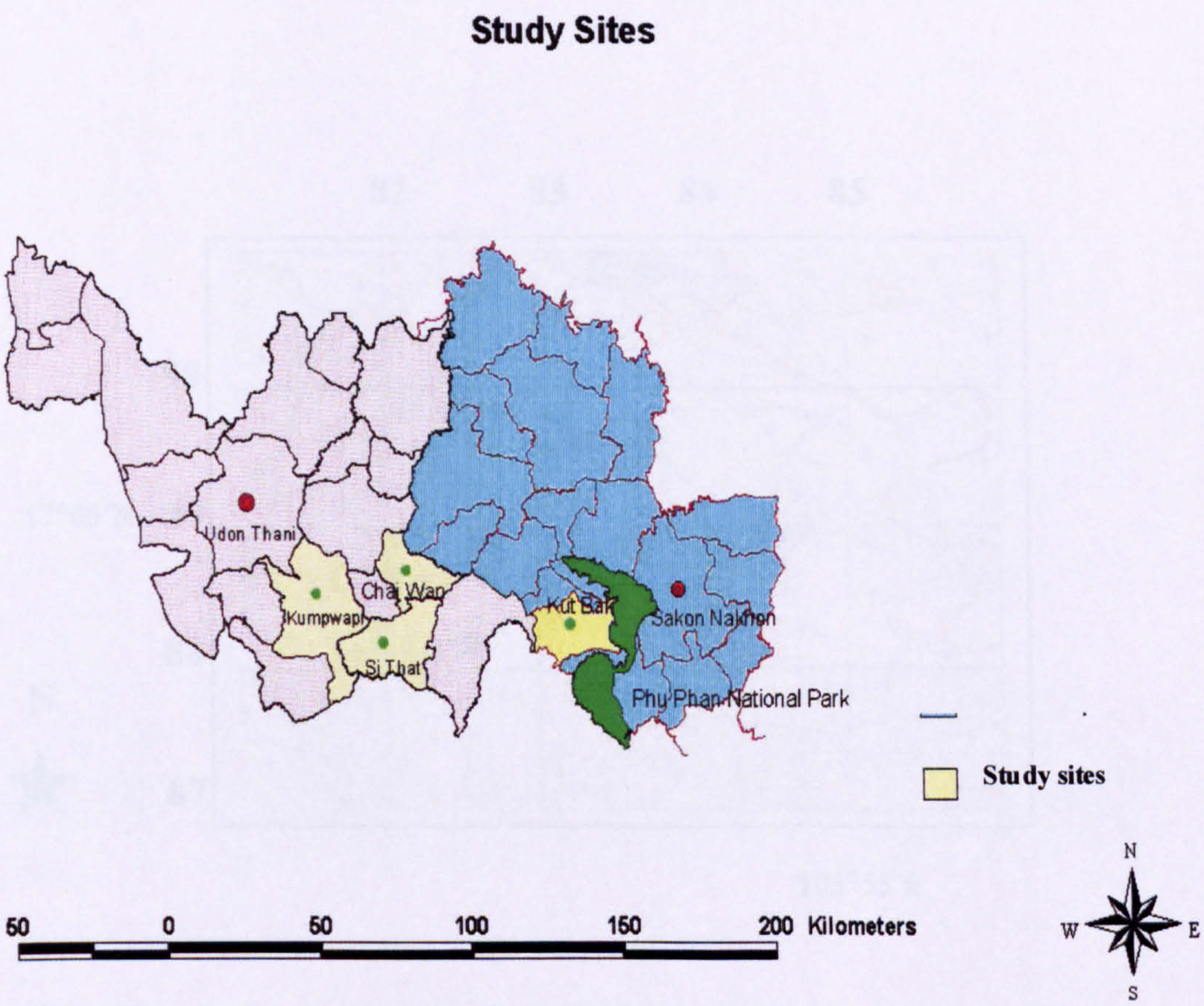


Figure 4.2 The study sites in Udon Thani and Sakon Nakhon Provinces.

4.1.1 Location

The Sakon Nakhon (SK) site lies between latitudes 17° 04'and 17°06'N, and between longitudes 103° 53'and 103° 55' E about 33 km to the South of Sakon Nakhon city and about 8 km to Northwest of the Phunphan National Park office. There are nine study plots at this site, namely, three dry Dipterocarp forest control plots (FA, FB and FC), three cassava 10-20 years old plots (C1a, C1b and C1c) and three cassava 20-30 years old plots (C2a, C2b and C2c). The locations of these study plots are shown in figure 4.2a and also detailed in profile description (Appendix I).

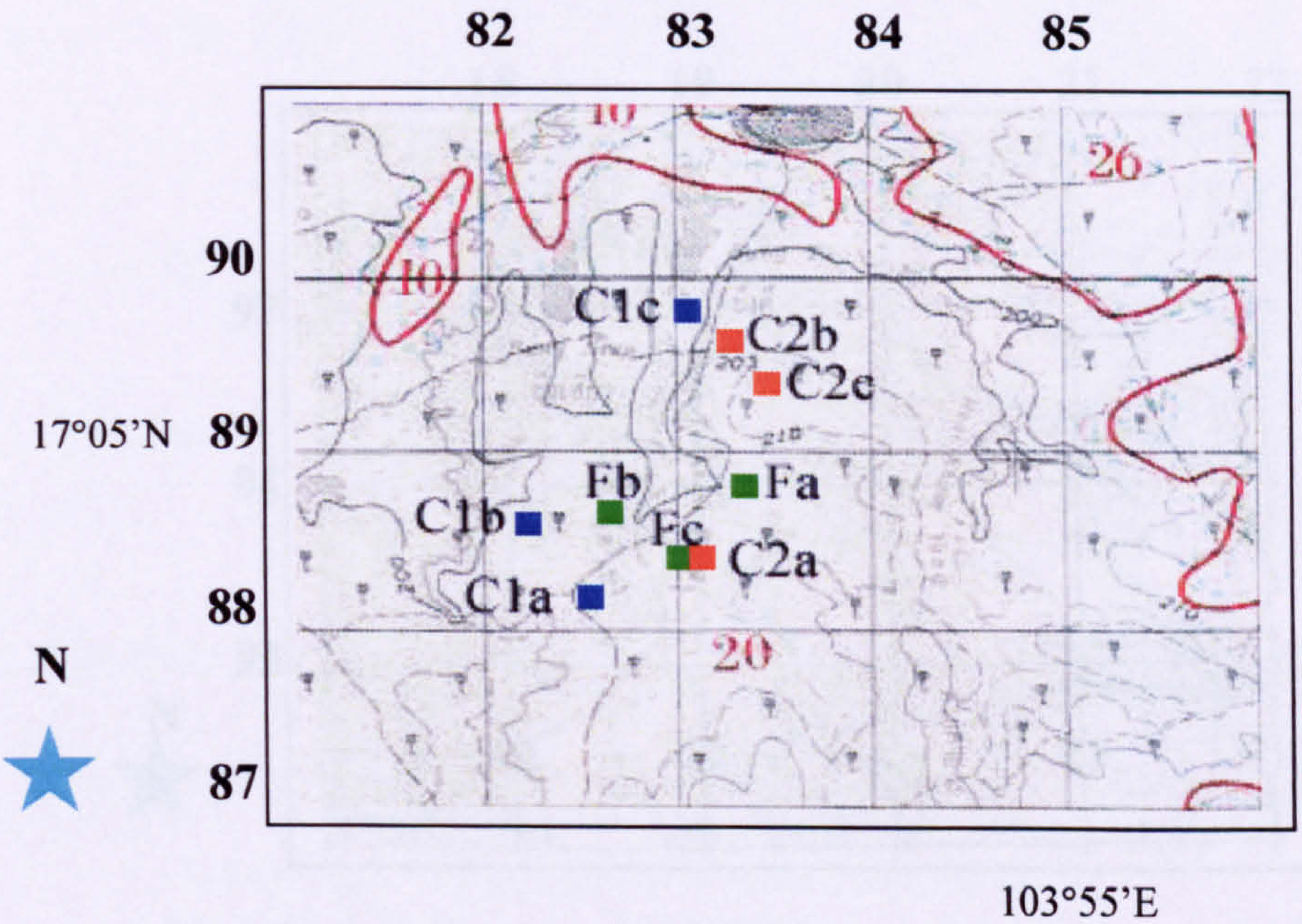


Figure 4.3a The study plots at the Sakon Nakhon site.

(modified from soil map of Sakon Nakhon, 1971, scale 1: 100,000)

Fa, Fb, Fc = Dry Dipterocarp forest plot A, B and C respectively
C1a, C1b, C1c = Cassava 10- 20 years old plot A, B and C respectively
C2a, C2b, C2c = Cassava 20-30 years old plot A, B and C respectively
10 = Roi Et series 20 = Korat series 26 = Nam Phong series

The Udon Thani (UD) sites lies between latitudes 17° 05'and 17°06'N, and between longitudes 103° 08'and 103° 22' E in the most important sugarcane growing area in North East Thailand and consist of three districts, Chai Wan, Si That and Kumpawapi which are about 62, 67 and 35 km respectively from Udon Thani. There are nine study plots at these sites, namely, one sugarcane plot 10-20 years old in Chai Wan district (S1a), two sugarcane plots 10-20 years old in Si That district (S1b and S1c), three sugarcane plots 30-40 years old (S2a, S2b and S2c) and three sugarcane plots 40 –50 years old plots (S3a, S3b and S3c) in Kumpawapi district (Figure 4.3 b-e and see details in profile description, Appendix I).

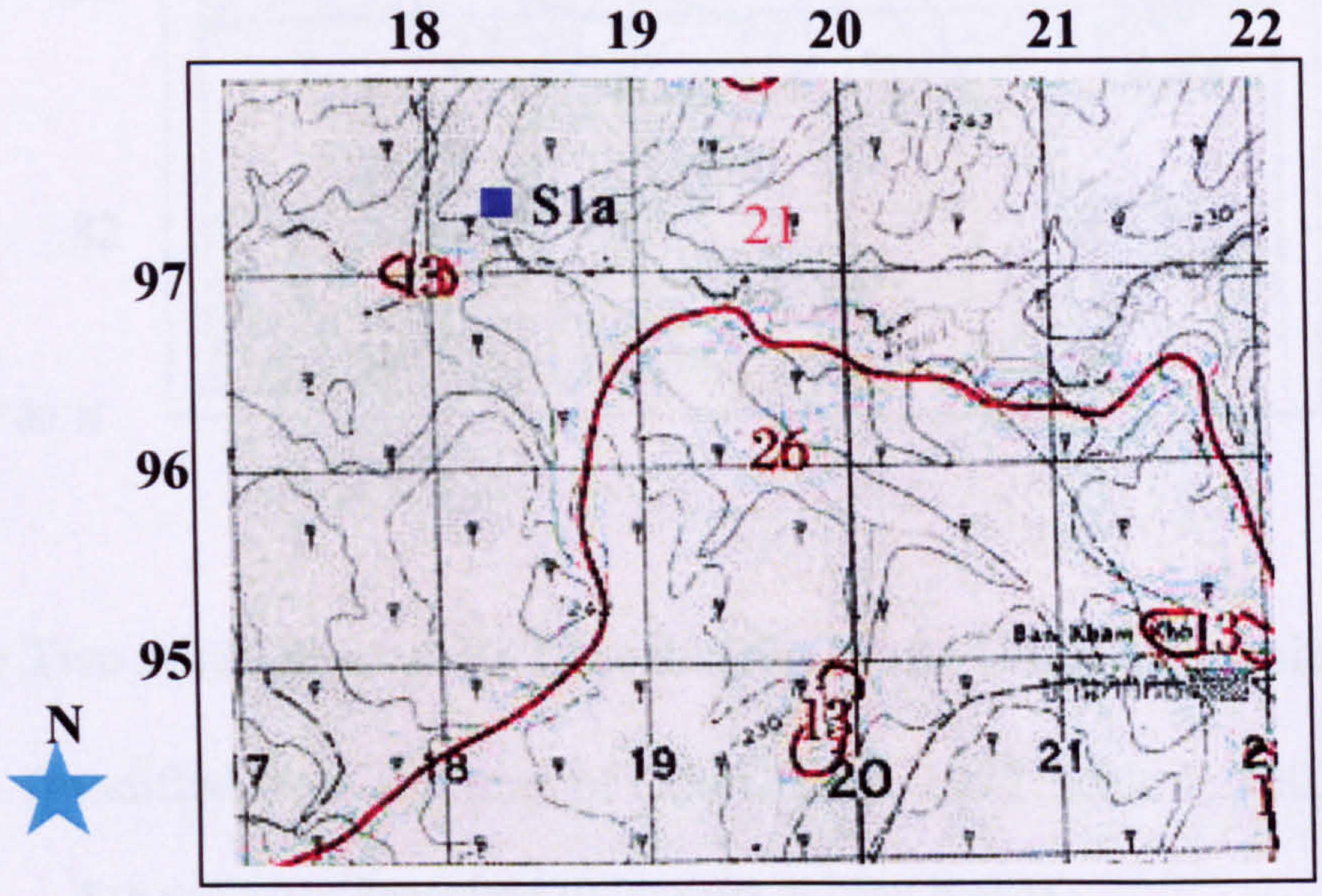


Figure 4.3b A study plot at Chai Wan district in the Udon Thani site.

(modified from soil map of Udon Thani, 1972, scale 1: 100,000)

S1a = Sugarcane 10-20 years old plot A
13 = Roi Et series 21 = Korat series 26 = Korat/ Phon Phisai association

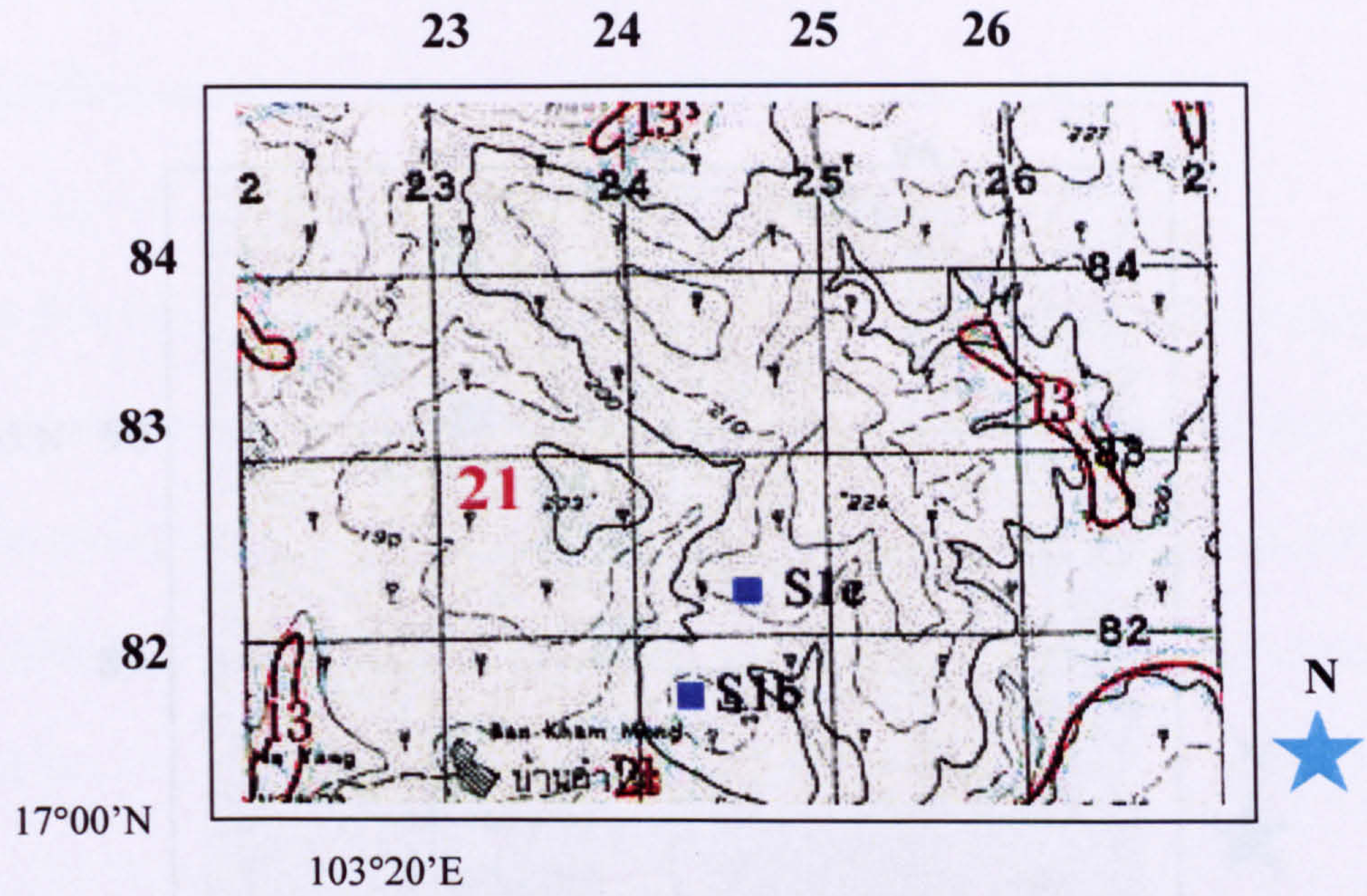


Figure 4.3c Two study plots at Si That district in the Udon Thani site.

(modified from soil map of Udon Thani, 1972, scale 1: 100,000)

S1b and S1c = Sugarcane 10-20 years old plot B and C,
13 = Roi Et series 21 = Korat series

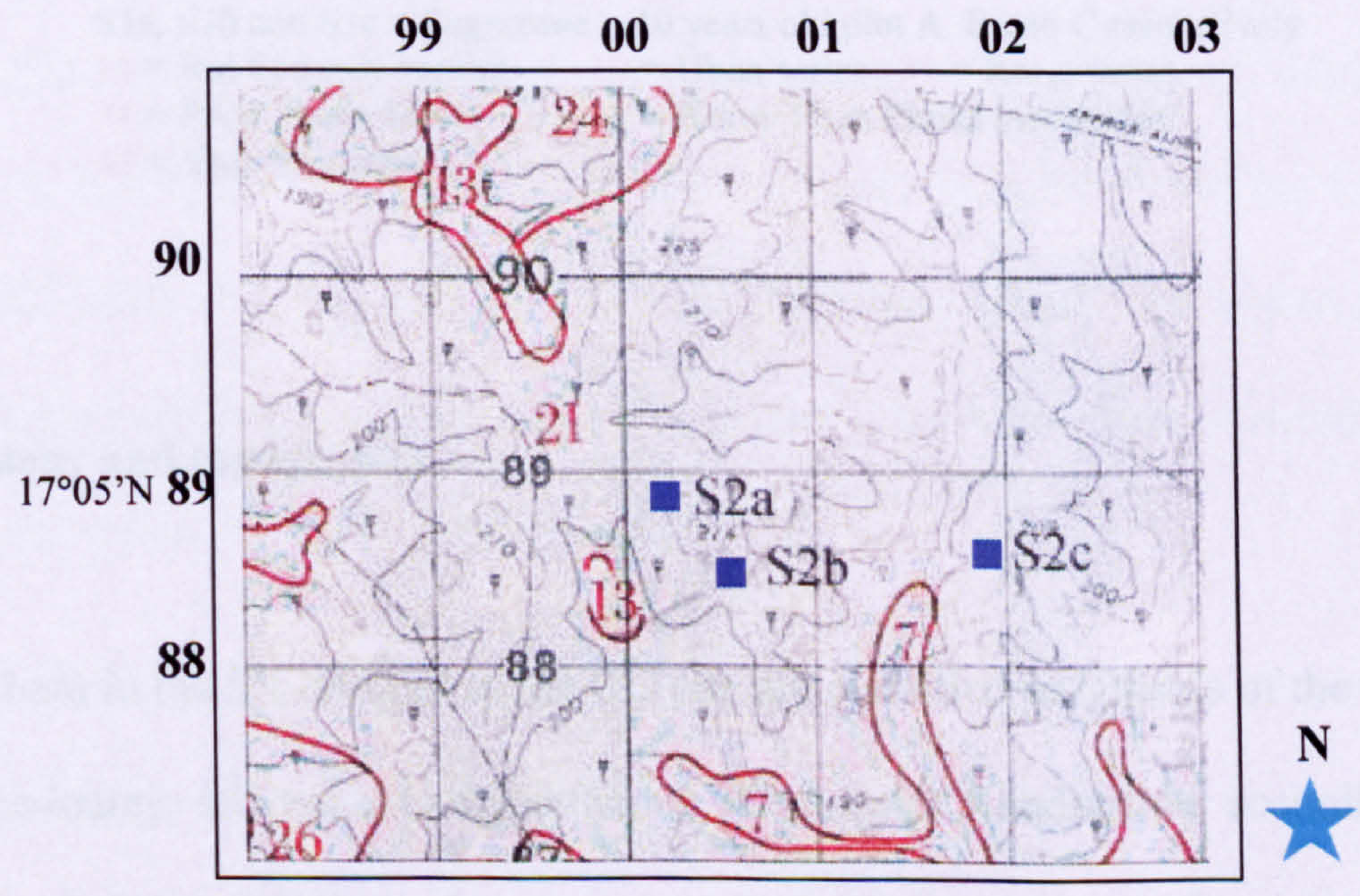


Figure 4.3 d Three study plots at Kumpwapi district in the Udon Thani site.

(modified from soil map of Udon Thani, 1972, scale 1: 100,000)

S2a, S2b and S2c = Sugarcane 30 - 40 years old plot A, B and C respectively
13 = Roi Et series 21 = Korat series 7 = Si thon series

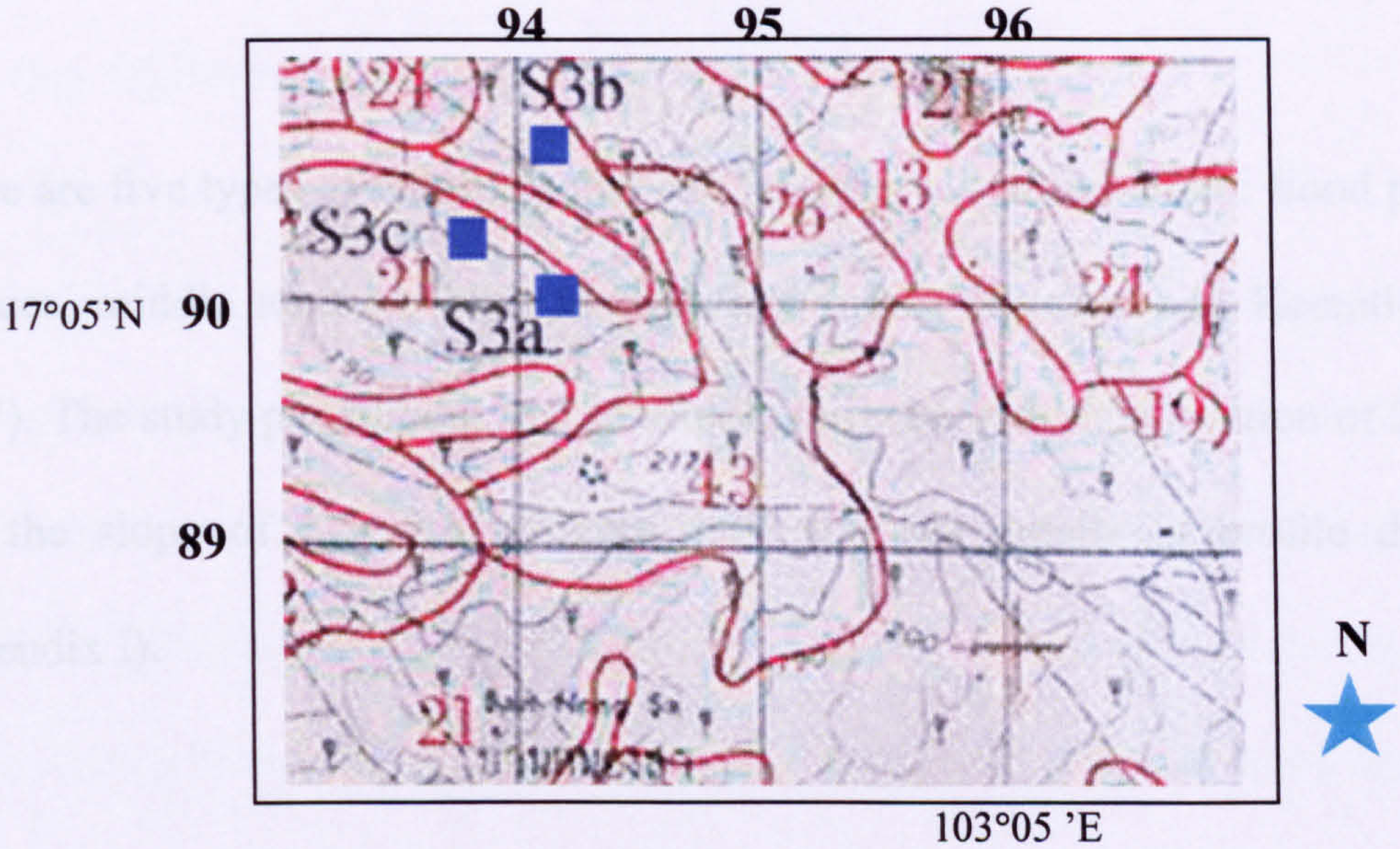


Figure 4.3e Three study plots at Kumpwapi district in the Udon Thani site.

(modified from soil map of Udon Thani, 1972, scale 1: 100,000)

S3a, S3b and S3c = Sugarcane > 40 years old plot A, B and C respectively
13 = Roi Et sandy variant 19 = Ubon series 21 = Korat series
24 = Phon Phisai Series 26 = Korat/ Phon Phisai association
43 = Yasothon series

4.1.2 Geology and topography

The soils both in the SK site and in the UD site are classified as Ultisols of the Korat series, fine-loamy, siliceous, isohyperthemic (Oxyaquic) Kandiustults according to Soil Map of Sakon Nakhon, Province and Soil Map of Udon Thani Province (Department of Land Development, 1971 and 1972) and 'Established Soil Series in the North East of Thailand' (Department of Land Development, 1999). The parent material is old Quaternary river alluvium underlain by various clastic sedimentary rocks, including sandstone, siltstone and shale (Kheoruenromne, 1991).

There are five types of landform that can be observed in this basin: flood plains, low terraces, middle terraces, high terraces and hills (Vityakon and Keerati-Kasikorn, 1987). The study plots lie on low to middle terraces with the elevation of 200-230 m and the slope of 1.5- 2.8° (Figure 4.14 and see details in profile description, Appendix I).

4.1.3 Climate

The climate is classified as tropical savanna (Aw), with annual mean temperatures of 26-27 °C (Kheoruenromme and Kesawapitak, 1989) and average annual rainfall of 1523 mm in the Sakon Nakhon site and 1109 mm in The Udon Thani site for the period 1987-1995 (Meteorological Department, 2000). There are three major seasons: a rainy season from May to October; a cool - dry season from November to February; and a hot - dry season from March to May.

4.2 Land use and management history of the study plots

4.2.1 Dry Dipterocarp forest plots

The study plots were located on a slightly undulating terrace with slopes of 2 - 2.5 ° and an elevation of 224 – 238 m above sea level. *Dipterocarpus tuberculatus*, *Shorea obtuse* and *Shorea simensis* are the dominant species of forest trees and *Arundinaria pusillia* is a dominant plant on the forest floor. The trees shed their leaves in the dry season during November to January. Annual fires in the dry season are common and the impact of rainfall on the dry surface soils at the beginning of the rainy season is often apparent, leading to soil erosion. Some evidence of annual fires, soil surface crust formation, soil pedestals and particle sorting were occasionally observed in the plots. Trampling by cattle and buffalo was also locally observed, as farmers use these forests to raise their animals during growing season, indicating that these forests are disturbed by human activity. Soil variability assessments were conducted before establishing three 50 x 50 m plots with similar and relatively uniform soils to act as the forest control plots (FA, FB and FC)

4.2.2 Cultivated plots

The history of cultivated plots was obtained by using the combination of semi-structured interviews of plot owners and group farmer interviews (Table 4.1 and 4.2),

Table 4.1 History, land use and management of the cassava plots at the Sakon Nakhon site.

Item	C1a	C1b	C1c	C2a	C2b	C2c
1.Plot age	10-20	10-20	10-20	20 -30	20-30	20 -30
2.Formerly forest	DF	DF	DF	DF	DF	DF
3.Main crop	C	C	C	C	K/C	K/C
4.Land preparation	2/4 T	A/2 T	2/4T	A/2T	A/2/4T	A/2/4T
5.Crop variety	R 3	R 3	R 5	R 5	R3	R3
6.Crop growing calendar	Oct.	Oct.	Oct.	Oct.	Oct.	Oct.
7.Weed control	A/Hoe	A/Hoe	A/Hoe	A/2T/Hoe	A/Hoe	A/Hoe
8.Fertilizer application	No	No	No	No	No	No
9.Harvesting method	Hoe	Hoe	Hoe	Hoe	Hoe	Hoe
10. Crop yield (ton ha^{-1})*	7	10	7	10	7	ND
11. Degraded soil perception	Crop growth	-*	Crop yield	Crop yield	Crop yield	Crop yield

DF = Dry Dipterocarp forest
C = Cassava as a main crop
K/C = Kenaf was grown in earlier period and then turn to cassava later.
2T = Two –wheel (walk follow) tractor
4T = Four-wheel tractor
A = animal (buffalo)
R = Rayong
Oct = October
No = Never used chemical fertilizers for cassava production but occasionally used manure for other crops growing during fallow period.
* = Estimated crop yield by farmers base on the last crop before interviewing
ND = No data, farmer could not harvest cassava roots due to unhealthy crop
-* = The farmer didn't recognize soil degradation. He thought that root yield decreased because of drought.

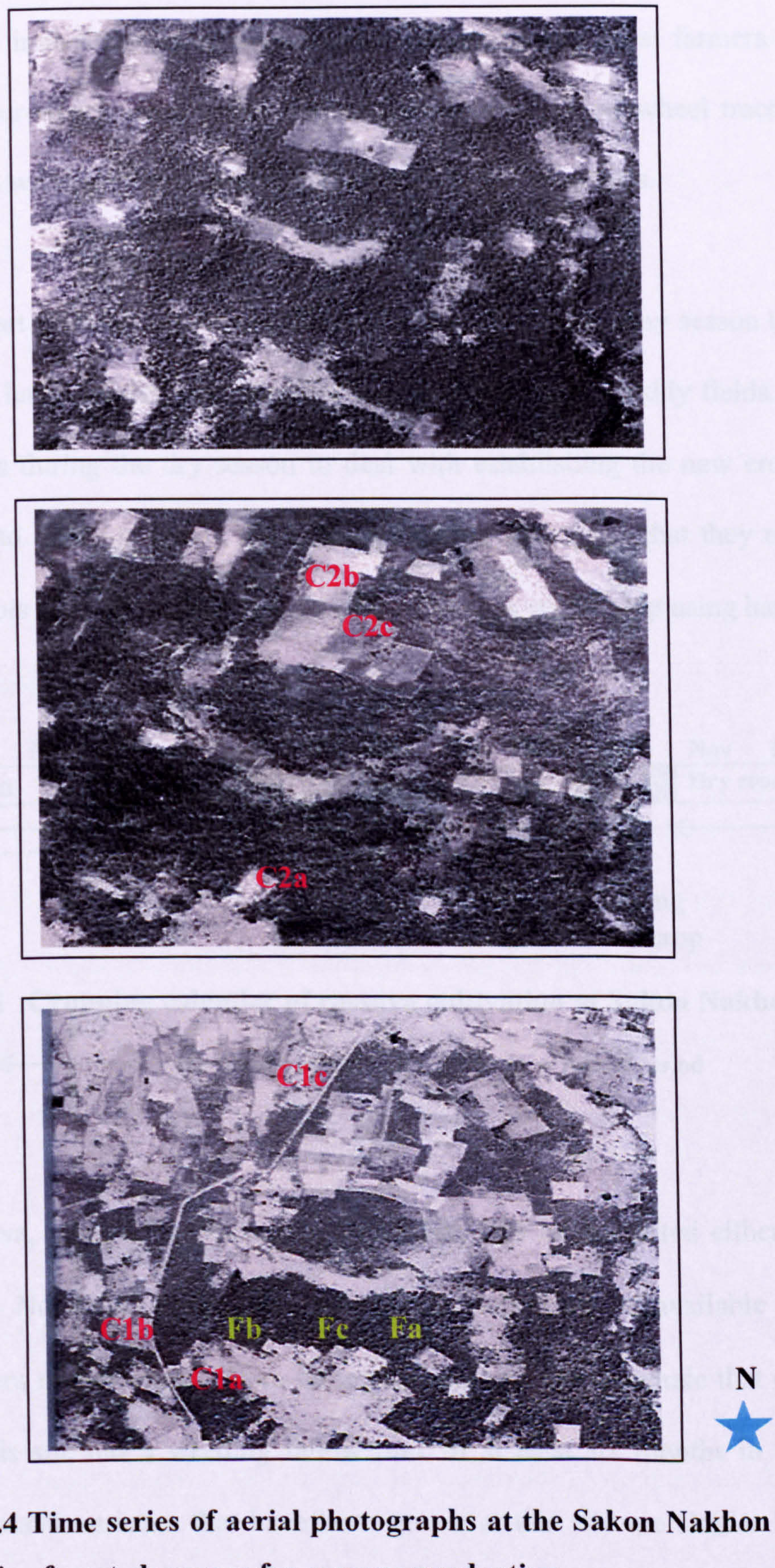
as well as the by interpretation of soil maps and aerial photographs. The results are summarized as follows.

(i) Cassava plots

The time since forest clearance could be established by the relative ages of the cultivated plots. As there was no exact record when the forests were cleared, the ages of the cassava plots were estimated from semi-structured interviews and group interviews with farmers and then double checked by the dates of serial aerial photography taken in the years of 1967, 1977 and 1996 (Figure 4.4 shows progressive forest clearance for cassava).

The ages of six cassava plots were thus established as ranging from 10 to 30 years old and were divided into two groups, 10-20 years old (C1a, C1b and C1c) and 20-30 years old (C2a, C2b and C2c). These cultivated plots were adjacent to the forest plots (Figure 4.4).

All of the cassava plots at this site were formerly covered by dry Dipterocarp forest. This information was obtained from plot owner interviews and in group interviews and then checked by observing natural trees remaining in the plots. Cassava is main crop, but in the older plots (C2b and C2c), kenaf was grown before cassava was introduced into this area. Cassava is occasionally rotated with other subsistence crops, for instance, vegetable, corn or chilli, during the fallow period, or when the situation for cassava production is inappropriate due to root yield decrease, shortage of farm labour and/or low product value in the markets.



a. 1967

b. 1977

c. 1996

Figure 4.4 Time series of aerial photographs at the Sakon Nakhon site showing progressive forest clearance for cassava production.

(taken in 1967 scale=1:50,000, 1977 scale=1: 40,00 and 1996scale=1:50,000)

Animals were used for land preparation and weed control before the two-wheel tractor was introduced approximately 20 – 25 years ago. Most farmers at this site have no four-wheel tractors, but they sometimes hire a four-wheel tractor for land preparation when there is a lack of labour or in urgent situations.

Farmers start growing cassava in October at the end of the rainy season (Figure 4.5) when they have finished transplanting rice seedlings in the paddy fields. They have 2-3 months during the dry season to deal with establishing the new crop and then they have to return to paddy fields for harvesting rice. After that they return to the cassava plots to harvest cassava roots of the previous year's crop using hand hoes.

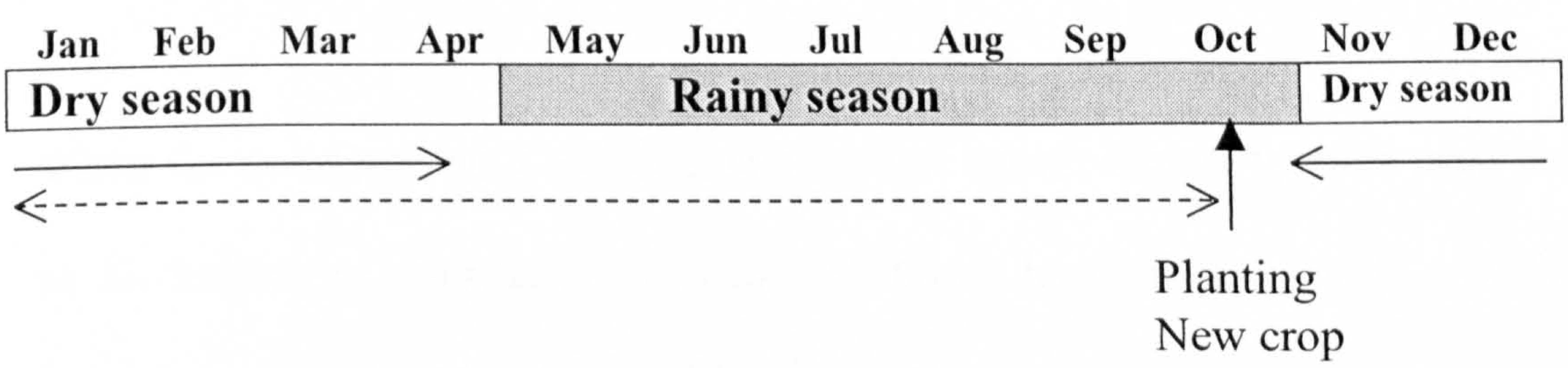


Figure 4.5 Cropping calendar of cassava cultivation at Sakon Nakhon site.

<——— = Harvesting period <-------> = Fallow period

The cassava, planted in October to December, will be harvested either in the next October – November or in February – April, depending on available time, labour and/or extra money needs. From these practices, we can conclude that each cassava plot in this site has a weeding fallow time of at least six months in the cropping cycle. Cassava varieties that have been grown at this site are similar because they have been promoted by field crop research institute via agricultural extension officers and then distributed within farmer communities. The popular varieties are Rayong 3 and 5, because the promotion document claimed that these varieties yielded high root production, for example, the average yield of Rayong 5 variety with fertilizer application is 27.6 ton ha^{-1}(Field crop research institute, 1999). However, the yield of Rayong 3 and 5 at this site ranges from 7-10 ton ha^{-1} according to the results of farmer interviews (Table 4.1).

Information from semi-structured interviews showed that the farmers at this site did not use any chemical fertilizers in cassava production. They would stop growing cassava when they experienced extreme decreases in cassava root yield and then turned to grow other crops, such as, vegetable, corn or chilli, or abandoned the cassava plots for a while.

When the question about soil degradation was asked, almost farmers used root yield as an indicator, whereas some said that they observed poor crop growth. Some argued that root yields decreased because of inadequate rainfall in that year, rather than soil degradation. However, all of them agreed that overall root yield of cassava production markedly decreased when compared with the first crop after forest clearance.

(ii) Sugarcane plots

Similar techniques were used to obtain land use history of the plots in the cassava site were also employed at the sugarcane site. The results are presented in Table 4.2.

Table 4.2 History, land use and management of the sugarcane plots at the Udon Thani site.

Item	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b	S3c
1.Plot age	10-20	10-20	10-20	30-40	30-40	30-40	40-50	40-50	40-50
2.Formerly forest	DF	DF	DF	DF	DF	DF	DF	DF	DF
3.Main crop	S	S	S	S	S	S	S	S	S
4.Land preparation	4T	4T	4T	4T	4T	4T	A/4T	A/4T	A/4T
5.Crop variety	F	F	F	P	P	P	P	P	P
6.Crop growing calendar	Oct	Oct	Oct	Oct	Oct	Oct	Oct	Oct	Oct
7.Weed control	A/2T	A/2T	A/2T	A/2T	A/2T	A/2T	A/2T	A/2T	A/2T
8.Fertilizer (kg ha^{-1})	600/U	400/U	_*	325	325	230	325	650	325
9.Harvesting method	BHC	BHC	BHC	BHC	BHC	BHC	BHC	BHC	BHC
10. Yield (ton ha^{-1})	78	65	39	50	50	43	40	58	30
11 Degraded soil perception	CY	SC	CY	SC	SE	SS	SE	CY	CY

DF = Deciduous forest
S = Sugarcane as a main crop
2T = Two –wheel (walk follow) tractor
4T = Four-wheel tractor
A = animal (buffalo)
Oct = October
-* = The farmer did not use fertilizer for this crop because of insect damages
F = F-38
P = Phill 58-260
U = Top dressing by Urea 300 kg ha^{-1}
BHC = Burning before manual cutting
CY = Crop yield
SC = Soil colour
SE = Soil erosion
SS = Soil stickiness

The ages of sugarcane plots ranged from 10 to 45 years and were divided into three groups, 10-20 years old (S1a, S1b and S1c), 30 – 40 years old (S2a, S2b and S2c) and 40-50 years old (S3a, S3b and S3c). It was more difficult to investigate plot history at this site, particularly of the older plots, because plots were cleared so long ago. The primary plot's owners were often too old to answer the questions properly, or some had moved out of the area. In such cases, the current plot's owner knew very little about the plot history, so most of the information on past land use was obtained by group interview.

Study plots at this site were located apart from each other. The oldest plots (S3a, b and c) were near the oldest sugar mill in this area, Kumpawapi sugar mill. The younger plots (S2 a, b and c) were located about 5 to 6 km east of the oldest ones and the youngest plots (S1 a, b and c) were located about 30 to 40 km east of the sugar mill. This progressive distance from the mill suggests that once the sugar mill was established, the farmers decided to clear the land close by for growing sugarcane for convenience of transportation and, subsequently, the growing areas were expanded deeper into the natural forests when the cane yield decreased, or greater yields were needed.

Most of the natural forests have now been cleared in this area, meaning that it was not possible to establish suitable forest control plots on soils similar to the time series of sugarcane plots at this site. However, all of study plots at this site were formerly dry Dipterocarp forest and were located on the same soil series as those of the cassava plots according to the soil map of Udon Thani. In the older plots, animal traction was used in the earlier stages of cultivation after forest clearance and farmers then turned to four-wheel tractors later on, whereas animal traction and/or two-wheel tractors were used for weed control. Sugarcane varieties were changed many times, depending on the promotion by the sugar mill owners, or the Field Crops Research Centre. At present Phil 58 - 260 is the most popular variety in this site.

Generally, farmers start growing sugarcane in October and harvest in December to March of the following year (15-18 months later) by hand cutting (Figure 4.6). Chemical fertilizers are normally used at this site. The compound fertilizer N-P-K formulas encountered were 16-8-8, 12-10-8, 16-12-8, with topdressing by urea (46-0-0) in S1a and S1b plot. The rate of fertilizer application varied from plot to plot, ranging from 230 –650 kg ha^{-1} for compound fertilizers and 300 kg ha^{-1} for urea.

