Factors Controlling Carbon Sequestration of Major Upland Soils in Northeast Plateau, Thailand

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Abstract

Soil characteristics and land uses can affect the ability of surface and subsurface soils on their organic carbon sequestration and their contribution to mitigation of the global greenhouse effect. In this study fifteen representative sites of major upland agricultural soils in Northeast Plateau, Thailand including Oxisols, Ultisols and Alfisols were selected for the analysis of these effects. Land uses at the time of sampling were uncultivated lands, corn fields, tree with forage crops and cassava fields. The results revealed that organic carbon sequestration (OC_{seq}) in their surface soils and subsoils interaction with soil types and land uses are different. The extreme value of soil organic carbon (SOC) stored in Ap horizons is in uncultivated lands but the amount of OC_{seq} in 2 m depth depends on land use types. The relationship of soil properties with OC_{seq} in Ap and subsoil horizons are different. These relationships depend on the dominating characteristics in each soil depth fraction. The differences among soil parent materials have a slight effect on SOC and OC_{seq}. Especially, OC_{seq} in Oxisols and Ultisols are not different among parent materials. For Alfisols however, there are significant differences in OC_{seq} among parent materials. The OC_{seq} values of soils on similar altitudes are affected by types of land use. Silt plus clay content is the important factor controlling OC_{seq} in these soils. However, in surface soils, SOC addition and land use types also have important effects on their OC_{seq}.

Keywords: soil carbon sequestration, upland soils, land uses, factor controlling carbon sequestration

Introduction

Soil carbon sequestration (OC_{seq}) is an important process to reserve carbon (C) in a form that is not immediately reemitted and as organic carbon (Gibson et al., 2002). This soil organic carbon (SOC) is the C component of soil organic matter (SOM) directly derived from plants and animals (Charman and Roper, 1991) and plays a central role in soil quality and the sustainability of soil fertility (Doran and Safley, 1997; Chan, 2001). Therefore, OC_{seq} or organic carbon stabilization in soil helps off-set emissions of carbon while enhancing soil quality and long-term agronomic productivity (Lal, 1997; Watson et al., 2000). The amount of SOC that exists in any given soil is determined by the balance between the rates of organic carbon input (vegetation, roots) and output (CO_2 from microbial decomposition) (Reicosky, 1997; Lal and Bruce, 1999). However, soil type, climate, management, mineral composition, topography, soil biota and the interactions between each of these are modifying factors that will affect the total amount of SOC in a profile as well as the distribution of SOC contents with depth (Baldock and Skjemstad, 1999; Abu-Hamdeh and Reeder, 2000). It is important to note that any change made to the natural status of the soil systems (e.g. conversion to agriculture, deforestation, plantation) will result in different conditions under which SOC enters and exits the system (Eshetu et al., 2004; Krull et al., 2004). In agricultural soils, SOC contributes positively to soil fertility, soil tilth, crop production, and overall soil sustainability (Bauer and Black, 1994; Hao et al., 2001), especially in tropical soils where nutrient poor, highly weathered soils are often managed with few external inputs (van Noordwijk et al., 1996). Land use management influences the ability of soils to serve as both a source and a sink of SOC and nutrients (Feller and Beare, 1997; Post and Kwon, 2000; Guo and Gifford, 2002).

Mineralization of SOC is generally more rapid in coarse textured than in fine textured soils and the protection of SOC by silt and clay particles is well established (Ladd and Amato, 1985; Hassink, 1997). Under similar climatic conditions, SOC content in fine-textured (clayey) soils is 2-4 times that of coarse-textured (sandy) soils (Hassink, 1997; Prasad and Power, 1997). Clay content is the best predictor in the soil deeper layers, this may be due to the increased proportion of slower cycling SOC pools at depth (Trumbore, 2000) since there are SOC pool strongly associated with clay particles and noncrystalline minerals that stabilize and protect SOC (Torn et al., 1997; Zech et al, 1997). McLauchlan et al. (2006) however, reported that clay concentration has no effect on SOC pool sizes or rate of accumulation.

Thus, there is a need to understand more clearly the factors which control SOC stabilization and OC_{seq} in the Tropics and to determine how these factors are influenced by land use management practices. In Thailand, there is less information about the effects of land uses and soil properties on the amount of SOC stabilization and OC_{seq} for subsurface soils as compared with that for surface soils. Therefore, the objective of this study was to define the major factors affecting organic carbon sequestration of upland agricultural soils in Northeast Plateau, Thailand.