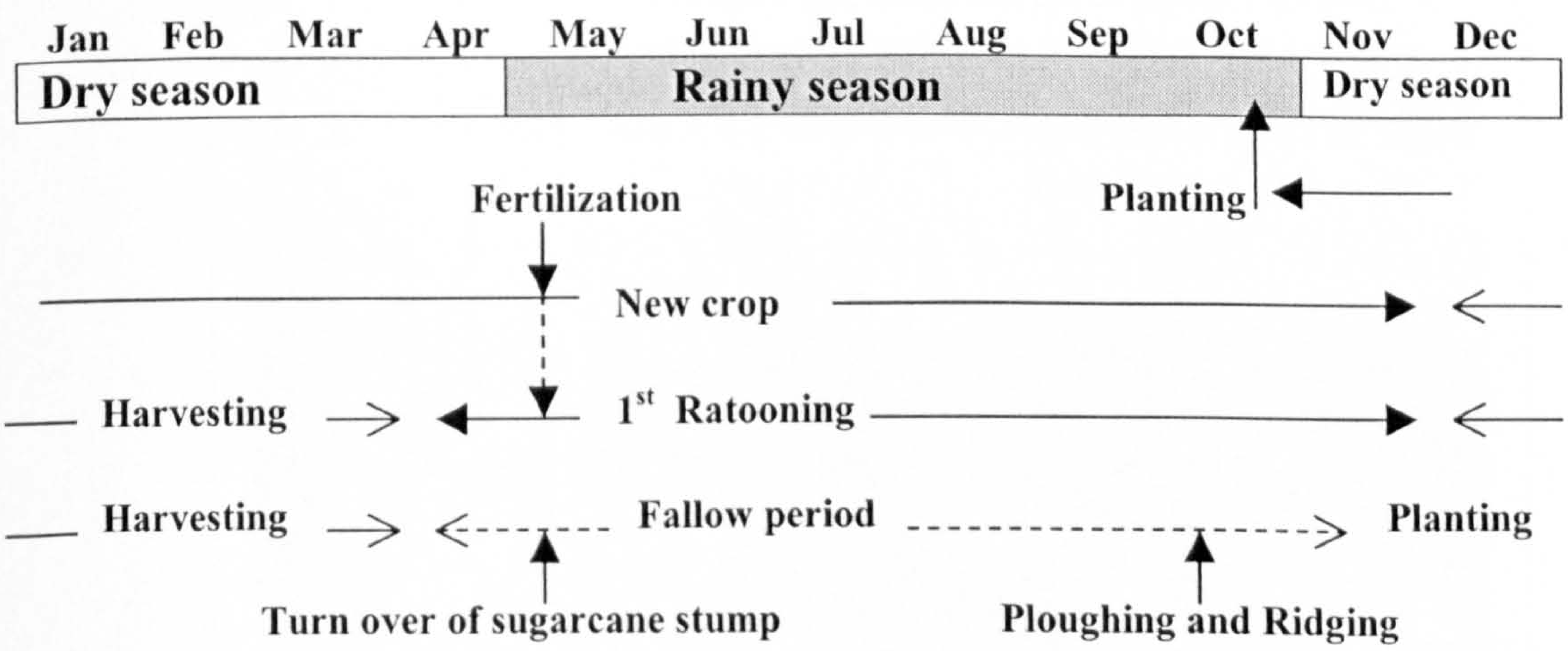


Figure 4.6 Cropping calendar of sugarcane cultivation at Udon Thani site.

Burning sugarcane before harvesting is widely practiced and all of sugarcane plots in this study were burnt before manually cutting by labourers (Figure 4.7).

a.

b.

Figure 4.7 Burning sugarcane (a.) and manually cutting by labourers (b.).

Although farmers have known that burning the cane plots would cause many problems to their land, to sugarcane production, and also to the environment, most of them could not avoid burning because of labour constraints. If they did not burn the plots before cutting the cane, labourers usually refused to work for them. So, they had to pay more money for either hiring extra labour or a cutting machine.

All respondents agreed that sugarcane yield in their plots markedly decreased when compared with the earlier stages after forest clearance. The yield was approximately 94 ton ha^{-1} at the first crop, whereas the yields at the date of interviewing were approximately 60, 47 and 42 ton ha^{-1} in the 10-20 years old plots, 30-40 years old plots and 40-50 years old plots respectively. Consequently, they started talking about the causes of yield decrease. Some pointed out that it was because of soil degradation, whilst others suggested that there were many causal factors, such as insect damage, inadequate rainfall and sugarcane variety. They also suggested that soil colour or soil stickiness should be a good indicator for assessing soil degradation.

4.3 Modal soil profile characteristics

4.3.1 Soil profile descriptions

(i). The dry Dipterocarp forest profiles (F):

Soil profile descriptions and laboratory analysis results are given in profile No. 1-3 in Appendix I. The modal soil profiles lie on the lower to middle parts of an undulating terrace with a 2 to 2. 5° slope. Soil profiles are more than 180 cm deep and consist of Ah, A, E, Bt and Btg horizons (Figure 4.8).

In the topsoil Ah, A or E horizons, soil depths range from 25 to 40 cm. Soil colours vary from very dark grey to light brown. All Ah, A and E horizons are sandy loams with weak fine sub-angular blocky structure and are non-sticky and non-plastic when wet, soft when dry, very friable to friable when moist. Soil reactions are moderately acid with the field pH values ranging from 5.5- 6.5.

Subsoil argillic or kandic horizons (Bt horizons), vary from light brown to yellowish red in colour, with paler colours in the lower Btg horizons. Pinkish grey and/or very pale brown colours with iron oxide mottles are found in Btg horizons at the depths of varying from 80 to more than 180 cm. Soil textures in the all argillic or kandic horizons are sandy clay loam and soil structure is massive. Soil consistence varies from slightly to moderately sticky and slightly to moderately plastic when wet, slightly hard to hard when dry, and friable to firm when moist. Soil reactions range from very strongly to moderately acid with field pH values of 4.5-5.5.

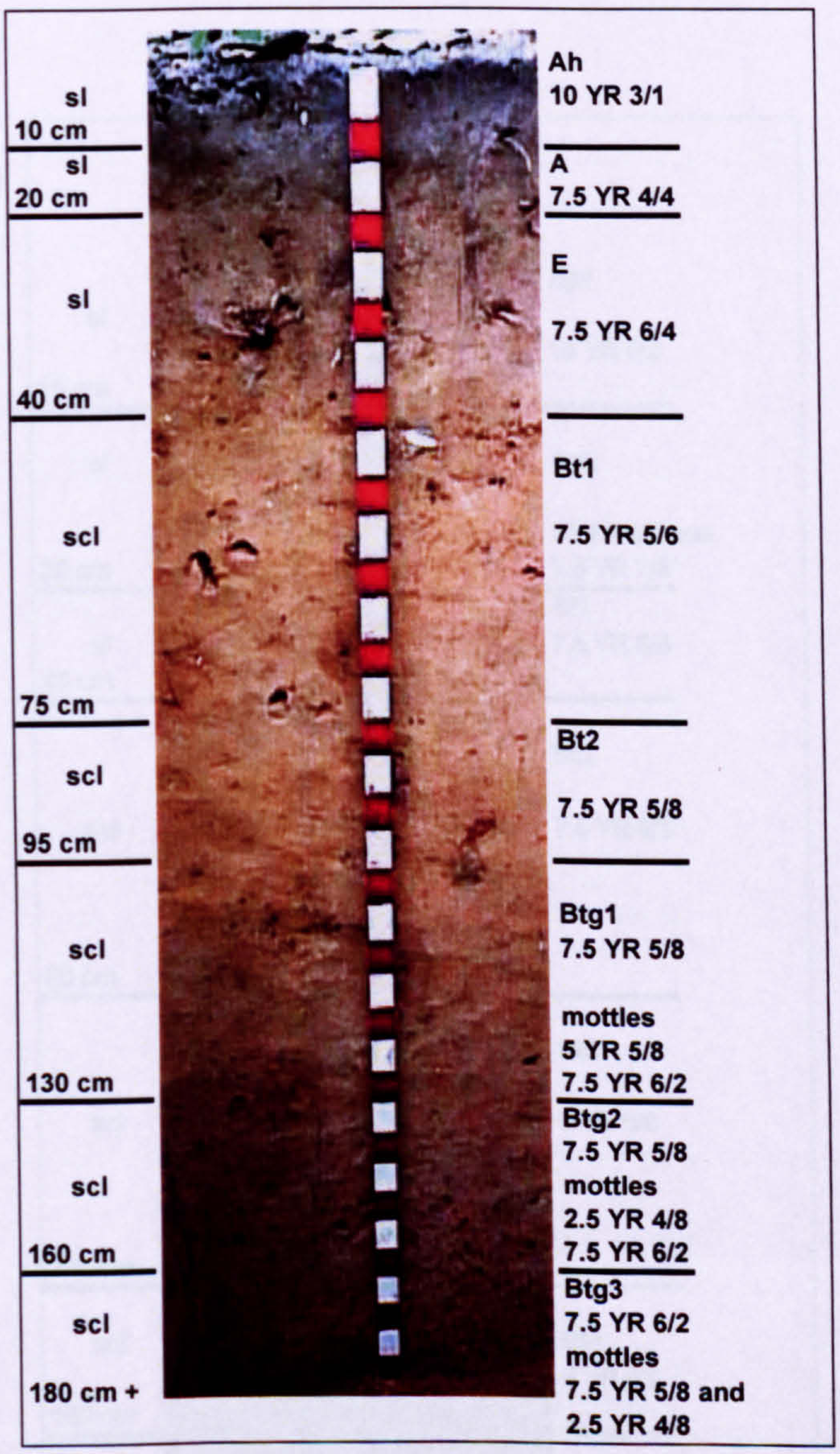


Figure 4.8 A soil profile of Oxyaquic Kandiustults under dry Dipterocarp forest.

(ii) The Cassava profiles (C):

Soil profile descriptions and laboratory analysis results are given in profile No.4-9 in Appendix I. The modal soil profiles lie on the lower to middle parts of an undulating terrace with a 1.5° to 2. 5° slope. Soil profiles are more than 180 cm deep and consist of Ap, E, Bt and Btg horizons (Figure 4.9 and 4.10).

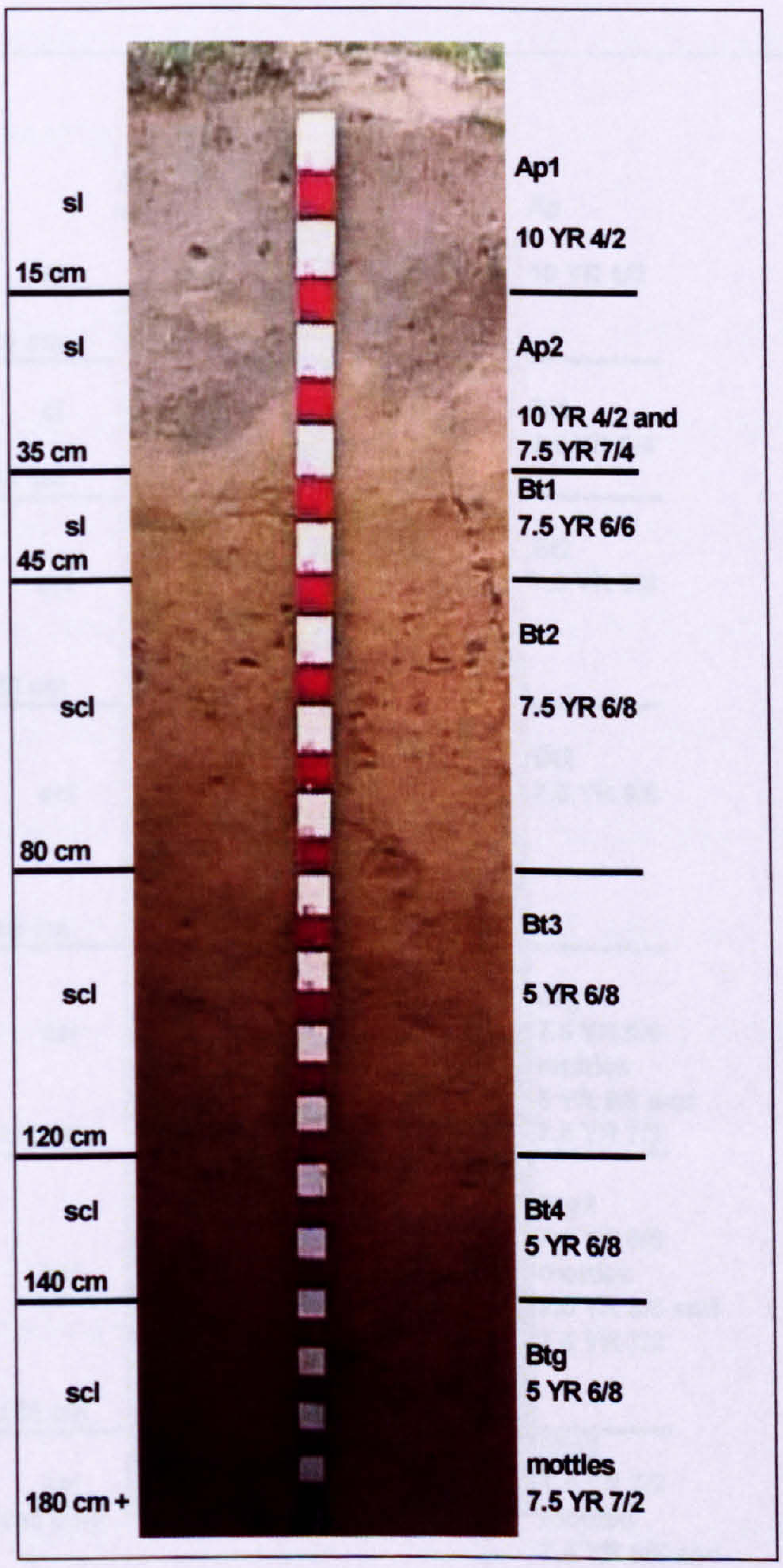


Figure 4.9 A soil profile of Typic Kandiustults under cassava 10-20 years old.

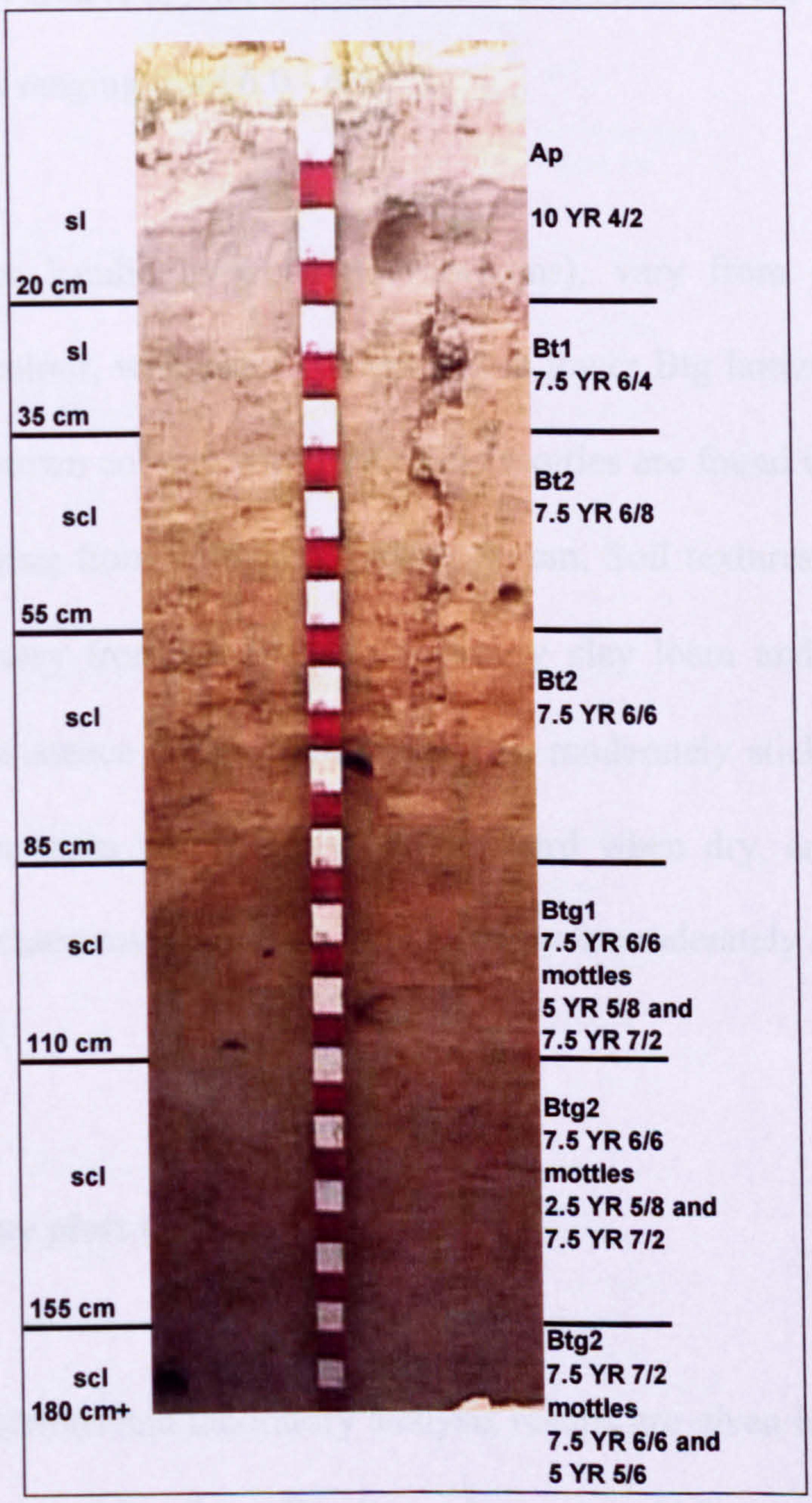


Figure 4.10 A soil profile of Oxyaquic Kandiustults under cassava 20-30 years old.

In the topsoil Ap or E horizons, soil depths range from 20 to 45 cm. Soil colours vary from dark greyish brown to light brown. All Ap and E horizons are sandy loams with weak fine sub-angular blocky structure and are non-sticky and non-plastic when wet, soft when dry, very friable to friable when moist. Soil reactions are slightly acid with the field pH values ranging from 6.0 - 6.5.

Subsoil argillic or kandic horizons (Bt horizons), vary from strong brown to yellowish red in colour, with paler colours in the lower Btg horizons. Pinkish grey and/or very pale brown colours with iron oxide mottles are found in Btg horizons at the depths of varying from 95 to more than 180 cm. Soil textures in the argillic or kandic horizons vary from sandy loam to sandy clay loam and soil structure is massive. Soil consistence varies from slightly to moderately sticky and slightly to moderately plastic when wet, slightly hard to hard when dry, and friable to firm when moist. Soil reactions range from very strongly to moderately acid with field pH values of 4.5 - 6.0.

(iii) The sugarcane plots (S):

Soil profile descriptions and laboratory analysis results are given in profile No.10-18 in Appendix I.The modal soil profiles lie on lower to middle parts of an undulating terrace with a 1.5 to 2. 9° slope. Soil profiles are more than 180 cm deep and consist of Ap, E, Bt and Btg horizons (Figure 4.11-13).

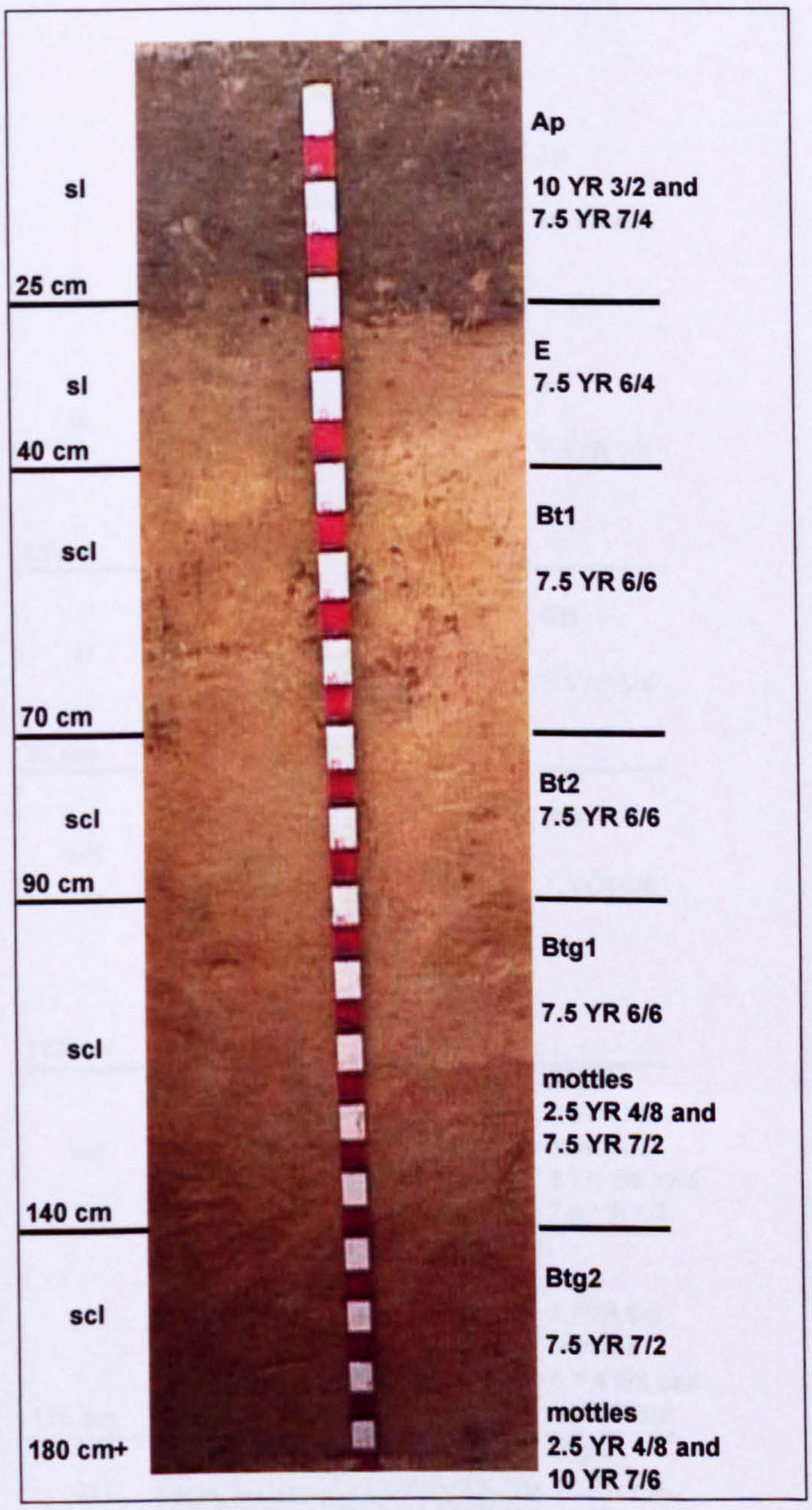


Figure 4.11 A soil profile of Oxyaquic Kandiustults under sugarcane 10-20 years old.

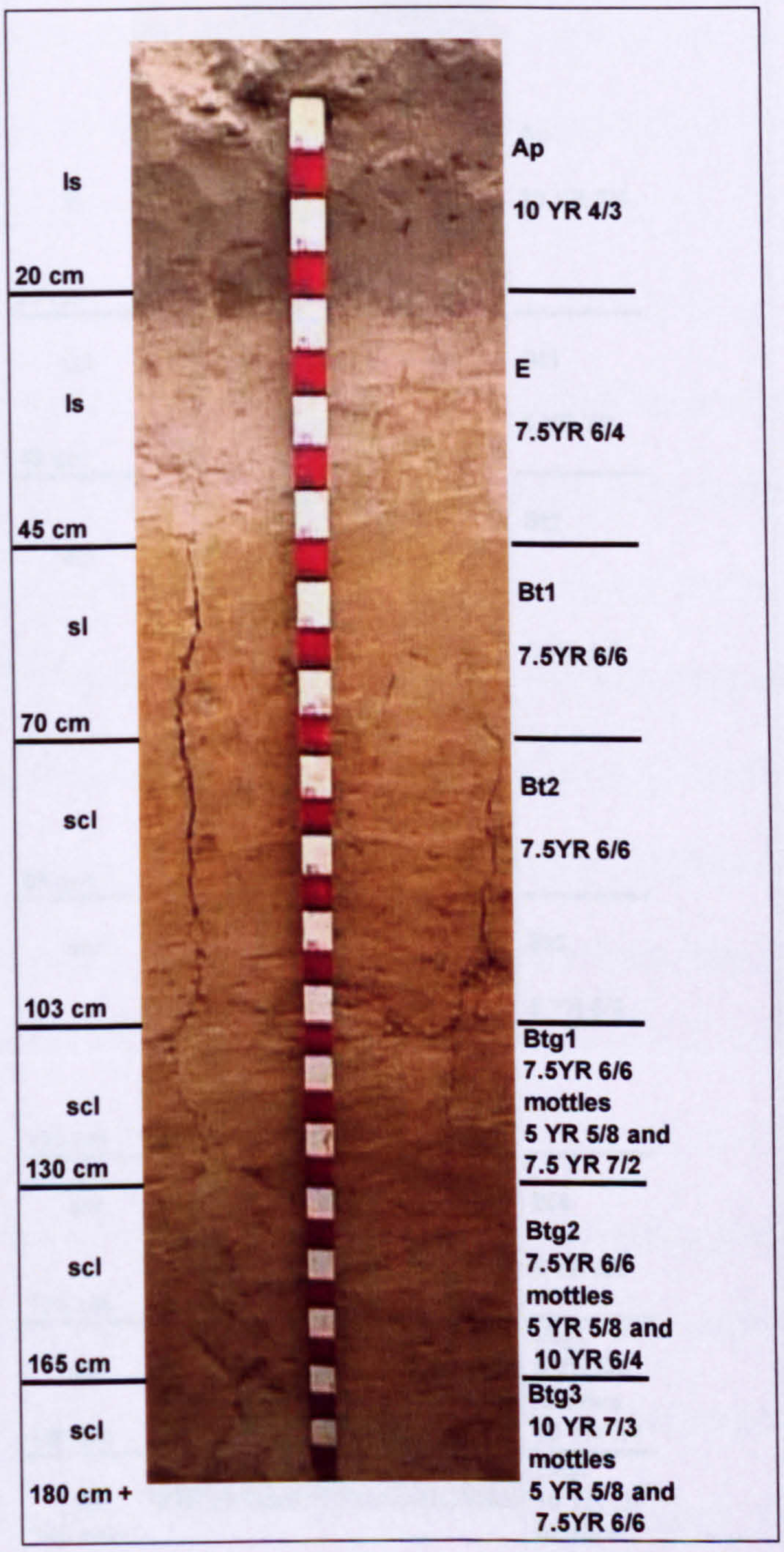


Figure 4.12 A soil profile of Typic Kandiustults under sugarcane 30 -40 years old.

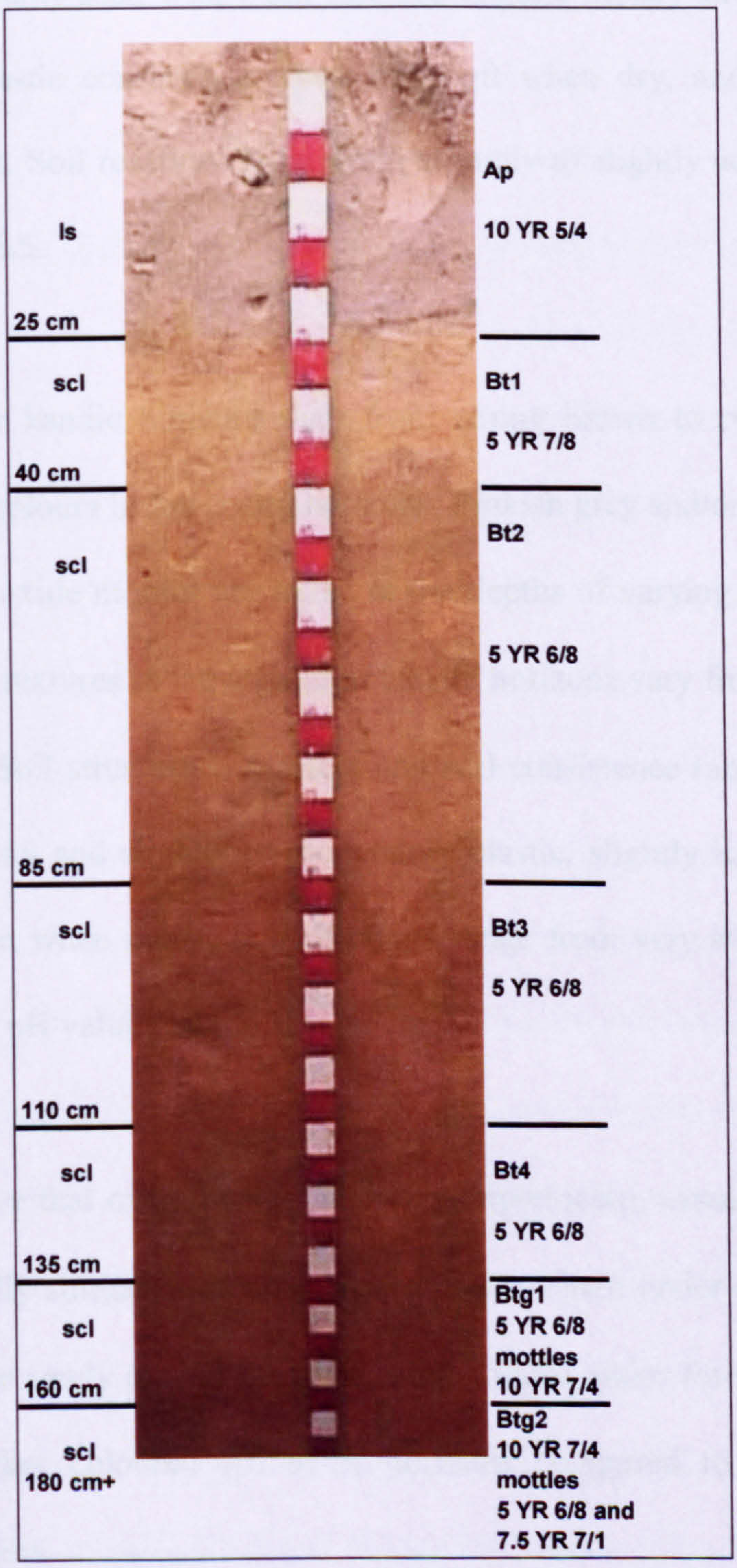


Figure 4.13 A soil profile of Typic Kandiustults under sugarcane 40-50 years old.

In the topsoil A or E horizons, soil depth ranges from 25 to 45 cm. Soil colours vary from very dark greyish brown to yellowish brown. A and E horizons vary between sandy loam and loamy sand with weak fine sub-angular blocky structures and non-sticky and non-plastic consistence when wet, soft when dry, and very friable to friable when moist. Soil reactions range from strongly to slightly acid with the field pH values of 5.0- 6.5.

Subsoil argillic or kandic horizons vary from strong brown to reddish yellow in colour with paler colours in lower Btg horizons. Pinkish grey and/or very pale brown colours with iron oxide mottles are found at the depths of varying from 90 to more than 180 cm. Soil textures in the argillic or kandic horizons vary from sandy loam to sandy clay loam. Soil structure is massive and soil consistence ranges from slightly to moderately sticky and slightly to moderately plastic, slightly hard to hard when dry, friable to firm when moist. Soil reactions range from very strongly to slightly acid with the field pH values of 4.5- 6.5.

These results prove that overall soils under dry Dipterocarp, cassava and sugarcane are morphologically similar, although those at Udon Thani under sugarcane tend to have slightly more sandy topsoil horizons, whilst those under forest or the younger plots have a darker coloured Ah or A horizons compared to those under the cultivated older plots.

4.3.2 Laboratory analysis results

Summary key analytical characteristics of modal profiles both in the SK site and the UD site are presented in the Appendix I.

The analytical results showed that these soils are dominated by fine sand and very fine sand in the sand fraction throughout the profiles. The silt fraction varies from 14 to 22 %, 13 to 27 % and 7 to 24 % throughout the profiles under dry Dipterocarp forest, cassava and sugarcane respectively. The clay fraction ranges from 9 to 18 %, 9-11 % and 5 to 13 % in the topsoil horizons and increase up to 18 to 27 %, 12-32 % and 11 to 34 % in the subsoil horizons under dry Dipterocarp forest, cassava and sugarcane respectively. The soils of both under forest and under cultivated plots are moderately acid in the topsoil horizons, with pH values in water ranging from 4.6 to 6.3 and strongly acid in the argillic or kandic horizons, with pH values in water ranging from 4.5 to 5.9. The soil pH values in KCl solution ranges from 4.0 to 5.5 and 3.7 to 5.3 for upper horizons and argillic or kandic horizons respectively. The values of the subsoil horizons decrease downwards to become very strongly acid both under forest and cultivated plots.

Organic carbon contents in the A horizons are very low to low with the values ranging from 3.5 to 10.7 g kg^{-1}, 2.1 to 6.7 g kg^{-1} and 0.8 to 4.6 g kg^{-1} for the forest, cassava and sugarcane plots respectively. These values are obviously lower in upper subsoil argillic or kandic horizons than those of the A horizons, ranging from 0.4 to 2.3 g kg^{-1} for both under the forest plots and the cultivated plots.

Cation exchange capacity (CEC) values in the topsoil horizons are very low to low, ranging from 3.3 to 4.7 cmol$^+$ kg^{-1}, 1.6 to 3.5 and 1.1 to 3.0 cmol$^+$ kg^{-1}under forest, cassava and sugarcane respectively. The values of the subsoil horizons increase slightly up to 3.9-5.2 cmol$^+$ kg^{-1}, 2.8-4.2 and 2.2-4.9 cmol$^+$ kg^{-1} respectively. In the topsoil horizons, base saturation percentages range from 53 to 67 %, 50 to 69 % under forest and cassava respectively, but those under sugarcane are generally lower, widely varying from 12 to 72 %. The values of the subsoil horizons vary from 10-30 % and 9 to 79 % under forest and cassava respectively, whereas these under sugarcane are mostly higher, ranging from 33 to 77 %.

4.4 Soil classification

The information from section 4.3.1 and 4.3.2 indicates that the soils of all study plots have clear increases of clay with depth in the profiles that meet the criteria for Ultisols (Soil Survey Staff 1999), with weakly structured loamy sand to sandy loam surface horizons over sandy loam to sandy clay loam subsoil horizons. Most soil horizons have very low to low organic carbon content, and very low to low CEC values that indicates the dominance of low activity clays, (i.e giving Kandic properties according to Soil Taxonomy). Very strongly acid to moderately acid argillic or kandic subsoil horizons predominate, with pH values in water less than 5.5 in their lower parts.

A base saturation less than 35% in the lower part of the subsoil is the one of the criteria that distinguishes the Ultisols from other soil orders in Soil Taxonomy (Soil Survey Staff 1999), particularly the Alfisols. In this study, almost all soils (eight of nine plots) in the Sakon Nakhon site meet this criterion, with at least part of the argillic or kandic horizon having a base saturation less than 35 %, the exception being the profile of the C1a plot. In contrast, only one plot (S3c) in the Udon Thani site meets this criterion because the rest have base saturation values slightly in excess of 35% throughout the argillic or kandic horizons of the soil profiles. Therefore, the soils under cassava at the Sakon Nakhon site, excluding the C1a plot, are clearly classed as Ultisols, whereas most of the soils under sugarcane at the Udon Thani site are technically not classified as Ultisols. However, all other criteria suggest that the soils of the Udon Thani site are indeed Ultisols. It is suggested that base saturation values slightly more than 35% are probably the result of land use for sugarcane and are associated soil management effects. In Ultisols of North Carolina, USA, it was found that long-term, high-input management significantly increased the levels of exchangeable bases in subsoil horizons. These results led (Buol 1996, cited in West *et al.*, 1997) to suggest that human-induced profile alterations can convert Ultisols to Alfisols. Such evidence, and that of my own results, shows that base saturation is not an efficient discriminator for distinguishing Ultisols from Alfisols in low CEC soils of the tropics, as also noted by Van Wambeke (1992).

In addition, the analytical evidence indicates that most have kandic horizons and should be classed as Kandiustults according criteria given in the US Soil Taxonomy (Soil Survey Staff 1999). However, when the CEC values given in Appendix II for the profiles under forest are recalculated on a clay basis, as required for classification purposes, only Profile FC has a Bt or Btg horizon with a CEC ≤16 $cmol^{+}$ kg^{-1} clay qualifying as a kandic horizon. Thus Profiles FA and FB are technically Kanhaplic Haplustults rather than Kandiustults. Most of the cassava and sugarcane plots do qualify as having kandic rather than argillic horizons and are Kandiustults. However, some (Profiles C1a, C1b, S2a and S2c) have Bt or Btg horizons marginally above the critical ≤16 $cmol^{+}$ kg^{-1} clay, but by no more than 2 $cmol^{+}$ kg^{-1} clay and within the margins of error for this calculated value. A similar range of CEC values is apparent from published analyses of the Korat series available from the Thai Soil Survey.

In conclusion, according to US Soil Taxonomy (Soil Survey Staff 1999) most soils of the study plots are classified as Kandiustults, but a few fall just within the Great Group of Haplustults because their CEC values when recalculated on a clay free basis are marginally above 16 $cmol^{+}$ kg^{-1} clay (see Appendix I and the soil profile photographs illustrated above in Figures 4.8-4.13). Likewise, not all exactly fulfill the the 'Oxyaquic' Subgroup criteria, because the presence of redoximorphic features occurs both just above and below the critical 100 cm depth. Nevertheless, these Ultisols are very similar in soil properties and in morphology, particularly in their upper horizons, which are of paramount importance for assessing soil degradation. Moreover, all of them were classified as Fine-loamy, siliceous, isohyperthemic (Oxyaquic) Kandiustults (Korat series) in the Thai National Soil Survey (Department of Land Development, 1971; 1972).

On the basis of the findings discussed above, the Ultisols of the present study will be separated into two groups for data analysis in following sections, namely, (i) Ultisols with base saturation less than 35 %. Most of them (8 plots) are under dry Dipterocarp forest and under extensive cassava production at the Sakon Nakhon site, excluding the C1a plot and (ii) altered Ultisols with base saturation more than 35%. Most of them (8 plots) are under intensive sugarcane production at the Udon Thani site, excluding the S3c plot. As soil degradation evaluation in each cropping regime of the study will be carried on similar soils and similar managements. The C1a and S3c plot may be not similar to their companions in management history that can be reflected by base saturation percentages as discussed earlier.

4.5 Soil variability

Soil variability at small scales is often caused by changes in topography that affect the transport and storage of water across and within the soil profile. Soil variation determined by slope position across a hill slope is usually called a catena (Mulla and Mcbratney, 2000). As mentioned in section 4.1, the topography of Northeast Thailand consists of undulating terraces that can be divided into five landscape positions, namely, summit, upper slope, middle slope, lower slope, and depression.

According to national soil survey reports referred to earlier, the Korat series is normally located on lower to middle slopes where deep subsoil drainage is affected by seasonal water logging. Satuk series, on the middle slopes, has particularly deep argillic horizons. Well-drained Kandiustults of the Warin series occur on middle to upper slopes, whilst Paleustults with slightly more active clays (Yasothon series) occupy upper slopes to summit areas. Poorly-drained Kandiaquults of the Roi-Et series occur in depressions. These soils only differ in colour and drainage status at the depth in their subsoil diagnostic horizons of clay increase.

The results of soil variability investigations at each of my own study sites showed similar soil catenary sequences that pass from well drained Typic Kandiustults on the convex summit and upper slopes, to moderately drained Oxyaquic Kandiustults on the lower slopes, to Arenic Kandiaquults in the concave depressions (Figure 4.14 and Appendix I).

The most prominent soil morphological features that distinguished the soils in each position of landscape were the depth of sandy surface horizons and the colours and mottles in loamy argillic horizons. The depth of sandy surface horizons was less than 50 cm on summit to lower slope, but increased, often markedly, to more than 50 cm, giving 'Arenic' properties according to Soil Taxonomy, on foot slopes or depressions. All study plots in the present study are located on lower - middle slopes, so the soils were moderately to well drained (see Appendix I profile descriptions for further details).

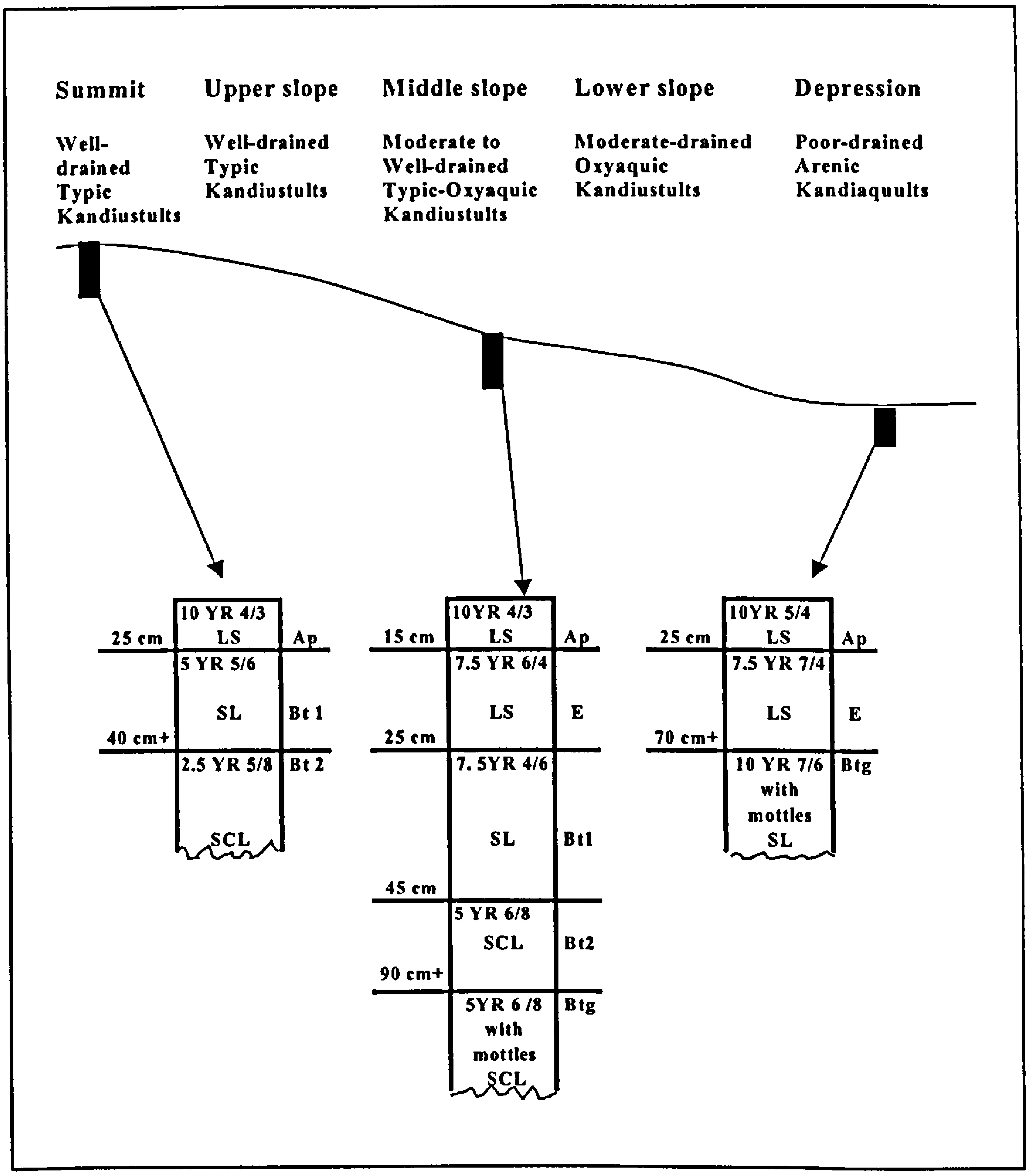


Figure 4.14 The main soil catena at the study sites.

The magnitudes of soil property variation of the study plots both in the profiles and plot scale measurements under each land use system investigated can be expressed by coefficients of variation (CVs). Results are showed in Table 4.3 and 4.4. Bulk density and pH were the least variable properties. Clay dispersion, labile carbon and ECEC were moderately variable, whilst exchangeable bases, exchangeable acidity and infiltration rate were the most variable. Organic carbon showed moderate variability in cultivated plots, but showed relatively high variability in forest plots. These results have a similar trend with soil property variation reported in previous studies (Wilding *et al.*, 1994; Banda, 2000), but the magnitude of variation in this study was lower than those of Wilding *et al.* (1994) and Banda (2000).

Table 4.3 Coefficient of variation (% CV) values of soil properties in Ah/Ap horizons of soil profiles under dry Dipterocarp forest (F), cassava(C) and sugarcane (S).

Soil Property	F	C1	C2	S1	S2	S3
Bulk density	2.7	2.7	4.0	3.4	2.7	3.3
Clay dispersion	5.3	10.5	12.8	16.2	7.4	8.1
pH_w 1:2.5	5.1	9.3	1.9	9.1	4.2	2.1
pH_{KCl} 1:2.5	10.4	6.7	4.7	12.8	12.5	5.1
Organic carbon	35.0	31.4	31.8	15.9	33.1	8.5
Labile carbon	14.3	9.1	9.1	12.7	3.8	9.6
Exchangeable K	27.3	20.0	66.7	60.0	50.0	75.0
Exchangeable Ca	57.6	15.5	54.7	41.6	51.5	85.7
Exchangeable Mg	27.3	42.2	32.1	28.0	50.0	57.1

Table 4.4 Coefficient of variation (% CV) values of soil properties in study plots under dry Dipterocarp forest (F), cassava(C) and sugarcane (S).

Soil properties	F	C1	C2	S1	S2	S3
Bulk Density						
Topsoil (10-15cm)	2.7	3.9	3.9	3.3	3.3	3.3
Subsoil (40-45cm)	2.6	4.3	3.2	4.9	3.6	4.2
Clay dispersion						
Topsoil (10-15cm)	26.8	38.8	26.9	21.1	26.3	23.0
Infiltration rate	51.9	46.9	50.1	61.9	50.6	54.4
pH_w 1:2.5						
Topsoil (10-15cm)	7.3	4.7	5.6	6.1	6.0	4.6
Subsoil (40-45cm)	7.2	7.3	9.7	10.7	6.0	6.0
pH_{KC} 1:2.5						
Topsoil (10-15cm)	8.5	6.4	8.3	7.9	7.0	2.0
Subsoil (40-45cm)	5.5	9.5	10.2	11.9	6.8	5.1
Topsoil (10-15cm)	60.0	66.7	65.2	26.7	35.0	15.4
Subsoil (40-45cm)	46.7	65.4	90.9	80.5	76.3	47.5
Organic Carbon						
Topsoil (10-15cm)	54.2	18.2	22.0	40.6	19.2	35.3
Labile Carbon						
Topsoil (10-15cm)	24.8	20.3	16.1	34.8	27.7	29.8
Exchangeable K						
Topsoil (10-15cm)	33.3	33.3	33.3	57.1	50.0	25.0
Subsoil (40-45cm)	50.0	66.7	66.7	80.0	33.3	66.7
Exchangeable Ca						
Topsoil (10-15cm)	68.4	35.2	31.8	44.03	42.86	43.75
Subsoil (40-45cm)	55.1	66.9	49.0	32.6	31.1	40.5
Exchangeable Mg						
Topsoil (10-15cm)	27.3	38.8	28.6	31.3	33.3	100.0
Subsoil (40-45cm)	40.9	48.2	54.8	35.4	32.6	51.1
ECEC						
Topsoil (10-15cm)	27.5	20.7	21.2	36.0	13.5	28.4
Subsoil (40-45cm)	19.6	44.0	17.5	15.8	21.9	32.1

4.6 Soil properties variability under dry Dipterocarp forest

Dry deciduous Dipterocarp forest is the main forest type in North East Thailand and most cultivated land in this area was formerly under such forest. In this study, Ultisols under this kind of forest have been used as a base line for assessing the change in soil properties over time in selected cropping systems after forest clearance. To act as an appropriate base line, natural forest should be undisturbed. Unfortunately, completely undisturbed forest rarely remains in the study area.

Therefore, three partially disturbed dry Dipterocarp forest plots within the National Park have been used as the base line. To assess the variability of soil properties between three forest plots, One-way ANOVA procedures were employed and the results are showed in Table 4.5.

The canopy gap percentage values of these plots vary between 34 and 48 % (Figure 4.15). The canopy gap percentage value of the FC plot is significantly larger than those of the FA plot and the FB plot. Dispersible clay, exchangeable Ca and effective CEC in the topsoil horizons of the FC plot are higher than those of the FA plot and the FB plot whereas, labile carbon in the topsoil horizons of the FC plot are lower than those of the FA plot and the FB plot. There are no significant differences between forest areas for any of these properties. Infiltration rate of the FC plot is significantly lower than those of the FA plot and the FB plot. Whereas, Soil bulk density and exchangeable K in the subsoil horizons of the FC plot is significantly higher than that of the FA plot, they are not significantly higher than those of the FB plot.

Table 4.5 Mean Physical and chemical properties of the dry Dipterocarp forest plots(F).

Soil property	Unit	Topsoil			Subsoil		
		Fa	Fb	Fc	Fa	Fb	Fc
Bulk density	($Mg\ m^{-3}$)	1.45	1.49	1.46	1.50 [a]	1.54 [ab]	1.56 [b]
Clay dispersion	(%)	16.39	18.89	20.54	-	-	-
Infiltration rate	($cm\ hr^{-1}$)	10.9 [a]	10.5 [a]	4.1 [b]	-	-	-
pH_w 1:2.5		5.0	5.2	5.3	4.8	5	4.9
pH_{KCl} 1:2.5		4.0	4.3	4.4	3.8	3.8	3.9
Exchangeable acidity	($cmol^+\ kg^{-1}$)	0.70	0.39	0.40	1.39	1.24	0.99
Organic carbon	($g\ kg^{-1}$)	5.1	7.8	5.6	-	-	-
Labile carbon	($mg\ kg^{-1}$)	141.8	137.6	110.3	-	-	-
Exchangeable K	($cmol^+\ kg^{-1}$)	0.05	0.06	0.06	0.04 [a]	0.06 [ab]	0.09 [b]
Exchangeable Ca	($cmol^+\ kg^{-1}$)	0.69	0.89	1.27	0.45	0.41	0.6
Exchangeable Mg	($cmol^+\ kg^{-1}$)	0.54	0.64	0.46	0.49	0.78	0.70
ECEC	($cmol^+\ kg^{-1}$)	1.99	2.01	2.21	2.39	2.65	2.29

Fa = forest plot A, Fb = forest plot B and Fc = forest plot C

^{ns}, * = not significant at $p < 0.05$ and significant at $p < 0.05$ respectively

In each row, means followed by a common letter are not significantly different at $p < 0.05$

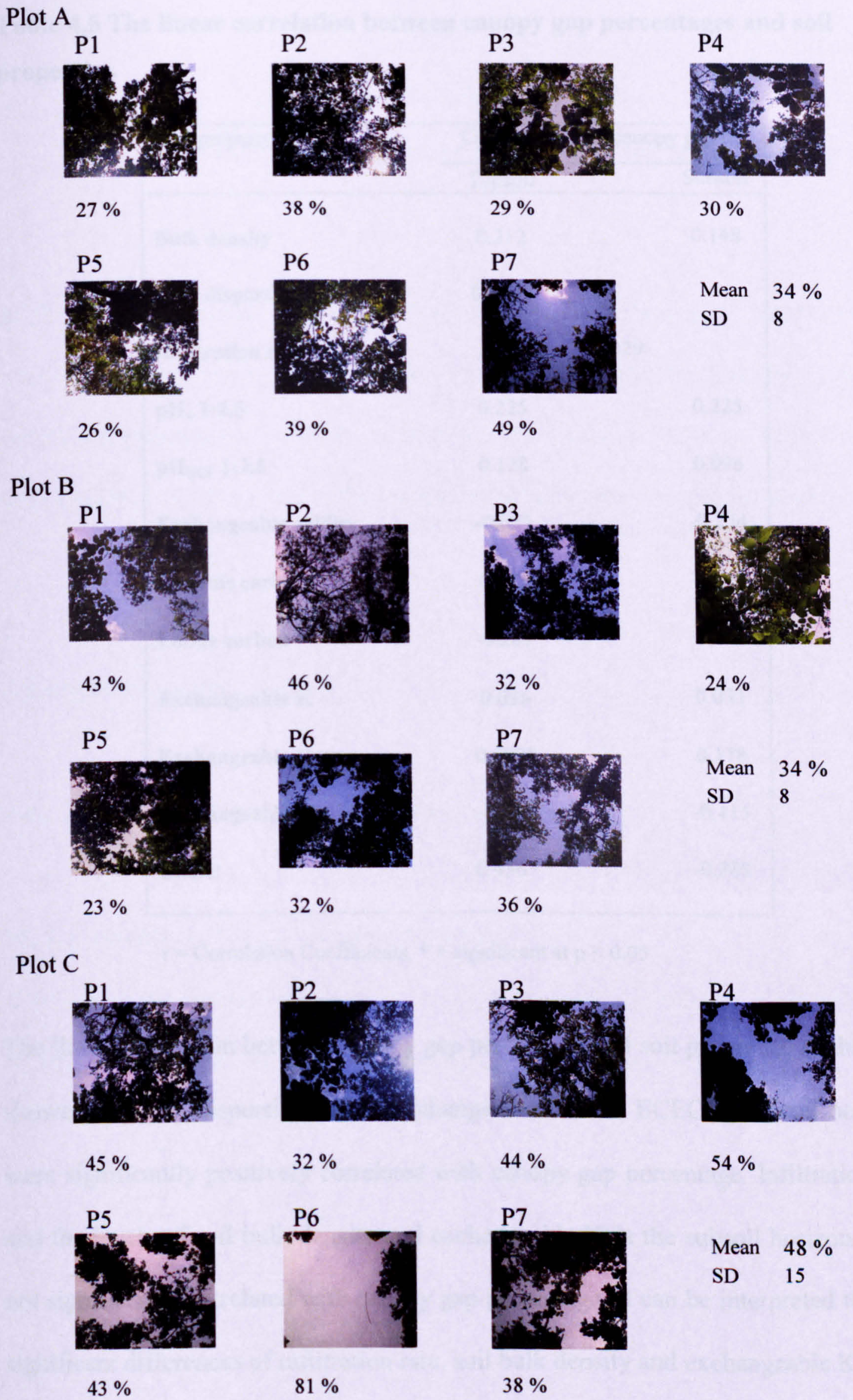


Figure 4.15 The canopy gap percentages of dry Diptercarp forests plots.

Table 4.6 The linear correlation between canopy gap percentages and soil properties.

Soil property (n=21)	Correlation with canopy gap (r)	
	Topsoil	Subsoil
Bulk density	0.312	0.148
Clay dispersion	0.462*	-
Infiltration rate	-0.329	
pH_w 1:2.5	0.225	0.225
pH_{KCl} 1:2.5	0.128	0.096
Exchangeable acidity	-0.087	-0.234
Organic carbon	0.273	-
Labile carbon	-0.287	-
Exchangeable K	0.036	0.031
Exchangeable Ca	0.507*	0.178
Exchangeable Mg	-0.397	-0.115
ECEC	0.436*	-0.288

r = Correlation Coefficients, * = significant at $p < 0.05$

The linear correlation between canopy gap percentage and soil properties (Table 4.6) showed that clay dispersion index, exchangeable Ca and ECEC of topsoil horizons were significantly positively correlated with canopy gap percentage. Infiltration rate and the levels of soil bulk density and exchangeable K in the subsoil horizons were not significantly correlated with canopy gap percentage. It can be interpreted that the significant differences of infiltration rate, soil bulk density and exchangeable K in the subsoil horizons between the FC plot and the FA and FB plots are not the effect of canopy gap percentage.

Chapter 5

Soil Property Changes Under Cassava and Sugarcane Cropping Regimes: Results

In this chapter, changes of soil physical, chemical and biological properties as a result of use for cassava and sugarcane were reported. Presented data also consist of means and medians of soil attributes which were measured in Ah or Ap horizons of soil profiles at 10-15 cm and in the subsoil horizons at 40-45 cm on the study plots.

5.1 Cassava cropping regime

5.1.1 Soil property changes under cassava regime

Measurements on Ah/Ap horizons of soil profiles:

Changes in soil properties over time, based on the measurements on Ah/Ap horizons of soil profiles under forest and cassava regime are shown in Table 5.1 to 5.3.

Table 5.1 Physical properties on the Ah/Ap horizons of soil profiles under forest and cassava regime and changes (Δ) relative to forest as a result of use.

Soil property		F	C1	C2
Bulk density	(Mg m^{-3})	1.46^{ns}	1.50^{ns}	1.50^{ns}
Δ	(Mg m^{-3})	-	0.04	0.04
Magnitude of change	% of F	-	2.7	2.7
Clay dispersion	%	16.9^{ns}	18.9^{ns}	18.8^{ns}
Δ		-	2.0	1.9
Magnitude of change	% of F	-	11.8	11.2

F= Dry Dipterocarp forest, C1 = Cassava 10-20 yrs, C2 = Cassava 20-30 yrs
^{ns} = not significant at $p< 0.05$

Soil bulk density and clay dispersion non-significantly increase at the first 20 years after forest clearance (C1) and reach equilibrium at the later stage (C2).

Table 5.2 Organic carbon and labile carbon on the Ah/Ap horizons of soil profiles under forest and cassava regime and changes (Δ) relative to forest as a result of use.

Soil property		F	C1	C2
Organic carbon	(g kg^{-1})	7.6^{ns}	5.3^{ns}	3.8^{ns}
Δ	(g kg^{-1})	-	-2.3	-3.8
Magnitude of change	% of F	-	-30.3	-50.0
Labile carbon *	(mg kg^{-1})	188.6^{a}	152.4^{ab}	131.4^{b}
Δ	(mg kg^{-1})	-	-36.0	-57.2
Magnitude of change	% of F	-	-19.2	-30.3

F= Dry Dipterocarp forest, C1 = Cassava 10-20 yrs, C2 = Cassava 20-30 yrs
^{ns} = not significant at $p< 0.05$, * = significant at $p< 0.05$
In each row, means followed by a common letter are not significantly different at $p < 0.05$ by Dunett multiple comparisons

Both organic carbon and labile carbon decreased progressively with that for labile carbon being significant after more than 20 years after forest clearance. Although the magnitude of changes in organic carbon are relatively greater than those in labile carbon, the changes is not significant due to larger variation that can be reflected in coefficient of variation (CV) (Table 4.3).

Table 5.3 Chemical properties on the Ah/Ap horizons of soil profiles under forest and cassava regime and changes (Δ) relative to forest as a result of use.

Soil property		F	C1	C2
pH $_w$ 1:2.5		5.9 ^{ns}	5.2 ^{ns}	5.3 ^{ns}
Δ		-	-0.7	-0.6
Magnitude of change	% of F	-	-11.9	-10.2
pH$_{KCl}$ 1:2.5		4.8 ^{ns}	4.4 ^{ns}	4.3 ^{ns}
Δ		-	-0.4	-0.5
Magnitude of change	% of F	-	-8.3	-10.4
Exchangeable K*	($cmol^+ kg^{-1}$)	0.11 ^{a}	0.04 ^{b}	0.03 ^{b}
Δ		-	-0.07	-0.08
Magnitude of change	% of F	-	-63.6	-72.7
Exchangeable Ca	($cmol^+ kg^{-1}$)	1.44 ^{ns}	1.09 ^{ns}	0.86 ^{ns}
Δ		-	-0.35	-0.58
Magnitude of change	% of F	-	-24.3	-40.3
Exchangeable Mg	($cmol^+ kg^{-1}$)	0.66 ^{ns}	0.52 ^{ns}	0.28 ^{ns}
Δ		-	-0.14	-0.38
Magnitude of change	% of F	-	-21.2	-57.6

F= Dry Dipterocarp forest, C1 = Cassava 10-20 yrs, C2 = Cassava 20-30 yrs
^{ns} = not significant at $p< 0.05$, In each row, means followed by a common letter are not significantly different at $p < 0.05$ by Dunett multiple comparisons

Non significant decrease in pH both in water and in KCl were observed particularly in first 20 years of the decreases in all cations, only exchangeable potassium was significant. The significant decreases of exchangeable potassium and non-significant decrease of exchangeable calcium and magnesium can be a reasonable explanation of acidification under cassava regime relative to forest.

Plot scale measurements:

Changes in soil properties over time, based on the plot scale measurements in the cassava plots, are shown in Table 5.4 to 5.7.

Table 5.4 Soil physical properties under forest and cassava regime and changes (Δ) relative to forest as a result of use.

Soil property		Topsoil F	Topsoil C1	Topsoil C2	Subsoil F	Subsoil C1	Subsoil C2
Bulk density	(Mg m^{-3})	1.47^{a}	1.52^{b}	1.54^{b}	1.53^{a}	1.65^{b}	1.58^{ab}
Δ	(Mg m^{-3})	-	0.05	0.07	-	0.12	0.05
Magnitude of change	% of F	-	3.4	4.8	-	7.8	3.3
Clay dispersion	(%)	18.6^{ns}	20.9^{ns}	22.8^{ns}	-	-	-
Δ	(%)	-	2.3	4.2	-	-	-
Magnitude of change	% of F	-	12.4	22.6			
Infiltration rate	(cm hr^{-1})	8.5^{ns}	9.6^{ns}	8.7^{ns}	-	-	-
Δ	(cm hr^{-1})	-	1.1	0.2	-	-	-
Magnitude of change	% of F	-	12.9	2.4	-	-	-

F= Dry Dipterocarp forest, C1 = Cassava 10-20 yrs, C2 = Cassava 20-30 yrs
^{ns} = not significant at $p< 0.05$
Means of soil bulk density in the topsoil horizons followed by a common letter are not significantly different at $p < 0.05$ by Dunett multiple comparisons
Medians of soil bulk density in the subsoil horizons followed by a common letter are not significantly different at $p < 0.05$ by Mood's median test

Generally, soil bulk density in the topsoil horizons is smaller than in the subsoil horizons both under forest and cultivated soils. The significant increases in bulk density levels were observed both in the topsoil and in the subsoil horizons at the early stage (C1) after forest clearance but changes of soil bulk density levels between the C1 and C2 were not significant. The pattern of changes in soil bulk density suggests that soil compaction rapidly occurs at earlier stage when forest is converted to cassava production and no further soil compact occurred. Also clay dispersion tend to increase with time after forest clearance, however, changes of this soil attribute as well as soil infiltration rate which varied inconsistently were not significant.

Table 5.5 Soil reaction under forest and cassava regime and changes (Δ) relative to forest as a result of use.

Soil property		Topsoil			Subsoil		
		F	C1	C2	F	C1	C2
pH_w 1:2.5		5.2 [a]	5.7 [b]	5.5 [b]	4.8 [a]	5.4 [b]	5.8 [b]
Δ		-	0.5	0.3	-	0.6	1.0
Magnitude of change	% of F	-	9.6	5.8	-	12.5	20.8
pH_{KCl} 1:2.5		4.2 [a]	4.7 [b]	4.6 [b]	3.8 [a]	4.2 [b]	4.2 [b]
Δ		-	0.5	0.4	-	0.4	0.4
Magnitude of change	% of F	-	11.8	9.5	-	10.5	10.5
Exchangeable acidity	($cmol^+ kg^{-1}$)	0.40 [a]	0.20 [b]	0.20 [b]	1.30 [a]	0.40 [b]	0.25 [b]
Δ	($cmol^+ kg^{-1}$)	-	-0.20	-0.20	-	-0.90	-1.05
Magnitude of change	% of F	-	50.0	50.0	-	-69.2	80.8

F= Dry Dipterocarp forest, C1 = Cassava 10-20 yrs, C2 = Cassava 20-30 yrs
In each row of each horizon, means followed by a common letter are not significantly different at $p < 0.05$ by Dunett multiple comparisons, Medians of pHw in the subsoil horizon and exchangeable acidity both in the topsoil and the subsoil horizons followed by a common letter are not significantly different at $p < 0.05$ by Mood's median test

The values of pH in water and in KCl solution significantly increased both in the topsoil horizons and in the subsoil horizons relative to forest. These changes can be reflected by the significant decreases in exchangeable acidity and are consistent with the significant increases of exchangeable calcium (Table 5.7). No statistical differences were observed for soil pH between the C1 and the C2 both in the topsoil and the subsoil horizons, indicating that soil pH levels changed most rapidly immediately after clearing, particularly, in the topsoil horizons with longed use. Overall pH values in the topsoil horizons are greater than in the subsoil horizons. Magnitudes of changes in soil reaction in the subsoil horizon are greater than in the topsoil horizons and are consistent with pattern of changes in exchangeable calcium (Table 5.7).

Table 5.6 Organic carbon and labile carbon in the topsoil horizons under forest and cassava regime and changes (Δ) relative to forest as a result of use.

Soil property		F	C1	C2
Organic carbon	(g kg^{-1})	5.9 [a]	5.5 [ab]	4.1 [b]
Δ	(g kg^{-1})	-	-0.4	-1.8
Magnitude of change	% of F	-	-6.8	-30.5
Labile carbon	(mg kg^{-1})	129.9 [a]	109.7 [b]	90.9 [b]
Δ	(mg kg^{-1})	-	-20.2	-39.0
Magnitude of change	% of F	-	-15.6	-30.0

F= Dry Dipterocarp forest, C1 = Cassava 10-20 yrs, C2 = Cassava 20-30 yrs
In each row of each soil horizon, means followed by a common letter are not significantly different at $p < 0.05$ by Dunett multiple comparisons

The content of soil organic carbon decreased at early stage (C1) after forest clearance and this became significant at the later stage (C2) relative to forest, indicating progressively changing pattern. In contrast, labile carbon levels significantly reduced in the C1 relative to forest and changes of labile carbon levels between the C1 and c2 were not significant. The pattern of changes in labile carbon indicates that labile carbon levels rapidly decrease at the earlier stage after forest clearance and both labile and organic carbon continue to decrease, though this was not significant at all stages.

Table 5.7 Exchangeable cation and ECEC under forest and cassava regime and changes (Δ) relative to forest as a result of use.

Soil property		Topsoil F	Topsoil C1	Topsoil C2	Subsoil F	Subsoil C1	Subsoil C2
Exchangeable K	($cmol^+ kg^{-1}$)	0.06^a	0.03^b	0.03^b	0.06^a	0.02^b	0.03^b
Δ	($cmol^+ kg^{-1}$)	-	-0.03	-0.03	-	-0.04	-0.03
Magnitude of change	% of F	-	-50.0	-50.0	-	-66.7	-50.0
Exchangeable Ca	($cmol^+ kg^{-1}$)	0.95^a	1.59^b	1.54^b	0.49^a	1.30^b	0.96^b
Δ	($cmol^+ kg^{-1}$)	-	0.64	0.59	-	0.81	0.47
Magnitude of change	% of F	-	67.4	62.1	-	165.3	95.9
Exchangeable Mg	($cmol^+ kg^{-1}$)	0.54^a	0.49^b	0.42^b	0.66^{ns}	0.56^{ns}	0.62^{ns}
Δ	($cmol^+ kg^{-1}$)	-	-0.05	-0.12	-	-0.10	-0.04
Magnitude of change	% of F	-	-9.1	-21.8	-	-15.2	-6.1
ECEC	($cmol^+ kg^{-1}$)	2.07^{ns}	2.51^{ns}	2.22^{ns}	2.45^{ns}	2.42^{ns}	2.29^{ns}
Δ	($cmol^+ kg^{-1}$)	-	0.44	0.15	-	-0.03	-0.24
Magnitude of change	% of F	-	21.3	7.2	-	-1.2	9.8

F= Dry Dipterocarp forest, C1 = Cassava 10-20 yrs, C2 = Cassava 20-30 yrs
^{ns} = not significant at $p < 0.05$,
In each row of each soil horizon, means followed by a common letter are not significantly different at $p < 0.05$ by Dunett multiple comparisons

The significant decreases of exchangeable potassium both in the topsoil and the subsoil horizons and of exchangeable magnesium in the topsoil horizons were observed at early stage (C1) in cassava production after forest clearance, whereas changes in exchangeable potassium and exchangeable magnesium between the C1 and C2 were not significant. This pattern of changes indicates that exchangeable potassium levels rapidly decrease at the earlier stage after forest clearance and then approach equilibrium stage later on. The pattern of changes of exchangeable magnesium in the topsoil horizons is similar to those of exchangeable potassium but the magnitude of changes was smaller and, more over, changes of exchangeable magnesium in the subsoil horizons were not significant. The results also indicate that losses of exchangeable potassium either by crop removal or leaching are greater than those of exchangeable magnesium.

In contrast, the levels of exchangeable calcium significantly increase both in the topsoil horizons and in the subsoil horizons for the C1 and C2 relative to the F, whereas changes of this cation between the C1 and the C2 both in the topsoil and the subsoil horizons were not significant, indicating that the exchangeable calcium levels markedly increase in early stage after forest clearance, reach equilibrium stage and tend to decline later on. Changes of ECEC levels were not significant both in the topsoil and the subsoil horizons.

5.1.2 Correlation between changes in soil properties and the times after forest clearance

Measurements on Ah/Ap horizons of soil profiles:

The results of simple linear correlations between changes in soil properties on Ah/Ap horizons of soil profiles and time are presented in Table 5.8.

Table 5.8 The linear correlation between changes in soil properties Ah/Ap horizons of soil profiles and the times after forest clearance at the Sakon Nakhon site.

Soil properties (n = 8)	Correlation with time (r)
Bulk density	0.501
Clay dispersion	0.482
pH_w 1:2.5	-0.760*
pH_{KCl} 1:2.5	-0.605
Organic carbon	-0.714*
Labile carbon	-0.850**
Exchangeable K	-0.916***
Exchangeable Ca	-0.466
Exchangeable Mg	-0.757*

r = Correlation Coefficients, p = Probability
* = Significant at $p < 0.05$, ** = Significant at $p < 0.01$,
*** = Significant at $p < 0.001$

Clay content, organic carbon content, labile carbon content, exchangeable potassium and exchangeable magnesium in the Ah/Ap horizons of soil profiles Some soil properties are significantly negatively correlated with time.

Plot scale measurements:

The results of simple linear correlations between changes in soil properties base on plot scale measurements and time after forest clearance are presented in Table 5.9.

Table 5.9 The linear correlation between changes in soil properties base on plot measurements and the times after forest clearance at the Sakon Nakhon site.

<table>
<tr><th rowspan="2">Soil property (n=56)</th><th colspan="2">Correlation with time (r)</th></tr>
<tr><th>Topsoil</th><th>Subsoil</th></tr>
<tr><td>Bulk density</td><td>0.512***</td><td>0.416**</td></tr>
<tr><td>Clay dispersion</td><td>0.282*</td><td>-</td></tr>
<tr><td>Infiltration rate</td><td colspan="2">0.029</td></tr>
<tr><td>pH_w 1:2.5</td><td>0.445**</td><td>0.529***</td></tr>
<tr><td>pH_{KCl} 1:2.5</td><td>0.451***</td><td>0.480***</td></tr>
<tr><td>Exchangeable acidity</td><td>-0.488***</td><td>-0.440**</td></tr>
<tr><td>Organic carbon</td><td>-0.316*</td><td>-</td></tr>
<tr><td>Labile carbon</td><td>-0.574***</td><td>-</td></tr>
<tr><td>Exchangeable K</td><td>-0.686***</td><td>-0.493***</td></tr>
<tr><td>Exchangeable Ca</td><td>0.437**</td><td>0.393**</td></tr>
<tr><td>Exchangeable Mg</td><td>-0.350**</td><td>-0.080</td></tr>
<tr><td>ECEC</td><td>0.172</td><td>-0.103</td></tr>
</table>

r = Correlation Coefficients, p = Probability
* = Significant at $p < 0.05$, ** = Significant at $p < 0.01$,
*** = Significant at $p < 0.001$

Soil bulk densities both in the topsoil and the subsoil horizons and water dispersible clay in the topsoil horizons were significantly positively correlated with time. Soil reaction with the pH values both in water and in KCl solution, exchangeable Ca values, both in the topsoil and the subsoil horizons were also significantly positively correlated with time.

In contrast, soil acidity and exchangeable K, both in the topsoil and the subsoil horizons, organic carbon contents, labile carbon contents and exchangeable Mg in the topsoil horizons were significantly negatively correlated with time.

5.1.3 Soil quality changes under cassava regime

Labile carbon and exchangeable K in the Ah/Ap horizons of soil profile measurements and in the plot scale measurements, organic carbon, labile carbon and exchangeable Mg in topsoil horizons, soil bulk density, pH in water, pH in KCl solution, exchangeable acidity, and exchangeable K and Ca both in topsoil and subsoil horizons were selected to calculate relative soil quality indices (RSQI).

Relative soil quality indices (RSQI) of the forest and cassava plots at the Sakon Nakorn site are presented in Table 5.10.

Table 5.10 Relative soil quality indices (RSQI) of the forest and cassava plots and change (Δ RSQI) relative to forest.

Horizon	F	C1	C2	p
Ah/Ap horizons of soil profiles				
RSQI (%)	93.3[a]	55.5[b]	45.0[b]	0.002
Δ RSQI	-	- 37.8	- 48.3	
Magnitude of change (% of F)	-	- 40.5	-51.8	
Plot scale measurements				
Topsoil (10-15cm)				
RSQI (%)	82.2[a]	76.8[ab]	70.9[b]	0.004
Δ RSQI	-	- 5.4	- 11.3	
Magnitude of change (% of F)	-	-6.5	-13.7	
Subsoil (40-45cm)				
RSQI (%)	82.5[a]	74.2[b]	76.3[b]	0.004
Δ RSQI	-	- 8.3	- 6.2	
Magnitude of change (% of F)	-	- 10.0	-7.5	

p = probability
Δ RSQI = Relative soil quality index of the C1 or the C2 – those of deciduous forest (F)

In Ah/Ap measurements, the significant decreases in RSQI levels were observed at the early stage (C1) after forest clearance but changes of RSQI levels between the C1 and C2 were not significant. The pattern of changes indicates that RSQI levels rapidly decrease at the earlier stage after forest clearance and then approach equilibrium later on. Similarly, this pattern of changes was also observed in the subsoil horizons of plot scale measurement. In contrast, in plot scale measurements, RSQI levels decreased non significant in the C1 and significantly decrease in the C2 relative to the F, suggesting progressive change pattern of RSQI levels in the topsoil horizons.

The magnitudes of ΔRSQI were greater in the upper horizons than in the lower horizons. An increase of ΔRSQI between the C1 and the C2 indicated the further degradation of soil quality in each soil horizon. The greater magnitudes of ΔRSQI indicated more severe degrees of soil quality deterioration.

Inaddition, the results showed that overall soil quality deterioration at all depths of the study and the pattern of changes was consistent with the key individual indicators, which could be demonstrated by the linear correlation between RSQI values and soil properties (Table 5.11 and 5.12).

Table 5.11 The linear correlation between soil properties and the RSQI values in Ah/Ap horizons of soil profiles under forest and cassava regime.

Soil properties	Correlation with RSQI (r)
Bulk density	-0.638
Clay dispersion	-0.567
pH_w 1:2.5	0.740*
pH_{KCl} 1:2.5	0.561
Organic carbon	0.594
Labile carbon	0.862**
Exchangeable K	0.973***
Exchangeable Ca	0.408
Exchangeable Mg	0.668

r = Correlation Coefficients, p = Probability
* = Significant at $p < 0.05$, ** = Significant at $p < 0.01$
*** = Significant at $p < 0.001$

In Ah/Ap horizons of soil profiles, pH in water values, labile carbon and exchangeable potassium are positively significantly correlated with RSQI value.

Table 5.11 The linear correlation between soil properties and the RSQI values base on plot scale measurements under forest and cassava regime.

Soil property	Correlation with RSQI (r)	
	Topsoil	Subsoil
Bulk density	-0.525***	-0.287*
Clay dispersion	-0.452***	-
Infiltration rate	0.023	
pH_w 1:2.5	0.146	-0.012
pH_{KCl} 1:2.5	0.239*	0.071
pH_{KCl} 1:2.5		
Exchangeable acidity	-0.037	0.114
Organic carbon	0.394**	-
Labile carbon	0.677***	-
Exchangeable K	0.710***	0.943***
Exchangeable Ca	-0.024	-0.175
Exchangeable Mg	0.628***	0.371**
ECEC	0.266*	0.118

r = Correlation Coefficients, p = Probability
* = Significant at $p < 0.05$, ** = Significant at $p < 0.01$
*** = Significant at $p < 0.001$

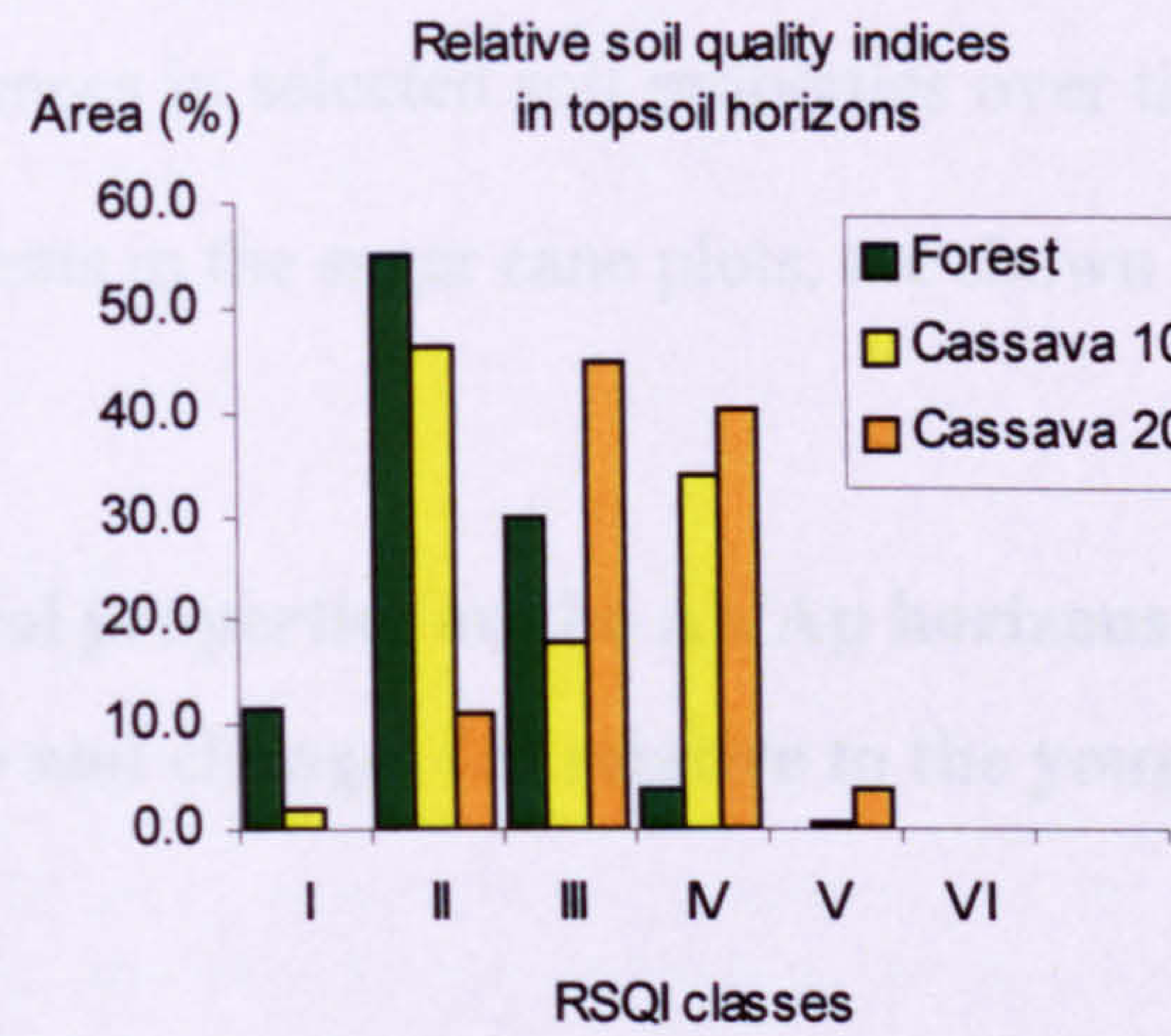
Soil bulk densities both in the topsoil and the subsoil horizons and water dispersible clay in the topsoil horizons were significantly negatively correlated with the RSQI values. In contrast, soil reaction with the pH values in KCl solution, organic carbon, labile carbon and ECEC in the topsoil horizons as well as exchangeable potassium and magnesium both in topsoil and subsoil horizons were significantly positively correlated with the RSQI values.

In contrast, soil acidity and exchangeable K, both in the topsoil and the subsoil horizons, organic carbon contents, labile carbon contents and exchangeable Mg in the topsoil horizons were significantly negatively correlated with time.

The relative soil quality indices (RSQI) classes in the topsoil horizons of the forest plots and cassava plots (50 x 50 m) are presented in Table A-1 in Appendix II. These results show that soil quality classes changed in the cassava plots when compared with the forest plots. Although the C1 plots had the same level of RSQI classes (class I-IV), the percentage of class I decreased from 11.2 % to 1.8 % and that of class IV increased from 4 % to 34 %. Whereas, in the C2 plots, soil quality classes changed markedly when compare with forest plots, there was no RSQI class I, and 85.6 % of total area was RSQI class III and IV (Figure 5.1a).

The results in subsoil horizons (Table A-2 in Appendix II) also show that soil quality classes changed markedly in the cassava plots when compared with the forest plots. The C1 and C2 plots had RSQI classes I-IV, whereas RSQI classes I-III were found in the forest plots. Moreover the percentage of class I decreased from 19.3 % to 1.5 and 1.6 % and that of class II decreased from 36.1 to 6.6 % and 21.1% for the C1 and C2 plots (Figure 5.1 b)

A decrease of high quality class, or an increase of low quality class, in older cassava plots, clearly indicates that progressive soil degradation has occurred under cassava cultivation after forest clearance.



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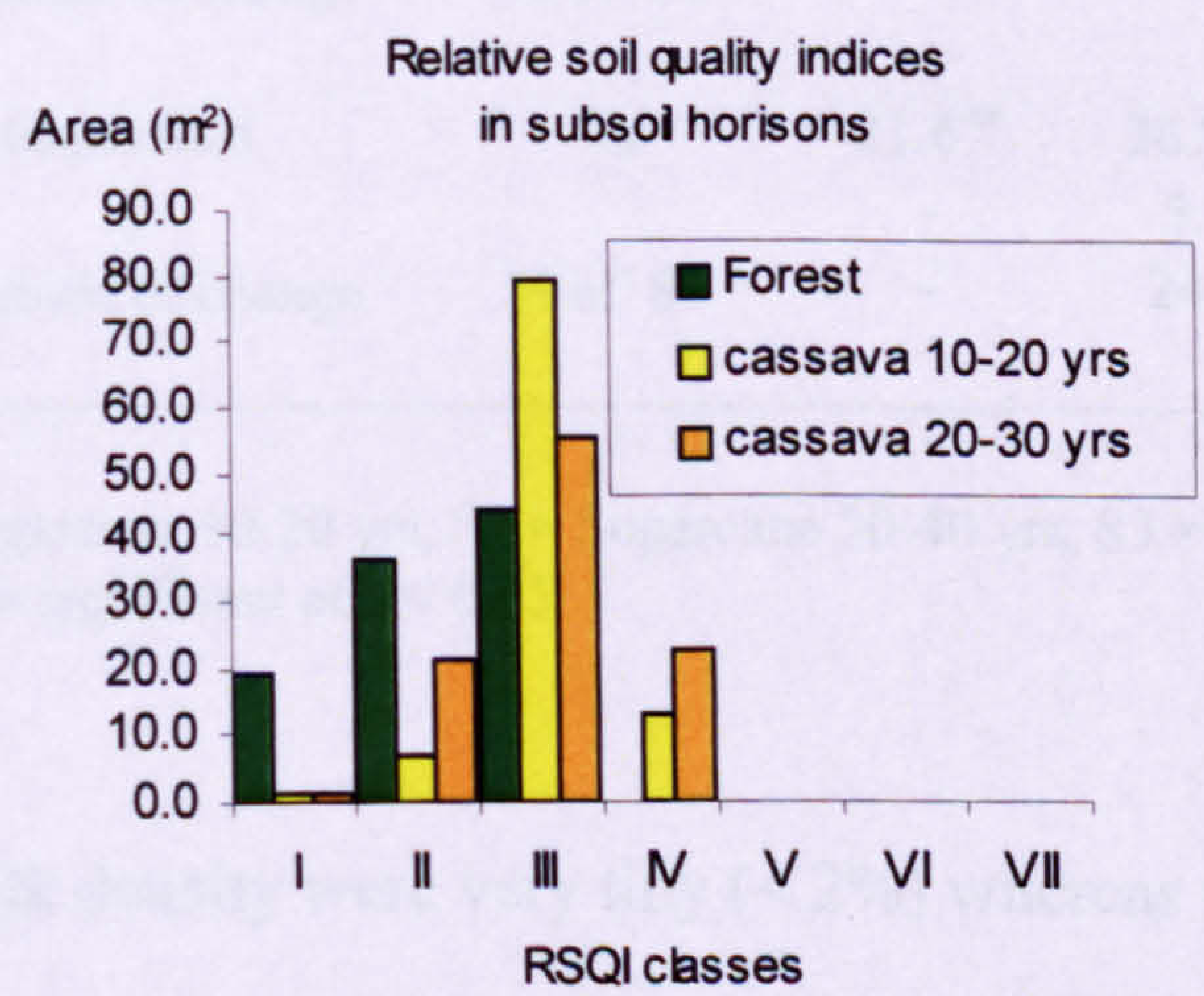


b.