Materials and Methods

Sampling Sites

Fifteen representative sites were selected in major upland agricultural areas which are well distributed in Nakhon Ratchasima, Maha Sarakham and Khon Kaen provinces. They are 12 soil series: Loei (Lo), Chok Chai (Ci), Pak Chong (Pc1, Pc2, Pc3, Pc4), Chum Phuang (Cpg), Sung Noen (Sn), Satuek (Suk), Yasothon (Yt), Phon Phisai (Pp), Borabue (Bb), Sikhio (Si), Nam Phong (Ng) and Chan Thuek (Cu) (Table 1). The study area is under tropical savanna climate (Aw) with an annual rainfall range of 1000-1400 mm and mean temperature range of 25-38 ^{o}C (Meteorological Department of Thailand, 2006). The soils have ustic soil moisture regime and isohyperthermic temperature regime (Soil Survey Division Staff, 2010). All soils are deep. Alfisols developed on calcareous sandstone, wash over local alluvium over mixed local alluvium and colluvium and granite. Oxisols developed on limestone and basalt while Ultisols developed on sandstone, sedimentary rock and siltstone (Table 1). Land uses at the time of sampling were uncultivated lands, corn fields, tree and forage crops and cassava fields. Historical management of tree with forage crops in this study indicates low soil management input whereas corn fields always have high surface input in cropping.

Laboratory Analyses

The physicochemical properties of the soils (<2 mm) were analyzed using standard methods (National Soil Survey Center, 1996). Particle size analysis was measured by pipette method, hydraulic conductivity by falling-head method and bulk density (BD) by clod method. Chemical analyses included soil pH determined in 1:1 soil:solution in H_2O and 1M KCl by pH meter, soil organic carbon by Walkley-Black method. Available P analysis was by Bray II and extractable bases (Ca^{2+}, Mg^{2+}, Na^+ and K^+) was by 1M NH_4OAc extraction at pH 7.0 and measured by atomic absosrption spectrophotometer (AAS). Extractable acidity was by barium chloride-triethanolamine solution at pH 8.2 and cation exchange capacity (CEC) was by saturating the exchange site and displacing by 1M NH_4OAc at pH 7.0. Iron and aluminum were extracted by

Table 1 Pedological characterization of major upland agricultural soils in this study.

Subgroup[1/]	Soil series	Site	Parent material	Physiographic position	Elevation (m MSL)	MAP (mm)	MAT (°C)	Slope (%)	Land use
Typic Kandiustox	Loei (Lo)	Nakhon Ratchasima	Limestone	Coalesing intermontane footslope	394	1,105	25.9	3	Corn field
Rhodic Kandiustox	Chok Chai (Ci)	Nakhon Ratchasima	Basalt	Lava corrosion plain	266	1,097	27	1	Cassava field
Rhodic Kandiustox	Pak Chong (Pc1)	Nakhon Ratchasima	Limestone	Karst corrosion plain	372	1,105	25.9	3	Corn field
Rhodic Kandiustox	Pak Chong (Pc2)	Nakhon Ratchasima	Limestone	Karst corrosion plain	375	1,105	25.9	1	Corn field
Rhodic Kandiustox	Pak Chong (Pc3)	Nakhon Ratchasima	Limestone	Karst corrosion footslope in limestone intermontane valley	418	1,105	25.9	3	Uncultivated land
Typic Kandiustox	Pak Chong (Pc4)	Nakhon Ratchasima	Basalt	Corrosion footslope	320	1,105	25.9	4	Tree with forage crop
Typic Kandiustult	Chum Phuang (Cpg)	Khon Kaen	Red sandstone	Upper backslope of residual low hill	178	1,242	27.4	3	Tree with forage crop
Typic Kandiustult	Sung Noen (Sn)	Nakhon Ratchasima	Siltstone	Rise on siltstone corrosion plain	252	1,182	27.7	3	Cassava field
Typic Haplustult	Satuek (Suk)	Khon Kaen	Sedimentary rocks	Lower part of high erosional terrace	167	1,379	27	3	Tree with forage crop
Typic Kandiustult	Yasothon (Yt)	Nakhon Ratchasima	Red sandstone	Residual plain (Corrosion plain)	245	1,182	27.7	3	Cassava field
Typic Plinthustult	Phon Phisai (Pp)	Khon Kaen	Metasedimentary rocks	Upper extended footslope	176	1,242	27.4	3	Cassava field
Plinthic Haplustult	Borabue (Bb)	Maha Sarakham	Sandstone	Shoulder slope of low residual hill	215	1,257	27.4	7	Cassava field
Typic Rhodustalfs	Sikhio (Si)	Nakhon Ratchasima	Calcareous sandstone	Corrosion plain (calcareous sandstone)	242	1,182	27.7	4	Cassava field
Psammentic Haplustalf	Nam Phong (Ng)	Khon Kaen	Local alluvium and colluvium	Shoulder slope on dissected lower footslope	202	1,242	27.4	6	Cassava field
Psammentic Haplustalf	Chan Thuek (Cu)	Nakhon Ratchasima	Granite	Upper midslope	333	1,105	25.9	5	Cassava field