Figure 5.1 Distribution of relative soil quality index (RSQI) classes under the forest and cassava regime.

5.2 Sugarcane cropping regime

5.2.1 Soil property changes under sugarcane regime

Soil profile measurements:

Significant differences in selected soil properties over time, based on the modal soil profile measurements in the sugar cane plots, are shown in Table 5.13 to 5.15.

Table 5.13 Physical properties on the Ah/Ap horizons of soil profiles under sugarcane regime and changes (Δ) relative to the youngest sugarcane plots (S1) as a result of use.

Soil property		S1	S2	S3
Bulk density	($Mg\ m^{-3}$)	1.48^{ns}	1.50^{ns}	1.50^{ns}
Δ	($Mg\ m^{-3}$)	-	0.02	0.02
Magnitude of change	% of S1	-	1.3	1.3
Clay dispersion	%	21.6^{ns}	26.9^{ns}	25.1^{ns}
Δ		-	5.3	3.5
Magnitude of change	% of S1	-	24.5	16.2

S1= Sugarcane 10-20 yrs, S2 = Sugarcane 30-40 yrs, S3 = Sugarcane 40-50 yrs
^{ns} = not significant at $p < 0.05$

Changes in soil bulk density were very tiny (< 2%) whereas clay dispersion markedly increased but was not significant.

Table 5.14 Organic carbon and labile carbon in the Ah/Ap horizons of soil profiles under sugarcane regime and changes (Δ) relative to the youngest sugarcane plots (S1) as a result of use.

Soil property		S1	S2	S3
Organic carbon	(g kg^{-1})	3.9^{ns}	3.2^{ns}	1.9^{ns}
Δ	(g kg^{-1})	-	-0.7	-2.0
Magnitude of change	% of S1	-	-17.9	-51.3
Labile carbon *	(mg kg^{-1})	127.5^{a}	94.7^{b}	87.2^{b}
Δ	(mg kg^{-1})	-	-32.8	-40.3
Magnitude of change	% of S1	-	-25.7	-31.6

S1= Sugarcane 10-20 yrs, S2 = Sugarcane 30-40 yrs, S3 = Sugarcane 40-50 yrs
^{ns} = not significant at $p < 0.05$, * = significant at $p< 0.05$
In each row, means followed by a common letter are not significantly different at $p < 0.05$ by Dunett multiple comparisons

The content of labile carbon significantly decreased in S2 and S3 relative to the S1. There was no significant change in labile carbon content between the S2 and S3 but the magnitudes of changes were continuous decrease, suggesting the progressive decline in labile carbon under sugarcane regime and also organic carbon continue to decrease, though this was not significant due to large variation and small replication (Table 4.3.).

Table 5.15 Chemical properties in the Ah/Ap horizons of soil profiles under sugarcane regime and changes (Δ) relative to the youngest sugarcane plots (S1) as a result of use.

Soil property		S1	S2	S3
pH_w 1:2.5 ^{ns}		5.5 ^{ns}	4.8 ^{ns}	4.9 ^{ns}
Δ		-	-0.7	-0.6
Magnitude of change	% of S1	-	-12.7	-10.9
pH_{KCl} 1:2.5 ^{ns}		4.7 ^{ns}	4.0 ^{ns}	3.9 ^{ns}
Δ		-	-0.7	-0.8
Magnitude of change	% of S1	-	-14.8	-17.0
Exchangeable K	($cmol^+ kg^{-1}$)	0.05 ^{ns}	0.04 ^{ns}	0.08 ^{ns}
Δ	($cmol^+ kg^{-1}$)	-	-0.01	0.03
Magnitude of change	% of S1	-	-20.0	60.0
Exchangeable Ca	($cmol^+ kg^{-1}$)	0.89 ^{a}	0.33 ^{b}	0.13 ^{b}
Δ	($cmol^+ kg^{-1}$)	-	-0.56	-0.76
Magnitude of change	% of S1	-	-62.9	-85.4
Exchangeable Mg	($cmol^+ kg^{-1}$)	0.25 ^{a}	0.06 ^{b}	0.09 ^{b}
Δ	($cmol^+ kg^{-1}$)	-	-0.19	-0.16
Magnitude of change	% of S1	-	-76.0	-64.0

S1= Sugarcane 10-20 yrs, S2 = Sugarcane 30-40 yrs, S3 = Sugarcane 40-50 yrs
^{ns} = not significant at $p< 0.05$, * = significant at $p< 0.05$
In each row, means followed by a common letter are not significantly different at $p < 0.05$ by Dunett multiple comparisons

The non significant decreases in soil pH (Table 5.15) were observed particularly after more than 20 years of land use. Soil exchangeable potassium values were very small and changed non significantly because of large variation and small replication, whereas progressive decreases in exchangeable calcium were significant and exchangeable magnesium values significantly fell quickly to small values.

Plot scale measurements:

Changes in soil properties over time, based on the plot scale measurements in the sugarcane plots, are shown in Table 5.16 to 5.19.

Table 5.16 Soil physical properties under sugarcane regime and changes (Δ) relative to the youngest sugarcane plot (S1) as a result of use.

Soil property		Topsoil			Subsoil		
		S1	S2	S3	S1	S2	S3
Bulk density	(Mg m^{-3})	1.52 ^{ns}	1.51 ^{ns}	1.51 ^{ns}	1.62 ^{ns}	1.65 ^{ns}	1.67 ^{ns}
Δ	(Mg m^{-3})	-	-0.01	-0.01	-	0.03	0.05
Magnitude of change	% of S1	-	-0.7	-0.7	-	1.9	3.1
Clay dispersion	(%)	20.1^{a}	21.6^{a}	27.4^{b}	-	-	-
Δ		-	1.5	7.3	-	-	-
Magnitude of change	% of S1	-	7.4	36.3	-	-	-
Infiltration rate	(cm hr^{-1})	5.1 ^{ns}	6.8 ^{ns}	4.9 ^{ns}	-	-	-
Δ	(cm hr^{-1})	-	1.7	-0.2	-	-	-
Magnitude of change	% of S1	-	33.3	-3.9	-	-	-

S1= Sugarcane 10-20 yrs, S2 = Sugarcane 30-40 yrs, S3 = Sugarcane 40-50 yrs
^{ns} = not significant at $p < 0.05$
Means of clay dispersion in the topsoil horizons followed by a common letter are not significantly different at $p < 0.05$ by Dunett multiple comparisons

Generally under sugarcane regime, soil bulk density in the topsoil horizons is smaller than in the subsoil horizons, suggesting that soil compaction is more severe in the subsoil horizons (Table 5.16). No significant changes in bulk density with duration of use were observed either in the topsoil or in the subsoil horizons. The pattern of changes indicates that no further soil compact occurs either in the topsoil or subsoil horizons, which can be reflected by no significant changes in soil infiltration rate. A small non significant increase in clay dispersion was observed in S2 relative to the youngest sugarcane plots (S1) and a significant increase of this soil attribute was found in the oldest sugarcane plots (S3) when compared with the S1 and S2.

Table 5.17 Soil reaction under sugarcane regime and changes (Δ) relative to the youngest sugarcane plot (S1) as a result of use.

Soil property		Topsoil S1	Topsoil S2	Topsoil S3	Subsoil S1	Subsoil S2	Subsoil S3
pH_w 1:2.5		5.9^{a}	5.3^{b}	4.9^{c}	5.8^{a}	5.3^{b}	5.0^{c}
Δ		-	-0.6	-1.0	-	-0.5	-0.8
Magnitude of change	% of S1	-	10.2	16.9	-	-8.64	-13.8
pH_{KCl} 1:2.5		4.9^{a}	4.0^{b}	3.9^{b}	4.5^{a}	4.0^{b}	3.9^{b}
Δ		-	-0.9	-1.0	-	-0.5	-0.6
Magnitude of change	% of S1	-	-18.4	-20.4	-	-11.9	-13.4
Exchangeable acidity	($cmol^{+}kg^{-1}$)	0.15^{a}	0.40^{b}	0.39^{b}	0.30^{a}	0.45^{ab}	0.83^{b}
Δ		-	0.25	0.24	-	0.15	0.53
Magnitude of change	% of S1	-	166.7	160.0	-	50.0	176.7

S1= Sugarcane 10-20 yrs, S2 = Sugarcane 30-40 yrs, S3 = Sugarcane 40-50 yrs
In each row of each soil horizon, means of followed by a common letter are not significantly different at $p < 0.05$ by Dunett multiple comparisons
Medians of pH in water and in KCl in the topsoil horizons and exchangeable acidity in the subsoil horizons followed by a common letter are not significantly different at $p < 0.05$ by Mood's median test

The values of pH in water and in KCl solution significantly decrease both in the topsoil horizons and in the subsoil horizons relative to the S1. These changes can be reflected by the significant increase in exchangeable acidity. A progressively decreasing pattern in magnitudes of changes in soil pH in water and in KCl solution, which were not significant between the S2 and S3, indicates that soil acidification continue to increase under sugarcane regime.

Table 5.18 Organic carbon and labile carbon in the topsoil horizons under sugarcane regime and changes (Δ) relative to the youngest sugarcane plots (S1) as a result of use.

Soil property		S1	S2	S3
Organic carbon	($g\ kg^{-1}$)	3.2 [a]	2.6 [a]	1.5 [b]
Δ	($g\ kg^{-1}$)	-	-0.6	-1.7
Magnitude of change	% of S1	-	-18.5	-53.1
Labile carbon	($mg\ kg^{-1}$)	84.7 [a]	65.4 [a]	52.2 [b]
Δ	($mg\ kg^{-1}$)	-	-19.3	-33.5
Magnitude of change	% of S1	-	-22.7	-38.4

S1= Sugarcane 10-20 yrs, S2 = Sugarcane 30-40 yrs, S3 = Sugarcane 40-50 yrs
In each row, means of clay dispersion in the topsoil horizons followed by a common letter are not significantly different at $p < 0.05$ by Dunett multiple comparisons

The content of soil organic carbon and labile carbon decreased in S2 and this became significant at the S3 relative to the S1, indicating a progressively changing pattern. Both organic carbon and labile carbon continue to decrease, though this was not significant at all stages.

Table 5.19 Exchangeable cation and ECEC under sugarcane regime and changes (Δ) relative to the youngest sugarcane plot (S1) as a result of use.

Soil property		Topsoil S1	Topsoil S2	Topsoil S3	Subsoil S1	Subsoil S2	Subsoil S3
Exchangeable K	($cmol^+ kg^{-1}$)	0.04 ^{a}	0.03 ^{b}	0.03 ^{b}	0.04 ^{ns}	0.05 ^{ns}	0.04 ^{ns}
Δ	($cmol^+ kg^{-1}$)	-	-0.01	-0.01	-	0.01	0.0
Magnitude of change	% of S1	-	-25.0	-25.0	-	25.0	0.0
Exchangeable Ca	($cmol^+ kg^{-1}$)	1.34 ^{a}	0.42 ^{b}	0.34 ^{b}	0.92 ^{a}	1.22 ^{b}	0.94 ^{a}
Δ	($cmol^+ kg^{-1}$)	-	-0.92	-1.00	-	0.30	0.02
Magnitude of change	% of S1	-	- 68.7	-74.6	-	32.6	2.2
Exchangeable Mg	($cmol^+ kg^{-1}$)	0.30 ^{a}	0.10 ^{b}	0.09 ^{b}	0.82 ^{a}	0.43 ^{b}	0.52 ^{b}
Δ	($cmol^+ kg^{-1}$)	-	0.20	0.21	-	-0.39	-0.30
Magnitude of change	% of S1	-	-66.7	-70.0	-	-47.6	-36.6
ECEC	($cmol^+ kg^{-1}$)	1.89 ^{a}	0.96 ^{b}	0.92 ^{b}	2.21 ^{ns}	2.33 ^{ns}	2.42 ^{ns}
Δ	($cmol^+ kg^{-1}$)	-	-0.93	-0.97	-	0.12	0.21
Magnitude of change	% of S1	-	-49.2	-51.3	-	5.4	9.5

S1= Sugarcane 10-20 yrs, S2 = Sugarcane 30-40 yrs, S3 = Sugarcane 40-50 yrs
^{ns} = not significant at $p < 0.05$
In each row of each soil horizon, means of followed by a common letter are not significantly different at $p < 0.05$ by Dunett multiple comparisons
Medians of exchangeable potassium and magnesium in the topsoil horizons followed by a common letter are not significantly different at $p < 0.05$ by Mood's median test

The significant decreases of exchangeable cations and ECEC in the topsoil horizons as well as exchangeable magnesium in the subsoil horizons were observed in the S2 and S3 relative to the S1. Changes of these soil properties between the S2 and S3 were not significant. This pattern of changes indicates that exchangeable cations and ECEC in the topsoil horizons and also exchangeable magnesium in the subsoil horizons rapidly decrease at the earlier stage relative to the S1 and then approach equilibrium. Whereas in the subsoil horizons, a significant change of exchangeable calcium was inconsistent and changes of exchangeable potassium and ECEC were not significant. The significant decreases of exchangeable cations either by crop removal or leaching can be one of the factors that contribute the increase of acidification under sugarcane regime (Table 5.17).

5.2.2 Correlation between changes in soil properties and the time of use under sugarcane regime

Measurements on Ap horizons of soil profiles:

The results of simple linear correlations between changes in soil properties in Ap horizons of soil profiles and time of use under sugarcane are presented in Table 5.20.

Table 5.20 The linear correlation between changes of soil properties in Ap horizons for soil profiles and time of use uder sugarcane at Udon Thani site.

Soil properties (n = 8)	Correlation with time (r)
Bulk density	0.215
Clay dispersion	0.595
pH_w 1:2.5	-0.714*
pH_{KCl} 1:2.5	-0.743*
Organic carbon	-0.723*
Labile carbon	-0.890**
Exchangeable K	0.020
Exchangeable Ca	-0.848**
Exchangeable Mg	-0.818*

r = Correlation Coefficients
p = Probability
* = Significant at $p < 0.05$, ** = Significant at $p < 0.01$

Soil reaction with pH in water and pH in KCl solution, organic carbon content, labile carbon content, exchangeable Ca and Mg, in the Ap horizons of the modal soil profiles were significantly negatively correlated with time.

Plot scale measurements:

The results of simple linear correlations between changes in soil properties base on plot scale measurements and time of use under sugarcane regime are presented in Table 5.21.

Table 5.21 The linear correlation between changes of soil properties in Ap horizons for soil profiles and time of use uder sugarcane at Udon Thani site.

Soil property (n = 56)	Correlation with time (r)	
	Topsoil	Subsoil
Bulk density	-0.083	0.302*
Clay dispersion index	0.408**	-
Infiltration rate	-0.059	
pH_w 1:2.5	-0.842***	-0.628***
pH_{KCl} 1:2.5	-0.818***	-0.590***
Exchangeable acidity	0.734***	0.409**
Organic carbon	-0.573***	-
Labile carbon	-0.516***	-
Exchangeable K	-0.446***	-0.056
Exchangeable Ca	-0.750***	0.161
Exchangeable Mg	-0.648***	-0.536***
ECEC	-0.697***	0.165

r = Correlation Coefficients
p = Probability
* = Significant at $p < 0.05$, ** = Significant at $p < 0.01$
*** = Significant at $p < 0.001$

Soil bulk densities in the subsoil horizons and water dispersible clay in the topsoil horizons, exchangeable acidity both in topsoil and subsoil horizons were significantly positively correlated with time. In contrast, soil pH values both in water and in KCl solution, exchangeable Mg values, both in the topsoil and the subsoil horizons, organic carbon content, labile carbon content, exchangeable K and Ca, and effective CEC in the topsoil horizons were significantly negatively correlated with time.

Soil variables that changed significantly both in magnitude (section 5.2.1) and over time were selected as sensitive individual indicators for assessing soil degradation, namely, labile carbon, exchangeable Ca and Mg in the Ap horizons of soil profiles. In the plot scale measurements, selected indicators were: clay dispersion index, organic carbon, labile carbon, exchangeable K and Ca, effective CEC in topsoil horizons, pH in water, pH in KCl solution, exchangeable acidity, and exchangeable Mg both in topsoil and subsoil horizons.

5.2.3 Soil quality changes under sugarcane regime

Relative soil quality indices (RSQI) of the sugarcane soils at the Udon Thani study site are presented in Table 5.22.

Table 5.22 Relative soil quality indices (RSQI) of the sugarcane plots and change (Δ RSQI) relative to the youngest sugarcane plots (S1).

Horizons	S1	S2	S3	p
Ap horizons of soil profiles				
RSQI (%)	83.0 [a]	37.7 [b]	32.5 [b]	0.007
Δ RSQI	-	- 45.3	- 50.5	
Magnitude of change (% of S1)	-	- 54.6	- 60.8	
Plot scale measurements				
Topsoil (10-15cm)				
RSQI (%)	69.0 [a]	49.0 [b]	41.0 [b]	0.000
Δ RSQI	-	- 20.0	- 28.0	
Magnitude of change (% of S1)	-	- 28.9	- 40.6	
Subsoil (40-45cm)				
RSQI (%)	80.7 [a]	59.7 [b]	60.6 [b]	0.000
Δ RSQI	-	-21.0	-20.1	
Magnitude of change (% of S1)	-	- 26.0	- 24.9	

p = Probability
Δ RSQI = Soil quality index of the S2 or the S3 – those of S1

Significant decreases of RSQI levels were observed in the S2 and S3 relative to the S1 in all aspects of measurements. Changes of RSQI levels between the S2 and S3 were not significant. This pattern of changes indicates that soil quality rapidly decrease at the earlier stage as a result of use and then approach equilibrium.

The magnitudes of changes in RSQI values were greater in the upper horizons than in the lower horizons. An increase of magnitude of changes in RSQI values between the S1 and the S2 indicates further degradation of soil quality in each soil horizon. The greater magnitudes of changes in RSQI values indicate greater severity of soil quality deterioration.

In addition, the results also showed that overall soil quality deteriorates over time at all depths studied, and that the pattern of changes was consistent with the key individual indicators, as demonstrated by the linear correlation between RSQI values and soil properties (Table 5.23 and 5.24).

Table 5.23 The linear correlation between soil properties and the RSQI values in Ap horizons of soil profiles under sugarcane.

Soil properties	Correlation with RSQI (r)
Bulk density	-0.313
Clay dispersion	-0.765*
pH_w 1:2.5	0.899**
pH_{KCl} 1:2.5	0.937**
Organic carbon	0.589
Labile carbon	0.901**
Exchangeable K	0.306
Exchangeable Ca	0.959***
Exchangeable Mg	0.975***

r = Correlation Coefficients, p = Probability
* = Significant at $p < 0.05$, ** = Significant at $p < 0.01$
*** = Significant at $p < 0.001$

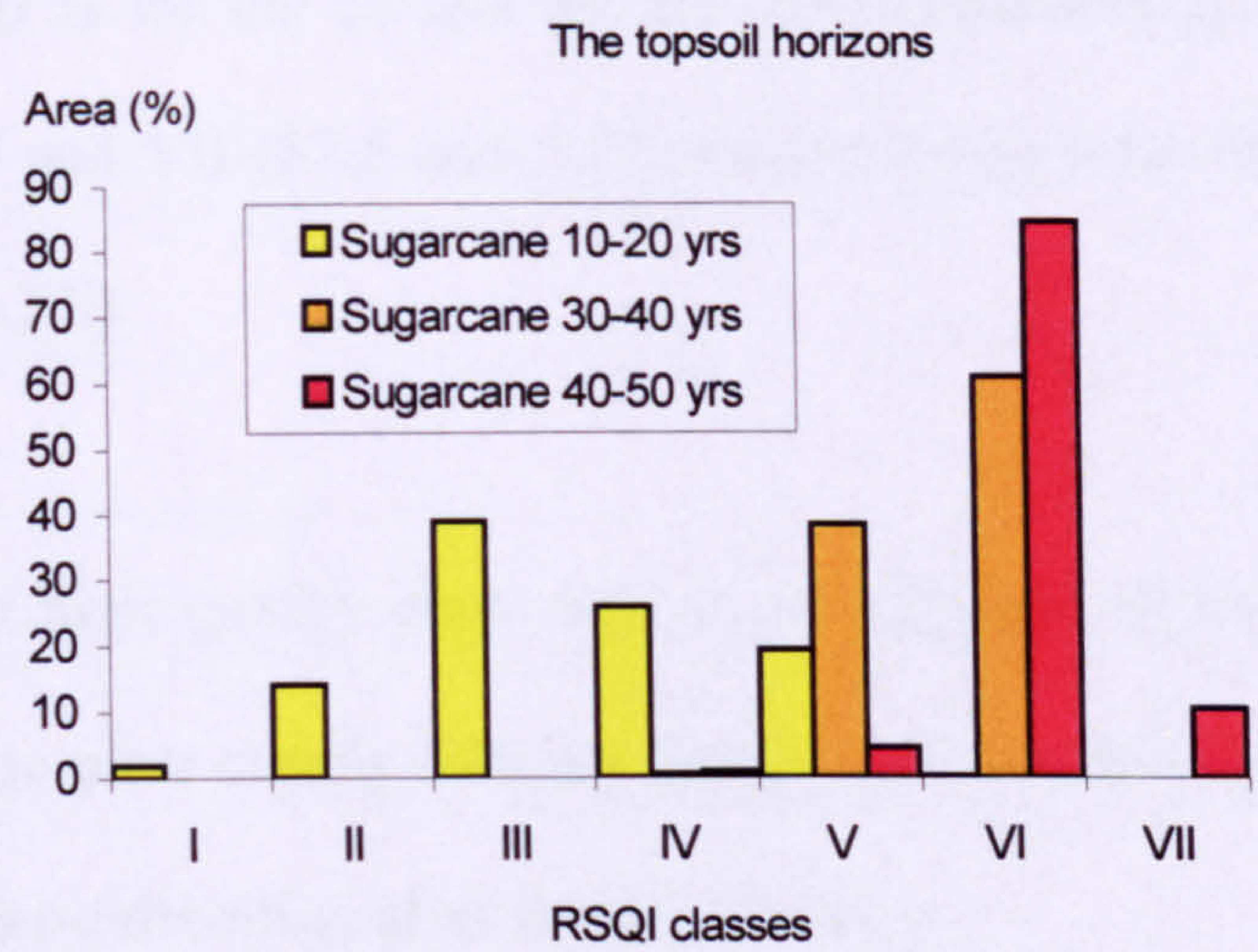
In Ap horizons of soil profiles, a significantly negative correlation between clay dispersion and the RSQI values was observed. In contrast, pH in water and in KCl values, labile carbon and exchangeable calcium and magnesium are significantly positively correlated with RSQI value.

Table 5.24 The linear correlation between soil properties and the RSQI values base on plot scale measurement under sugarcane.

Plot scale measurement	Correlation with time (r)	
	Topsoil	Subsoil
Bulk density	0.176	0.043
Clay dispersion index	-0.447**	-
Infiltration rate	0.024	
pH_w 1:2.5	0.797***	0.465***
pH_{KCl} 1:2.5	0.788***	0.453***
Exchangeable acidity	-0.652***	-0.306*
Organic carbon	0.763***	-
Labile carbon	0.699***	-
Exchangeable K	0.678***	0.023
Exchangeable Ca	0.890***	-0.007
Exchangeable Mg	0.832***	0.953***
ECEC	0.901***	0.272*

r = Correlation Coefficients, p = Probability
* = Significant at $p < 0.05$, ** = Significant at $p < 0.01$
*** = Significant at $p < 0.001$

The relative soil quality indices (RSQI) classes in the topsoil horizons of the sugarcane plots (50 x 50 m) are presented in Table A-3 and A-4 in Appendix II. These results show that soil quality classes changed markedly over time since forest clearance in the sugarcane plots. There were no RSQI class I – III in the older plots (S2 and S3 plots) which RSQI classes were mostly in class VI (60.9 and 84.5 % for S2 and S3 plots respectively). Moreover, the greatest area of RSQI class VII (10.3 %) was found in the oldest (S3) plots. These evidences clearly show the progressive degradation of soil quality in the topsoil horizons of the sugarcane regime (Figure 5.2 a).



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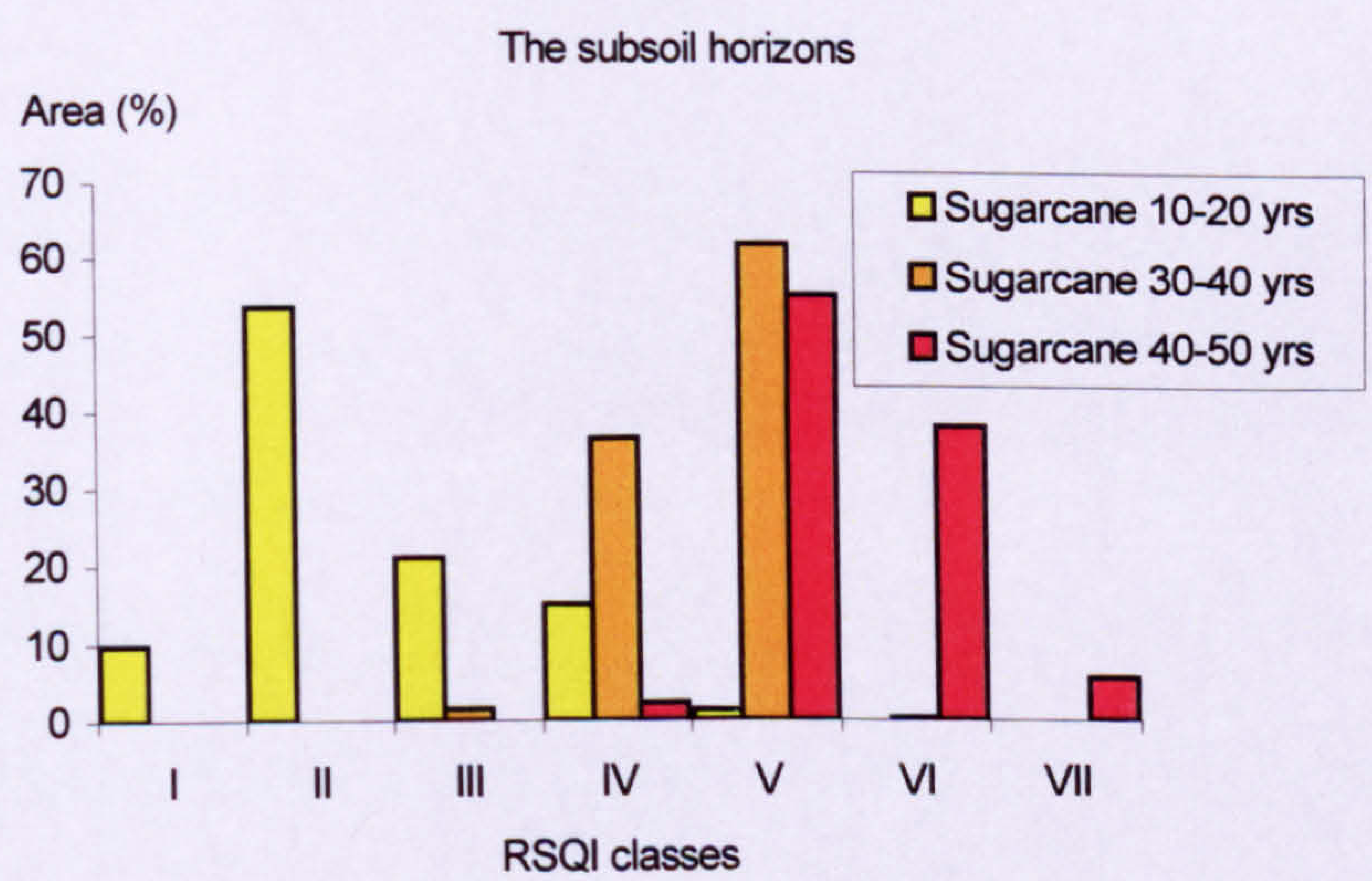

b.

Figure 5.2 Distribution of relative soil quality index (RSQI) classes under sugarcane regime.

The results also show that soil quality classes changed markedly in the subsoil horizons of the sugarcane over time. There were no RSQI class I – II in the S2 plots and no RSQI class I – III in the S3 plots, with RSQI classes falling mainly in class V (61 .8 and 55.0 % for the S2 and the S3 plots respectively). Moreover, the area of RSQI class VI and VII (37.6 and 5.2% respectively) were found in the oldest (S3) plots (Figure 5.2 b).

A decrease of high quality class area, or an increase of low quality class area in older sugarcane plots clearly indicate that progressive soil degradation has occurred under sugarcane cultivation after forest clearance.

Chapter 6

Discussion

There is substantial evidence from recent research that land use change from natural forest to agriculture in the tropics has lead to soil degradation, as demonstrated in Chapter 2 of this thesis. In Thailand, soil degradation following forest clearance for crop production is particularly evident in the North East where Ultisols with weakly structured sandy surface soils overlie clay-enriched subsoil (argillic or kandic) horizons (Vityakon, 1991; Ota *et al.*, 1992; Vityakon *et al.*, 2000a; Tangtrakarnpong and Vityakon, 2002).

The soil morphological investigations and accompanying soil profile analyses reported in this thesis confirm that all of the soils investigated have sandy to coarse loamy, weakly structured surface horizons, often with subsurface pale brown eluvial E horizons of similar texture, overlying clay-enriched subsoil Bt and Btg horizons. It is clear from the results outlined in Section 4.3, and given in more detail in Appendix I, that only some of the soils investigated would be classed as Oxyaquic Kandiustults, as evidence of redoximorphic features in the form of mottles occurs both just above and below the critical 100cm depth. However, in all profiles except Profile C2c (see Appendix I), Btg horizons were present at some depth between 100-150 cm indicating some degree of drainage impedance at that depth. This probably explains the use of the (Oxyaquic) qualification in brackets used in the Thai National Soil Survey descriptions and publications.

It was postulated in Chapter 1 that forest clearance and the subsequent utilization of these Kandiustults for cassava and sugarcane production is leading to soil degradation. The results presented in Chapter 4 and 5 generally support this hypothesis and are discussed below.

6.1 Soil erosion

Evidence for soil degradation that supports the statement above is confirmed by observations of soil erosion in the field study plots and their surroundings reported in Chapter 4 and from farmer responses given in key informant interviews (Chapter 4, Section 4.2.2). The observed evidence of annual fires, soil surface crust formation, soil pedestals left after sheet and rill erosion, and particle sorting in micro-depressions in the soil surface in these forest plots suggests that soil erosion of Ultisols is already active when they are still under dry Dipterocarp forest in this region. Dry Dipterocarp forest is a deciduous forest type that has an open canopy and the trees shed their leaves in the hot dry season. Annual fires in the dry season are common and these frequently burn forest floor litter, resulting in patches of exposed soil. The impact of rainfall on the dry surface soils at the beginning of the rainy season is thus maximized, leading to inter-rill and rill erosion that forms the erosion features recorded from my research plots under forest. The organic carbon content under forest showed relatively high variability with coefficient of variation of 54.2 % (Table 4.4). The variable impact of annual fires on the destruction of organic matter in surface horizons of the forest plot soils is a possible cause of this phenomenon. It can further be argued that the smaller soil organic matter contents of the more severely burnt areas would result in decreased soil aggregate stability and, thereby, an increased incidence of rain drop impact and soil erosion by water contributing to the erosion features recorded.

Similar effects of burning on soil erosion under dry Diptercarp forest in the region have been reported by Sakurai and Tanaka (1998). Soil loss under dry Dipterocarp forest in the region ranges from 5 Mg $ha^{-1}yr^{-1}$ to more than 150 Mg $ha^{-1}yr^{-1}$ depending on degree of the slope (Sriwongsa, 1994; Vityakon *et al.*, 2000). It is debateable whether the high frequency of soil erosion features observed in the forest plots of the current study is a natural phenomenon related to the climatic regime and the growth habits of the forest, or whether this is aggravated by disturbance of the forest by human activities. Such disturbances might include the removal of larger trees for timber and/or removal of smaller trees and fallen branches for wood fuel, particularly around clearings for cassava plantations. The high frequency of gaps in the forest studied at Sakon Nakhon may in part be a natural phenomenon, but is likely to be also related to increased disturbance around clearings for cassava. The effect of forest gaps on soil properties, regardless of whether they were natural (i.e. tree fall or related to annual fires) or human-induced, was investigated in this study. The results presented in Chapter 4 are further discussed below.

In the dry Dipterocarp forest plots, soil property variability analysis shown that Infiltration rate, soil bulk density and exchangeable K in the subsoil horizons were significantly different between forest plots but were not correlated with canopy gaps, whereas clay dispersion index, exchangeable calcium and ECEC of topsoil horizons were not significantly different between forest plots but were significantly correlated with canopy gaps; no significant differences for the rest of the soil properties were observed (Table 4.5 and 4.6). These results suggested that the variation of soil properties under the forest plots could be also affected by other factors, such as animal trampling, burning, and biotic factors rather than canopy gap percentage. Luizao *et al.* (1998) concluded that there was little consistent effect of gap size on soil chemical properties during 12 months of their study. A possible explanation is that canopy gaps have rapidly changed with time due to vegetation cover changes. Over a short period of time, the impact of canopy gaps is most likely to influence only the immediate soil surface and would therefore not be so obviously reflected in the properties of soil samples taken at 10-15 cm for this study. This helps to explain the clear evidence for soil erosion in the field investigation of soil profiles (see Appendix I, profile descriptions for Profile No. 1-3) that appears to be related to gaps, though little effect of canopy gap percentage on soil property variation at the depths sampled (10 –15 cm and 40-45 cm) was observed. A further factor that goes towards explaining the lack of significant differences of soil properties at 10-15 cm is that pedoturbation and biotic mixing of the material at the soil surface, particularly by soil-ingesting earthworms, obscures the effect of surface erosion and particle sorting in the Ah horizons and thus moderates the effects and impact of soil erosion processes at depth of 10-15 cm. Evidence for substantial earthworm casting was seen on the soil surface of the forest plots, as reported in forest soil profile descriptions (Figure 6.1 and the results for Profile Nos.1 and 2 in Appendix I).

Figure 6.1 Earthworm casts on the soil surface of the forest plot B.

In addition, the results from the present study also suggested that further study on the use of canopy gap analysis correlated with soil properties is needed for more understanding the effect of canopy gaps on soil properties. As a canopy gap is dynamic, a series of digital photographs of canopy gap changes over times should be taken as well as soil sampling.

In the cultivated plots, soil erosion can be detected by visual observation of sand deposits on foot slopes and in depressions, and by the presence of rill and inter-rill erosion on cassava and sugarcane plots (Figure 6.2). The results of soil variability assessment by application of the soil catena concept (Section 4.5) also showed that soils on foot –slopes or in depressions mostly have a sandy surface horizons more

a.

b.

Figure 6.2 Sand deposits on foot slopes and in depressions (a), rill and inter-rill erosion on a sugarcane plot (b) at the Udon Thani site.

than 50 cm deep (i.e. these soils qualify as having 'Arenic' properties according to the US Soil Taxonomy). Sometimes sand deposits were excessively thick, as in the depression of the S2 b sugarcane plot, where sand deposits were found to be more than 100 cm deep (i.e. 'Grossarenic' according to the US Soil Taxonomy). Indigenous farmer knowledge indicated that most of the depressions at the sugarcane sites were formerly small stream valleys in dry Dipterocarp forest before deforestation. Alluvial deposits in such valleys are clayey or loamy rather than sandy. The presence of sandy slope deposits burying these alluvial sediments indicates deposition from rain splash, sheet (inter-rill) and rill erosion that relates to soil loss higher in the soil catena. These findings show that soil loss through water erosion is a serious problem resulting from the monoculture of sugarcane on upland Ultisols in North East Thailand. Other researchers have reported that soil loss under cassava and sugarcane production rages from 10 Mg ha^{-1} yr^{-1} to more than 150 Mg ha^{-1} yr^{-1} depending on degree of the slope and cultivation practice (Sriwongsa, 1994; Vityakon *et al.*, 2000). In the present study, thickening of sandy surface horizons on footslopes was less obvious, partly because of the relatively recent establishment of cassava in the study area with areas of forest surrounding or surviving in the plots, and partly because of the less marked slopes.

In addition to the direct field evidence of soil erosion, soil degradation in this region is widely recognised by local farmers. The results from key informant interviews showed that most of the respondents agreed that the decrease of crop yields experienced when compared to the earlier crops after forest clearance was due to soil deterioration (section 4.2.2). This information show that the decrease of crop yields is consistent with the evidence of observed soil erosion as discussed above, suggesting that the relationships between poor crop yields and clear signs of soil degradation such as soil erosion is helpful indicator in assessing soil degradation as propose by Hartemink (2003).

However, some respondents argued that a decrease of crop yield was not appropriate as a useful indicator for assessing soil deterioration because there were many other factors that affected crop yield, such as insect pests, diseases and drought. They suggested that observations of actual soil erosion and soil colour changes should be better indicators of soil degradation. This comment is supported by the evidence of soil erosion in their plots and the results of statistical analysis using ANOVA (Table A-7 in Appendix II), which showed that soil colours (Munsell Chroma) in surface horizons of soil profiles in the baseline plots compared to cultivated plots were significantly lower under the sugarcane cropping regime and were significantly correlated with time both in the cassava regime ($r = 0.722$, $p = 0.043$) and the sugarcane regime ($r = 0.926$, $p = 0.001$). Moreover, soil colours in surface horizons were significantly negatively correlated with soil organic carbon ($r = -0.785$, $p < 0.001$) and labile carbon ($r = -0.849$, $p < 0.001$), suggesting a significant decrease in organic matter over time.

This finding is consistent with Schulze *et al.* (1993) who studied relationships between soil colour and organic matter content in Ap horizons from Indiana and Illinois soils and found that relationship between Munsell value and organic matter content was predictable ($r^2 > 0.9$) within soil landscapes if soil textures did not vary widely. Moreover, Viscarra and Walter (2002) used qualitative Munsell soil colour and quantitative digital image soil colour to establish relationships between soil colour and soil organic carbon. They found that quantitative soil colour measurement by a digital camera showed a good response for soil organic carbon and suggested that using an appropriate calibration model, accurate predictions of soil organic carbon in a field may be possible in real-time. Recently, De Clerck *et al.* (2003) studied soil quality changes over the past 60 years in California and used soil colour (Chroma) measured by a Minolta Chroma Meter CR- 200 as a one of soil quality indicators. These research findings, and the results of my own study, suggest that soil colour can be a useful indicator for assessing soil quality.

6.2 Soil property dynamics

The significant changes of each soil property in the cultivated soils when compared with the reference soils at each study site are used as indicators for assessing soil degradation processes. Sensitive individual indicators for the cassava and sugarcane cropping regimes are presented in Section 5.1 and 5.2

6.2.1 Physical properties

In this study, the soil property changes that most evidently reflect physical degradation of Ultisols are the increase of soil bulk density in the cassava cropping regime and the increase of clay dispersion in the sugarcane cropping regime.

Soil bulk density

The bulk density of Ultisols under dry Dipterocarp forest in this study ranged from 1.45 to 1.49 $Mg.m^{-3}$ in the topsoil horizons. This is slightly higher than results reported elsewhere in North East Thailand, where bulk density of Ultisols under dry Dipterocarp forest ranged from 1.29 to 1.47 Mg m^{-3} in the sandy loam to loamy sand topsoil horizons (Ota *et al.*, 1992). The bulk density of Ultisols reported in the research literature ranges widely from 0.54 to 1.85 Mg m^{-3} for A horizons and 1.05 – 1.70 for Bt horizons (West *et al.*, 1997), but, in general, topsoil horizons of Ultisols under natural forest have low bulk densities. Values range from 0.85 to 0.88 Mg m^{-3} in fine textured topsoil horizons and 1.05 to 1.08 Mg m^{-3} in coarse textured topsoil horizons under tropical rainforest in Colombian Amazonia (Martinez and Zinck, 2004), to 1.22 Mg m^{-3} in the silt loam topsoil horizons of Ultisols under tropical deciduous forest of *Shorea robusta* in Bangladesh (Islam and Weil 2000).

My own results suggest that soil compaction or structural collapse has occurred in the Ah horizons of these Ultisols under dry Dipterocarp forest in North East Thailand. This is attributed, at least in part, to animal trampling, as cattle and buffalo foot – prints were observed in the field investigation and the information presented in

Chapter 1, section 1.2 shows that the farmers normally use these forests for raising their animals. Similar, significant negative effects of cattle trampling on soil porosity have been reported in the study of Koutika *et al.* (1997). Another possible explanation for higher soil bulk density under dry Dipterocarp forest in this area is soil structural collapse following destruction of forest floor litter by annual fires in the dry season and consequent lower organic matter contents, resulting in soil structural instability and the exposure of the mineral soil surface to rain drop impact.

These reasons can be used to explain the small significant increases over time of soil bulk density in the topsoil horizons and in the kandic subsoil horizons of the younger (10-20 years) and the older (20-30 years) cassava plots in the present study (Table 5. 4). The results are interpreted as the result of soil physical degradation that has developed through the soil compaction processes associated with land preparation. Land preparation and tillage under wet conditions is a possible cause of soil compaction under cassava because farmers normally grow cassava in the rainy season (see section 4.2.2). Soil bulk density increases, accompanied by corresponding decreases in soil porosity, are commonly reported in cultivated soils when compared with natural forest or uncultivated soils. Elsewhere in North East Thailand, Ota *et al.* (1992) have reported that the bulk densities of cultivated Ultisol A horizons increased by approximately 6 to 16 % compared to similar horizons under dry Dipterocarp forest. Martinez and Zinck (2004) reported that bulk density in topsoil horizons under pasture on Amazonian Ultisols increased 28 – 42 % when compared with those of natural forest. However, in that case it was suggested that the soil compaction occurred due to animal trampling.

The small significant increase of soil bulk density in the topsoil horizons of 10-20 year old cassava plots, when compared with the natural forest plots of the present study, is attributed to rapid compaction in the early stage of land conversion. The lack of a significant increase in the 20-30 year cassava plots suggests that further soil compaction is negligible and that an equilibrium level is reached after about 20 years. This observed pattern of soil bulk density changes found under cassava cultivation agrees with previous studies in Fiji (Morrison and Masilaca, 1989) and in Jamaica (McDonald *et al.*, 2002). The lack of significant increases of soil bulk density under sugarcane in the present study is attributed to the fact that the baseline for comparison was the 10-20 year old sugarcane plots. It seems that the soils in 10-20 year old sugarcane plots, with a bulk density value of 1.52 Mg m^{-3}, had already become compacted if compared with the lower value of 1. 47 Mg m^{-3} found for the dry Dipterocarp forest soils. No significant increase of bulk density occurred after 10-20 years under sugarcane, with values remaining constant after this time. Hartemink (1998) reported that increases in the topsoil bulk density, or decreases in porosity, were found in the inter-rows of sugarcane plots when compared with the adjoining natural grassland plots on Vertisols and Entisols in Papua and New Guinea and this was interpreted as the result of vehicular traffic. Unfortunately, no evidence indicated that soil bulk density either further increased or remained constant in his study.

According to Arshad *et al.* (1996) in Table 3.1, bulk densities of 1.75 and 1.80 Mg m^{-3} are threshold values for root restriction in sandy loam and loamy sand soils, such as those of the present study. Thus bulk densities of 1.52 –1.54 Mg m^{-3} in the cassava cropping regime, and of 1.51-1.52 Mg m^{-3} in the sugarcane cropping regime, has not therefore reached the critical threshold values and has remained constant, presumeably because little heavy machinery and/or vehicles have been using for land preparation and cultivation practices in the study plots.

Clay dispersion index

The degree of clay dispersion in soil is a useful surrogate method for evaluating soil susceptibility to degradation by raindrop impact, surface sealing, and rill or inter-rill erosion. In general, the clay dispersion indices reported in the research literature under natural forest are lower than in cultivated soils. In my own study, the clay dispersion index of sandy Ultisols under dry Dipterocarp forest was 18.6 % and increased up to 20.9% under younger cassava plots and 22.8 % under older cassava plots, however, no statistically significant changes were observed. Non- significant increases of clay dispersion in cultivated soils when compared with forest soils also have been reported by Mbagwu and Piccolo (1998) on loamy Ultisols in Nigeria and by Westerhof *et al.*(1999) on clayey Oxisols in Brazil.

In contrast to this result, a significant increase of the clay dispersion index up to 27.4 % was found in the 40-50 year old plots under the sugarcane cropping regime when compared with the younger sugar cane plots (Table 5. 16). These results indicate that soils cultivated for sugarcane are more susceptible to clay dispersion and therefore are at a greater risk of rain drop impact, surface sealing, runoff and soil erosion than either the undisturbed forest soils, or the soils under cassava. The significant increase of clay dispersion index detected in long-term cultivated Ultisols under this land management system could relate to the growth habit and crop pattern of sugarcane that results in a greater exposure of bare soil to rain drop impact between rows, as well as the burning of sugarcane residues after harvest. The latter practice leaves large areas of dry soil with lowered organic matter content with little protection by a mulch of crop residues at a critical time of year at the start of the rains. This will increase the susceptibility to dispersion on rapid wetting and raindrop impact.

Clay dispersion is usually negatively related with organic carbon content. Mbagwu and Piccolo (1998) reported that deforestation and the long-term cultivation of tropical soils increases clay dispersion due to the reduction of organic carbon, particularly, the labile fraction (carbohydrate carbon) and the humic acid fraction.

The results of linear correlation analysis in this study showed that although clay dispersion index values were generally negatively related with soil organic carbon, different fractions of the organic matter are responsible for stabilisation under the two cropping regimes investigated. A highly significant correlation with labile carbon ($r = -0.438$, $p < 0.01$) was observed in the cassava regime, whereas a highly significant correlation with total organic carbon ($r = -0.393$, $p < 0.01$) was observed in the sugarcane regime. This finding suggests that labile carbon content, which relates to micro-organism activities, affects soil structure stability under cassava cropping regime and organic carbon content influences soil structure stability under sugarcane cropping regime. A possible explanation is that organic residues under cassava cropping regime (C: N ratio of cassava leaf = 24 – 30) are more easily decomposed than that under sugarcane cropping regime (C: N ratio of sugarcane leaf = 110 – 137), as suggested by Tangtrakarnpong and Vityakon (2002). Moreover, micro-organism population numbers and activities under sugarcane are probably smaller than those under cassava because of intensive land use and burning practices.

6.2.2 Chemical properties

Soil chemical degradation has been evaluated by soil acidification and fertility decline. In this study, the selected sensitive indicators for assessing soil acidification were soil pH and exchangeable acidity and those for assessing fertility decline were exchangeable potassium, calcium, magnesium and effective cation exchange capacity.

Acidification

In general, surface horizons of most Ultisols under natural forest have acid soil. The results of the present study showed pHs of 5.9 in the Ah horizons (0-10 cm) of forest soil profiles, whereas pHs of 5.2 and 4.8 were observed in the topsoil horizons (10-15cm) and in the kandic subsoil horizons (40-45 cm) of forest plots, respectively (Table 5.3 and 5.5). The pH values of the surface horizons are relatively higher than those reported in the Ultisols under natural forest in Peru and Bangladesh (Sanchez *et al.*, 1983; Islam and Weil, 2000). These results and those reported elsewhere in North East Thailand (Vityakon, 1991; Ota *et al.*, 1992; Tangtrakarnpong and Vityakon, 2002) suggest that the higher soil pH of the surface horizons of forest Ultisols in North East Thailand is due to added ash from annual fires and its accumulation at or near the soil surface (i.e. approximately 0-10 cm). It was reported that after burning forest, pH value of 9.1 and 6.5 were observed in ash and soil immediately underlying the ash respectively (Sillitoe and Shilel, 1999). In addition, under natural forest vegetation most of the bases, such as calcium and magnesium, which can affect soil pH are commonly held in the vegetation biomass and are released through litter decay in the upper few centimetres of the soil and taken up again in the course of efficient nutrient cycling by the forest trees (Kheoruenromne, 1991).

The results of other research reviewed in section 2.2 indicate that the change in land use, together with the management practices adopted for cassava and sugarcane on Ultisols in North East Thailand, is leading to soil chemical degradation through acidification (Vityakon, 1991; Ota *et al.*, 1992; Tangtrakarnpong and Vityakon, 2002). This conclusion is supported by significant decrease over time of soil pH that can be reflected by the significant increase of exchangeable acidity, both in the topsoil (10-15 cm) and the kandic subsoil (40-45 cm) horizons, under sugarcane found in my own study. This finding agrees with the results of similar studies on other tropical soil orders reported by several authors that have been reviewed in Chapter 2 (Wood, 1985; Morrison and Masilaca, 1989; Hartemink, 1998a). Hartemink (1998a) explained that nitrification of ammonium from fertilizers was the main cause of acidification in sugarcane production in Papua and New Guinea. It seems that added ash from annual burning of the sugarcane plots cannot neutralise the amount of acidity derived from nitrification processes of applied nitrogen fertilizer (Table 4.2).

In the case of Ultisols in my own study, another possible explanation is that basic cations, such as calcium and magnesium, may be leached from coarser textured topsoil Ap horizons to accumulate in the deeper and finer textured kandic horizons of the soil profiles because of the break in the nutrient cycle caused by the clearance of natural forest. This can be demonstrated by the increase with depth of exchangeable calcium and magnesium in most of the modal profile analyses in the present study (Table Profile Nos. 10-18 in Appendix I). The amount of these basic cations is not enough to neutralize the inherent acidity in the kandic horizons of Ultisols, but may be enough to affect base saturation percentage in soil horizons with low cation exchange capacity such as these.

In contrast to the acidification under sugarcane, the significant increase of soil pH, reflected in a significant decrease of exchangeable acidity, both in the topsoil (10-15 cm) and the kandic subsoil (40-45 cm) horizons, under cassava is not unusual for slashed and burnt acid Ultisols in the tropics. Added ash from annually burnt plant residues, grasses and weeds during fallow period is a possible reason that explains an increase of soil pH, exchangeable calcium and a decrease of exchangeable acidity in the Ultisols under cassava relative to forest in the current study. Sillitoe and Shiel (1999) reported that burning grasses and weeds was sufficient to increase pH after several cultivations. This finding is consistent with results discussed by other researchers (Islam and Weil, 2000; Sanchez *et al.*, 1983). Moreover, a relatively high soil pH of 5.5 for the youngest sugarcane plots (10 –20 years old) was observed when compared with the pH values of Ultisols under natural forest. This suggests that ash from burning during the original forest clearing process, as well as ash from annual burning of sugarcane trash before harvesting, can raise the pH levels of the sugarcane plots in the early stages after deforestation but, thereafter, pH decreases when the amount of added ash and the amount of acidity derived from nitrification processes do not balance.

The pH values of oldest plot dropped to 4.7 in the topsoil horizons. This pH level should affect sugarcane growth because the optimum pH for sugarcane is about 6.5 (Yates, 1978 *cited in* Hartemink, 1998) and Field Crops Research Institute (1999) also suggests that soil pH values of 5.5 to 7.0 are suitable for sugarcane production. However, sugarcane is successfully grown on soils with pH value of 4.0 as in Guyana (Hartemink, 2003), suggesting that pH level of 4.7 in the oldest sugarcane of the present study might be not directly affect sugarcane production.

Soil fertility

Ultisols, in general, have lower inherent fertility than other soil orders such as Mollisols and Alfisols. In my own study, the range of exchangeable calcium, magnesium and potassium contents in the surface horizons (0-15 cm) of the forest soil profiles (0.61 – 2.26, 0.45 – 0.80 and 0.09 – 0.14 $cmol^{+}\ kg^{-1}$ respectively) was similar to that of the topsoil horizons (10 –15 cm) of the forest plots (0.69 – 1.27, 0.46 – 0.64, 0.05 – 0.06), whilst ECEC values ranged from 1.99 – 2.21 $cmol^{+}\ kg^{-1}$. These values are close to those reported by Ota *et al.* (1992), who studied the properties of virgin Paleustults (under natural forest) in North East Thailand, and those reported by Sanchez *et al.* (1983), who investigated in the topsoils horizons (0-10 cm) of Ultisols under natural forest in Peru. It can be concluded that Ultisols under natural forest in North East Thailand are similarly low in soil fertility to those elsewhere in the humid to sub-humid tropics. In particular, exchangeable calcium, magnesium, potassium contents and ECEC levels of Ultisols in North East Thailand are close to, or lower than, critical levels for crop production of 1, 0.3, 0.2 and 4 $cmol^+ kg^{-1}$ for exchangeable calcium, magnesium, potassium, and ECEC respectively, according to critical levels given in Sanchez *et al.*, (1983).

The research evidence demonstrates that the fertility of Ultisols decreases rapidly when these soils are converted from natural forest to intensive cultivation. It has been reported that without fertilizer inputs into the system, the level of exchangeable potassium, magnesium and calcium reduces significantly within 12, 24 and 30 months, respectively, after forest clearance (Sanchez *et al.*, 1983). The results of the present study also showed that in the topsoil horizons, exchangeable potassium and magnesium levels significantly decreased in the early stages of land use for crop production and then remained relatively constant over time. The pattern of these changes is similar under cassava and sugarcane cropping regimes. Elsewhere in North East Thailand, a similar decline in soils fertility under both cassava and sugarcane production on Ultisols have been reported by Ota *el al.* (1992); and Tangtrakarnpong and Vityakon (2002).

In the kandic subsoil horizons of the Ultisols in the present study, a significant decrease of exchangeable potassium was observed under the cassava, but no significant changes were observed under sugarcane. Conversely, a significant decrease of exchangeable magnesium was observed under the sugarcane regime, but no significant changes were observed under the cassava regime. Exchangeable calcium significantly increased both in the cassava and sugarcane regimes (Table 5. 7 and 5.19).

These findings indicate that exchangeable potassium levels clearly deplete after forest clearance for crop production, both without and with chemical fertilizer application in the study areas. A depletion of this element was observed both in topsoil and kandic subsoil horizons in the cassava regime (without chemical fertilizer application). However, in the sugarcane regime (with chemical fertilizer application) the depletion of this element could be detected only in topsoil horizons, whereas, in the subsoil horizons, the levels of exchangeable potassium were maintained at a constant level. This is attributed to leaching of potassium derived from annual fertilizer application into the subsoil.

Magnesium is a secondary macronutrient element, which is rarely included in fertilizer formulae used in this region. A depletion of exchangeable magnesium was observed in topsoil horizons under both cassava and sugarcane, whereas magnesium depletion in the kandic subsoil horizons was only observed under sugarcane. This finding indicates that cassava production depletes subsoil magnesium reserves less than sugarcane production.

The tendency for exchangeable calcium to accumulate is probably due to the ash from annual burning of crop residues both in the cassava and sugarcane regimes. A depletion of exchangeable calcium was observed only in topsoil horizons under sugarcane, this again confirms that cassava production depletes calcium reserves much less than sugarcane.

These results indicate that the decline in exchangeable K under cassava and sugarcane production on Ultisols in North East Thailand is extreme in relation to the levels deemed to be critical by Sanchez *et al.* (1983). Moreover, exchangeable calcium, magnesium and ECEC levels in the topsoil horizons of 30-40 year old and 40-50 year old plots under sugarcane have reached critical levels.

The significant decline of effective cation exchange capacity (ECEC) in topsoil horizons of the sugarcane regime is highly significantly correlated ($r = 0.641$, $p < 0.001$) with an associated observed decline in organic matter content. This finding suggests that ECEC in the topsoil horizons of upland Ultisols in this region is mostly contributed by soil organic matter, rather than clay content. Analyses of modal soil profiles on the plots (Appendix I) indicated that clay content under cultivated soils decreased over time, both under cassava and sugarcane, however, significant differences were not observed when compared with the clay content of the baseline profiles and was not significantly related to cation exchange capacity (CEC). Islam and Weil (2000) also reported that the cultivated soils were slightly lower in clay content than the adjacent soils under natural forest in Bangladesh. This may be due to increased vertical clay migration and/or lateral loss of suspended clay down slope after forest clearance, as discussed in Van Wambeke (1992). In addition, the burning of crop residues and soil organic matter under the sugarcane management regime is likely to have increased clay dispersion and the tendency for clay migration.

6.2.3 Soil organic matter

Ultisols generally have lower amounts of organic carbon than other soil orders such as Mollisols, Oxisols, and Andisols, but levels of organic carbon in Ultisols can be similar to those in Alfisols (West *et al.,* 1997). In the present study, levels of organic carbon in the topsoil horizons of Ultisols under dry Dipterocarp forest range from 5.9 to 7.6 g kg^{-1}. These values are at the lower end of the range of 5.5 –15.2 g kg^{-1} reported for Ultisols under tropical forest elsewhere (Sanchez *et al.*, 1983; Vityakorn, 1991; Ota *et al.*, 1992; Islam and Weil, 2000; Tangtrakarnpong and Vityakon, 2002). Many studies (see Chapter 2, section 2.1.4) have demonstrated a decline of soil organic carbon in the topsoil horizons of Ultisols when natural vegetation is converted to cropland, or when cultivated land is compared with uncultivated land. The results in the present study (Table 5.2, 5.6, 5.14 and 5.18) also demonstrated that a significant decrease of soil organic matter over time after forest clearance, measured in terms of organic carbon and labile carbon fractions, was found in the topsoil horizons both in the cassava and sugarcane cropping regimes relative to uncleared forest vegetation. The relative decreases of organic carbon (31-50 %) in the surface horizons under cassava compared to natural forest are slightly lower than those of previous studies by Vityakorn (1991) and Ota *et al.* (1992) elsewhere in North East Thailand, which ranged from 57 to 67 %. However, the relative decreases of organic carbon (49-76 %) in the surface horizons under sugarcane are markedly higher than those (27%) reported by Tangtrakarnpong and Vityakon (2002).

This body of evidence indicates that soil organic matter inputs for the cassava and sugarcane cropping regimes are inadequate to recover the loss of soil organic matter resulting from cultivation practices. Generally, organic matter content of soils under natural forest is added through annual litter-fall and roots decomposition processes, whereas that under cultivated soils it is returned by crop residues. However, it was found that organic matter return under cassava and sugarcane in North East Thailand was lower than that under the dry Dipterocarp forest system and that, without burning, organic matter return from the crop residues under sugarcane was higher than that under cassava (Tangtrakarnpong and Vityakon, 2002). Burning cultivated plots before harvesting is a cause of organic matter decline in agricultural soils (Wood, 1985; Blair, 2000). Cultivation practices stimulate soil organic matter decomposition. Decomposition processes of organic matter are mostly biological and are influenced by the same factors that govern the activity of the organism, such as, soil aeration, soil temperature and soil moisture conditions. Under undisturbed natural forest, organic matter accumulation on the forest floor is due to the annual rate of decomposition being less than the annual amount of litter-fall. When forest ecosystems are converted to agriculture, the canopy is opened and the litter cover is turned over, and there is generally a marked decline of soil organic matter because the rate of organic matter decomposition increases due to the increase of temperature, aeration and microorganism activities (Luizao *et al.*, 1998; Islam and Weil, 2000).

In addition, the effects of more frequent ploughing under sugarcane in the present study probably results in the greater decline of soil organic matter observed compared to that under cassava. Wongwiwatchai *et al.* (2002) reported that the frequency of ploughing for weed management and water conservation ranged from 1 to 7 times per crop in sugarcane production in North East Thailand. They suggest that soil aggregate disturbance by frequent ploughing brings about organic matter decline. A possible explanation is that organic matter is a major cementing agent, particularly in low clay content soils, binding individual soil particles into aggregates. This portion of organic matter under the forest soils, which is physically protected within soil aggregates, is difficult to access by biological decomposition processes. When forest soils are converted for cultivation, previously protected organic matter in such soil aggregates is periodically broken down by tillage practices and exposed to biological decomposition processes. Mbagwu and Piccolo (1998) found that in cultivated soils there is a decrease of macro-aggregates and an increase of micro-aggregates associated with the reduction of soil organic matter when compared with those in forest soils.

It has been well documented that soil organic matter plays many important roles in soil physical, chemical and biological processes. In the present study, the results of linear correlation analysis showed that soil organic carbon and labile carbon were significantly related with several other properties (Table A-5 and A-6 in Appendix II). Therefore, it can be concluded that soil organic matter decline is the most important problem and the change of soil organic matter status should be the key indicator for evaluation of soil quality and the degree of soil degradation in this area. Labile carbon has proved to be a more sensitive indicator than organic carbon because the significant changes of labile carbon could be clearly observed both in profile and plot scale measurements (Table 5.2, 5.6, 5.14 and 5.18), and labile carbon was significantly correlated with soil organic carbon and other soil properties (Table A-5 and A-6 in Appendix II). These results are similar with those reported by Sparling *et al.* (1998), Ghani *et al.* (2002 and 2003). It is concluded that labile carbon by hot water-extraction is one of the more sensitive methods for monitoring changes in soil quality over time.

6.3 Soil quality deterioration

The calculated relative soil quality index (ΔRSQI < 0) in this study reflects soil quality deterioration in the cultivated soilsSoil quality changes over time are detected both under cassava and sugarcane regimes. The RSQIs were significantly negatively correlated with time after forest clearance (Table A-8 in Appendix II). The results in Section 5.1.3 and 5.2.3 also showed the negative changes of relative soil quality index (ΔRSQI < 0) that indicated overall progressive soil degradation at all soil depths, both under cassava and sugarcane. These results are similar with a significant decrease of soil quality deterioration index under cultivation when compared with the soils under natural forest in Bangladesh observed by Islam and Weil (2000).

The degree of soil quality deterioration in each cropping regime can be expressed by the magnitude changes of the RSQI (ΔRSQI). The magnitudes of ΔRSQI at each depth suggest that soil quality deterioration is greater in topsoil horizons (10-15 cm) than in kandic subsoil horizons (40 –50 cm). These findings agree with the results of previous studies that showed soil degradation was greater in upper soil horizons rather than lower horizons using individual indicators such as organic carbon (e.g. Sanchez *et al.* 1983; Wood, 1985; Morrison and Masilaca, 1989; Hartemink, 1998c). This range of research evidence suggest that the upper soil horizons are more frequently disturbed than the lower soil horizons and are changed in soil quality over shorter period of times than in the subsoil. For evaluation of soil degradation over time, soil quality of the upper soil horizons should therefore be a useful short- term indicator, whereas that of the lower soil horizons should be a useful long- term indicator for tracing soil quality change under various land use and management practices.

The magnitudes of ΔRSQI under the sugarcane cultivation regime were greater than under cassava regime at all soil depths (Table 5.10 and 5.22) and the results of distributions of RSQI class area (Figure 5.1 and 5.2) showed a decrease of high soil quality class area, or an increase of low soil quality class area in older cultivated plots, and clearly indicated that progressive soil degradation had occurred under cassava and sugarcane both in topsoil and subsoil horizons. The RSQI classes under cassava ranged from class I to V whereas those of under sugarcane ranged from I to VII. The lowest soil quality classes, appearing in the sugarcane plots indicate the degree of soil degradation in sugarcane plots is greater than in cassava plots.

In addition, the results presented in Section 5.1.3 and 5.2.3 suggest that RSQI is a useful tool for assessing soil quality dynamics. Soil quality in different regions can be compared by RSQI values and the magnitude of relative soil quality changes (ΔRSQI) can be compared between two regions, even though they are evaluated with different baseline, or by a different evaluation system (Wang and Gong, 1998). Moreover, in the present study, RSQI values were significantly correlated with a number of individual soil properties (Table 5. 11, 5.12, 5.23 and 5.24). This evidence indicates that RSQI values for individual soil properties are appropriate parameters for expressing overall soil conditions. Changes in the area of RSQI classes can also be quantified and this information is useful for decision- making in land use and management.

6.4 Sustainability of cassava and sugarcane production on upland Ultisols

Overall soil quality deterioration associated with negative changes of individual soil properties clearly indicates that land use change from natural forest to cassava and sugarcane production on upland Ultisols in North East Thailand has led to soil degradation and is unsustainable (Section 6.1, 6.2 and 6.3). Crop yield is another important indicator of sustainable land management (Hartemink, 2003). In the present study, crop yield was not directly measured under cassava and sugarcane regimes but was obtained by farmers' estimation (Table 4.1 and 4.2). A decline of estimated crop yield, which is consistent with negative changes of individual soil properties and soil quality confirms soil degradation and unsustainable management of soil under cassava and sugarcane production.

The degree of soil quality deterioration and the progressive degradation were severer in sugarcane cropping regime than in cassava cropping regime. These findings suggest that the intensive land use and inappropriate land management, such as, using chemical fertilizer without liming and more frequent burnings and ploughings under sugarcane, have brought about more rapid soil degradation through nutrient depletion, acidification, organic matter decline and soil erosion processes than in the extensive land management practices under cassava, which is grown without chemical fertilizer application and includes longer fallow periods. Under cassava regime, farmers generally practice weed-fallowing by laying the land fallow for a year or two after two or three cassava crops. Some farmers practice crop rotation by using a cassava plot or a patch of cassava plot for growing subsistent crops for a while. However, root yield is still lower when compared with the earlier stage after forest clearance, this is probably because fallow periods are not long enough to accumulate organic matter and plant nutrients.

Sugarcane production is more profitable for farmers in the early stages after forest clearance than other crops, such as cassava and kenaf, and the profit motive acts as a driver to favour this form of extractive and unsustainable land use. In the later stages of sugarcane production, when soil degradation problems occur, it is too expensive to reverse the problem. Then, remedial action, such as chemical fertilizer application, is not worthwhile and may even increase the problem. Most farmers' solution is to clear another area of forest, or use other fields for sugarcane growing. So far, new sugarcane growing areas are many miles away from the sugar mills and this increases the costs of transportation. Moreover, sugarcane production aggravates both ecological and social problems in the region. Atmospheric pollution and wind-blown ash and dust during the burning of sugarcane residues are widespread and this affects crops growing in neighboring areas during the sugarcane harvesting season. Many public roads are damaged due to heavy transportation vehicles. This demonstrates that unsustainable sugarcane production has impact, not only on the immediate agro-ecosystem, but also on off-site environmental systems. This is probably due to the fact that farmers in this region have not enough information to allow them to understand how extremely fragile their soils are. There is misunderstanding about the inherent properties of upland Ultisols, leading to unawareness and careless land use employing inappropriate soil and land management techniques for intensive commercial sugarcane production.

Chapter 7

Conclusions and Recommendations

Ultisols in North East Thailand are fragile and susceptible to soil degradation. The results of the present investigations demonstrate that initial soil degradation processes are active under remaining areas of natural dry Dipterocarp forest in the region (section 6.1). Soil surface crust formation, soil pedestals formation caused by sheet (inter-rill) and rill erosion, and particle sorting into micro-depressions are active processes and are evident from features observed on the forest floor. The current studies have suggested that such features are related to gaps in the forest canopy (appendix I profile FA, FB and FC). The origin of such gaps is related both to natural gap formation by tree fall and/or fire effects, and to disturbance by human activities. However, there was no significant effect of canopy gap percentages on soil property below 10 cm depth. It is suggested that the impact of canopy gaps on soil degradation processes is concentrated at the soil surface and is moderated over short timescales by remixing of degraded soil materials by biotic activity. Numerous large earthworm casts were a prominent feature of the forest floor (e.g. Profile FB, Appendix I).

7.1 Soil properties and soil quality changes

The study has conclusively shown that the degree of soil degradation on the upland Ultisols increases substantially over time after forest clearance for cassava and sugarcane production and that soil degradation processes can be evaluated by the significant changes of key individual soil properties and soil quality deterioration indices.

Physical degradation of soil properties through processes of soil compaction and soil structure decline are indicated by the increases of soil bulk density and clay dispersion index. Small, but statistically significant increases of soil bulk density values are found both in the topsoil horizons (3-5 %) and the subsoil horizons (3-7%) of the plot scale measurements of the cassava cropping regime compared with those of dry Dipterocarp forest (Table 5. 4). The pattern of soil bulk density changes in the study suggests that when the Ultisols under natural forest are cleared for crop production, soil compaction processes occur in the early stages (i.e. 10-20 years after forest clearance) and then reach an equilibrium. No further soil compaction is found under either the cassava or the sugarcane cropping regimes practiced in this area.

On the other hand, the significant increase of clay dispersion index (7.3%) in the topsoil horizons found in the oldest sugarcane plots when compared with that of the youngest. It is concluded to indicate a decrease in soil structural stability over time. This indicates that soil structural stability has continued to decline over a 40-year period and is still ongoing. Changes in soil structure stability are difficult to detect over short periods between soils under natural forest and those that have been recently cleared for cultivation. However, when the time scale is extended, a significant increase of clay dispersion index is apparent. This suggests that clay dispersion index is a useful long-term indicator for assessing soil physical degradation in tropical Ultisols of this kind (section 6.2.1)

The results of the study have shown that soil chemical fertility decline is rapid after forest clearance, particularly under sugarcane monoculture. However, the degradation of soil chemical properties through nutrient depletion occurs at different rates and to differing degrees under the two cropping regimes investigated. During the first 10 to 20 years after forest clearance there are significant decreases of exchangeable potassium under both cassava (50% decrease) and sugarcane (25% decrease) (Table 5.7 and 5.19). There is also a significant decrease of exchangeable magnesium (67%) under sugarcane during this early period, but under cassava significant decreases (21%) in this element are only observed 20 to 30 years after forest clearance. This decrease is most marked in topsoils. Decreases of exchangeable calcium (69 %) are only significant under sugarcane when compared with those under the youngest sugarcane plots. The sugarcane cropping regime, unlike cassava, also causes marked soil acidification, as indicated by progressively significant decreases of soil pH values (9-17 %) and increases in exchangeable acidity (50-177 %) over 45 years. Moreover, under sugarcane, deterioration in nutrient holding capacity is evident from decreases of 50 % in effective cation exchange capacity over time (Table 5.19).

Progressive significant decreases of soil organic carbon 7-13% and labile carbon levels 16-30 % under cassava and of 19-53% and 23-38 % respectively under sugarcane over 20-30 years indicate relatively soil biological degradation and suggest that soil organic matter decline is a crucial factor to be addressed for the continued sustainability of crop production on these upland Ultisols. The results of the present study particularly demonstrate a greater decline in organic carbon of 49-76% in the surface horizons over 45 years following forest clearance for sugarcane production than has been previously been shown for Ultisols (section 6.2.3). This is a worrying trend for the sustainability of sugarcane production in North East Thailand.

Soil degradation expressed in terms of soil quality deterioration indices shows that significant negative changes of Δ RSQI < 0 are found in the Ah/Ap horizons of soil profile measurements and in both the topsoil (Ap) horizons and the kandic subsoil horizons of plot scale measurements in the cassava and sugarcane cropping regimes. The magnitude of soil quality deterioration in the upper horizons is greater than in the lower horizons. Results indicate that progressive soil degradation has occurred during crop production since forest clearance (Section 5.1.3 and 5.2.3)

The degree of soil quality deterioration and the progressive degradation are more severe under sugarcane production than under cassava production (Table 5.10 and 5.22). This is because of the more intensive land use, greater frequency of ploughing and shorter fallow periods in the sugarcane cropping regime (Section 4.2.2). These practices, and the associated annual burning of crop residues, aggravates organic matter loss, soil structure decline and soil compaction, leading to significantly lower organic carbon contents and observably increased soil erosion. In addition, other crucial problems that also occur in the sugarcane cropping regime are soil acidification and nutrient depletion. The combination of these soil property changes threatens the sustainability of long-term sugarcane production in the region. Cassava cropping has been shown to have a lesser impact on soil quality deterioration because of longer fallow periods that allow organic matter and nutrients to accumulate in the soils (Section 4.2.2). Growth habit and the provision of greater crop cover may also be a relevant factor.

7.2 Recommendation

The evidence of the present study (section 7.1) clearly show that land use change from natural forest to agriculture on upland Ultisols in North East Thailand has led to soil degradation and a decline in soil quality both under the cassava and sugarcane cropping regimes practiced in the region, and that this trend is unsustainable in the longer term. Nevertheless, although Ultisols are at a high risk of soil degradation and soil quality decline, they are the major source of food and income for the rural population. Therefore, rigorous monitoring of soil degradation, careful and a change in strategy in land use and management are required to sustain agricultural production.

The levels of most soil properties significantly decrease in early stage (10-20 years) and some (bulk density) approach equilibrium stage (section 7.1) whereas a key critical property such as organic matter, expressed in forms of organic carbon and labile carbon, continue to decrease. These changes of soil properties are consistent with the decrease of crop yield in farmers' perception both under cassava and sugarcane regime. Under cassava regime, farmers' solution is to lay the land fallow for a year or two years after two or three cassava crops and use a patch of this fallowed cassava plot for growing subsistent crops and then return to grow cassava. However, root yield is still lower when compared with the earlier stage after forest clearance, this is probably because fallow periods are not long enough to accumulate organic matter and plant nutrients; Juo *et al.* (1995) reported that under natural bush fallow, soil organic carbon is restored to the original level of approximately 20 g kg^{-1} at 12 years.

In contrast, under sugarcane regime although chemical fertilizers are normally used, a decline of sugarcane yields could not be avoided, because there are other problems remaining such as organic matter decline, soil erosion, soil acidification and also exchangeable calcium and magnesium depletion (section 6.1 and 6.2). Some farmers (personal communication with leader farmers) in this area have been realised the deterioration of their soils and have their own solutions, such as, (i) using bagasse from sugar mills as a source of organic matter inputs, (ii) clearing another area of forest, (iii) renting other fields for sugarcane growing for 2-3 crops and then move to other areas when sugarcane yield decline, (iv) using sugarcane plots or a patch of plots for growing other crops for a while and (v) practicing fallowing. These farmers' options have some limitations, such as the problem of transporting bagasse from a sugar mill to farmers' plots in option (i) or the limited supply of natural forest outside National Parks in option (ii) and others impacts as discussed in section 6.4.

However, fallowing practice is a common solution to solve the problem of crop yield decline both under cassava and sugarcane regime. Juo *et al.*(1995) also suggest that fallowing is good for restoring chemical, physical and biological properties of soils. Nature bush fallow is an efficient for nutrient recycling and biomass accumulation because it consists of many species of plants with different root system. However, natural bush fallow slowly grows at the earlier stage, particularly, in the severely degraded soils. Planted fallow system including several species with root systems and growth rates should be a good alternative way to combine the advantages of rapid ground coverage with efficient biological N fixation and cycling of subsoil mineral nutrient (Juo *et al.*, 1995).

If fallow practice is to be recommended as a means of improving sustainability of crop production in this region, further research on the appropriate length of fallow periods and suitable alternative crops is required. In order to be shorter fallow period combination between planted fallow systems and an appropriate time and rate of chemical fertilizer application should be enough to sustain soil productivity under cassava regime. In contrast, under sugarcane where soil degradation is greater, planted fallow systems associated with appropriate soil conservation method and chemical fertilizer with liming in puts are required to sustain soil productivity.

The RSQI classification concept as demonstrated by the research reported in this thesis can be applied to the smaller scale, such as, farm scale for individual farmer, regional scale for sugar mill and/or policy maker to help them assess the status of their soils and to inform them where critical levels of soil quality decline and soil degradation require fallow practice as remedial action. The early warning indicators and monitoring programmes are also needed to inform them when such action must be started.

As soil organic matter plays many roles in soil quality maintenance and progressively decreases in this region, it is recommended that the labile carbon extraction method employed in this research should be incorporated in any monitoring programmes. It has proved more sensitive than total carbon or organic carbon extraction methods. It is also easier to use, more economic and less time consuming than many other assessment methods and does not require toxic fumigants. Soil samples can conveniently be stored in an air-dry state at room temperature until analysed. In addition, further studies using quantitative digital image analysis to establish relationships between soil colour and soil organic carbon and labile carbon contents on upland Ultisols should be helpful to develop real-time and accurate predictions of soil organic carbon in a field.

Such recommendations as well as those of other researchers in the region may be little adopted by local farmers. Part of the problem is that scientists experience different condition from those of the farmers. Despite the benefit of technologies, if ideas are imposed on farmers, they will be not adopted widely (Pretty, 1995).

Therefore, participatory learning and researching are required for sustainable productivity in the region, which needs not only new technologies and practice but also adoption by farmers, supports from external and local institutions, local groups and above all, agricultural policies of the government.

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APPENDIX I

A. SOIL PROFILE DESCRIPTIONS

1. Profile FA

Soil name: Korat series (Detailed Reconnaissance Soil Maps of Sakon Nakhon Province, 1971).
Soil Classification: Fine-loamy, siliceous, isohyperthemic Kanhaplic Haplustults (Soil Survey Staff, 1999)
Location: Phuphan National Park, Kut Bak, Sakon Nakhon, NE Thailand, 8 km WNW of Phuphan National Park Office.
Map Ref: 1: 50,000 Series L7017 Sheet 5743/11 Amphoe Kut Bak
Grid Ref: 832888 (N 17 ° 04'. 961, E 103 ° 54'. 063)
Described by: S. Soisungwan Date: 2. 04. 01
Elevation: 210m. Slope: 2° straight Aspect: 0 ° N
Relief: Undulating middle alluvial terrace (Quaternary). Lower slope leading down to concave depression 100 m. to N and up onto summit 250m to S.
Parent Material: Old Quaternary river alluvium
Annual rainfall: 1523.1 mm. (period 1975-1995, Meteorological Department, 2000)
Vegetation: Deciduous Dipterocarp forest, dominated by Shorea obtus and Shorea simensis
Land Use: Slightly disturbed natural forest.
Soil Surface: Occasionally covered with fresh plant litter. Some earthworm casts and some evidences of annual fire and of trampling by cattle and buffalo were observed.
Soil degradation evidence: Few surface crust, particularly where there is no litter cover.
Soil Variability: Profile lies on lower slope position of a soil catena that passes from well drained soils (Typic Kandiustults) on the convex summit to moderately drained soils (Oxyaquic Kandisustults) on the lower slope to Arenic Kandiaqults in the concave depression.

0-10 cm Ah
Very dark gray (10YR 3/1) stoneless sandy loam; weak fine and medium subangular blocky; soft when dry; friable when moist; non-sticky and non-plastic when wet; many fine fibrous roots and common medium woody roots; clear wavy boundary; slightly acid (field pH 6. 5).

10-25cm A
Dark brown (7. 5YR 4/2) stoneless sandy loam; weak fine and medium subangular blocky; soft when dry; friable when moist; non-sticky and non-plastic when wet; many fine fibrous roots and common medium woody roots; clear wavy boundary; medium acid (field pH 6. 0).

25-35 cm E
Light brown (7. 5YR 6/4) stoneless sandy loam; massive structure; soft when dry; very friable when moist; non-sticky and non-plastic when wet; few fine fibrous roots and common medium woody roots; clear wavy boundary; medium acid (field pH 6. 0).

35-70 cm Bt1
Strong brown (7. 5 YR 5/6) stoneless sandy clay loam; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; common fine fibrous roots, medium and many coarse woody roots; some termite holes; gradual smooth boundary; very strongly acid (field pH 4. 5).

70-90 cm Bt2
Strong brown (7. 5YR 5/6) stoneless sandy clay loam; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; common finefibrious roots and medium woody roots; some termite holes; gradual smooth boundary; very strongly acid (field pH 5.0).

90-140 cm Btg1
Reddish yellow (7. 5YR 6/8) moist stoneless sandy clay loam with few fine distinct yellow (10YR 7/6) and gray (10 YR 6/1) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; few fine fibrous roots; gradual smooth boundary; very strongly acid (field pH 4. 5).

140 -180 cm + Btg2
Light brownish grey (10YR 6/2) moist stoneless sandy clay loam with common fine distinct very dark gray (7. 5 YR 3/0) mottles of manganese oxide and few fine distinct yellowish red (5YR 5/8) mottles of iron oxide; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; few fine roots; lower boundary not seen; very strongly acid (field pH 5. 0).

2. Profile FB

Soil name: Korat series (Detailed Reconnaissance Soil Maps of Sakon Nakhon Province, 1971).
Soil Classification: Fine-loamy, siliceous, isohyperthemic Kanhaplic Haplustults (Soil Survey Staff, 1999)
Location: Phuphan National Park, Kut Bak, Sakon Nakhon, NE Thailand, 8 km WNW of Phuphan National Park Office.
Map Ref: 1: 50,000 Series L7017 Sheet 5743/11 Amphoe Kut Bak
Grid Ref: 827887 (N 17 ° 04'. 943, E 103 ° 53'. 914)
Described by: S. Soisungwan Date: 4. 04. 01
Elevation: 200m Slope: 2. 5 ° straight Aspect: 120 ° ESE
Relief: Undulating middle alluvial terrace (Quaternary). Lower slope leading down to the stream 100m to ESE and up onto summit 250m to WNW.
Parent Material: Old Quaternary river alluvium

Annual rainfall: 1523.1 mm. (period 1975-1995, Meteorological Department, 2000)
Vegetation: Deciduous Dipterocarp forest, dominated by Shorea obtus and Shorea simensis .
Land Use: Slightly disturbed natural forest.
Soil Surface: Occasionally covered with fresh plant litter. Numerous earthworm casts and some evidences of annual fire and of trampling by cattle and buffalo were observed.
Soil degradation evidence: Few surface crust, particularly where there is no litter cover.
Soil Variability: Profile lies on lower slope position of a soil catena that passes from well drained soils (Typic Kandiustults) on the convex summit to moderately drained soils (Oxyaquic Kandisustults) on the lower slope to Arenic Kandiaqults in the concave depression.

0-10 cm Ah
Very dark grey (10YR 3/1) stoneless sandy loam; weak fine and medium subangular blocky; soft when dry; friable when moist; non-sticky and non-plastic when wet; many fine fibrous roots and common medium woody roots; clear wavy boundary; slightly acid (field pH 6. 5).

10-20cm A
Dark brown (7. 5YR 4/4) stoneless sandy loam; weak fine and medium subangular blocky; soft when dry; very friable when moist; non-sticky and non-plastic when wet; many fine fibrous roots and common medium woody roots; clear wavy boundary; medium acid (field pH 6. 0).

20-37/40 cm E
Light brown (7. 5YR 6/4) stoneless sandy loam; massive structure; soft when dry; very friable when moist; non-sticky and non-plastic when wet; few fine fibrous roots and common medium woody roots; clear wavy boundary; strongly acid (field pH 5. 5).

37/40-75 cm Bt1
Strong brown (7. 5YR 5/6) stoneless sandy clay loam; massive structure; slightly hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; common fine fibrous roots and medium and many coarse woody roots; many termite holes; gradual smooth boundary; very strongly acid (field pH 5. 0).

75-95 cm Bt2
Strong brown (7.5YR 5/8) moist stoneless sandy clay loam with common very fine distinct yellowish red (5YR 5/8) mottle; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; common fine fibrous roots and medium woody roots; some termite holes; gradual smooth boundary; very strongly acid (field pH 4. 5).

95-130 cm Btg1
Strong brown (7. 5YR 5/8) moist stoneless sandy clay loam with common fine distinct yellowish red (5YR 5/8) and pinkish gray (7. 5YR 6/2) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; common fine fibrous roots; some termite holes; gradual smooth boundary; strongly acid (field pH 5. 5).

130-160 cm Btg2
Strong brown (7. 5YR 5/8) moist stoneless sandy clay loam with common fine distinct red (2. 5YR 4/8) and pinkish grey (7. 5YR 6/2) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; common fine fibrous roots; some termite holes; gradual smooth boundary; very strongly acid (field pH 5. 0)

160 -180 cm + Btg3
Pinkish gray (7.5YR 6/2) moist stoneless sandy clay loam with common fine distinct strong brown (7.5YR 5/8) and red (2.5YR 4/8) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; common fine fibrous roots; some termite holes; lower boundary not seen; very strongly acid (field pH 5.0).

3. Profile FC

Soil name: Korat series (Detailed Reconnaissance Soil Maps of Sakon Nakhon Province, 1971).
Soil Classification: Fine-loamy, siliceous, isohyperthemic Oxyaquic Kandiustults (Soil Survey Staff, 1999)
Location: Phuphan National Park, Kut Bak, Sakon Nakhon, NE Thailand, 8 km WNW of Phuphan National Park Office.
Map Ref: 1: 50,000 Series L7017 Sheet 5743/11 Amphoe Kut Bak
Grid Ref: 831885 (N 17 ° 04'. 816, E 103 ° 54'. 041)
Described by: S. Soisungwan Date: 6. 04. 01
Elevation: 210m Slope: 2 ° straight Aspect: 210 ° SSW
Relief: Undulating middle alluvial terrace (Quaternary). Lower slope leading down to the concave depression 100m to SSW and up onto summit 200m to NNE.
Parent Material: Old Quaternary river alluvium
Annual rainfall: 1523.1 mm. (period 1975-1995, Meteorological Department, 2000)
Vegetation: Deciduous Dipterocarp forest, dominated by Shorea obtus and Shorea simensis.
Land Use: Slightly disturbed natural forest.
Soil Surface: Occasionally covered with fresh plant litter. Some evidence of annual fire and of trampling by cattle and buffalo were observed.
Soil degradation evidence: More surface degradation than plot A and B and more open canopy.
Soil Variability: Profile lies on lower slope position of a soil catena that passes from well drained soils (Typic Kandiustults) on the convex summit to moderately drained

soils (Oxyaquic Kandisustults) on the lower slope to Arenic Kandiaqults in the concave depression.

0-10/15 cm A

Very dark greyish brown (10YR 3/2) moist stoneless sandy loam; weak fine and medium subangular blocky; soft when dry; friable when moist; non-sticky and non-plastic when wet; many finefibrous roots and common medium woody roots; some termite holes; clear wavy boundary; slightly acid (field pH 6. 5).