[1/] Taxonomic name (Soil Soil Survey Staff, 2010); Lat = Latitude, Long = Longitude; MAP = mean annual precipitation; MAT = mean annual temperature

dithionite-citrate-bicarbonate solution (DCB) (Fe_d, Al_d) and by 0.2 M ammonium oxalate solution at pH 3.0 (Fe_o, Al_o). The OC_{seq} was calculated from SOC concentration and bulk density (BD_d) for each depth sections (D);

$$OC_{seq}\ (\mathrm{Mg\ C\ ha^{-1}}) = \mathrm{SOC\ layer\ (kg\ Mg^{-1})} \times BD_d\ \mathrm{layer\ (Mg\ m^{-3})} \times D\ (\mathrm{m}) \times 10^{-3}\ \mathrm{Mg\ kg^{-1}} \times 10^{4}\ \mathrm{m^2\ ha^{-1}}$$

Results and Discussion

General Soil Characteristics

Soil texture varies from clay to loamy sand and with a range from 254-935 g kg^{-1} of silt plus clay content (Table 2). The soils can be divided into two broad textural groups as coarser textured and fine textured soils. A coarse textured group contains

Table 2 Mean values of general properties for major upland agricultural soils on various parent materials in major upland agricultural soils in Northeast Plateau, Thailand.

Property	Alfisols			Oxisols		Ultisols		
	Calcareous sandstone	Local alluvium[1/]	Granite	Limestone	Basalt	Sandstone	Sedimentary rock	Siltstone
	(n=6)	(n=8)	(n=8)	(n=32)	(n=17)	(n=22)	(n=17)	(n=6)
Silt+clay (g kg^{-1})	595	254	290	935	911	295	444	531
Sand (g kg^{-1})	406	746	710	65	89	705	556	469
Bulk density (Mg m^{-3})	1.6	1.6	1.7	1.3	1.3	1.6	1.8	1.6
pH (H_2O)	7	5.7	6.9	6.1	4.7	5	5.6	5.1
OM (g kg^{-1})	8.1	2	6.6	8.3	8.8	3.6	3.3	4.5
Total nitrogen (g kg^{-1})	0.65	0.34	0.5	0.7	0.64	0.44	0.35	0.37
Ca (cmol kg^{-1})	21	0.52	3.2	6.5	4.3	1	1.7	3.6
EA (cmol kg^{-1})	1.8	2	2.3	9.3	12	4	7.3	6.8
CEC (cmol kg^{-1})	11	1.8	4.7	12	9.8	4.3	7.8	6.9
Fe_d (g kg^{-1})	12	5.2	0.77	65	54	7.1	23	7.9
Al_d (g kg^{-1})	10	3.1	1.6	14	10	9.6	8	7.6
Fe_o (g kg^{-1})	1.2	0.23	0.24	2.1	2.4	0.63	1.6	0.76
Al_o (g kg^{-1})	2.0	2.37	2.6	2.5	2.1	2.5	2.4	2.6
Fe_o/Fe_d	0.09	0.04	0.3	0.03	0.04	0.09	0.07	0.1

[1/] Wash over local alluvium over mixed local alluvium and colluviums.

high amount of sand particles (>556 g kg^{-1}) reflecting their parent materials. The bulk density (BD) values of Oxisols are lower than that of Ultisols and Alfisols averaging 1.30, 1.65 and 1.70 Mg m^{-3}, respectively. The pH-H_2O values of the soils range from extremely acid (pH 3.9) to neutral (pH 7.3). The pH-H_2O of these soils is highest in Alfisols (calcareous sandstone) and lowest in Oxisols (basalt) averaging 7.0 and 4.7, respectively. Soil organic matter (SOM) is highest in Oxisols (3.6-34 g kg^{-1}) followed by Alfisols (0.62-14 g kg^{-1}) and Ultisols (0.26-9 g kg^{-1}). The average SOM are highest in basalt derived soils (5.8 g kg^{-1}) and lowest in soils formed on wash over local alluvium over mixed local alluvium and colluvium (2.0 g kg^{1}). Total nitrogen shows the same distribution trend with OM and they have a close relationship. Calcium is the major exchangeable base in Alfisols, Oxisols and Ultisols soils and averaging 7.0, 5.8, 1.1 $cmol_c$ kg^{-1}, respectively. Comparison of Ca in soils developed on various parent materials being calcareous sandstone >> limestone > basalt > siltstone > granite > sedimentary rock > sandstone > wash over local alluvium over mixed local alluvium and colluvium. Extractable acidity (EA) values of Ultisols and Oxisols are medium to high. This demonstrates the effective leaching of alkaline cations and the displacement of H^+ in the soil and indicates that they are moderately to highly developed soils. Oxisols have moderately low to high CEC (5.4-22.5 $cmol_c$ kg^{-1}) reflecting their heavier texture followed by Alfisols that have very low to medium CEC (0.3-14.5 $cmol_c$ kg^{-1}) and Ultisols having very low to low CEC (0.25-8.25 $cmol_c$ kg^{-1}). The CEC values of soils developed on limestone and calcareous sandstone are higher than that of soils developed on the other parent materials. Extractable Fe_d, Al_d, Mn_d, Fe_o and Mn_o concentrations in Oxisols are higher than in Ultisols and Alfisols. The lowest of Fe_o/Fe_d values (0.03) is for soils developed on limestone, indicating that iron oxides in these soils have a high degree of crystallinity as compared to that in the others (Blume and Schwertmann, 1969).

Soil Organic Carbon Sequestration

The organic carbon sequestration (OC_{seq}) in different soil types and land uses was calculated from SOC concentration and bulk density from depth sections (Table 3). The bulk density values in different soil and land use types show no clear difference. Soil organic carbon contents of Oxisols are highest averaging 12 g kg^{-1} in Ap horizon and 4.4 g kg^{-1} in 0-2 m depth. Soils under uncultivated lands have more SOC in Ap horizons than do soils under corn fields, cassava fields and tree with forage crops. The average values of SOC in Ap horizons and in 0-2 m depth of uncultivated soils are markedly different due to their high accumulation of SOM in surface soils. The C/N in these soils is higher in the Ap horizons and lower in subsoil horizons with a decreasing trend with depth. The average C/N in Ap horizons of Oxisols are highest (10/1) and no clearly different among land uses. The organic carbon sequestration (OC_{seq}) in these soils is highest in the surface soils and it tends to decrease with depth. In Ap horizons, the OC_{seq} are 31, 14 and 10 Mg ha^{-1} in Oxisols, Alfisols and Ultisols, respectively and 43, 24, 14 and 8.7 Mg ha^{-1} in uncultivated land, corn fields, cassava fields and tree with forage crops, respectively (Table 3). The extreme value of C stored in Ap horizons is in uncultivated land but the amount of OC_{seq} in 2 m depth of uncultivated land and corn fields are similar. The amounts of OC_{seq} in 2 m depth of Oxisols are higher than that in Alfisols and Ultisols averaging 112, 85 and 53 Mg ha^{-1}, respectively. Therefore, the interaction of OC_{seq} in Ap horizons and in 2 m depth of these soils with soil types and land uses are different.

Table 3 Range and mean values of bulk density, organic carbon, carbon and nitrogen ratio (C/N) and organic carbon sequestration (OC_{seq}) of surface soils (Ap) and 0-2 m depth for difference soil types and land uses.

	Depth	Bulk density ($Mg\ m^{-3}$)			Soil organic carbon ($g\ kg^{-1}$)			C/N			OC_{seq} ($Mg\ ha^{-1}$)		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Soil type													
Alfisols	Ap	1.5	1.7	1.6	2.3	5.7	4.5	7.6	9.5	8.7	6.7	19	14
	0-2 m	1.5	1.7	1.6	0.5	5.6	3.2	4.8	11	8.4	33	127	85
Oxisols	Ap	1.1	1.6	1.4	7.8	20	12	7.8	11	10.0	24	52	31
	0-2 m	1.1	1.5	1.3	3.0	5.3	4.4	6.7	10	8.6	74	143	112
Ultisols	Ap	1.5	1.7	1.6	2.6	4.9	3.3	5.5	12	8.8	8.4	15	10
	0-2 m	1.5	2.0	1.6	0.7	3.6	2.1	3.3	13	9.1	25	81	53
Land use													
Uncultivated	Ap	1.3	1.6	1.4	11	20	15	9.9	9.8	9.8	34	52	43
	0-2 m	1.2	1.5	1.4	4.4	4.8	4.6	7.2	8.7	7.9	73	143	108
Tree and forage	Ap	1.6	1.7	1.6	2.6	2.7	2.7	5.5	11	8.2	8.5	8.8	8.7
	0-2 m	1.6	1.6	1.6	0.7	1.4	1.0	3.3	11	7.1	25	137	64
Corn	Ap	1.2	1.6	1.4	5.7	11	8.5	7.8	11	9.6	19	26	24
	0-2 m	1.2	1.4	1.3	3.0	4.8	3.8	6.7	9.8	8.6	91	122	105
Cassava	Ap	1.1	1.7	1.5	2.3	11	4.8	7.6	12	9.2	6.7	24	14
	0-2 m	1.1	2.0	1.6	0.5	5.6	3.1	4.8	13	9.5	33	127	77