10/15-25cm E

Light brown (7. 5YR 6/4) stoneless sandy loam; massive structure; soft when dry; very friable when moist; non-sticky and non-plastic when wet; few fine fibrous roots and common medium woody roots; gradual smooth boundary; medium acid (field pH 6. 0).

25-50 cm Bt1

Reddish yellow (7. 5YR 6/8) stoneless sandy clay loam; massive structure; slightly hard when dry; friable when moist; slightly sticky and slightly plastic when wet; few fine pores; common fine fibrous roots and medium woody roots; some termite holes; some pieces of charcoal; gradual smooth boundary; strongly acid (field pH 5. 5).

50-80 cm Bt2

Reddish yellow (7.5YR 6/8) stoneless sandy clay loam with common fine distinct yellowish red (5YR 5/8) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; common fine fibrous roots and medium woody roots; some termite holes; gradual smooth boundary; very strongly acid (field pH 5. 0).

80-110 cm Btg1

Reddish yellow (7.5YR 6/6) moist stoneless sandy clay loam with common fine distinct yellowish red (5YR 5/8) and pinkish gray (7.5YR 6/2) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; gradual smooth boundary; very strong acid (field pH 5. 0).

110-140 cm Btg2

Reddish yellow (7.5YR 6/6) moist stoneless sandy clay loam with common fine distinct red (2.5YR 4/8) and pinkish gray (7.5YR 6/2) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine roots; gradual smooth boundary; strongly acid (field pH 5. 5).

140 -180 cm + Btg3

Pinkish gray (7.5YR 7/2) sandy clay loam with common fine distinct reddish yellow (7.5YR 6/8) and strong brown (7.5YR 5/6) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; lower boundary not seen; strongly acid (field pH 5. 5)

4. Profile C1a

Soil name: Korat series (Detailed Reconnaissance Soil Maps of Sakon Nakhon Province, 1971).
Soil Classification: Fine-loamy, siliceous, isohyperthemic Kanhaplic /Haplustults Oxyaquic Kandiustults intergrade (Soil Survey Staff, 1999)
Location: Phuphan National Park, Kut Bak, Sakon Nakhon, NE Thailand, 8 km WNW of Phuphan National Park Office.
Map Ref: 1: 50,000 Series L7017 Sheet 5743/11 Amphoe Kut Bak
Grid Ref: 827882 (N 17 ° 04'. 676, E 103 ° 53'. 902)
Described by: S. Soisungwan Date: 29. 04. 01
Elevation: 200 m Slope: 1. 5 ° straight Aspect: 60 ° NEE
Relief: Undulating middle alluvial terrace (Quaternary). Midslope leading down to the concave depression 100 m to NEE and up onto summit 150m to SWW.
Parent Material: Old Quaternary river alluvium
Annual rainfall: 1523.1 mm. (period 1975-1995, Meteorological Department, 2000)
Vegetation: Cassava was harvested two months ago. There were some unhealthy cassava plants remaining in the plot and many kinds of weed growing in the plot, such as Lamperata cylindrica.
Land Use: Cassava plot with occasionally original forest trees in the fields
Soil Surface: mounded, result of harvest processing.
Soil degradation evidence: Partly slaked of mounded can be observed.
Soil Variability: Profile lies on midslope position of a soil catena that passes from well drain soils (Typic Kandiustults) on the convex summit to moderately drain soils (Oxyaquic Kandisustults) on the midslope to Arenic Kandiaqults in the concave depression.

0-15 cm Ap
Dark Brown (10YR 4/3) stoneless sandy loam; weak fine and medium subangular blocky; soft when dry; friable when moist; non-sticky and non-plastic when wet; common fine fibrous roots; some termite holes; clear wavy boundary; medium acid (field pH 6. 0).

15-30cm E
Light brown (7. 5YR 6/4) stoneless sandy loam; massive structure; soft when dry; friable when moist; non-sticky and non-plastic when wet; common fine fibrous roots; gradual smooth boundary; slightly acid (field pH 6. 5).

30-65cm Bt1
Reddish yellow (7. 5YR 6/6) stoneless sandy loam; massive structure; slightly hard when dry; friable when moist; slightly sticky and slightly plastic when wet; few fine pores; common fine fibrous roots; some termite holes; some pieces of charcoal; gradual smooth boundary; very strongly acid (field pH 5. 0).

65-95 cm Bt2
Reddish yellow (7. 5YR 6/8) moist stoneless sandy clay loam with common fine distinct yellowish red (5YR 5/8) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; many fine pores;

common fine fibrous roots; many termite holes; gradual smooth boundary; very strongly acid (field pH 5. 0).

95-120 cm Btgl
Reddish yellow (7. 5YR 6/8) moist stoneless sandy clay loam with common fine distinct yellowish red (5YR 5/8) and pinkish gray (7. 5YR 7/2) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; common fine fibrous roots; some termite holes; gradual smooth boundary; (field pH 5. 0).

120-150 cm Btg2
Reddish yellow (7. 5YR 6/8) moist stoneless sandy clay loam with common fine distinct pinkish gray (7. 5YR 7/2) and few medium red (2. 5YR 4/8) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; few fine fibrous roots; gradual smooth boundary; strongly acid (field pH 5. 5).

150-180 cm + Btg3
Pinkish gray (7. 5YR 7/2) moist stoneless sandy clay loam with common fine distinct red (2. 5YR 4/8) and reddish yellow (5YR 6/8) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; few fine fibrous roots; lower boundary not seen ; strongly acid (field pH 5. 5).

5. Profile C1b

Soil name: Korat series (Detailed Reconnaissance Soil Maps of Sakon Nakhon Province, 1971).
Soil Classification: Fine-loamy, siliceous, isohyperthemic Kanhaplic Haplustuls/ Typic Kandiustults intergrade (Soil Survey Staff, 1999)
Location: Phuphan National Park, Kut Bak , Sakon Nakhon, NE Thailand, 8 km WNW of Phuphan National Park Office.
Map Ref: 1: 50,000 Series L7017 Sheet 5743/11 Amphoe Kut Bak
Grid Ref: 826887 (N 17 ° 04'. 929, E 103 ° 53'. 782)
Described by: S. Soisungwan Date: 24. 04. 01
Elevation: 200m Slope: 1. 5 ° straight Aspect: 270 ° W
Relief: Undulating middle alluvial terrace (Quaternary). Midslope leading down to the concave depression 200 m to W and up onto summit 150m to E.
Parent Material: Old Quaternary river alluvium
Annual rainfall: 1523.1 mm. (period 1975-1995, Meteorological Department, 2000)
Vegetation: Cassava was harvested 6 months ago. There are some species of grasses growing in the plot.
Land Use: Cassava plot with occasionally original forest trees in the fields.
Soil Surface: Partly slaked mounded, result of harvest processing.
Soil degradation evidence: Partial slaking of mounded can be observed.
Soil Variability: Profile lies on midslope position of a soil catena that passes from well drained soils (Typic Kandiustults) on the convex summit to moderately drained

soils (Oxyaquic Kandisustults) on the midslope to Arenic Kandiaqults in the concave depression.

0-30 cm Ap
Dark greyish brown (10YR 4/2) stoneless sandy loam; weak fine and medium subangular blocky; soft when dry; friable when moist; non-sticky and non-plastic when wet; many very fine and fine fibrous roots; some termite holes; sharp wavy boundary; slightly acid (field pH 6. 0).

30-45cm E
Light brown (7. 5YR 6/4) stoneless sandy loam; massive structure; soft when dry; very friable when moist; non-sticky and non-plastic when wet; few fine fibrous roots; clear wavy boundary; slightly acid (field pH 6. 5).

45-80 cm Bt1
Strong brown (7. 5YR 5/8) stoneless sandy clay loam; massive structure; firm when moist; slightly sticky and moderately plastic when wet; few fine pores; few fine fibrous roots; some termite holes; gradual smooth boundary; very strongly acid (field pH 5. 0).

80-110 cm Bt2
Reddish yellow (7. 5YR 7/8) moist stoneless sandy clay loam with common fine distinct yellowish red (5YR 5/8) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; some termite holes; gradual smooth boundary; very strongly acid (field pH 4. 5).

110-130 cm Btg1
Reddish yellow (7. 5YR 7/6) moist stoneless sandy clay loam with common fine and medium distinct yellowish red (5YR 5/8) and fine pinkish grey (7.5YR 7/2) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; gradual smooth boundary; very strongly acid (field pH 5. 0).

130-180 cm +Btg2
Pinkish grey (7.5YR 7/2) sandy clay loam with common fine distinct red (2.5YR 4/8) and yellow (10YR 7/6) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; few fine fibrous roots; lower boundary not seen; strongly acid (field pH 5. 5).

6. Profile C1c

Soil name: Korat series (Detailed Reconnaissance Soil Maps of Sakon Nakhon Province, 1971).
Soil Classification: Fine-loamy, siliceous, isohyperthemic Typic Kandiustults (Soil Survey Staff, 1999)
Location: Phuphan National Park, Kut Bak, Sakon Nakhon, NE Thailand, 8 km WNW of Phuphan National Park Office.

Map Ref: 1: 50,000 Series L7017 Sheet 5743/11 Amphoe Kut Bak
Grid Ref: 832900 (N 17 ° 05'. 599, E 103 ° 54'. 141)
Described by: S. Soisungwan Date: 28. 04. 01
Elevation: 200 m Slope: 2. 8 ° straight Aspect: 270 ° W
Relief: Undulating middle alluvial terrace (Quaternary). Lower slope leading down to the concave depression 100 m to W and up onto summit 250m to E.
Parent Material: Old Quaternary river alluvium
Annual rainfall: 1523.1 mm. (period 1975-1995, Meteorological department, 2000)
Vegetation: Cassava was harvested 6 months ago. There are some species of grasses growing in the plot.
Land Use: Cassava plot with occasionally original forest trees in the fields.
Soil Surface: Partly slaked mounded, result of harvest processing.
Soil degradation evidence: Partly slaked of mounded and some rill erosion within the plot about 50 m. from profile to W. can be observed.
Soil Variability: Profile lies on lower slope position of a soil catena that passes from well drain soils (Typic Kandiustults) on the convex summit to Arenic Kandiustults on the footslope about 60 m from profile and to Arenic Kandiaqults in the concave depression.

0-15 cm Ap1
Dark grayish brown (10YR4/2) stoneless sandy loam; weak fine and medium subangular blocky; soft when dry; very friable when moist; non-sticky and non-plastic when wet; many fine fibrous roots; clear wavy boundary; medium acid (field pH 6. 0).

15-25/35 cm Ap2
Dark grayish brown (10YR4/2) and pink (7. 5 YR 7/4) stoneless sandy loam; massive structure; soft when dry; very friable when moist; non-sticky and non-plastic when wet; common fine fibrous roots; some pieces of charcoal; sharp wavy boundary; medium acid (field pH 6. 0).

25/35-45 cm Bt1
Reddish yellow (7. 5YR 6/6) stoneless sandy loam; massive structure; hard when dry; friable when moist; slightly sticky and slightly plastic when wet; common fine pores; few fine fibrous roots; some termite holes; gradual smooth boundary; medium acid (field pH 6. 0).

45-80 cm Bt2
Reddish yellow (7. 5YR 6/8) stoneless sandy clay loam; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; some termite holes; some pieces of charcoal; gradual smooth boundary; strongly acid (field pH 5. 5).

80-120 cm Bt3
Reddish yellow (5YR 6/8) stoneless sandy clay loam; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; some termite holes; gradual smooth boundary; strongly acid (field pH 5. 5).

120-140 cm Bt4

Reddish yellow (5YR 6/8) miost stoneless sandy clay loam; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; gradual smooth boundary; very strongly acid (field pH 5. 0).

140-180 cm + Btg

Reddish yellow (5YR 6 /8) miost stoneless sandy clay loam with few fine distinct pinkish grey (7. 5YR 7/2) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; lower boundary not seen; very strongly acid (field pH 5. 0).

7. Profile C2a

Soil name: Korat series (Detailed Reconnaissance Soil Maps of Sakon Nakhon Province, 1971).
Soil Classification: Fine-loamy, siliceous, isohyperthemic (Oxyaquic) Kandiustults (Soil Survey Staff, 1999)
Location: Phuphan National Park, Kut Bak , Sakon Nakhon, NE Thailand, 8 km WNW of Phuphan National Park Office.
Map Ref: 1: 50,000 Series L7017 Sheet 5743/11 Amphoe Kut Bak
Grid Ref: 832884 (N 17 ° 04'. 784, E 103 ° 54'. 075)
Described by: S. Soisungwan Date: 22. 04. 01
Elevation: 210 m Slope: 1. 5 ° straight Aspect: 220 ° SSW
Relief: Undulating middle alluvial terrace (Quaternary). Lower slope leading down to the concave depression 100 m to SSW and up onto summit 200m to NEE.
Parent Material: Old Quaternary river alluvium
Annual rainfall: 1523.1 mm. (period 1975-1995, Meteorological Department, 2000)
Vegetation: Cassava was harvested 6 months ago. There were some species of grasses growing in the plot.
Land Use: Cassava plot with occasionally original forest trees in the fields.
Soil Surface: Partly slaked, furrowed.
Soil degradation evidence: Partly slaked of furrowed.
Soil Variability: Profile lies on lower slope position of a soil catena that passes from well drained soils (Typic Kandiustults) on the convex summit to moderately drained soils (Oxyaquic Kandiustults) on the lower slope to Arenic Kandiaquults in the concave depression.

0-20 cm Ap

Dark greyish brown (10YR 4/2) stoneless sandy loam; weak fine and medium subangular blocky; soft when dry; friable when moist; non-sticky and non-plastic When wet; many fine fibrous roots and medium woody roots; some termite holes; some pieces of charcoal; sharp wavy boundary; medium acid (field pH 6. 0).

20-35cm Bt1
Light brown (7. 5YR 6/4) stoneless sandy loam; massive structure; slightly hard when dry; friable when moist; slightly sticky and slightly plastic when wet; few very fine and fine fibrous roots; clear wavy boundary; strongly acid (field pH 5. 5).

35-55cm Bt2
Reddish yellow (7. 5YR 6/8) stoneless sandy clay loam; massive structure; slightly hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few very fine fibrous roots; some termite holes; gradual smooth boundary; very strongly acid (field pH 5. 0).

55-85 cm Bt3
Reddish yellow (7. 5YR 6/6) moist stoneless sandy clay loam with common fine distinct yellowish red (5YR 5/8) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few very fine fibrous roots; some termite holes; gradual smooth boundary; very strongly (field pH 5. 0).

85-110 cm Btg1
Reddish yellow (7. 5YR 6/6) moist stoneless sandy clay loam with common fine distinct yellowish red (5YR 5/8) and few fine pinkish grey (7. 5 YR7/2) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; few very fine fibrous roots; some termite holes; gradually smooth boundary; very strongly acid (field pH 5.0).

110-155 cm Btg2
Reddish yellow (7. 5YR 6/6) moist stoneless sandy clay loam with common fine distinct red (2. 5YR 5/8) and pinkish grey (7. 5YR 7/2) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; few very fine fibrous roots; some termite holes; some pieces of charcoal; gradual smooth boundary; strongly acid (field pH 5. 5).

155-180 cm + Btg3
Pinkish grey (7. 5YR 7/2) moist stoneless sandy clay loam with common fine distinct reddish yellow (7. 5YR 6/6) and yellowish red (5YR 5/6) mottles; massive structure; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few very fine fibrous roots; some termite holes; lower boundary not seen; strongly acid (field pH 5. 5).

8. Profile C2b

Soil name: Korat series (Detailed Reconnaissance Soil Maps of Sakon Nakhon Province, 1971).
Soil Classification: Fine-loamy, siliceous, isohyperthemic Typic Kandiustults (Soil Survey Staff, 1999)
Location: Phuphan National Park, Kut Bak , Sakon Nakhon, NE Thailand, 8 km WNW of Phuphan National Park Office.

Map Ref: 1: 50,000 Series L7017 Sheet 5743/11 Amphoe Kut Bak
Grid Ref: 833897 (N 17 ° 04'. 441, E 103 ° 54'. 197)
Described by: S. Soisungwan Date: 22. 04. 01
Elevation: 203m Slope: 2 ° straight Aspect: 270 ° W
Relief: Undulating middle alluvial terrace (Quaternary). Midslope leading down to the steam 300 m to W and up onto summit 250m to E.
Parent Material: Old Quaternary river alluvium
Annual rainfall: 1523.1 mm. (period 1975-1995, Meteorological Department, 2000)
Vegetation: Cassava was harvested 4 months ago. There were some species of grasses growing in the plot.
Land Use: Cassava plot
Soil Surface: partly slaked mounded.
Soil degradation evidence: slaking of mounds.
Soil Variability: Profile lies on midslope position of a soil catena that passes from well drained soils (Typic Kandiustults) on the convex summit to Arenic Kandiustults on the foot slope about 100m from profile.

0-30 cm Ap
Dark Brown (10YR 4/2) stoneless sandy loam; weak fine and medium subangular blocky; soft when dry; very friable when moist; non-sticky and non-plastic when wet; many fine fibrous roots and common medium woody roots; abrupt wavy boundary; slightly acid (field pH 6. 5).

30-40cm E
Light brown (7. 5YR 6/4) stoneless sandy loam; massive structure; soft when dry; very friable when moist; non- sticky and non- plastic when wet; few fine pores; few fine fibrous roots; clear wavy boundary; slightly acid (field pH 6. 5).

40-65 cm Bt1
Reddish yellow (7. 5YR 6/6) stoneless sandy loam; massive structure; hard when dry; friable when moist; slightly sticky and slightly plastic when wet; few fine pores; some termite holes; gradual smooth boundary; medium acid (field pH 6. 0).

65-105 cm Bt2
Reddish yellow (7. 5YR 6/8) moist stoneless sandy clay loam; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; some termite holes; gradual smooth boundary; very strongly acid
(field pH 5. 0).

105-130 cm Bt3
Reddish yellow (5YR 6/6) moist stoneless sandy clay loam with few fine distinct very pale brown (10YR 7/3) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; gradual smooth boundary; very strongly acid (field pH 4. 5).

130-160 cm Btg1
Reddish yellow (5YR 6/8) moist stoneless sandy clay loam with common fine distinct very pale brown (10YR 7/3) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; gradual smooth boundary; very strongly acid (field pH 4. 5).

160-180 cm + Btg2
Very pale brown (10YR 7/3) moist stoneless sandy clay loam with common fine distinct yellowish red (5YR5/8) and reddish yellow (7. 5YR 6/8) mottles; massive structure; hard when firm when moist; moderately sticky and moderately plastic when wet; few fine pores; lower boundary not seen; very strongly acid (field pH 4.5).

9. Profile C2c

Soil name: Korat series (Detailed Reconnaissance Soil Maps of Sakon Nakhon Province, 1971).
Soil Classification: Fine-loamy, siliceous, isohyperthemic Typic Kandiustults (Soil Survey Staff, 1999)
Location: Phuphan National Park, Kut Bak , Sakon Nakhon, NE Thailand, 8 km WNW of Phuphan National Park Office.
Map Ref: 1: 50,000 Series L7017 Sheet 5743/11 Amphoe Kut Bak
Grid Ref: 834895 (N 17 ° 04'. 441, E 103 ° 54'. 155)
Described by: S. Soisungwan Date: 22. 04. 01
Elevation: 210m Slope: 1. 5 ° straight Aspect: 270 ° W
Relief: Undulating middle alluvial terrace (Quaternary). Midslope leading down to the steam 300 m to W and up onto summit 150m to E.
Parent Material: Old Quaternary river alluvium
Annual rainfall: 1523.1 mm. (period 1975-1995, Meteorological Department, 2000)
Vegetation: There were some species of grass growing in the plot. Abandoned plot, it failed to grow cassava last year.
Land Use: Cassava plot
Soil Surface: Partly slaked, furrowed.
Soil degradation evidence: Slaked on the ridge and capped in furrow.
Soil Variability: Profile lies on midslope position of a soil catena that passes from well drained soils (Typic Kandiustults) on the convex summit to Arenic Kandiustults on the foot slope about 200m from profile.

0-25 cm Ap1
Dark Brown (10YR 4/3) stoneless sandy loam; weak fine and medium subangular blocky; soft when dry; very friable when moist; non-sticky and non-plastic when wet; many very fine fibrous roots; clear wavy boundary; medium acid (field pH 6. 0).

25-30/35 cm Ap2
Dark Brown (10YR 4/3) and light brown (7. 5YR 6/4) stoneless sandy loam; massive structure; soft when dry; very friable when moist; non-sticky and non-plastic when wet; few fine fibrous roots; abrupt wavy boundary; medium acid (field pH 6. 0).

30/35-55 cm Bt1
Strong brown (7. 5YR 5/6) stoneless sandy loam; massive structure; hard when dry; friable when moist; slightly sticky and slightly plastic when wet; common fine pores; few fine fibrous roots; gradual smooth boundary; (field pH 6. 0).

55-80 cm Bt2
Strong brown (7. 5YR 5/8) moist stoneless sandy clay loam; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; some termite holes; gradual smooth boundary; strongly acid (field pH 5. 5).

80-115 cm Bt3
Reddish yellow (5YR 6/6) moist stoneless sandy clay loam; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; few medium woody roots; some termite holes; some pieces of charcoal; gradual smooth boundary; very strongly acid (field pH 4. 5).

115-150 cm Bt4
Reddish yellow (5YR 6/8) moist stoneless sandy clay loam with few fine distinct pink (7. 5YR 8/4) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; few fine fibrous roots; gradual smooth boundary; very strongly acid (field pH 4. 5).

150-180 cm + Bt5
Reddish yellow (5YR 6/8) moist stoneless sandy clay loam with common fine distinct pink (7. 5YR 8/4) mottles; massive structure; hard when firm when moist; moderately sticky and moderately plastic when wet; few fine pores; few fine fibrous roots; some termite holes; lower boundary not seen; very strong acid (field pH 5. 0).

10. Profile S1a

Soil name: Korat series (Detailed Reconnaissance Soil Maps of Udon Thani Province, 1972).
Soil Classification: Fine-loamy, siliceous, isohyperthemic Oxyaquic Kandiustults (Soil Survey Staff, 1999)
Location: Non Sombun, ChaiWan, Udon Thani, NE Thailand, 27km NEE of Kumphawapi District.
Map Ref: 1: 50,000 Series L7017 Sheet 5643/II Ban Kham Kho
Grid Ref: 183973 (N 17° 09'. 414, E 103° 17'. 587)
Described by: S. Soisungwan Date: 31. 03. 01
Elevation: 230m Slope: 2° straight Aspect: 180° S
Relief: Undulating middle alluvial terrace (Quaternary). Midslope leading down to concave depression 300 m to S and up onto summit 500 m to N.
Parent Material: Old Quaternary river alluvium
Annual rainfall: 1133.6 mm. (period 1987-1995, Meteorological Department, 2000)
Vegetation: Formerly Deciduous Forest cleared for sugarcane.
Land Use: Sugarcane plot with occasionally original forest trees in the fields.

Soil Surface: Furrowed, bunt before harvesting, and some earthworm activities.
Soil degradation evidence: partly slaked and moderately weak crust surface.
Soil Variability: Profile lies on lowerslope position of a soil catena that passes from well drained soils (Haplic Kandiustults) on the summit to moderately drained soils (Oxyaquic Kandiustults) on the midslope and to Arenic soils and the steam in the concave depression.

0-25cm Ap1
Very dark grayish brown (10YR 3/2) and pink (7. 5 YR 7/4) moist stoneless sandy loam; weak fine and medium subangular blocky; soft when dry; very friable when moist; non-sticky and non-plastic when wet; many very fine and fine fibrous roots; ; sharp wavy boundary; very strongly acid (field pH 5. 0).

25-35/40 cm E
Light brown (7. 5YR 6/4) moist stoneless sandy loam; massive structure; soft when dry; very friable when moist; non-sticky and non-plastic when wet; few very fine fibrous roots; clear wavy boundary; strongly acid (field pH 5. 5).

35/40-70 cm Bt1
Reddish yellow (7. 5YR 6/6) moist stoneless sandy clay loam; massive structure; hard when dry; friable when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; some termite holes; gradual smooth boundary; very strongly acid (field pH 5. 0).

70-90 cm Bt2
Reddish yellow (7. 5YR 6/6) moist stoneless sandy clay loam with common fine distinct yellowish red (5YR 5/8) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; some pieces of charcoal; gradual smooth boundary; very strongly acid (field pH 4. 5).

90-140 cm Btg1
Reddish yellow (7. 5YR 6/8) sandy clay loam with common fine and medium distinct red (2. 5YR 4/8) and pinkish gray (7. 5YR 7/2) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; gradual smooth boundary; very strongly acid (field pH 5. 0).

140-180 cm + Btg2
Pinkish gray (7. 5YR 7/2) moist stoneless sandy clay loam with many fine and medium distinct red (2. 5YR 4/8) and yellow (10YR 7/6) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine roots; lower boundary not seen; very strongly acid (field pH 5. 0).

11. Profile S1b

Soil name: Korat series (Detailed Reconnaissance Soil Maps of Udon Thani Province, 1972).
Soil Classification: Fine-loamy, siliceous, isohyperthemic (Oxyaquic) Kandiustults (Soil Survey Staff, 1998)
Location: Kham Mong, Si That, Udon Thani, NE Thailand, 33km ESE of Amphoe Kumphawapi.
Map Ref: 1: 50,000 Series L7017 Sheet 5643/II Ban Kham Kho
Grid Ref: 242817 (N 17 ° 00'. 914, E 103 ° 20'. 907)
Described by: S. Soisungwan Date: 15. 03. 01
Elevation: 210m Slope: 1. 5 ° straight Aspect: 270 ° W
Relief: Undulating middle alluvial terrace (Quaternary). Midslope leading down to concave depression 200 m to W and up onto summit 300 m to E.
Parent Material: Old Quaternary river alluvium
Annual rainfall: 1086. 6 mm. (period 1987-1995, Meteorological Department, 2000)
Vegetation: Formerly Deciduous Dipterocarp Forest cleared for sugarcane.
Land Use: Sugarcane plot with occasionally original forest trees in the fields.
Soil Surface: Furrowed, burnt before harvesting
Soil degradation evidence: partly slaked on ridges, capped on furrow, moderately weak crust at surface and some gully erosion on foot slope.
Soil Variability: Profile lies on midslope position of a soil catena that passes from well drained soils (Haplic Kandiustults) on the summit to Arenic soils in the concave depression

0-20 cm Ap1
Very dark greyish brown (10YR 3/2) stoneless loamy sand; weak fine and medium subangular blocky; soft when dry; very friable when moist; non-sticky and non-plastic when wet; many very fine and fine fibrous roots; sharp wavy boundary; medium acid
(field pH 6. 0).

20-35cm E
Light brown (7. 5YR 6/4) stoneless sandy loam; massive structure; soft when dry; very friable when moist; non-sticky and non-plastic when wet; few fine fibrous roots; clear wavy boundary; slightly acid (field pH 6. 5).

35-60 cm Bt1
Strong brown (7. 5YR 5/6) stoneless sandy loam; massive structure; slightly hard when dry; friable when moist; slightly sticky and slightly plastic when wet; many fine pores; few fine fibrous roots; some termite holes; gradual smooth boundary; slightly acid (field pH 6. 5).

60-95 cm Bt2
Strong brown (7. 5YR 5/8) moist stoneless sandy clay loam; massive structure; slightly hard when dry; friable when moist; moderately sticky and moderately

plastic when wet; many fine pores; few fine woody roots; some termite holes; gradual smooth boundary; strongly acid (field pH 5. 5).

95-130 cm Btgl
Reddish yellow (7. 5YR 6/6) moist stoneless sandy clay loam with few fine distinct very pale brown (10YR 7/4) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; gradual smooth boundary; very strongly acid (field pH 5. 0).

130-180 cm+ Btg2
Very pale brown (10YR 7/4) moist stoneless sandy clay loam with common very fine distinct strong brown (7. 5YR 5/8) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; lower boundary not seen; very strongly acid (field pH 4. 5).

12. Profile S1c

Soil name: Korat series (Detailed Reconnaissance Soil Maps of Udon Thani Province, 1972).
Soil Classification: Fine-loamy, siliceous, isohyperthemic Typic Kandiustults (Soil Survey Staff, 1999)
Location: Kham Mong, Sri That, Udon Thani, NE Thailand, 33km ESE of Amphoe Kumphawapi.
Map Ref: 1:50,000 Series L7017 Sheet 5643/II Ban Kham Kho
Grid Ref: 248822 (N 17° 01'. 177, E 103° 21'.103)
Described by: S. Soisungwan Date: 17. 03. 01
Elevation: 210 m Slope: 2° straight Aspect: 230° SWW
Relief: Undulating middle alluvial terrace (Quaternary). Midslope leading down to concave depression 200 m to SWW and up onto summit 300 m to NEE.
Parent Material: Old Quaternary river alluvium
Annual rainfall: 1086. 6 mm. (period 1987-1995, Meteorological Department, 2000)
Vegetation: Formerly Deciduous Dipterocarp Forest cleared for sugarcane.
Land Use: Sugarcane plot with occasionally original forest trees in the fields.
Soil Surface: Furrowed, burnt before harvesting
Soil degradation evidence: Partly slaked on ridges, capped in furrow, moderately weak crust at surface and some gully erosion on foot slope.
Soil Variability: Profile lies on midslope position of a soil catena that passes from well drained soils (Haplic Kandiustults) on the summit to Arenic soils in the concave depression

0-15 cm Ap
Very dark greyish brown (10YR 3/2) and Light brown (7. 5YR 6/4) stoneless loamy sand; weak fine and medium sub angular blocky; soft when dry; very friable when moist; non-sticky and non-plastic when wet; many very fine and few fine fibrous roots; sharp wavy boundary; strongly acid (field pH 5. 5).

15-30cm E
Light brown (7. 5YR 6/4) stoneless loamy sand; massive structure; soft when dry; very friable when moist; non-sticky; non-plastic when wet; few very fine fibrous roots; abrupt wavy boundary; medium acid (field pH 6. 0).

30-45 cm Bt1
Strong brown (7. 5YR 5/6) stoneless sandy loam; massive structure; hard when dry; friable when moist; slightly sticky and slightly plastic when wet; common fine pores; few very fine fibrous roots; some termite holes; clear wavy smooth boundary; slightly acid (field pH 6. 5).

45-85 cm Bt2
Strong brown (7. 5YR 5/6) moist stoneless sandy clay loam; massive structure; hard when dry; friable when moist; slightly sticky and moderately plastic when wet; common fine pores; few very fine fibrous roots; gradual smooth boundary; strongly acid (field pH 5. 5).

85-110 cm Bt3
Strong brown (7. 5YR 5/6) moist stoneless sandy clay loam with few very fine distinct brownish yellow (10YR 6/6) mottles; massive structure; hard when dry; friable when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; gradual smooth boundary; very strongly acid (field pH 5. 0).

110-140 cm Bt4
Reddish yellow (7. 5YR 6/6) moist stoneless sandy clay loam with few very fine distinct brownish yellow (10YR 6/6) and yellowish red (5YR 5/8) mottles; massive structure; hard when dry; friable when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; gradual smooth boundary; very strongly acid (field pH 5. 0).

140-180 cm+ Btg
Brownish yellow (10YR 6/6) moist stoneless sandy clay loam with many fine distinct yellowish red (5YR 5/8) and pinkish grey (7. 5YR 7/1) mottles; massive structure; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; lower boundary not seen; strongly acid (field pH 5. 5).

13. Profile S2a

Soil name: Korat series (Detailed Reconnaissance Soil Maps of Udon Thani Province, 1972).
Soil Classification: Fine-loamy, siliceous, isohyperthemic Oxyaquic Kandiustults (Soil Survey Staff, 1999)
Location: Hinloeng, Kumphawapi, Udon Thani, NE Thailand, 12 km ESE of Amphoe Kumphawapi.
Map Ref: 1: 50,000 Series L7017 Sheet 5643/111 Amphoe Kumphawapi

Grid Ref: 002889 (N 17° 04'. 735, E 103° 07'. 383)
Described by: S. Soisungwan Date: 30. 03. 01
Elevation: 214m Slope: 2. 5° straight Aspect: 300° WNW
Relief: Undulating middle alluvial terrace (Quaternary). Lower slope leading down to concave depression 150 m to WNW and up onto summit 300m to ESE.
Parent Material: Old Quaternary river alluvium
Annual rainfall: 1136. 6 mm. (period 1975-1995, Meteorological Department, 2000)
Vegetation: Formerly Deciduous Dipterocarp forest cleared for sugarcane.
Land Use: Sugarcane plot with few original forest trees in the fields.
Soil Surface: Furrowed, burnt plot before harvesting,
Soil degradation evidence: Partly slaked on ridges, capped in furrow, moderately weak crust at surface.
Soil Variability: Profile lies on lower slope position of a soil catena that passes from well drained soils (Typic Kandiustults) on the convex summit to moderately drained soils (Oxyaquic Kandisustults) on the lower slope to Arenic Kandiaqults in the concave depression.

0-15/25 cm Ap
Dark Brown (10YR 4/3) stoneless sandy loam; very weak fine and medium subangular blocky; soft when dry; very friable when moist; non-sticky and non-plastic when wet; common very fine fibrous roots; some pieces of charcoal; sharp wavy boundary; slightly acid (field pH 6. 5).

10/15-25/35cm E
Light brown (7. 5YR 6/4) stoneless sand loam; massive structure; soft when dry; very friable when moist; non-sticky; non-plastic when wet; few fine fibrous roots; gradual smooth boundary; medium acid (field pH 6. 0).

25/35-50 cm Bt1
Strong brown (7. 5YR 5/6) stoneless sandy loam; massive structure; hard when dry; friable when moist; slightly sticky and slightly plastic when wet; common fine pores; few fine roots; gradual smooth boundary; strongly acid (field pH 5. 5).

50-70 cm Bt2
Strong brown (7. 5YR 5/8) moist stoneless sandy clay loam; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; gradual smooth boundary; very strongly acid (field pH 5. 0).

70-90 cm Bt3
Reddish yellow (7. 5YR 6/6) moist stoneless sandy clay loam with common very fine distinct yellowish red (5YR 5/8) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; few fine fibrous roots; gradual smooth boundary; very strongly acid (field pH 5. 0).

90-130 cm Btg1
Reddish yellow (7. 5YR 7/8) moist stoneless sandy clay loam with few fine distinct yellowish red (5YR 5/8) and pinkish gray (7. 5YR 7/2) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; gradual smooth boundary; very strongly acid (field pH 5. 0).

130-160 cm Btg2
Reddish yellow (7. 5YR 7/8) moist stoneless sandy clay loam with common fine distinct pinkish gray (7. 5YR 7/2) and few fine distinct yellowish red (5YR 5/8) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; few fine fibrous roots; gradual smooth boundary; very strongly acid (field pH 5. 0).

160-180 cm + Btg3
Pinkish gray (7. 5YR 6/2) moist stoneless sandy clay loam with common fine distinct reddish yellow (7. 5YR 6/8) and few fine distinct yellowish red (5YR 5/8) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; few fine fibrous roots; lower boundary not seen; very strongly acid (field pH 5. 0).

14. Profile S2b

Soil name: Korat series (Detailed Reconnaissance Soil Maps of Udon Thani Province, 1972).
Soil Classification: Fine-loamy, siliceous, isohyperthemic Typic Kandiustults (Soil Survey Staff, 1999)
Location: Hinloeng, Kumphawapi, Udon Thani, NE Thailand, 12 km ESE of Amphoe Kumphawapi.
Map Ref: 1: 50,000 Series L7017 Sheet 5643/111 Amphoe Kumphawapi
Grid Ref: 006886 (N 17° 04'. 506, E 103° 07'. 591)
Described by: S. Soisungwan Date: 10. 03. 01
Elevation: 214m Slope: 2. 9° straight Aspect: 180° S
Relief: Undulating middle alluvial terrace (Quaternary). Midslope leading down to concave depression 200 m to S and up onto summit 300 m to N.
Parent Material: Old Quaternary river alluvium
Annual rainfall: 1136. 6 mm. (period 1975-1995, Meteorological department, 2000)
Vegetation: Formerly Deciduous forest cleared for sugarcane.
Land Use: Sugarcane plot with occasionally original forest trees in fields.
Soil Surface: Furrowed, bunt plot before harvesting,
Soil degradation evidence: Partly slaked on ridges, capped in furrow, moderately weak crust at surface and some gully erosion about 60m from profile to E.
Soil Variability: Profile lies on midslope position of a soil catena that passes from well drained soils (Typic Kandiustults) on the convex summit to moderately drained soils (Oxyaquic Kandisustults) on the midslope to Arenic Kandiaqults in the concave depression.

0- 20 cm Ap
Dark Brown (10YR 4/3) stoneless loamy sand; very weak fine and medium subangular blocky; soft when dry; very friable when moist; non-sticky and non-plastic when wet; many very fine and fine fibrous roots; some pieces of charcoal; abrupt smooth boundary; slightly acid (field pH 6. 5).

20-45cm E
Light brown (7. 5YR 6/4) stoneless loamy sand; massive structure; soft when dry; very friable when moist; non-sticky and non-plastic when wet; common fine and medium fibrous roots; clear smooth boundary; strongly acid (field pH 5. 5).

45-70 cm Bt1
Reddish yellow (7. 5YR 6/6) stoneless sandy loam; massive structure; slightly hard when dry; friable when moist; slightly sticky and slightly plastic when wet; few fine pores; few fine fibrous roots; clear smooth boundary; strongly acid (field pH 5. 5).

70-103 cm Bt2
Reddish yellow (7. 5YR 6/6) moist stoneless sandy clay loam; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; gradual smooth boundary; very strongly acid (field pH 4. 5).

103-130 cm Btg1
Reddish yellow (7. 5YR 6/6) moist stoneless sandy clay loam with common very fine distinct yellowish red (5YR 5/8) and few fine distinct pinkish grey (7. 5YR 7/2) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; gradual smooth boundary; very strongly acid (field pH 4. 5).

130-165 cm Btg2
Reddish yellow (7. 5YR 6/6) moist stoneless sandy clay loam with few fine distinct yellowish red (5YR 5/8) and light yellowish brown (10YR 6/4) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; gradual wavy boundary; very strongly acid (field pH 5. 0).

165-180 cm + Btg3
Very pale brown (10YR 7/3) moist stoneless sandy clay loam with common fine distinct common fine distinct yellowish red (5YR 5/8) and reddish yellow (7. 5YR 6/6) mottles; massive structure; hard when dry; friable when moist; moderately sticky and moderately plastic when wet; few fine pores; few fine fibrous roots; gradual smooth boundary; very strongly acid (field pH 5. 0).

15. Profile S2c

Soil name: Korat series (Detailed Reconnaissance Soil Maps of Udon Thani Province, 1972).

Soil Classification: Fine-loamy, siliceous, isohyperthemic Typic Kandiustults (Soil Survey Staff, 1999)
Location: Hinloeng, Kumphawapi, Udon Thani, NE Thailand, 12 km ESE of Amphoe Kumphawapi.
Map Ref: 1:50,000 Series L7017 Sheet 5643/111 Amphoe Kumphawapi
Grid Ref: 019887 (N 17° 04'. 580, E 103° 08'. 256)
Described by: S. Soisungwan Date: 27. 03. 01
Elevation: 200m Slope: 2. 7° straight Aspect: 270° W
Relief: Undulating middle alluvial terrace (Quaternary). Midslope leading down to concave depression 200 m to W and up onto summit 250 m to E.
Parent Material: Old Quaternary river alluvium
Annual rainfall: 1136. 6 mm. (period 1975-1995, Meteorological Department, 2000)
Vegetation: Formerly Deciduous forest cleared for sugarcane.
Land Use: Sugarcane plot with occasionally original forest trees in the fields.
Soil Surface: Furrowed, burnt plot before harvesting.
Soil degradation evidence: Partly slaked on ridges, capped in furrow, moderately weak crust at surface and some gully erosion about 40 m from profile to N.
Soil Variability: Profile lies on midslope position of a soil catena that passes from well drained soils (Typic Kandiustults) on the convex summit to moderately drained soils (Oxyaquic Kandisustults) on the midslope to Arenic Kandiaqults in the concave depression.

0- 30/40 cm Ap
Dark Brown (10YR 4/3) stoneless loamy sand; very weak fine and medium subangular blocky; soft when dry; very friable when moist; non-sticky and non-plastic when wet; many fine fibrous roots; sharp wavy boundary; slightly acid (field pH 6. 0).

30/40-40/50 cm E
Light brown (7. 5YR 5/4) stoneless loamy sand; massive structure; soft when dry; very friable when moist; non-sticky and non-plastic when wet; few fine fibrous roots and common coarse woody roots; some termite holes; some pieces of charcoal; clear wavy boundary; slightly acid (field pH 6. 5).

40/50-60/70 cm Bt1
Strong brown (7. 5YR 5/6) moist stoneless sandy loam; massive structure; hard when dry; friable when moist; slightly sticky and slightly plastic when wet; few fine pores; few fine fibrous roots and common coarse roots; graul wavy boundary; slightly acid (field pH 6. 0).

60/70-90 cm Bt2
Strong brown (7. 5YR 5/6) moist stoneless sandy clay loam; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few very fine fibrous roots; gradual smooth boundary; strongly acid (field pH 5. 5).

90-110 cm Bt3
Reddish yellow (7. 5YR 6/8) moist stoneless sandy clay loam with few fine distinct light yellowish brown (10YR 6/4) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few very fine fibrous roots; some termite holes; gradual smooth boundary; very strongly acid (field pH 5. 0).

110-130 cm Btg1
Reddish yellow (7. 5YR 6/8) moist stoneless sandy clay loam with common fine distinct light yellowish brown (10YR 6/4) and light brown (7.5YR 6/4) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; gradual smooth boundary; very strongly acid (field pH 5. 0).

130-160 cm Btg2
Light yellowish brown (10YR 6/4) moist stoneless sandy clay loam with common fine distinct common fine distinct yellowish red (5YR 5/8) and pinkish grey (7. 5YR 7/2) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; few fine fibrous roots; some termite holes; gradual smooth boundary; strongly acid (field pH 5. 5).

160-180 cm + Btg3
Light yellowish brown (7. 5YR 6/4) moist stoneless sandy clay loam with common fine distinct yellowish red (5YR 5/8) and few fine faint grey (10 YR 6/1) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; few fine fibrous roots; lower boundary not seen; very strongly acid (field pH 5. 0).