Relationship between Soil Organic Carbon Sequestrations with Soil Properties

Principal component analysis was used to provide a better understanding of relationships between OC_{seq} and some soil properties in Ap (Figure 1a) and subsoil horizons (Figure 1b). Two factors explain eighty and seventy percent of the variation in data describing OC_{seq}, which may be considered as an acceptable prediction considering the diverse nature of these soils (Kaiser, 1960). Organic carbon sequestration in Ap horizons of Oxisols shows positive relationships with silt plus clay content, cation exchange capacity (CEC) and free iron oxides (Fe_d). The OC_{seq} in Ap horizons of Ultisols and Alfisols shows negative relationships with sand content. Calcium, pH, BD and EA have weak effect on SOC storage in Ap horizons. The effects of sand content, BD and EA on SOC storage in subsoils horizons have the same trend with that on SOC storage in Ap horizons (Figure 1a, b). Calcium and pH show stronger effect storage in subsoils than that in Ap horizons, especially in the subsoils of Alfisols. The group of silt plus clay content, Fe_d and EA properties in subsoils has a weaker relationship with SOC storage than that in Ap horizons particularly in Oxisols (Figure 1b). These results clearly indicate the difference in the relationships of soil properties with organic carbon sequestration in Ap and subsoil horizons as affected by the dominating characteristics in each soil particularly silt plus clay content, sand content, CEC, Fe_d and Ca.

(a)

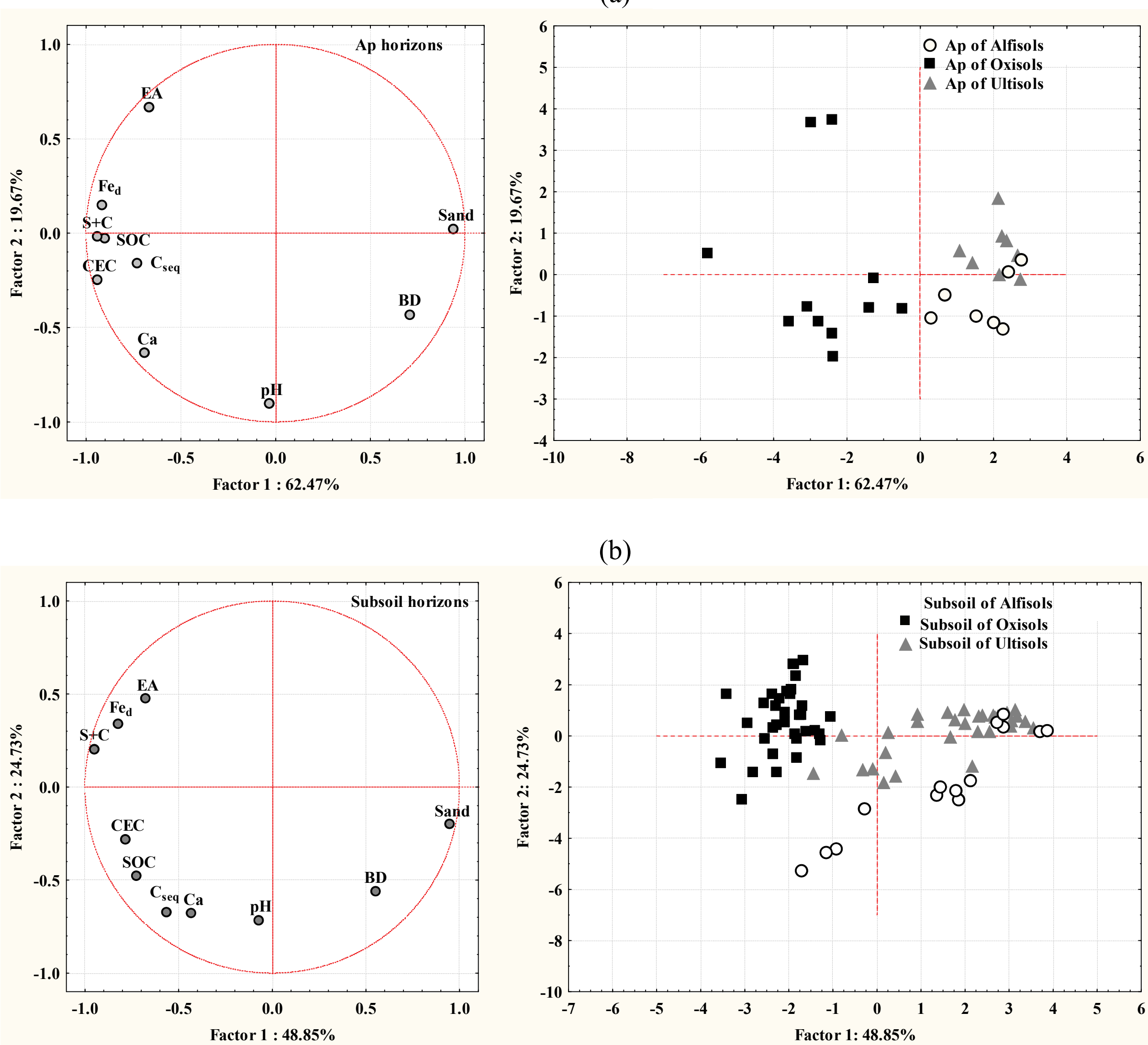

Figure 1 Distribution of soil variables and soil samples for (a) Ap horizons and (b) subsoil horizons.

Effect of Soil Parent Material

The quantity and quality of SOC stored can vary according to the type of parent materials. One-way ANOVA was used to describe the effect of parent material on SOC, OC_{seq}, and some soil properties. In Alfisols, parent material have significant effects ($P<0.001$) on SOC and OC_{seq} (Table 4). There is a significant difference in SOC between local colluvium and alluvium, granite and calcareous sandstone. The SOC are largest in calcareous sandstone, followed by granite and local colluvium and alluvium in descending order. This reflects the influence of silt plus clay content, calcium concentration and free iron oxides (Fe_d) in calcareous sandstone (Table 4). Limestone and basalt have significant effects on the amorphous forms of inorganic Al (Al_o) ($P<0.01$) and crystallinity of free iron oxides (Fe_o/Fe_d) ($P<0.05$). The Fe_o/Fe_d values of soils derived from basalt are higher than that of soils derived from limestone. Limestone have low Fe_o/Fe_d (<0.1) indicating the maturity, well drained condition and the dominance of crystalline iron oxides (e.g. hematite and goethite) (Blume and Schwertmann, 1969). The highest concentration of Al_o and Al_d for soils developed on limestone suggests that the substitution of Al in crystalline Fe oxides is greater than in non-crystalline Fe oxides (Holmgren, 1967). Ultisols do not show differences of SOC among parent materials whereas some soil characteristics (silt+clay, Ca, Na, Fe_o, and Al_o) differ significantly. These results indicate that properties of iron oxides, such as crystallinity and Al substitution, are related to stage of soil development and parent material (Buol et al., 2003). For Alfisols, there are significant differences in OC_{seq} among parent materials. However, the differences among soil parent materials have only slight effect on SOC and OC_{seq} of major upland agricultural soils in Northeast Plateau, Thailand. Especially, OC_{seq} in Oxisols and Ultisols are not different among parent materials.

Table 4 One way ANOVA and least significant different (*P*=0.05) among parent materials of carbon sequestration in 2 m depth, organic carbon and some chemical properties in these soils. Values are the mean and standard deviation in parenthesis.

Alfisols	$OC_{seq\ (0\text{-}2\ m)}$	SOC	Silt+clay	Ca	Fe_d
Calcareous sandstone (n=6)	96	4.7 (1.3) a	595 (99) a	20.7 (11.7) a	12.4 (2.8) a
Local alluvium and colluviums (n=8)	33	1.1 (0.8) b	254 (95) b	0.5 (0.3) b	5.2 (5.1) b
Granite (n=8)	127	3.8 (1.7) a	290 (76) b	3.2 (0.6) b	0.8 (0.2) b
P	***	***	***	***	***
LSD	*	*	*	*	*

Oxisols	$OC_{seq\ (0\text{-}2\ m)}$	SOC	Fe_o/Fe_d	Al_o
Limestone (n=31)	115	5.5 (4.6)	0.03 (0.1)	2.48 (0.2)
Basalt (n=17)	105	5.4 (3.4)	0.56 (0.3)	2.08 (0.4)
P	0.91	0.98	*	**