16. Profile S3a

Soil name: Korat series (Detailed Reconnaissance Soil Maps of Udon Thani Province, 1972).
Soil Classification: Fine-loamy, siliceous, isohyperthemic Typic Kandiustults (Soil Survey Staff, 1999)
Location: Na Baek, Kumphawapi, Udon Thani, NE Thailand, 4 km ESE of Amphoe Kumphawapi.
Map Ref: 1: 50,000 Series L7017 Sheet 5643/111 Amphoe Kumphawapi
Grid Ref: 941913 (N 17° 05'. 852, E 103° 03'. 847)
Described by: S. Soisungwan Date: 2. 05. 01
Elevation: 200m Slope: 2. 5° straight Aspect: 60° NEE
Relief: Undulating middle alluvial terrace (Quaternary). Midslope leading down to concave depression 150 m to NEE and up onto summit 250m to SWW.
Parent Material: Old Quaternary river alluvium
Annual rainfall: 1136. 6 mm. (period 1975-1995, Meteorological Department, 2000)
Vegetation: Formerly Deciduous forest cleared for sugarcane.
Land Use: Sugarcane plot

Soil Surface: Furrowed, burnt plot before harvesting,
Soil degradation evidence: Partly slaked on ridges, capped in furrows, moderately weak crust at surface and some gully erosion about 50 m from profile to E.
Soil Variability: Profile lies on midslope position of a soil catena that passes from well drained soils (Typic Kandiustults) on the convex summit to moderately drained soils (Oxyaquic Arenic Kandisustults) on the lower slope to Arenic Kandiaqults in the concave depression.

0- 25 cm Ap
Brown (10YR 5/4) stoneless loamy sand; very weak fine and medium subangular blocky; soft when dry; very friable when moist; non-sticky and non-plastic when wet; few fine pore; common very fine fibrous roots; Abrupt wavy boundary; Strongly acid (field pH 5. 5).

25-40 cm Bt1
Strong brown (7. 5YR 5/8) stoneless sandy clay loam with some patches of yellow (10 YR 7/6); massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; few fine fibrous roots; some termite holes; clear smooth boundary; very strongly acid (field pH 5. 0).

40-85 cm Bt2
Reddish yellow (5YR 7/8) stoneless sandy clay loam with some patches of yellow (10 YR 7/6); massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; gradual wavy boundary; very strongly acid (field pH 5. 0).

85-110 cm Bt3
Reddish yellow (5YR 6/8) moist stoneless sandy clay loam with some patches of yellow (10 YR 7/8); massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few very fine fibrous roots; gradual smooth boundary; very strongly acid (field pH 5. 0).

110-135 cm Bt4
Reddish yellow (5YR 6/8) moist stoneless sandy clay loam with some patches of yellow (10 YR 7/6); and few fine distinct very pale brown (10YR 8/4) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few very fine fibrous roots; some termite holes; gradual smooth boundary; very strongly acid (field pH 5. 0).

135-160 cm Btg1
Reddish yellow (5YR 6/8) moist stoneless sandy clay loam with some patches of very pale brown (10 YR 7/4) and few fine distinct light grey (10YR 7/1) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; gradual smooth boundary; very strongly acid (field pH 5. 0).

160-180 cm + Btg2
Very pale brown (10YR 7/4) moist stoneless sandy clay loam with common fine distinct common fine distinct reddish yellow (5YR 6/8) and light grey (7. 5YR 7/1) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; few fine fibrous roots; lower boundary not see; strongly acid (field pH 5. 5).

17. Profile S3b

Soil name: Korat series (Detailed Reconnaissance Soil Maps of Udon Thani Province, 1972).
Soil Classification: Fine-loamy, siliceous, isohyperthemic Typic Kandiustults (Soil Survey Staff, 1999)
Location: Na Baek, Kumphawapi, Udon Thani, NE Thailand, 4 km ESE of Amphoe Kumphawapi.
Map Ref: 1: 50,000 Series L7017 Sheet 5643/111 Amphoe Kumphawapi
Grid Ref: 943916 (N 17 ° 05'. 995, E 103 ° 03'. 932)
Described by: S. Soisungwan Date: 3. 05. 01
Elevation: 200m Slope: 2 ° straight Aspect: 210 ° SSW
Relief: Undulating middle alluvial terrace (Quaternary). Lower slope leading down to concave depression 120 m to SSW and up onto summit 200m to NNE.
Parent Material: Old Quaternary river alluvium
Annual rainfall: 1136. 6 mm. (period 1975-1995, Meteorological department, 2000)
Vegetation: Formerly Deciduous forest cleared for sugarcane.
Land Use: Sugarcane plot
Soil Surface: Furrowed, bunt plot before harvesting,
Soil degradation evidence: Partly slaked on ridges, capped in furrow, moderately weak crust at surface, some rill erosion within the plot and some gully erosion about 50 m from profile to W.
Soil Variability: Profile lies on midslope position of a soil catena that passes from well drained soils (Typic Kandiustults) on the convex summit to moderately drained soils (Oxyaquic Arenic Kandisustults) on the lower slope to Arenic Kandiaqults in the concave depression.

0-15 cm Ap
Dark Brown (10YR 4/3) stoneless loamy sand; very weak fine and medium subangular blocky; soft when dry; very friable when moist; non-sticky and non-plastic when wet; many very fine and fine and few medium fibrous roots; clear wavy boundary; slightly acid (field pH 6.0).

15-25 cm E
Dark Brown (10YR 4/3) and light brown (7. 5YR 6/4) moist stoneless loamy sand; massive structure; soft when dry; firm when moist; non- sticky and non-plastic when wet; few fine fibrous roots; abrupt wavy boundary; strongly acid (field pH 5. 5).

25-45 cm Bt1
Strong brown (7. 5YR 4/6) moist stoneless sandy loam with some patches of yellow (10 YR 7/6); massive structure; slightly hard when dry; friable when moist; slightly sticky and slightly plastic when wet; few fine pores; few fine fibrous roots; some pieces of charcoal; gradual wavy boundary; very strongly acid (field pH4. 5).

45-70 cm Bt2
Reddish yellow (5YR 6/8) stoneless sandy clay loam; massive structure; hard when dry; firm when moist; slightly sticky and moderately plastic when wet; few fine pores; few fine fibrous roots; gradual smooth boundary; very strongly acid (field pH 5. 0).

70-110 cm Bt3
Reddish yellow (5YR 6/8) moist stoneless sandy clay loam with some patches of yellow (10 YR 7/6); massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; few fine fibrous roots; some termite holes; gradual smooth boundary; very strongly acid (field pH 5. 0).

110-140 cm Btg1
Reddish yellow (5YR 6/8) moist stoneless sandy clay loam with some patches of very pale brown (10 YR 7/6) and few fine distinct pinkish gray (10YR 7/2) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; some termite holes; gradual smooth boundary; strongly acid (field pH 5. 5).

140-180 cm + Btg2
Reddish yellow (5YR 6/8) moist stoneless sandy clay loam with some patches of very pale brown (10 YR 7/6) and common fine distinct pinkish grey (10YR 7/2) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; some termite holes; lower boundary not seen; strongly acid (field pH 5. 5).

18. Profile S3c

Soil name: Korat series (Detailed Reconnaissance Soil Maps of Udon Thani Province, 1972).
Soil Classification: Fine-loamy, siliceous, isohyperthemic Kanhaplis Haplustult /Typic Kandiustult intergrade (Soil Survey Staff, 1999)
Location: Na Baek, Kumphawapi, Udon Thani, NE Thailand, 4 km ESE of Amphoe Kumphawapi.
Map Ref: 1: 50,000 Series L7017 Sheet 5643/111 Amphoe Kumphawapi
Grid Ref: 938915 (N 17° 05'. 961, E 103° 03'. 650)
Described by: S. Soisungwan Date: 4. 05. 01
Elevation: 200m Slope: 2. 5° straight Aspect: 20° N.
Relief: Undulating middle alluvial terrace (Quaternary). Midslope leading down to concave depression 160 m to N and up onto summit 210m to S.
Parent Material: Old Quaternary river alluvium

Annual rainfall: 1136. 6 mm. (period 1975-1995, Meteorological Department, 2000)
Vegetation: Formerly Deciduous forest cleared for sugarcane.
Land Use: Sugarcane plot
Soil Surface: Furrowed, bunt plot before harvesting,
Soil degradation evidence: partly slaked on ridges, capped in furrow, moderately weak at crust surface.
Soil Variability: Profile lies on midslope position of a soil catena that passes from well drained soils (Typic Kandiustults) on the convex summit to moderately drained soils (Oxyaquic Arenic Kandisustults) on the lower slope to Arenic Kandiaqults in the concave depression.

0-15 cm Ap1
Brown (10YR 5/2) stoneless loamy sand; very weak fine and medium subangular blocky; soft when dry; very friable when moist; non-sticky and non-plastic when wet; many fine fibrous roots; clear wavy boundary; slightly acid (field pH 6. 0).

15-25 cm Ap2
Brown (10YR 5/2) and light brown (7. 5YR 6/4) stoneless loamy sand; massive structure; soft when dry; firm when moist; non- sticky and non-plastic when wet; few fine fibrous roots; abrupt wavy boundary; slightly acid (field pH 6.0).

25-40 cm Bt1
Reddish yellow (7. 5YR 6/8) stoneless sandy loam; massive structure; slightly hard when dry; friable when moist; slightly sticky and slightly plastic when wet; few fine pores; few fine fibrous roots; some termite holes; some pieces of charcoal; gradual smooth boundary; very strongly acid (field pH 5. 0).

40-65 cm Bt2
Reddish yellow (7. 5YR 6/8) moist stoneless sandy clay loam; massive structure; hard when dry; firm when moist; moderately sticky and slightly plastic when wet; common fine pores; few fine fibrous roots; gradual smooth boundary; very strongly acid (field pH 4. 5).

65-100 cm Bt3
Reddish yellow (5YR 6/8) moist stoneless sandy clay loam with some patches of yellow (10 YR 7/6); massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; few fine fibrous roots; gradual smooth boundary; strongly acid (field pH 5. 5).

100-140 cm Bt 4
Reddish yellow (5YR 6/8) moist stoneless sandy clay loam with few fine distinct very pale brown (10YR 7/4) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; common fine pores; some termite holes; gradual smooth boundary; very strongly acid (field pH 5. 0).

140-180 cm + Btg

Reddish yellow (5YR 6/8) moist stoneless sandy clay loam with common fine distinct pale brown (10YR 6/3) mottles; massive structure; hard when dry; firm when moist; moderately sticky and moderately plastic when wet; few fine pores; some termite holes; lower boundary not seen; strongly acid (field pH 5. 5).

B. Analysis physical and chemical data of soil profiles

1. Forest A

Horizon	Ah	A	E	Bt1	Bt2	Btg1	Btg2
Depth (cm)	0-10	10-25	25-35	35-70	70-90	90-140	140-180+
Particle size analysis (%)							
Coarse sand	0.2	0.2	0.2	0.2	0.3	0.3	0.3
Medium sand	8.6	8.2	8.3	6.0	6.6	5.7	7.2
Fine sand	35.9	34.4	32.3	30.9	28.6	28.9	28.8
Very fine sand	29.3	24.0	22.5	21.1	20.5	21.9	21.0
Silt	14.4	21.8	18.5	17.9	20.4	20.6	21.1
Clay	11.7	11.3	18.2	24.0	23.7	22.6	21.7
Texture	sl	sl	sl	scl	scl	scl	scl
Bulk density (Mg m^{-3})	1.50	1.44	1.49	1.43	1.36	1.47	1.54
pHw (1:2.5)	6.0	5.5	5.1	5.1	5.1	5.1	5.1
pHKCl (1:2.5)	4.8	4.0	3.8	3.8	3.8	3.8	3.8
Organic carbon (g kg^{-1})	10.7	3.3	2.1	_	_	_	_
Exchangeable Ca ($cmol^{+}$ kg^{-1})	1.45	_	_	0.27	0.21	0.17	_
Exchangeable Mg ($cmol^{+}$ kg^{-1})	0.73	_	_	0.53	0.46	0.32	_
Exchangeable K ($cmol^{+}$ kg^{-1})	0.09	_	_	0.03	0.04	0.03	_
Exchangeable Na ($cmol^{+}$ kg^{-1})	0.03	_	_	0.03	0.03	0.02	_
Sum of basic cation ($cmol^{+}$ kg^{-1})	2.32	_	_	0.86	0.74	0.54	_
CEC ($cmol^{+}$ kg^{-1})	4.4	_	_	5.1	5.0	5.2	_
Base saturation (%)	53			17	15	10	.

2. Forest B

Horizon	Ah1	A	E	Bt1	Bt2	Btg1	Btg2	Btg3
Depth (cm)	0-10	10-20	20-37/40	37/40-75	75-95	95-130	130-160	160-180+
Particle size analysis (%)								
Coarse sand	0.3	0.2	0.3	0.3	0.2	0.3	0.3	0.3
Medium sand	8.5	6.3	6.8	6.8	5.5	8.2	6.2	7.8
Fine sand	36.4	40.1	37.5	34.0	35.3	29.6	30.6	32.5
Very fine sand	24.3	23.3	24.4	23.1	20.5	20.6	20.5	19.0
Silt	20.6	21.7	20.6	18.1	18.7	18.6	20.6	18.4
Clay	10.0	8.5	10.4	17.8	20.3	22.7	21.9	22.0
Texture	sl	sl	sl	sl	scl	scl	scl	scl
Bulk density (Mg m^{-3})	1.43	1.40	1.47	1.52	1.54	1.54	1.60	1.59
pHw (1:2.5)	6.2	5.5	5.0	4.9	4.9	5.0	5.0	5.1
pHKCl (1:2.5)	5.3	4.2	3.9	3.8	3.8	3.7	3.7	3.8
Organic carbon (g kg^{-1})	6.4	3.5	2.8	_	_	_	_	_
Exchangeable Ca ($cmol^{+}$ kg^{-1})	2.26	_	_	0.44	0.14	0.23	_	_
Exchangeable Mg ($cmol^{+}$ kg^{-1})	0.80	_	_	0.51	0.43	0.49	_	_
Exchangeable K ($cmol^{+}$ kg^{-1})	0.10	_	_	0.04	0.03	0.03	_	_
Exchangeable Na ($cmol^{+}$ kg^{-1})	0.03	_	_	0.03	0.02	0.03	_	_
Sum of basic cation ($cmol^{+}$ kg^{-1})	3.18	_	_	1.01	0.62	0.78	_	_
CEC ($cmol^{+}$ kg^{-1})	4.7	_	_	3.9	5.2	4.8	_	_
Base saturation (%)	67	_	_	26	12	16	_	_

3. Forest C

Horizon	A	E	Bt1	Bt2	Btg1	Btg2	Btg3
Depth (cm)	0-10/15	10/15-25	25-50	50-80	80-110	110-140	140-180+
Particle size analysis (%)							
Coarse sand	0.2	0.2	0.1	0.1	0.1	0.1	0.1
Medium sand	4.2	3.2	2.3	3.4	3.0	2.0	3.9
Fine sand	35.3	37.6	37.0	29.2	30.1	34.1	29.1
Very fine sand	29.1	28.1	22.1	22.0	23.1	22.3	21.0
Silt	21.5	21.4	18.5	18.5	19.8	19.3	18.6
Clay	9.6	9.5	20.1	26.8	23.9	22.1	27.0
Texture	sl	sl	scl	scl	scl	scl	scl
Bulk density (Mg m^{-3})	1.44	1.51	1.50	1.50	1.49	1.54	1.56
pHw (1:2.5)	5.6	5.3	5.4	5.3	5.4	5.3	5.5
pHKCl (1:2.5)	4.3	4.1	4.1	3.9	3.9	4.0	4.0
Organic carbon (g kg^{-1})	5.8	2.3	1.4	_	_	_	_
Exchangeable Ca ($cmol^{+}$ kg^{-1})	0.61	_	_	_	0.69	_	_
Exchangeable Mg ($cmol^{+}$ kg^{-1})	0.45	_	_	_	0.28	_	_
Exchangeable K ($cmol^{+}$ kg^{-1})	0.14	_	_	_	0.17	_	_
Exchangeable Na ($cmol^{+}$ kg^{-1})	0.02	_	_	_	0.02	_	_
Sum of basic cation ($cmol^{+}$ kg^{-1})	1.23	_	_	_	1.16	_	_
CEC ($cmol^{+}$ kg^{-1})	3.3	_	_	_	3.9	_	_
Base saturation (%)	53	_	_	_	30	_	_

4. Cassava 10-20 years A (C1a)

Horizon	Ap	E	Bt1	Bt2	Btg1	Btg2	Btg3
Depth (cm)	0-15	15-30	30-65	65-95	95-120	120-150	150-180+
Particle size analysis (%)							
Coarse sand	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Medium sand	4.1	5.6	4.2	3.8	6.0	4.7	3.7
Fine sand	42.0	37.7	37.0	36.8	31.6	32.9	35.7
Very fine sand	20.8	24.0	24.1	17.1	19.1	21.8	20.0
Silt	26.6	24.5	22.7	20.4	20.2	21.2	22.3
Clay	6.3	8.2	11.9	21.9	22.6	19.4	18.2
Texture	sl	sl	sl	sl	scl	sl	sl
Bulk density (Mg m^{-3})	1.42	1.52	1.56	1.56	1.59	1.60	1.68
pHw (1:2.5)	5.8	6.0	5.9	5.6	5.4	5.3	5.3
pHKCl (1:2.5)	4.9	4.8	4.2	3.9	3.8	3.8	3.8
Organic carbon (g kg^{-1})	4.3	2.1	0.8	_	_	_	_
Exchangeable Ca ($cmol^{+}$ kg^{-1})	1.31	_	_	_	0.72	_	_
Exchangeable Mg ($cmol^{+}$ kg^{-1})	0.31	_	_	_	1.47	_	_
Exchangeable K ($cmol^{+}$ kg^{-1})	0.06	_	_	_	0.07	_	_
Exchangeable Na ($cmol^{+}$ kg^{-1})	0.02	_	_	_	0.01	_	_
Sum of basic cation ($cmol^{+}$ kg^{-1})	1.70	_	_	_	2.27	_	_
CEC ($cmol^{+}$ kg^{-1})	2.5	_	_	_	4.2	_	_
Base saturation (%)	69	_	_	_	54	_	_

5. Cassava 10-20 years B (C1b)

Horizon	Ap	E	Bt1	Bt2	Btg1	Btg2
Depth (cm)	0-30	30-45	45-80	80-110	110-130	130-180+
Particle size analysis (%)						
Coarse sand	0.3	0.1	0.1	0.2	0.1	0.1
Medium sand	7.2	5.6	4.9	6.4	5.2	4.5
Fine sand	36.5	35.5	34.9	30.4	31.4	33.7
Very fine sand	22.2	23.9	18.6	18.8	20.6	17.5
Silt	23.8	24.4	19.6	20.2	20.3	20.9
Clay	10.0	10.7	22.1	24.1	22.4	23.3
Texture	sl	sl	scl	scl	scl	scl
Bulk density (Mg m^{-3})	1.50	1.57	1.55	1.55	1.59	1.60
pHw (1:2.5)	5.5	5.5	5.1	5.0	5.0	4.8
pHKCl (1:2.5)	4.3	4.0	3.7	3.7	3.7	3.7
Organic carbon (g kg^{-1})	6.7	2.3	0.9	_	_	_
Exchangeable Ca ($cmol^+ kg^{-1}$)	1.22	_	_	_	0.27	_
Exchangeable Mg ($cmol^+ kg^{-1}$)	0.67	_	_	_	0.30	_
Exchangeable K ($cmol^+ kg^{-1}$)	0.04	_	_	_	0.04	_
Exchangeable Na ($cmol^+ kg^{-1}$)	0.02	_	_	_	0.02	_
Sum of basic cation ($cmol^+ kg^{-1}$)	1.94	_	_	_	0.62	_
CEC ($cmol^+ kg^{-1}$)	3.5	_	_	_	3.9	_
Base saturation (%)	55	_	_	_	16	_

6. Cassava 10-20 years C (C1c)

Horizon	Ap1	Ap2	Bt1	Bt2	Bt3	Bt4	Btg
Depth (cm)	0-15	15-25/35	25/35-45	45-80	80-120	120-140	140-180+
Particle size analysis (%)							
Coarse sand	1.0	1.2	1.2	1.3	1.4	1.7	1.4
Medium sand	9.5	11.8	10.7	11.3	8.9	10.6	7.3
Fine sand	43.6	39.1	37.1	32.1	35.3	31.9	37.0
Very fine sand	19.6	20.5	18.8	15.9	14.9	14.9	15.8
Silt	17.2	17.3	17.2	15.3	15.5	15.3	15.3
Clay	9.2	10.1	15.0	24.1	24.1	24.6	22.5
Texture	sl	sl	sl	scl	scl	scl	scl
Bulk density (Mg m^{-3})	1.49	1.65	1.61	1.47	1.49	1.53	1.53
pHw (1:2.5)	4.9	5.2	5.5	5.0	5.0	5.0	4.9
pHKCl (1:2.5)	4.4	4.4	4.1	3.8	3.9	3.9	3.9
Organic carbon (g kg^{-1})	3.8	4.2	1.2	_	_	_	_
Exchangeable Ca ($cmol^+ kg^{-1}$)	0.95	_	_	_	0.24	_	_
Exchangeable Mg ($cmol^+ kg^{-1}$)	0.37	_	_	_	0.48	_	_
Exchangeable K ($cmol^+ kg^{-1}$)	0.04	_	_	_	0.03	_	_
Exchangeable Na ($cmol^+ kg^{-1}$)	0.02	_	_	_	0.01	_	_
Sum of basic cation ($cmol^+ kg^{-1}$)	1.38	_	_	_	0.75	_	_
CEC ($cmol^+ kg^{-1}$)	2.2	_	_	_	3.6	_	_
Base saturation (%)	63	_	_	_	21	_	_

7. Cassava 20-30 years A (C2a)

Horizon	Ap	Bt1	Bt2	Bt3	Btg1	Btg2	Btg3
Depth (cm)	0-20	20-35	35-55	55-85	85-110	110-155	155-180+
Particle size analysis (%)							
Coarse sand	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Medium sand	3.1	2.6	4.0	3.3	2.9	3.5	2.5
Fine sand	32.9	32.7	28.7	20.5	22.2	24.6	24.8
Very fine sand	33.3	26.3	26.7	28.1	26.8	24.5	24.9
Silt	22.2	21.8	20.6	21.5	23.9	22.1	22.1
Clay	8.5	16.5	20.0	26.5	24.1	25.2	25.7
Texture	sl	sl	sl	scl	scl	scl	scl
Bulk density (Mg m^{-3})	1.45	1.57	1.52	1.46	1.52	1.49	1.57
pHw (1:2.5)	5.2	5.1	5.1	4.7	4.9	5.1	5.1
pHKCl (1:2.5)	4.2	3.9	3.8	3.8	3.9	3.9	3.9
Organic carbon (g kg^{-1})	3.6	2.3	1.3	_	_	_	_
Exchangeable Ca ($cmol^+$ kg^{-1})	0.56	_	_	_	0.17	_	_
Exchangeable Mg ($cmol^+$ kg^{-1})	0.22	_	_	_	0.52	_	_
Exchangeable K ($cmol^+$ kg^{-1})	0.04	_	_	_	0.06	_	_
Exchangeable Na ($cmol^+$ kg^{-1})	0.01	_	_	_	0.02	_	_
Sum of basic cation ($cmol^+$ kg^{-1})	0.84	_	_	_	0.76	_	_
CEC ($cmol^+$ kg^{-1})	1.6	_	_	_	3.8	_	_
Base saturation (%)	51	_	_	_	20	_	_

8. Cassava 20-30 years B (C2b)

Horizon	Ap	EB	Bt1	Bt2	Btg1	Btg2	Btg3
Depth (cm)	0-30	30-40	40-65	65-105	105-130	130-160	160-180+
Particle size analysis (%)							
Coarse sand	0.8	1.3	1.3	1.5	1.6	1.6	1.7
Medium sand	10.3	8.6	8.2	9.7	8.3	6.2	9.1
Fine sand	39.7	38.5	45.2	29.9	29.5	36.6	27.3
Very fine sand	20.9	20.8	16.1	15.2	15.4	13.3	15.2
Silt	19.1	16.9	15.3	14.8	14.4	13.7	15.1
Clay	9.2	13.9	13.9	28.8	30.9	28.7	31.6
Texture	sl	sl	sl	scl	scl	scl	scl
Bulk density (Mg m^{-3})	1.56	1.63	1.58	1.55	1.58	1.55	1.48
pHw (1:2.5)	5.4	5.8	5.9	5.2	5.1	5.1	5.1
pHKCl (1:2.5)	4.6	4.5	4.3	3.8	3.8	3.9	3.9
Organic carbon (g kg^{-1})	5.1	2.0	1.9	_	_	_	_
Exchangeable Ca ($cmol^+$ kg^{-1})	1.40	_	_	_	0.32	_	_
Exchangeable Mg ($cmol^+$ kg^{-1})	0.39	_	_	_	0.24	_	_
Exchangeable K ($cmol^+$ kg^{-1})	0.03	_	_	_	0.04	_	_
Exchangeable Na ($cmol^+$ kg^{-1})	0.01	_	_	_	0.02	_	_
Sum of basic cation ($cmol^+$ kg^{-1})	1.84	_	_	_	0.61	_	_
CEC ($cmol^+$ kg^{-1})	3.3	_	_	_	3.9	_	_
Base saturation (%)	56	_	_	_	16	_	_

9. Cassava 20-30 years C (C2c)

Horizon	Ap1	Ap2	Bt1	Bt2	Bt3	Bt4	Bt5
Depth (cm)	0-25	25-30/35	30/35-55	55-80	80-115	115-150	150-180+
Particle size analysis (%)							
Coarse sand	1.1	1.1	1.0	1.2	1.3	1.3	1.6
Medium sand	9.2	8.4	10.0	8.8	7.6	10.2	11.0
Fine sand	42.2	40.9	39.6	35.2	36.3	34.5	33.3
Very fine sand	23.9	24.3	21.7	19.2	16.6	18.0	17.4
Silt	14.6	14.7	14.9	13.6	13.3	14.3	13.8
Clay	9.0	10.7	12.8	22.1	25.0	21.7	23.0
Texture	sl	sl	sl	scl	scl	scl	scl
Bulk density (Mg m^{-3})	1.49	1.56	1.55	1.52	1.48	1.48	1.57
pHw (1:2.5)	5.3	5.2	5.4	5.0	5.0	5.0	5.1
pHKCl (1:2.5)	4.2	4.2	4.1	3.9	3.9	3.9	3.9
Organic carbon (g kg^{-1})	2.7	2.1	1.1	_	_	_	_
Exchangeable Ca ($cmol^+$ kg^{-1})	0.62	_	_	_	0.06	_	_
Exchangeable Mg ($cmol^+$ kg^{-1})	0.23	_	_	_	0.25	_	_
Exchangeable K ($cmol^+$ kg^{-1})	0.01	_	_	_	0.02	_	_
Exchangeable Na ($cmol^+$ kg^{-1})	0.02	_	_	_	0.02	_	_
Sum of basic cation ($cmol^+$ kg^{-1})	0.87	_	_	_	0.34	_	_
CEC ($cmol^+$ kg^{-1})	1.8	_	_	_	3.3	_	_
Base saturation (%)	50	_	_	_	10	_	_

10. Sugarcane10-20 years A (S1a)

Horizon	Ap	E	Bt1	Bt2	Btg1	Btg2
Depth (cm)	0.25	25-35/40	35/40-70	70-90	90-140	140-180+
Particle size analysis (%)						
Coarse sand	0.6	0.6	0.5	0.8	0.8	1.2
Medium sand	12.6	10.7	8.2	11.7	10.1	7.4
Fine sand	39.2	36.9	34.9	30.0	30.3	29.0
Very fine sand	20.8	20.7	16.9	15.3	16.9	13.8
Silt	19.1	20.9	24.0	15.7	14.6	14.4
Clay	8.2	10.3	15.5	26.6	27.5	34.1
Texture	sl	sl	sl	scl	scl	scl
Bulk density (Mg m^{-3})	1.53	1.79	1.47	1.56	1.59	1.66
pHw (1:2.5)	5.0	5.4	5.5	5.1	5.2	5.3
pHKCl (1:2.5)	4.2	4.3	4.1	3.9	3.8	3.9
Organic carbon (g kg^{-1})	3.4	0.8	1.6	_	_	_
Exchangeable Ca ($cmol^+$ kg^{-1})	0.71	_	_	0.62	0.90	1.24
Exchangeable Mg ($cmol^+$ kg^{-1})	0.21	_	_	1.15	0.75	1.5
Exchangeable K ($cmol^+$ kg^{-1})	0.05	_	_	0.05	0.07	0.05
Exchangeable Na ($cmol^+$ kg^{-1})	0.03	_	_	0.02	0.03	0.03
Sum of basic cation ($cmol^+$ kg^{-1})	1.00	_	_	1.85	1.75	2.82
CEC ($cmol^+$ kg^{-1})	2.2	_	_	4.0	4.1	5.1
Base saturation (%)	45	_	_	46	42	55

11.Sugarcane10-20 years B (S1b)

Horizon	Ap1	E	Bt1	Bt2	Btg1	Btg2
Depth (cm)	0-20	20-35	35-60	60-95	95-130	130-180+
Particle size analysis (%)						
Coarse sand	0.1	0.1	0.1	0.1	0.1	0.2
Medium sand	9.3	7.6	5.1	8.6	7.0	6.7
Fine sand	49.7	48.5	51.8	40.1	40.1	45.5
Very fine sand	18.8	19.0	12.0	14.7	15.7	13.1
Silt	14.8	13.9	7.3	16.4	12.7	12.1
Clay	7.3	11.0	23.6	20.2	24.4	22.3
Texture	ls	sl	scl	scl	scl	scl
Bulk density (Mg m^{-3})	1.43	1.55	1.61	1.49	1.48	1.49
pHw (1:2.5)	5.9	6.3	5.9	5.1	4.9	4.8
pHKCl (1:2.5)	5.3	5.0	4.5	3.9	3.9	3.9
Organic carbon (g kg^{-1})	4.6	1.2	1.6	–	–	–
Exchangeable Ca (cmol^{+} kg^{-1})	1.31	–	–	0.13	0.22	0.35
Exchangeable Mg (cmol^{+} kg^{-1})	0.33	–	–	0.86	0.90	0.93
Exchangeable K (cmol^{+} kg^{-1})	0.08	–	–	0.04	0.05	0.06
Exchangeable Na (cmol^{+} kg^{-1})	0.02	–	–	0.02	0.02	0.02
Sum of basic cation (cmol^{+} kg^{-1})	1.74	–	–	1.05	1.18	1.36
CEC (cmol^{+} kg^{-1})	3.0	–	–	2.6	3.2	2.9
Base saturation (%)	57	–	–	40	37	47

12. Sugarcane10-20 years C (S1c)

Horizon	Ap1	E	Bt1	Bt2	Bt3	Bt4	Btg
Depth (cm)	0-15	15-30	30-45	45-85	85-110	110-140	140-180+
Particle size analysis (%)							
Coarse sand	0.2	0.1	0.1	0.2	0.1	0.2	0.3
Medium sand	12.0	9.7	7.4	9.5	9.8	7.7	10.9
Fine sand	48.4	50.0	49.9	38.5	39.4	42.2	38.3
Very fine sand	18.1	17.8	16.6	14.8	14.7	13.4	14.0
Silt	15.3	15.7	15.5	14.1	13.4	14.1	14.0
Clay	6.0	6.7	10.5	23.1	22.6	22.4	22.5
Texture	ls	ls	sl	scl	scl	scl	scl
Bulk density (Mg m^{-3})	1.48	1.68	1.48	1.57	1.61	1.63	1.67
pHw (1:2.5)	5.6	5.9	5.7	4.5	4.7	5.0	5.1
pHKCl (1:2.5)	4.6	4.6	4.1	3.9	4.1	4.1	4.1
Organic carbon (g kg^{-1})	3.7	1.2	1.3	–	–	–	–
Exchangeable Ca (cmol^{+} kg^{-1})	0.64	–	–	0.51	0.63	0.76	0.95
Exchangeable Mg (cmol^{+} kg^{-1})	0.20	–	–	1.09	1.27	1.04	0.95
Exchangeable K (cmol^{+} kg^{-1})	0.03	–	–	0.05	0.04	0.04	0.07
Exchangeable Na (cmol^{+} kg^{-1})	0.02	–	–	0.02	0.02	0.03	0.04
Sum of basic cation (cmol^{+} kg^{-1})	0.89	–	–	1.67	1.97	1.87	2.01
CEC (cmol^{+} kg^{-1})	1.3	–	–	3.14	3.08	3.04	3.06
Base saturation (%)	72	–	–	53	64	61	66

13. Sugarcane 30-40 years A (S2a)

Horizon	Ap1	E	Bt1	Bt2	Bt3	Btg1	Btg2	Btg3
Depth (cm)	0-15/25	15/25-25/30	25/30-50	50-70	70-90	90-130	130-160	160-180+
Particle size analysis (%)								
Coarse sand	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Medium sand	5.6	3.8	5.4	5.0	3.1	7.6	4.1	3.2
Fine sand	41.8	42.0	38.4	41.9	37.7	35.4	30.1	30.6
Very fine sand	27.1	22.9	24.0	21.4	19.6	12.9	19.3	16.1
Silt	19.2	18.0	18.3	15.0	17.4	13.1	16.5	16.0
Clay	6.3	13.3	13.8	16.5	22.1	30.8	29.9	34.1
Texture	sl	sl	sl	sl	scl	scl	scl	scl
Bulk density (Mg m^{-3})	1.55	1.70	1.62	1.64	1.63	1.63	1.80	1.80
pHw (1:2.5)	4.9	4.8	5.0	4.9	4.7	4.8	5.3	5.4
pHKCl (1:2.5)	3.9	3.7	3.8	3.7	3.6	3.7	3.8	3.8
Organic carbon (g kg^{-1})	3.9	1.8	1.7	_	_	_	_	_
Exchangeable Ca (cmol$^+$ kg^{-1})	0.40	_	_	0.96	0.59	0.70	1.56	1.54
Exchangeable Mg (cmol$^+$ kg^{-1})	0.06	_	_	0.38	0.93	0.73	1.33	1.49
Exchangeable K (cmol$^+$ kg^{-1})	0.04	_	_	0.06	0.05	0.06	0.05	0.04
Exchangeable Na (cmol$^+$ kg^{-1})	0.02	_	_	0.02	0.02	0.03	0.04	0.04
Sum of basic cation (cmol$^+$ kg^{-1})	0.53	_	_	1.42	1.58	1.52	2.98	3.11
CEC (cmol$^+$ kg^{-1})	2.5	_	_	2.2	2.9	4.1	4.0	4.5
Base saturation (%)	21	_	_	65	54	37	75	69

14. Sugarcane 30-40 years B (S2b)

Horizon	Ap	E	Bt1	Bt2	Btg1	Btg2	Btg3
Depth (cm)	0-20	20-45	45-70	70-103	103-130	130-165	165-180+
Particle size analysis (%)							
Coarse sand	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Medium sand	8.8	8.0	9.1	7.3	3.4	7.9	7.0
Fine sand	52.6	54.7	40.1	35.3	35.3	38.0	39.9
Very fine sand	20.1	18.0	15.3	13.3	18.1	14.5	16.3
Silt	12.9	12.3	12.4	16.3	16.8	14.1	13.9
Clay	5.6	7.0	23.0	27.7	26.3	25.4	22.7
Texture	ls	ls	scl	scl	scl	scl	scl
Bulk density (Mg m^{-3})	1.48	1.62	1.70	1.65	1.65	1.68	1.77
pHw (1:2.5)	4.6	5.1	5.0	4.9	4.8	4.5	5.0
pHKCl (1:2.5)	3.7	4.0	3.7	3.7	3.7	3.8	3.9
Organic carbon (g kg^{-1})	3.8	0.0	1.2	_	_	_	_
Exchangeable Ca (cmol$^+$ kg^{-1})	0.14	_	_	0.32	0.64	0.68	0.89
Exchangeable Mg (cmol$^+$ kg^{-1})	0.04	_	_	1.29	1.45	0.59	0.62
Exchangeable K (cmol$^+$ kg^{-1})	0.03	_	_	0.06	0.06	0.11	0.1
Exchangeable Na (cmol$^+$ kg^{-1})	0.01	_	_	0.03	0.03	0.07	0.08
Sum of basic cation (cmol$^+$ kg^{-1})	0.21	_	_	1.70	2.19	1.45	1.69
CEC (cmol$^+$ kg^{-1})	2.5	_	_	4.2	4.0	3.9	3.5
Base saturation (%)	9	_	_	41	55	38	49

15. Sugarcane 30-40 years C (S2c)

Horizon	Ap	E	Bt1	Bt2	Bt3	Btg1	Btg2	Btg3
Depth (cm)	0-30/40	30/40-40/50	40/50-60/70	60/70-90	90-110	110-130	130-160	160-180+
Particle size analysis (%)								
Coarse sand	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Medium sand	5.6	7.8	6.3	4.8	8.0	7.4	5.2	7.5
Fine sand	56.6	51.8	47.7	49.1	46.5	44.3	44.4	41.1
Very fine sand	18.6	18.2	18.5	15.3	16.3	15.6	14.3	14.7
Silt	13.4	15.5	13.5	12.7	12.9	13.7	14.1	13.2
Clay	5.8	*6.7*	*14.0*	*17.9*	16.3	19.0	21.9	23.4
Texture	ls	sl	sl	sl	sl	sl	scl	scl
Bulk density (Mg m^{-3})	1.47	1.54	1.72	1.58	1.61	1.63	1.71	1.72
pHw (1:2.5)	5.0	5.3	5.4	5.3	5.0	4.7	4.8	4.9
pHKCl (1:2.5)	4.3	4.2	4.1	4.0	3.8	3.7	3.7	3.7
Organic carbon (g kg^{-1})	2.0	1.2	1.4	_	_	_	_	_
Exchangeable Ca ($cmol^+$ kg^{-1})	0.46	_	_	1.28	0.46	0.44	_	1.10
Exchangeable Mg ($cmol^+$ kg^{-1})	0.09	_	_	0.81	0.51	0.66	_	0.55
Exchangeable K ($cmol^+$ kg^{-1})	0.06	_	_	0.12	0.06	0.06	_	0.09
Exchangeable Na ($cmol^+$ kg^{-1})	0.02	_	_	0.02	0.01	0.01	_	0.12
Sum of basic cation ($cmol^+$ kg^{-1})	0.63	_	_	2.23	1.03	1.16	_	1.86
CEC ($cmol^+$ kg^{-1})	1.8	_	_	2.89	2.62	3.06	_	3.77
Base saturation (%)	34	_	_	77	39	38	_	49

16. Sugarcane 40-50 years A (S3a)

Horizon	Ap	Bt1	Bt2	Bt3	Bt4	Btg1	Btg2
Depth (cm)	0-25	25-40	40-85	85-110	110-135	135-160	160-180+
Particle size analysis (%)							
Coarse sand	0.1	0.2	0.1	0.2	0.2	0.1	0.3
Medium sand	10.9	9.2	8.5	12.2	8.8	6.3	11.2
Fine sand	53.1	44.8	44.5	39.1	40.1	41.6	36.3
Very fine sand	16.9	14.0	11.2	10.7	12.2	12.2	11.0
Silt	12.3	14.3	13.6	13.9	13.7	13.7	12.7
Clay	6.7	17.6	22.1	23.9	25.0	26.2	28.5
Texture	ls	sl	scl	scl	scl	scl	scl
Bulk density (Mg m^{-3})	1.55	1.74	1.57	1.56	1.58	1.60	1.66
pHw (1:2.5)	4.9	5.2	5.4	5.2	5.3	5.5	5.5
pHKCl (1:2.5)	4.0	3.9	4.0	3.9	3.7	4.0	4.1
Organic carbon (g kg^{-1})	1.8	1.7	0.8	_	_	_	_
Exchangeable Ca ($cmol^+$ kg^{-1})	0.15	_	_	0.71	0.92	1.35	1.44
Exchangeable Mg ($cmol^+$ kg^{-1})	0.12	_	_	0.94	0.82	0.89	0.75
Exchangeable K ($cmol^+$ kg^{-1})	0.10	_	_	0.04	0.04	0.17	0.07
Exchangeable Na ($cmol^+$ kg^{-1})	0.02	_	_	0.02	0.02	0.08	0.06
Sum of basic cation ($cmol^+$ kg^{-1})	0.38	_	_	1.70	1.79	2.49	2.32
CEC ($cmol^+$ kg^{-1})	1.7	_	_	4.1	4.3	4.5	4.9
Base saturation (%)	23	_	_	41	42	55	47

17. Sugarcane 40-50 years B (S3b)

Horizon	Ap	E	Bt1	Bt2	Bt3	Btg1	Btg2
Depth (cm)	0-15	15-25	25-45	45-70	70-110	110-140	140-180+
Particle size analysis (%)							
Coarse sand	0.3	0.2	0.2	0.2	0.3	0.2	0.2
Medium sand	11.1	9.4	11.7	10.7	9.1	11.9	10.9
Fine sand	53.2	54.8	44.0	43.5	44.2	42.0	42.7
Very fine sand	16.0	13.6	12.8	12.4	10.7	11.3	12.1
Silt	14.0	15.6	14.3	13.1	12.8	12.7	12.4
Clay	5.4	6.4	17.1	20.2	23.0	21.9	21.7
Texture	ls	ls	sl	scl	scl	scl	scl
Bulk density (Mg m^{-3})	1.45	1.59	1.74	1.54	1.53	1.57	1.57
pHw (1:2.5)	4.9	4.7	5.1	5.0	5.1	5.4	5.1
pHKCl (1:2.5)	3.7	3.8	3.9	3.8	3.9	4.2	4.5
Organic carbon (g kg^{-1})	1.9	0.8	0.4	_	_	_	_
Exchangeable Ca ($cmol^{+}$ kg^{-1})	0.11	_	_	0.61	0.60	0.62	0.9
Exchangeable Mg ($cmol^{+}$ kg^{-1})	0.05	_	_	0.42	1.06	0.37	1.22
Exchangeable K ($cmol^{+}$ kg^{-1})	0.02	_	_	0.12	0.08	0.16	0.09
Exchangeable Na ($cmol^{+}$ kg^{-1})	0.02	_	_	0.01	0.01	0.15	0.09
Sum of basic cation ($cmol^{+}$ kg^{-1})	0.21	_	_	1.16	1.76	1.30	2.30
CEC ($cmol^{+}$ kg^{-1})	1.8	_	_	3.1	3.5	3.3	3.3
Base saturation (%)	11	_	_	38	50	39	69

18.Sugarcane 40-50 years C (S3c)

Horizon	Ap1	Ap2	Bt1	Bt2	Bt3	Bt4	Btg
Depth (cm)	0-15	15-25	25-40	40-65	65-100	100-140	140-180+
Particle size analysis (%)							
Coarse sand	0.2	0.1	0.2	0.2	0.3	0.3	0.3
Medium sand	6.3	9.5	8.3	5.7	9.9	9.3	6.3
Fine sand	53.2	49.5	45.4	47.7	42.3	43.1	46.3
Very fine sand	18.9	18.0	16.7	14.9	14.2	14.7	14.4
Silt	15.5	17.0	15.4	15.8	14.6	14.3	15.1
Clay	6.0	5.8	14.1	15.7	18.7	18.2	17.6
Texture	ls	ls	sl	sl	sl	sl	sl
Bulk density (Mg m^{-3})	1.49	1.59	1.68	1.62	1.54	1.55	1.57
pHw (1:2.5)	4.7	4.5	4.6	4.9	5.0	5.1	5.0
pHKCl (1:2.5)	3.9	3.7	3.7	3.9	4.1	4.0	4.0
Organic carbon (g.kg^{-1})	1.6	1.9	1.2	_	_	_	_
Exchangeable Ca ($cmol^{+}$ kg^{-1})	0.04	_	_	0.68	0.65	0.38	0.28
Exchangeable Mg ($cmol^{+}$ kg^{-1})	0.04	_	_	0.47	1.13	0.96	0.69
Exchangeable K ($cmol^{+}$ kg^{-1})	0.14	_	_	0.11	0.07	0.08	0.07
Exchangeable Na ($cmol^{+}$ kg^{-1})	0.01	_	_	0.01	0.02	0.07	0.05
Sum of basic cation ($cmol^{+}$ kg^{-1})	0.23	_	_	1.27	1.86	1.49	1.09
CEC ($cmol^{+}$ kg^{-1})	1.9	_	_	2.9	3.5	3.4	3.3
Base saturation (%)	12	_	_	43	54	44	33

Appendix II

Table A-1 Mean area of RSQI classes in the topsoil horizons of cassava plots and dry Dipterocarp forest plots.