Ultisols	$OC_{seq\ (0\text{-}2\ m)}$	SOC	Silt+clay	Ca	Na	Fe_o	Al_o
Sandstone (n=12)	51	2.1 (1.2)	295 (71) b	1.0 (1.0) b	0.1 (0.1) b	0.6 (0.3) b	2.5 (0.3) b
Sedimentary rock (n=8)	56	1.9 (0.9)	444 (158)ab	1.7 (1.3) b	0.2 (0.1) ab	1.6 (0.8) a	3.7 (1.7) a
Siltstone (n=4)	52	2.6 (1.6)	531 (84) a	3.6 (1.3) a	0.3 (0.1) a	0.8 (0.1) b	2.6 (0.2) b
P	0.81	0.66	**	**	*	**	*
LSD	ns	ns	*	*	*	*	*

*, **, *** significant at $P<0.05$, $P<0.01$ and $P<0.001$ respectively.

Effect of Topography and Land Use

The associations between elevation and vegetation types are important for SOC and OC_{seq} in these soils. Data in Figure 2 indicated that OC_{seq} and OC are consistently (i) highest under uncultivated lands especially in Ap horizons and (ii) tending to increase with elevation. The types of land use arranged in order of descending elevation is corn fields occupying higher elevation than cassava fields followed by tree and forage crops. The OC_{seq} and OC have positive relationships with land use (R^2=0.93**) and elevation (R^2=0.63**). Physiographic position of karst corrosion plain and coalescing intermontanae footslope (370-400 m MSL), corrosion plain (170-330 m MSL), backslope of residual low hill and erosional terrace (160-180 m MSL) are under corn fields, cassava fields and tree with forage crops, respectively. Soils under the tree with forage crops have lower C_{seq} and OC than those under the other land uses followed by that under cassava fields, corn fields and uncultivated lands. This result is different from the findings of many studies that reported the effect of higher C inputs and rooting depth of trees and grasses on significant sequestered C in soil profile (Ludwig and Esteban, 2000; Blanco-Canqui and Lal, 2004; Lorenz and Lal, 2005). This is attributed to low soil management input in the tree with forage crop areas whereas corn fields always have high surface input in cropping. There are generally strong correlations between the OC_{seq} and SOC in the Ap horizons and the selected site variables (elevation and land use) and the other individual variables for these soils.

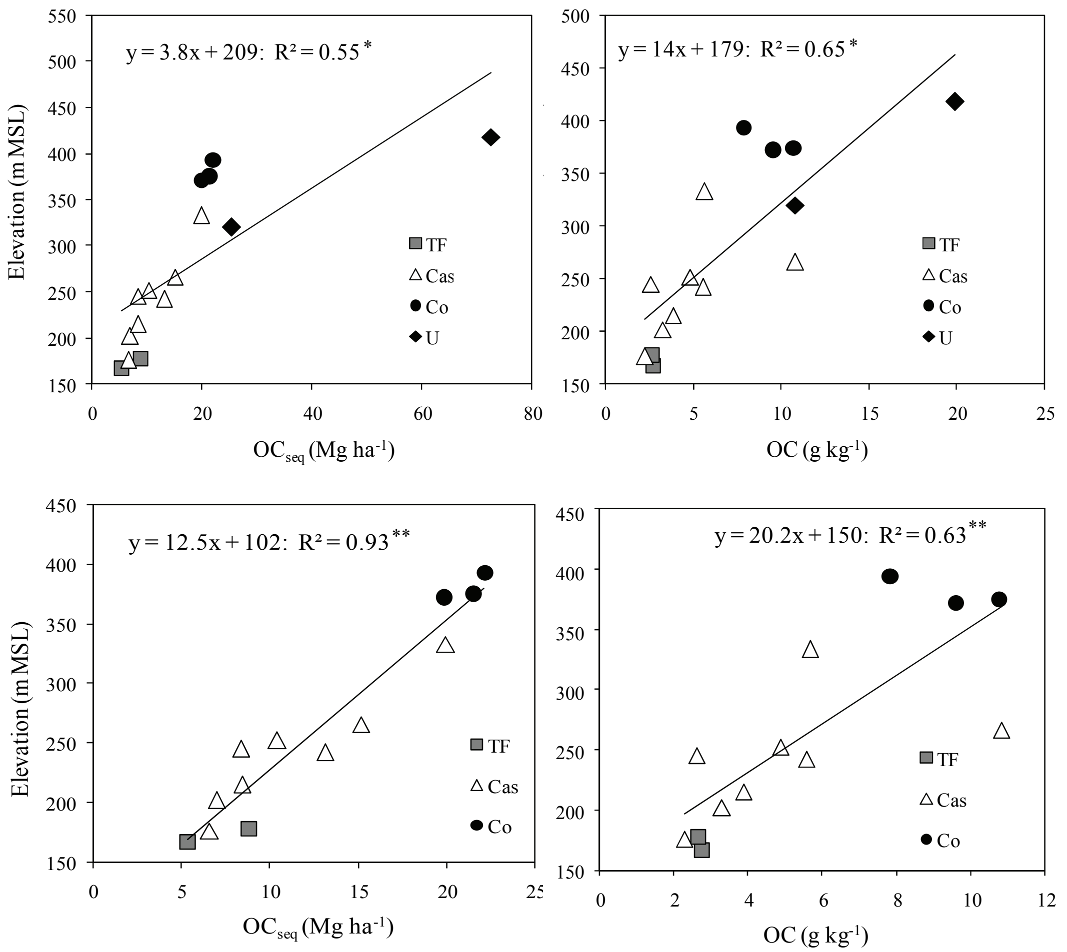

Figure 2 Scattering plot between elevation and carbon sequestration (OC_{seq}) and organic carbon concentration (OC) in different land uses of upland agricultural soils.

The correlation between OC_{seq} and clay content are positive under uncultivated lands (r=0.92) and corn fields (r=0.90) (Figure 3). The correlation between OC_{seq} and clay content under cassava fields are not significant (r=0.13) and OC_{seq} under tree with forage crops are negatively correlated with clay content (r=-0.97). Correlation coefficients indicated that OC_{seq} in Ap horizons of most soils increased with the increasing correlation of OC_{seq} and clay content. Although, there was an increase of OC_{seq} with increasing clay content, the differences of land use types also markly influenced the extent of OC_{seq} in Ap horizons of these soils. The uncultivated lands and corn fields showed the similar correlation of OC_{seq} with clay content (r=0.92, 0.90, respectively) but the highest OC_{seq} was observed in uncultivated lands (41 Mg ha^{-1}) in comparison to corn fields (27 Mg ha^{-1}). These results support the importance of land use types, and additional SOC have important effects on OC_{seq} in surface soils aside from the nature of their textural content.

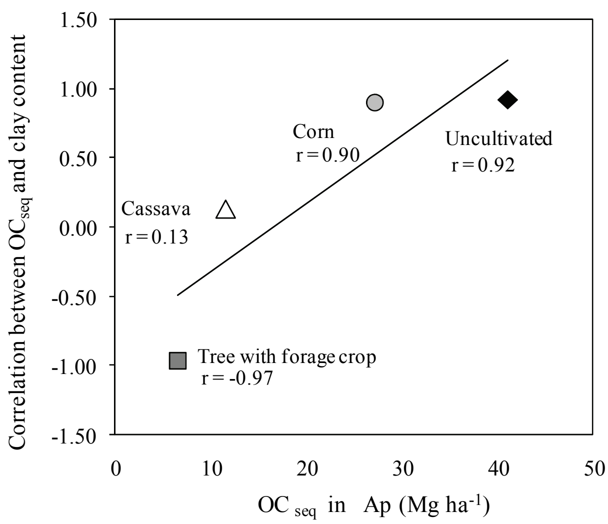

Figure 3 Correlation coefficients (Spearman rank) for the relationship between carbon sequestration (OC_{seq}) and clay in upland agricultural soils for different land use types.

Conclusions

The soil organic carbon contents of Oxisols are higher than that of the other soil types. The uncultivated soils have higher SOC in Ap horizons than that in soils under corn fields followed by cassava fields, tree and forage crops, respectively in descending order. The C/N shows no clear differences among land uses. In Ap horizons, organic carbon sequestration averages are 31, 14 and 10 Mg ha^{-1} in Oxisols, Alfisols and Ultisols, respectively and averaging 43, 24, 14 and 8.7 Mg ha^{-1} in uncultivated land, corn fields, cassava fields and tree with forage crops, respectively. The extreme value of C stored in Ap horizons is in soils under uncultivated lands. The amounts of OC_{seq} in 2 m depth of Oxisols are higher than that of Alfisols and Ultisols averaging 112, 85 and 53 Mg ha^{-1}, respectively. Organic carbon sequestration in Ap horizons of Oxisols are affected by silt plus clay content, cation exchange capacity (CEC) and free iron oxides (Fe_d). Organic carbon sequestration in soils is negatively related with sand content. In Alfisols, parent materials have significant effects on SOC and OC_{seq} while in Oxisols and Ultisols are no different among parent materials. The SOC and OC_{seq} and OC have positive relationships with land use (R^2=0.93**) and elevation (R^2=0.63**). There are generally strong correlations between the OC_{seq} and SOC in the Ap horizons and the selected site variables including elevation and land use.

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