Class	RSQI value	Land use	Area (m^2)	(%)
I	90 -100	Forest	281	11.2
		C1	46	1.8
		C2	0	0.0
II	80 -90	Forest	1376	55.0
		C1	1157	46.3
		C2	273	10.9
III	70 - 80	Forest	754	30.2
		C1	439	17.6
		C2	1130	45.2
IV	60 - 70	Forest	89	3.6
		C1	852	34.1
		C2	1009	40.4
V	50 - 60	Forest	0	0.0
		C1	7	0.3
		C2	88	3.5
VI	40 - 50	Forest	0	0.0
		C1	0	0.0
		C2	0	0.0
VII	30 - 40	Forest	0	0.0
		C1	0	0.0
		C2	0	0.0
VIII	< 30	Forest	0	0.0
		C1	0	0.0
		C2	0	0.0

C1 = Cassava 10-20 yrs
C2 = Cassava 20-30 yrs

Table A-2 Mean area of RSQI classes in the subsoil horizons of cassava plots and dry Dipterocarp forest plots.

Class	RSQI value	Land use	Area (m^2)	Area (%)
I	90 -100	Forest	483	19.3
		C1	39	1.5
		C2	39	1.6
II	80 -90	Forest	903	36.1
		C1	164	6.6
		C2	528	21.1
III	70 - 80	Forest	1115	44.6
		C1	1974	78.9
		C2	1376	55.1
IV	60 - 70	Forest	0	0.0
		C1	324	13.0
		C2	556	22.2
V	50 - 60	Forest	0	0.0
		C1	0	0.0
		C2	0	0.0
VI	40 - 50	Forest	0	0.0
		C1	0	0.0
		C2	0	0.0
VII	30 - 40	Forest	0	0.0
		C1	0	0.0
		C2	0	0.0
VIII	< 30	Forest	0	0.0
		C1	0	0.0
		C2	0	0.0

C1 = Cassava 10-20 yrs
C2 = Cassava 20-30 yrs

Table A-3 Mean area of RSQI classes in the topsoil horizons of sugarcane plots.

Class	RSQI values	Land uses	Area (m^2)	(%)
I	90 -100	S1	48	2
		S2	0	0
		S3	0	0
II	80 -90	S1	351	14
		S2	0	0
		S3	0	0
III	70 - 80	S1	972	39
		S2	0	0
		S3	0	0
IV	60 - 70	S1	644	26
		S2	11	0
		S3	22	1
V	50 - 60	S1	481	19
		S2	967	39
		S3	110	4
VI	40 - 50	S1	4	0
		S2	1522	61
		S3	2111	84
VII	30 - 40	S1	0	0
		S2	0	0
		S3	256	10
VIII	< 30	S1	0	0
		S2	0	0
		S3	0	0

S1 = Sugarcane 10-20 yrs
S2 = Sugarcane 30-40 yrs
S3 = Sugarcane 40 -50 yrs

Table A-4 Mean area of RSQI classes in the subsoil horizons of sugarcane plots.

Class	RSQI values	Land uses	Area (m^2)	Area (%)
I	90 - 100	S1	242	10
		S2	0	0
		S3	0	0
II	80 - 90	S1	1337	53
		S2	0	0
		S3	0	0
III	70 - 80	S1	527	21
		S2	38	2
		S3	0	0
IV	60 - 70	S1	362	15
		S2	909	36
		S3	56	2
V	50 - 60	S1	31	1
		S2	1546	62
		S3	1360	55
VI	40 - 50	S1	0	0
		S2	7	0
		S3	948	38
VII	30 - 40	S1	0	0
		S2	0	0
		S3	137	5
VIII	< 30	S1	0	0
		S2	0	0
		S3	0	0

S1 = Sugarcane 10-20 yrs
S2 = Sugarcane 30-40 yrs
S3 = Sugarcane 40 -50 yrs

Table A-5 The linear correlation between organic carbon, labile carbon content and soil properties at the Sakon Nakhon site.

Soil properties	Organic C (r)	Labile C (r)
Soil profile measurement (n = 8)		
Bulk density	0.067	-0.638
Clay dispersion index	-0.469	-0.506
pH_w 1:2.5	0.736*	0.826*
pH_{KCl} 1:2.5	0.528	0.761*
Organic carbon	-	0.583
Labile carbon	0.583	-
Exchangeable K	0.540	0.722*
Exchangeable Ca	0.526	0.685
Exchangeable Mg	0.820*	0.834*
CEC	0.831*	0.776*
Plot scale measurement (n = 56)		
Bulk density	-0.214	-0.586***
Clay dispersion index	-0.134	-0.438**
pH_w 1:2.5	-0.180	-0.298*
pH_{KCl} 1:2.5	-0.115	-0.192
Exchangeable acidity	0.112	0.397**
Organic carbon	-	0.542***
Labile carbon	0.542***	-
Exchangeable K	0.326*	0.535***
Exchangeable Ca	-0.079	-0.255
Exchangeable Mg	0.371**	0.505***
ECEC	0.211	0.080

r = Correlation Coefficients
* = Significant at $p < 0.05$, ** = Significant at $p < 0.01$, *** = Significant at $p < 0.001$

Table A-6 The linear correlation between organic carbon, labile carbon content and soil properties at the Udon Thani site.

Soil properties	Organic C (r)	Labile C (r)
Soil profile measurement (n = 8)		
Bulk density	-0.150	-0.211
Clay dispersion index	-0.544	-0.587
pH_w 1:2.5	0.486	0.644
pH_{KCl} 1:2.5	0.505	0.754*
Organic carbon	-	0.616
Labile carbon	0.616	-
Exchangeable K	-0.141	0.267
Exchangeable Ca	0.670	0.884**
Exchangeable Mg	0.516	0.895**
CEC	0.713*	0.539
Plot scale measurement (n = 56)		
Bulk density	0.107	0.156
Clay dispersion index	-0.393**	-0.181
pH_w 1:2.5	0.602***	0.493***
pH_{KCl} 1:2.5	0.527***	0.450**
Exchangeable acidity	-0.382**	-0.420**
Organic carbon	-	0.560***
Labile carbon	0.560***	-
Exchangeable K	0.380**	0.794***
Exchangeable Ca	0.655***	0.553***
Exchangeable Mg	0.448**	0.443**
ECEC	0.641***	0.556***

r = Correlation Coefficients
* = Significant at $p < 0.05$, ** = Significant at $p < 0.01$, *** = Significant at $p < 0.001$

Table A-7 One-Way Analysis of Variance for soil colour in the surface horizons of soil profiles with the times after forest clearance as source of variation.

Cropping regime	Between Time variance	Within Time variance	p-values
Cassava	0.771	0.267	0.146
Sugarcane	1.500	0.100	0.008

Table A-8 The linear correlation between RSQI and the times after forest Clearance.

RSOI	Correlation with time (r)
Cassava cropping regime	
Ah/Ap horizons	-0.924***
Topsoil (10-15cm)	-0.432**
Subsoil (40-45cm)	-0.336**
Sugarcane cropping regime	
Ah/Ap horizons	-0.903**
Topsoil (10-15cm)	-0.779***
Subsoil (40-45cm)	-0.672***

r = Correlation Coefficients
* = Significant at $p < 0.05$, ** = Significant at $p < 0.01$, *** = Significant at $p < 0.001$

Appendix III

Analysis physical and chemical data of profile and plot scale measurements at the Sakon Nakhon and Udon Thani sites

Table B-1 Physical and chemical properties in the Ah/Ap horizons of soil profiles.

Soil property	FA	FB	FC	C1b	C1c	C2a	C2b	C2c
Bulk density (Mg m^{-3})	1.50	1.43	1.44	1.50	1.49	1.45	1.56	1.49
Clay dispersion index (%)	16.3	17.9	16.4	17.0	20.9	16.3	21.1	19.0
pHw (1:2.5)	6.0	6.2	5.6	5.5	4.9	5.2	5.4	5.3
pHkcl (1:2.5)	4.8	5.3	4.3	4.3	4.4	4.2	4.6	4.2
Organic carbon (g kg^{-1})	10.7	6.4	5.8	6.7	3.8	3.6	5.1	2.7
Labile carbon (mg kg^{-1})	178.6	219.2	168.0	161.6	143.2	144.9	122.3	126.9
Exchangeable Ca (cmol^{+} kg^{-1})	1.45	2.26	0.61	1.22	0.95	0.56	1.40	0.62
Exchangeable Mg (cmol^{+} kg^{-1})	0.73	0.8	0.45	0.67	0.37	0.22	0.39	0.23
Exchangeable K (cmol^{+} kg^{-1})	0.09	0.1	0.14	0.04	0.04	0.04	0.03	0.01

Soil property	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
Bulk density (Mg m^{-3})	1.53	1.43	1.48	1.55	1.48	1.47	1.55	1.45
Clay dispersion index (%)	24.7	17.9	22.2	24.7	28.2	27.9	26.7	23.5
pHw (1:2.5)	5.0	5.9	5.6	4.9	4.6	5.0	4.9	4.9
pHkcl (1:2.5)	4.2	5.3	4.6	3.9	3.7	4.3	4.0	3.7
Organic carbon (g kg^{-1})	3.4	4.6	3.7	3.9	3.8	2.0	1.8	1.9
Labile carbon (mg kg^{-1})	135.6	138.0	108.9	90.6	96.9	96.6	90.9	83.6
Exchangeable Ca (cmol^{+} kg^{-1})	0.71	1.31	0.64	0.40	0.14	0.46	0.15	0.03
Exchangeable Mg (cmol^{+} kg^{-1})	0.21	0.33	0.2	0.06	0.04	0.09	0.12	0.05
Exchangeable K (cmol^{+} kg^{-1})	0.05	0.08	0.03	0.04	0.03	0.06	0.1	0.02

Table B-2 Soil bulk density (Mg kg^{-1}) of the study plots.

a. The topsoil horizons (10-15 cm)

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	1.47	1.52	1.43	1.44	1.57	1.58	1.45	1.57	1.55	1.50	1.48	1.54	1.47	1.52	1.50	1.58
P2	1.46	1.46	1.42	1.45	1.57	1.46	1.58	1.64	1.62	1.49	1.49	1.60	1.48	1.47	1.52	1.50
P3	1.44	1.50	1.47	1.48	1.52	1.62	1.43	1.63	1.57	1.56	1.52	1.59	1.64	1.48	1.46	1.59
P4	1.34	1.5	1.43	1.48	1.53	1.56	1.51	1.57	1.52	1.48	1.46	1.56	1.48	1.47	1.53	1.43
P5	1.45	1.50	1.50	1.50	1.52	1.58	1.43	1.54	1.64	1.49	1.45	1.53	1.49	1.47	1.48	1.53
P6	1.48	1.47	1.53	1.45	1.62	1.52	1.51	1.51	1.59	1.52	1.48	1.47	1.48	1.48	1.50	1.54
P7	1.53	1.45	1.47	1.46	1.64	1.57	1.54	1.57	1.46	1.48	1.55	1.51	1.44	1.48	1.54	1.46
Mean	1.45	1.49	1.46	1.47	1.57	1.56	1.49	1.58	1.56	1.50	1.49	1.54	1.50	1.48	1.50	1.52
SD	0.06	0.03	0.04	0.02	0.05	0.05	0.06	0.05	0.06	0.03	0.03	0.05	0.06	0.02	0.03	0.06

Table B-2 Soil bulk density (Mg kg^{-1}) of the study plots.

b. The subsoil horizons (40-45 cm)

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	1.47	1.54	1.56	1.76	1.65	1.51	1.56	1.63	1.67	1.54	1.54	1.69	1.64	1.63	1.58	1.62
P2	1.44	1.49	1.60	1.53	1.63	1.58	1.58	1.54	1.67	1.58	1.53	1.62	1.62	1.62	1.63	1.75
P3	1.50	1.58	1.52	1.62	1.68	1.56	1.55	1.58	1.62	1.52	1.82	1.64	1.64	1.74	1.73	1.65
P4	1.49	1.53	1.58	1.69	1.65	1.50	1.59	1.67	1.66	1.61	1.58	1.77	1.57	1.73	1.60	1.58
P5	1.54	1.60	1.52	1.65	1.64	1.54	1.60	1.63	1.69	1.57	1.75	1.62	1.57	1.68	1.69	1.77
P6	1.53	1.53	1.57	1.65	1.70	1.54	1.61	1.62	1.63	1.54	1.63	1.72	1.65	1.60	1.81	1.73
P7	1.52	1.49	1.60	1.50	1.66	1.57	1.61	1.67	1.64	1.56	1.62	1.60	1.58	1.74	1.56	1.72
Mean	1.50	1.54	1.56	1.63	1.66	1.54	1.59	1.62	1.65	1.56	1.64	1.67	1.61	1.68	1.66	1.69
SD	0.04	0.04	0.03	0.09	0.02	0.03	0.02	0.05	0.03	0.03	0.11	0.06	0.04	0.06	0.09	0.07

Table B-3 Clay dispersion index (%) in the topsoil horizons (10-15 cm) of the study plots.

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	16.7	29.3	12.6	17.4	25.7	21.6	21.1	18.1	21.8	13.4	19.5	24.7	16.9	21.1	25.5	18.2
P2	18.4	20.8	15.6	10.9	26.2	29.8	14.5	23.1	26.2	19.0	24.9	19.5	26.8	21.8	27.4	39.4
P3	16.3	19.9	15.1	16.6	27.5	22.6	17.2	27.6	19.3	21.8	22.2	27.9	11.6	17.6	31.1	29.5
P4	18.1	12.2	28.6	12.5	28.0	35.6	18.9	22.2	13.9	22.3	20.8	12.3	26.1	31.6	38.3	20.5
P5	16.7	19.5	24.8	12.1	27.5	33.2	18.5	20.8	24.7	21.8	18.8	22.7	23.9	24.6	24.3	20.5
P6	13.2	12.6	24.4	12.9	28.8	25.5	26.0	12.7	25.7	19.5	10.8	21.4	17.4	24.6	29.8	25.0
P7	15.3	17.9	22.7	12.1	34.2	31.7	15.9	22.2	13.4	20.6	22.9	20.1	11.6	30.2	32.2	22.0
Mean	16.4	18.9	20.5	13.5	28.3	28.6	18.9	21.0	20.7	19.8	20.0	21.2	19.2	24.5	29.8	25.0
SD	1.76	5.75	6.05	2.46	2.80	5.40	3.80	4.63	5.41	3.07	4.55	4.87	6.47	5.01	4.72	7.36

Table B-4 Infiltration rate (cm hr^{-1}) of the study plots.

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	13.8	9.7	6.5	14.4	3.5	4.9	11.0	5.3	1.2	1.8	3.8	2.5	19.1	4.2	0.8	3.4
P2	19.7	9.7	2.4	6.3	19.2	2.3	15.9	6.3	1.1	16.9	3.8	8.5	7.0	5.1	3.0	7.1
P3	2.6	13.3	2.7	6.2	14.3	3.5	15.7	7.1	0.7	3.0	4.0	2.5	6.3	8.1	3.0	4.4
P4	16.9	16.6	7.0	13.5	1.4	8.9	7.9	19.8	0.6	7.1	7.7	5.4	10.7	9.3	2.8	10.9
P5	7.3	8.9	1.8	10.9	13.9	3.9	16.6	9.2	2.8	7.1	3.7	3.0	2.3	3.4	4.3	11.7
P6	4.8	11.6	3.7	10.1	9.6	2.7	13.3	5.8	2.6	8.4	10.0	6.6	15.4	8.7	2.8	4.9
P7	11.2	3.8	4.3	10.4	1.2	3.4	7.1	11.3	1.8	9.7	10.2	1.6	8.9	5.1	1.7	8.1
Mean	10.9	10.5	4.1	10.3	9.0	4.2	12.5	9.3	1.5	7.7	6.2	4.3	10.0	6.3	2.6	7.2
SD	6.3	4.0	2.0	3.2	7.1	2.2	3.9	5.1	0.9	4.9	3.0	2.6	5.7	2.4	1.1	3.2

Table B-5 pH in water (pHw) of the study plots.

a. The topsoil horizons (10-15 cm)

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	4.6	5.1	5.3	6.1	5.7	5.3	5.7	5.8	5.8	6.2	5.6	5.2	5.2	5.4	4.8	5.0
P2	4.7	4.8	5.6	5.9	5.1	5.6	5.8	5.5	5.6	6.6	5.8	4.9	5.3	6.2	4.8	4.7
P3	5.1	5.1	5.4	5.6	5.6	6.3	5.6	5.4	5.8	6.4	6.3	4.9	5.0	5.3	4.3	4.7
P4	4.7	5.3	5.0	5.9	5.7	5.0	5.2	5.5	6.2	6.4	5.8	5.0	5.0	5.6	4.5	4.6
P5	4.7	5.8	5.0	5.7	5.2	5.2	5.0	5.9	5.8	6.7	5.6	5.2	5.1	5.5	4.6	5.2
P6	5.4	5.2	5.6	6.1	5.8	5.4	5.9	5.6	5.8	5.4	5.8	4.9	5.1	5.4	4.9	4.6
P7	5.7	5.1	5.8	5.8	5.5	5.8	5.4	5.3	5.6	5.8	5.7	5.1	4.7	5.3	4.7	4.9
Mean	5.0	5.2	5.4	5.9	5.5	5.5	5.5	5.6	5.8	6.2	5.8	5.0	5.0	5.5	4.6	4.8
SD	0.4	0.3	0.3	0.2	0.3	0.4	0.3	0.2	0.2	0.4	0.3	0.1	0.2	0.3	0.2	0.2

b. The subsoil horizons (40-45 cm)

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	4.5	4.5	4.8	5.4	6.1	5.1	5.8	6.0	5.8	6.2	5.6	5.2	5.2	5.4	4.8	5.0
P2	4.6	4.6	4.7	5.4	5.9	4.6	5.9	5.8	5.6	6.6	5.8	4.9	5.3	6.2	4.8	4.7
P3	4.8	4.6	5.5	4.9	5.6	6.4	5.9	4.9	5.8	6.4	6.3	4.9	5.0	5.3	4.3	4.7
P4	4.5	4.8	5.1	5.5	5.6	4.9	4.9	5.8	6.2	6.4	5.8	5.0	5.0	5.6	4.5	4.6
P5	4.7	5.5	4.7	5.3	5.1	4.7	5.8	5.2	5.8	6.7	5.6	5.2	5.1	5.5	4.6	5.2
P6	5.2	4.8	5.2	6.2	5.3	4.8	5.7	5.8	5.8	5.4	5.8	4.9	5.1	5.4	4.9	4.6
P7	5.0	4.8	5.7	5.9	5.0	6.0	5.6	4.9	5.6	5.8	5.7	5.1	4.7	5.3	4.7	4.9
Mean	4.7	4.8	5.1	5.5	5.5	5.2	5.7	5.5	5.8	6.2	5.8	5.0	5.0	5.5	4.6	4.8
SD	0.3	0.3	0.4	0.4	0.4	0.7	0.3	0.4	0.2	0.4	0.3	0.1	0.2	0.3	0.2	0.2

Table B-6 pH in KCl solution (pHKCl) of the study plots.

a. The topsoil horizons (10-15 cm)

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	3.8	4.3	4.3	5.2	4.7	4.3	4.9	4.8	4.7	5.2	4.5	3.8	4.0	4.4	4.0	3.8
P2	3.9	3.9	4.6	4.8	4.7	4.7	4.8	4.4	4.6	5.7	4.9	3.8	4.0	4.8	3.9	4.0
P3	4.2	4.1	4.6	4.5	4.6	5.7	4.8	4.3	4.7	5.3	5.3	3.7	3.9	4.2	3.9	3.9
P4	3.8	4.5	3.9	4.7	4.5	4.0	4.2	4.4	5.3	5.4	4.7	3.7	3.9	4.4	4.1	3.9
P5	3.9	5.0	3.9	4.8	4.2	4.1	4.5	4.8	4.7	5.9	4.6	3.9	4.0	4.3	3.9	4.2
P6	4.5	4.0	4.8	5.3	4.6	4.5	5.1	4.9	4.7	4.9	4.8	3.8	3.8	4.2	4.0	3.9
P7	4.1	4.1	4.7	4.8	4.3	4.9	4.6	4.4	4.5	5.0	4.9	4.0	3.6	4.2	3.9	3.9
Mean	4.0	4.3	4.4	4.9	4.5	4.6	4.7	4.6	4.7	5.3	4.8	3.8	3.9	4.3	4.0	4.0
SD	0.3	0.4	0.4	0.3	0.2	0.6	0.3	0.2	0.2	0.4	0.2	0.1	0.1	0.2	0.1	0.1

Table B-6 pH in KCl solution (pHKCl) of the study plots.

b. The subsoil horizons (40-45 cm)

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	3.7	3.7	3.7	4.0	4.7	4.0	4.5	4.5	4.1	4.9	3.7	3.7	3.8	4.1	4.0	3.8
P2	3.7	3.6	3.7	4.1	4.2	3.8	4.5	4.5	4.3	5.3	4.0	4.4	3.7	4.3	3.9	3.8
P3	3.8	3.6	4.1	3.8	4.5	5.3	4.7	4.7	3.9	5.0	4.7	3.8	4.0	4.2	3.8	3.7
P4	3.6	3.8	3.9	4.2	4.2	3.9	3.7	3.7	4.5	5.1	4.7	4.0	3.8	4.3	3.8	4.0
P5	3.7	4.4	3.8	4.0	3.8	3.7	4.4	4.4	4.3	5.7	4.7	3.8	3.9	3.9	3.8	4.2
P6	3.9	3.8	4.0	5.0	3.9	3.6	4.3	4.3	3.9	3.9	4.1	3.6	4.1	4.4	3.7	4.0
P7	3.9	3.7	4.3	4.3	3.8	4.6	4.2	4.2	3.9	4.7	4.5	3.7	3.6	4.3	3.7	3.9
Mean	3.8	3.8	3.9	4.2	4.2	4.1	4.4	4.4	4.1	4.9	4.3	3.9	3.8	4.2	3.8	3.9
SD	0.1	0.3	0.2	0.4	0.3	0.6	0.3	0.3	0.2	0.6	0.4	0.3	0.2	0.2	0.1	0.1

Table B-7 Soil organic carbon content (g kg^{-1}) in the topsoil horizons (10-15 cm) of the study plots.

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	4.2	11.9	3.2	5.1	5.2	3.5	3.7	4.2	1.8	3.4	1.5	2.4	2.0	2.9	1.4	1.3
P2	3.9	15.6	5.7	5.1	6.1	5.3	4.2	3.5	3.2	3.4	1.6	2.1	2.5	2.5	1.4	0.5
P3	2.7	6.3	6.2	5.8	5.0	3.9	5.6	3.8	5.1	2.2	6.2	2.5	1.9	2.3	1.2	1.6
P4	6.3	7.8	5.2	4.2	4.7	3.8	4.5	3.4	4.2	3.4	2.2	3.1	3.1	3.6	1.0	1.1
P5	3.7	2.7	3.9	5.5	4.7	2.4	6.7	3.2	4.2	5.1	1.2	2.9	2.6	2.4	1.7	1.8
P6	7.6	6.0	6.9	6.2	7.0	4.1	4.3	3.6	2.8	3.8	4.0	2.7	3.4	2.5	1.9	2.2
P7	7.3	4.5	1.9	9.2	3.7	3.6	5.4	4.3	3.6	1.6	3.6	2.9	3.1	1.7	1.2	2.1
Mean	5.1	7.8	4.7	5.9	5.2	3.8	4.9	3.7	3.6	3.3	2.9	2.7	2.7	2.6	1.4	1.5
SD	1.9	4.5	1.8	1.6	1.1	0.9	1.0	0.4	1.1	1.1	1.8	0.3	0.6	0.6	0.3	0.6

Table B-8 Soil labile carbon content (mg kg^{-1}) in the topsoil horizons (10-15 cm) of the study plots.

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	129.6	142.9	109.7	135.9	96.2	84.1	101.0	87.0	117.8	85.5	58.6	60.8	42.3	60.0	48.8	34.1
P2	146.8	171.9	156.7	148.1	114.3	127.3	94.8	90.7	98.5	72.0	71.0	57.2	58.9	95.7	47.2	36.6
P3	113.9	167.7	125.3	127.0	89.8	112.2	107.5	84.7	121.9	59.6	65.0	70.3	57.8	57.1	55.9	47.6
P4	209.5	168.7	100.3	108.7	77.7	80.9	80.6	102.1	127.0	95.2	58.1	52.6	75.0	80.5	47.0	59.2
P5	136.6	90.5	95.1	130.4	75.8	74.6	98.3	93.4	152.1	107.5	52.3	14.2	59.1	68.7	55.1	51.4
P6	140.4	107.8	103.9	122.5	94.9	97.1	92.5	88.6	104.7	63.8	42.8	78.4	88.5	79.0	74.3	54.4
P7	115.6	113.7	80.8	121.3	92.9	64.8	73.2	73.4	99.9	55.9	69.0	73.9	89.2	54.8	46.8	72.0
Mean	141.8	137.6	110.3	127.7	91.6	91.6	92.5	88.5	117.4	77.1	59.5	58.2	67.3	70.8	53.6	50.8
SD	32.3	33.6	24.6	12.4	12.9	22.0	11.9	8.7	18.9	19.5	9.9	21.5	17.5	15.0	9.9	13.1

Table B-9 Exchangeable acidity (cmol$^+$ kg^{-1}) of the study plots.

a. The topsoil horizons (10-15 cm)

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	0.70	0.30	0.20	0.20	0.10	0.25	0.15	0.15	0.15	0.15	0.15	0.45	0.35	0.25	0.45	0.40
P2	0.70	0.60	0.20	0.20	0.20	0.20	0.10	0.30	0.20	0.10	0.15	0.60	0.40	0.20	0.40	0.45
P3	0.40	0.40	0.20	0.20	0.20	0.10	0.15	0.25	0.15	0.10	0.15	0.50	0.45	0.40	0.35	0.50
P4	1.30	0.2	0.80	0.10	0.20	0.80	0.25	0.20	0.15	0.15	0.15	0.65	0.45	0.20	0.30	0.35
P5	0.90	0.20	0.90	0.70	0.50	0.40	0.30	0.15	0.10	0.10	0.20	0.35	0.35	0.25	0.40	0.25
P6	0.30	0.50	0.30	0.20	0.20	0.25	0.10	0.15	0.20	0.10	0.15	0.50	0.45	0.25	0.30	0.45
P7	0.6	0.50	0.20	0.20	0.20	0.10	0.20	0.25	0.15	0.20	0.25	0.35	0.65	0.25	0.45	0.35
Mean	0.70	0.39	0.40	0.26	0.23	0.30	0.18	0.21	0.16	0.13	0.17	0.49	0.44	0.26	0.38	0.39
SD	0.33	0.16	0.31	0.20	0.13	0.24	0.08	0.06	0.03	0.04	0.04	0.11	0.10	0.07	0.06	0.08

b. The subsoil horizons (40-45 cm)

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	2.40	1.30	1.70	0.70	0.20	0.80	0.20	0.15	0.35	0.10	1.50	0.80	1.05	0.25	0.65	0.50
P2	1.70	1.80	1.60	0.40	0.20	1.70	0.20	0.25	0.30	0.15	0.75	0.20	1.80	0.20	0.85	0.80
P3	1.10	1.30	0.40	1.20	0.30	0.15	0.20	1.35	0.70	0.20	0.20	0.55	0.30	0.35	1.00	1.65
P4	1.80	1.00	0.70	0.40	0.30	0.95	1.25	0.25	0.25	0.25	0.25	0.30	0.60	0.30	1.00	0.55
P5	1.10	0.40	1.60	0.50	0.70	1.80	0.20	0.70	0.30	0.15	0.15	0.45	0.50	0.65	0.90	0.30
P6	0.70	1.40	0.70	0.20	0.70	1.80	0.25	0.20	0.55	0.90	0.45	1.05	0.25	0.20	1.45	0.55
P7	0.90	1.50	0.20	0.30	1.20	0.15	0.35	0.95	0.55	0.30	0.25	0.85	1.55	0.25	1.55	0.75
Mean	1.39	1.24	0.99	0.53	0.51	1.05	0.38	0.55	0.43	0.29	0.51	0.60	0.86	0.31	1.06	0.73
SD	0.60	0.44	0.63	0.34	0.37	0.73	0.39	0.46	0.17	0.28	0.48	0.31	0.62	0.16	0.33	0.44

Table B-10 Exchangeable potassium (cmol$^+$ kg^{-1}) of the study plots.

a. The topsoil horizons (10-15 cm)

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	0.03	0.04	0.06	0.03	0.05	0.03	0.03	0.03	0.13	0.04	0.03	0.03	0.03	0.04	0.03	0.03
P2	0.06	0.07	0.05	0.05	0.04	0.06	0.04	0.03	0.14	0.05	0.04	0.03	0.04	0.10	0.04	0.02
P3	0.03	0.09	0.09	0.02	0.02	0.02	0.04	0.02	0.10	0.04	0.04	0.03	0.03	0.03	0.05	0.03
P4	0.06	0.06	0.05	0.02	0.02	0.03	0.02	0.01	0.12	0.07	0.04	0.03	0.04	0.04	0.04	0.04
P5	0.04	0.05	0.08	0.03	0.04	0.03	0.02	0.02	0.13	0.09	0.04	0.03	0.03	0.06	0.04	0.08
P6	0.08	0.05	0.04	0.06	0.03	0.03	0.04	0.01	0.08	0.03	0.03	0.06	0.03	0.04	0.03	0.02
P7	0.05	0.05	0.07	0.04	0.03	0.02	0.03	0.01	0.09	0.03	0.04	0.06	0.03	0.03	0.04	0.03
Mean	0.05	0.06	0.06	0.04	0.03	0.03	0.03	0.02	0.11	0.05	0.04	0.04	0.03	0.05	0.04	0.04
SD	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.00	0.01	0.00	0.02	0.01	0.02

Table B-10 Exchangeable potassium (cmol$^+$ kg^{-1}) of the study plots.

b. The subsoil horizons (40-45 cm)

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	0.04	0.03	0.12	0.02	0.03	0.04	0.03	0.03	0.08	0.05	0.03	0.08	0.04	0.07	0.03	0.06
P2	0.04	0.06	0.13	0.04	0.01	0.12	0.04	0.02	0.06	0.05	0.03	0.05	0.03	0.05	0.03	0.10
P3	0.03	0.09	0.07	0.02	0.02	0.03	0.04	0.01	0.04	0.04	0.06	0.07	0.04	0.08	0.03	0.04
P4	0.08	0.04	0.07	0.03	0.02	0.04	0.03	0.01	0.20	0.05	0.04	0.06	0.07	0.05	0.03	0.05
P5	0.03	0.07	0.07	0.03	0.02	0.04	0.02	0.02	0.04	0.06	0.04	0.07	0.05	0.05	0.03	0.07
P6	0.03	0.04	0.05	0.08	0.02	0.03	0.03	0.01	0.06	0.03	0.04	0.10	0.05	0.05	0.03	0.07
P7	0.04	0.06	0.09	0.03	0.02	0.04	0.03	0.01	0.09	0.02	0.04	0.05	0.08	0.07	0.03	0.06
Mean	0.04	0.06	0.09	0.04	0.02	0.05	0.03	0.02	0.08	0.04	0.04	0.07	0.05	0.06	0.03	0.06
SD	0.02	0.02	0.03	0.02	0.01	0.03	0.01	0.01	0.06	0.01	0.01	0.02	0.02	0.01	0.00	0.02

Table B-11 Exchangeable calcium (cmol$^+$ kg^{-1}) of the study plots.

a. The topsoil horizons (10-15 cm)

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	0.40	1.00	0.74	1.58	1.78	0.88	2.44	1.58	0.78	1.54	0.78	0.38	0.32	0.42	0.34	0.62
P2	0.46	0.48	1.64	1.74	1.94	1.52	1.52	1.34	0.94	1.98	0.76	0.28	0.52	0.74	0.18	0.26
P3	0.74	0.64	1.44	1.44	1.62	1.46	1.72	1.06	1.68	1.30	1.36	0.38	0.24	0.46	0.56	0.24
P4	0.80	1.42	0.56	1.34	1.54	0.64	1.06	1.14	2.10	1.84	1.30	0.12	0.50	0.76	0.50	0.44
P5	0.58	1.38	0.36	1.86	1.06	1.10	1.90	1.56	1.46	3.10	0.44	0.50	0.36	0.46	0.28	0.20
P6	1.26	0.58	3.24	2.38	2.34	1.50	2.32	1.70	1.16	1.54	0.90	0.14	0.28	0.64	0.28	0.34
P7	0.58	0.74	0.90	0.06	1.62	2.56	1.84	1.44	1.02	0.84	1.34	0.62	0.24	0.44	0.38	0.16
Mean	0.69	0.89	1.27	1.49	1.70	1.38	1.83	1.40	1.31	1.73	0.98	0.35	0.35	0.56	0.36	0.32
SD	0.29	0.38	0.98	0.72	0.39	0.62	0.47	0.24	0.47	0.71	0.36	0.18	0.12	0.15	0.13	0.16

b. The subsoil horizons (40-45 cm)

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	0.30	0.20	0.20	0.64	1.56	0.44	1.10	1.48	1.06	1.18	0.36	1.16	1.08	1.06	0.78	0.80
P2	0.32	0.66	0.44	1.16	1.38	0.26	1.32	1.68	1.02	1.80	0.72	1.56	0.94	1.78	0.58	1.74
P3	0.84	0.30	0.70	0.44	1.50	1.12	1.08	0.48	0.90	0.62	0.94	1.34	1.20	1.52	0.88	1.38
P4	0.36	0.50	0.44	0.94	1.46	0.46	0.40	1.04	0.74	0.82	0.76	1.54	0.98	1.90	1.08	0.96
P5	0.40	0.66	0.30	0.42	0.88	0.24	0.98	0.84	1.14	1.26	1.12	1.00	0.52	1.08	0.84	1.18
P6	0.56	0.38	0.82	1.80	3.94	0.48	1.30	1.80	0.72	0.54	0.86	1.18	1.18	1.12	0.76	0.72
P7	0.40	0.14	1.30	1.18	0.86	1.48	1.18	1.04	0.82	0.92	0.94	0.80	0.76	2.00	0.76	0.82
Mean	0.45	0.41	0.60	0.94	1.65	0.64	1.05	1.19	0.91	1.02	0.81	1.23	0.95	1.49	0.81	1.09
SD	0.19	0.21	0.38	0.49	1.05	0.47	0.31	0.48	0.16	0.43	0.24	0.28	0.24	0.41	0.15	0.37

Table B-12 Exchangeable magnesium ($cmol^+ kg^{-1}$) of the study plots.

a. The topsoil horizons (10-15 cm)

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	0.32	0.64	0.50	0.54	0.30	0.34	0.48	0.44	0.24	0.28	0.24	0.10	0.06	0.14	0.14	0.60
P2	0.36	0.48	0.44	0.52	0.40	0.60	0.34	0.32	0.24	0.38	0.32	0.06	0.10	0.12	0.10	0.06
P3	0.38	0.64	0.40	0.60	0.30	0.34	0.46	0.28	0.42	0.28	0.30	0.08	0.06	0.10	0.26	0.04
P4	0.78	0.8	0.60	0.38	0.34	0.52	0.32	0.30	0.46	0.46	0.22	0.04	0.12	0.14	0.18	0.06
P5	0.66	0.70	0.40	0.74	0.26	0.54	0.56	0.28	0.38	0.58	0.18	0.12	0.08	0.08	0.12	0.06
P6	0.72	0.58	0.34	0.62	0.48	0.52	0.50	0.46	0.38	0.34	0.20	0.04	0.06	0.10	0.08	0.06
P7	0.54	0.68	0.54	0.96	0.40	0.26	0.62	0.28	0.30	0.22	0.36	0.14	0.04	0.12	0.14	0.06
Mean	0.54	0.64	0.46	0.62	0.35	0.45	0.47	0.34	0.35	0.36	0.26	0.08	0.07	0.11	0.15	0.13
SD	0.19	0.09	0.09	0.18	0.08	0.13	0.11	0.08	0.09	0.12	0.07	0.04	0.03	0.02	0.06	0.21

b. The subsoil horizons (40-45 cm)

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	0.56	0.64	0.84	0.56	0.54	1.14	0.58	1.04	1.06	0.24	0.34	0.40	0.78	0.32	0.72	0.24
P2	0.58	0.52	0.66	0.56	0.36	0.58	0.30	0.42	0.94	0.56	0.86	0.42	0.64	0.32	0.40	0.50
P3	0.66	0.98	0.98	0.42	0.28	0.76	0.60	0.32	1.08	0.74	0.78	0.56	0.38	0.64	0.50	0.68
P4	0.54	0.60	0.82	1.00	0.56	1.06	0.40	0.34	1.06	1.04	0.70	0.46	0.42	0.54	0.88	0.36
P5	0.34	1.42	0.32	0.56	0.24	0.66	0.74	0.30	1.22	0.26	1.22	0.38	0.20	0.44	0.72	0.60
P6	0.12	0.64	0.56	0.60	1.18	0.48	0.44	0.34	0.68	0.58	1.08	0.38	0.36	0.28	0.68	0.04
P7	0.68	0.66	0.74	0.76	0.26	1.58	0.54	0.36	0.94	1.00	0.80	0.28	0.40	0.44	0.62	0.30
Mean	0.50	0.78	0.70	0.64	0.49	0.89	0.51	0.45	1.00	0.63	0.83	0.41	0.45	0.43	0.65	0.39
SD	0.20	0.32	0.22	0.19	0.33	0.39	0.15	0.26	0.17	0.32	0.28	0.09	0.19	0.13	0.16	0.22

Table B-13 Effective CEC ($cmol^+ kg^{-1}$) of the study plots.

a. The topsoil horizons (10-15 cm)

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	1.48	2.10	1.51	2.36	2.25	1.51	3.12	2.19	1.31	2.02	1.20	0.98	0.81	0.87	0.97	1.67
P2	1.61	1.65	2.37	2.52	2.59	2.40	2.00	2.00	1.54	2.53	1.28	0.98	1.09	1.16	0.73	0.83
P3	1.57	1.79	2.15	2.27	2.15	1.94	2.38	1.61	2.37	1.73	1.85	1.00	0.81	1.00	1.25	0.84
P4	2.90	2.5	2.02	1.85	2.12	2.01	1.67	1.66	2.83	2.53	1.72	0.85	1.13	1.13	1.04	0.90
P5	2.20	2.34	1.78	3.33	1.87	2.10	2.78	2.02	2.08	3.89	0.88	1.00	0.83	0.85	0.84	0.61
P6	2.37	1.74	3.94	3.28	3.05	2.31	2.98	2.33	1.83	2.01	1.29	0.77	0.83	1.04	0.70	0.88
P7	1.78	1.99	1.73	3.27	2.27	2.95	2.70	2.01	1.57	1.30	1.98	1.20	0.96	0.85	1.02	0.60
Mean	1.99	2.01	2.21	2.70	2.33	2.17	2.52	1.97	1.93	2.29	1.46	0.97	0.92	0.99	0.94	0.90
SD	0.52	0.31	0.81	0.59	0.38	0.45	0.53	0.26	0.53	0.83	0.40	0.13	0.14	0.13	0.19	0.36

Table B-13 Effective CEC ($cmol^+ kg^{-1}$) of the study plots.

b. The subsoil horizons (40-45 cm)

	FA	FB	FC	C1b	C1c	C2a	C2b	C2c	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b
P1	3.30	2.17	2.14	1.94	2.34	2.45	1.90	2.72	2.72	1.56	2.23	2.46	2.98	1.71	2.19	1.61
P2	2.66	3.04	2.86	2.16	1.96	2.67	1.87	2.39	2.39	2.58	2.37	2.23	3.44	2.37	1.86	3.17
P3	2.64	2.70	2.16	2.08	2.11	2.09	1.93	2.16	2.16	1.61	1.97	2.54	1.97	2.59	2.41	3.75
P4	2.80	2.16	2.06	2.37	2.34	2.53	2.09	1.66	1.66	2.15	1.77	2.39	2.07	2.80	3.00	1.94
P5	1.87	2.57	2.33	1.51	1.86	2.76	1.95	1.88	1.88	1.73	2.55	1.93	1.27	2.24	2.50	2.16
P6	1.44	2.45	2.15	2.71	5.87	2.80	2.02	2.37	2.37	2.01	2.44	2.74	1.85	1.67	2.93	1.38
P7	2.05	3.47	2.36	2.29	2.35	3.26	2.11	2.39	2.39	2.26	2.04	2.01	2.80	2.77	2.97	1.94
Mean	2.39	2.65	2.29	2.15	2.69	2.65	1.98	2.22	2.22	1.99	2.20	2.33	2.34	2.31	2.55	2.28
SD	0.64	0.47	0.27	0.37	1.42	0.36	0.09	0.36	0.36	0.38	0.28	0.29	0.76	0.47	0.44	0.86

Note

P = sampling point
FA, FB, FC = Dry Dipterocarps forest plot A, B and C respectively
C1b and C1c = Cassava 10-20 years old plot B and C respectively
C2a, C2b and C2c = Cassava 20-30 years old plot A, B and C respectively
S1a, S1b and S1c = Sugarcane 10-20 years old plot A, B and C respectively
S2a, S2b and S2c = Sugarcane 30-40 years old plot A, B and C respectively
S3a and S3b = Sugarcane 40-50 years old plot A and B respectively
SD = Standard deviation