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Effects of land use on some physical, chemical, and mineralogical characteristics of Thai Oxisols

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ABSTRACT: Thai Oxisols in land subjected to various use with two types of soil moisture regimes were analysed for some chemical properties such as pH, cation exchange capacity (CEC), carbon concentration, and content of Fe, Al, and Mn oxides in crystalline, noncrystalline, and organic form. We also determined clay content, bulk density (BD), aggregate size distribution, mean weight diameter (MWD), water stable aggregate, and strength in large (LMA; $>$ 2000 µm) and small macroaggregates (SMA; 250–2000 µm). Type and amount of minerals including kaolin crystal size were also evaluated. Soil samples of surface (0–5 cm) and subsurface (5–20 cm) layers were collected from the perennial crops: durian (*Durio zibethinus*) and rubber (*Hevea brasiliensis*) plantation; and annual crops: maize (*Zea mays*), sugarcane (*Saccharum officinarum*), and cassava (*Manihot esculenta*) plantation. Two sites in each land use were chosen in this study. Clay content did not differ significantly for all soils. BD was significantly higher for annual crops. Mean pH ranged from 3.95–5.48 and 3.99–5.49, and mean CEC ranged from 8.1–13.4 cmol/kg and 3.9–7.1 cmol/kg for surface and subsurface, respectively. Carbon concentration was 2.37–4.09 and 1.15–1.36% for surface and subsurface, respectively. The values were lower for annual crops than for perennial crops for both surface and subsurface layers. All forms and contents of Fe, Al, and Mn oxides were significantly higher for perennial crops than for annual crops except for content of crystalline Fe which was not statistically different. These oxide contents correlated positively to MWD, carbon concentration, and LMA strength with $r > 0.70$. The perennial crop soils had higher average MWD (0.92–1.31 nm), amount of LMA (17.0–41.2%), LMA strength (5.8–9.0 N), and SMA strength (2.2–3.2 N) than those of the annual crop soils. Microaggregates (28.2–39.2%) were more abundant for annual crops. Amount of SMA (41.3–49.1%) did not differ significantly between land uses. The amount of LMA and MWD depended largely on the concentration of carbon with $r = 0.96$ and 0.94, respectively. Kaolin crystal size was significantly smaller for perennial crops (82.0–114.5 nm) than for annual crops (140.0–163.0 nm). Kaolin crystal size of both types of land use were negatively correlated to aggregation, carbon, and oxides content with $r < -0.70$.

KEYWORDS: carbon content, soil health, soil-organic carbon, land management

INTRODUCTION

Land use, management, and local climate influence soil aggregation, aggregate stability[1–3], and soil health[4]. Soil organic carbon (SOC) and soil texture, which depends on associated SOC and clay contents[5], are the main determinants of soil physical properties such as bulk density and aggregate stability[6]. Conversion of soil from forest to other land uses results in higher bulk density, lower hydraulic conductivity, and higher susceptibility to erosion[7], resulting in soil degradation and declining SOC concentration[8]. Farming practices affect SOC concentration and physical properties[9]. Storage of C in Ferrosols (Oxisols) soil in rainforest and pasture is greater than in plantation where land use has changed[10]. The carbon concentration for these soils relates to macro- and microaggregate formation. In tropical climate, natural undisturbed forest, artificial forests, and grassland store more carbon than cultivated and continuously cropped lands[11]. Annual crop management disrupts soil structure and induces a loss of C-rich macroaggregate and gain of C-depleted microaggregate[12] because of higher decomposition rate of microbial activity. In contrast, perennial crop management maintains aggregation and SOC content[8]. Warmer temperatures cause higher soil respiration and biological activity, which reduces the stock of SOC[13]. During wetting, clay particles tend to disperse and then form bridges and coatings during drying. Wet-dry cycles tend to aggregate soils in arid, semi-arid, and sub-humid regimes[14]. In most of Asia including Thailand, research on effects of land use on physical, chemical, and mineralogical properties of agricultural soils is proceeding slowly. Thus data on soil carbon concentration, aggregate properties, chemical and mineralogical characteristic are lacking for most common agro-ecosystems.

Relationship between soil organic carbon, Fe, and Al oxides with aggregation

Soil organic carbon acts as a binding agent and as a nucleus for the formation of aggregates. SOC creates soil aggregates by forming organo-mineral complexes. However, the role of organic carbon on soil physical properties is not always clearly defined[15]. Organic carbon and water stable aggregate (WSA) have been found to be not correlated[16] or positively correlated[17,18]. The stability of soil structure is closely related to the young and active soil organic matter fraction[19]. The size distribution and stability of aggregates are important indicators of the degree of soil degradation[5]. These properties provide measurements of the impacts of land use, soil management, and environmental factors on soil properties in a red latosols[3].

Pedogenic oxide in both crystalline and amorphous forms are important aggregants in soils. These oxides form bridges between mineral and organo-mineral particles. Clay also acts as an aggregant, binding particles together and influencing SOC decomposition and turnover. In Oxisols, both Al and Fe control aggregation in acidic soils with low clay and SOC contents[20,21]. Amorphous Fe and SOC form fine stable particles in soils with high SOC content. Coarse-grained particles are formed from Fe oxides, which increase the tensile strength of aggregates in Oxisols and improve aggregate stability in others[21]. Content of crystalline and amorphous forms of Fe and Al may be responsible for the prolonged dry season[22]. Drying at the elevated temperature of tropical soils causes the amorphous Fe and Al oxides to dehydrate and subsequently to shift to a system of greater crystallinity[23]. Losing amorphous materials results in significant changes in physical and chemical properties, such as decrease in cation exchange capacity (CEC), aggregate stability, and increase bulk density.

Oxisols are mainly distributed in the south-east coast, north-east plateau, and peninsular regions of Thailand, supporting important economic crops constituting about 231 120 hectares of agricultural area. These Oxisols typically developed by extreme weathering of basalt or limestone[24] under udic or ustic moisture regimes. History has shown that land uses have been changed from tropical rain forest to perennial rubber and durian plantation under udic conditions and from a savannah to annual crops under ustic soil moisture regime. These soils are deep, with well developed granular structure, and have good internal drainage. Their bulk densities are low to moderately low. Their texture is clay and has low available water capacity. Their pH, OM, CEC, and %BS are generally low. High phosphorus adsorption is found because of their high Fe contents[25]. Major clay minerals are predominantly kaolin with minor amounts of quartz and gibbsite, particularly in soils derived from basalt under high amount of rainfall. Minor amount of anatase, illite, and smectite are also present in some Thai Oxisols[26]. Land management practices may alter these soil properties such as carbon accumulation, bulk density. The objectives of the present study were: (a) to determine the effects of land use and environmental factors on some physical, chemical, and mineralogical properties; and (b) to relate carbon concentration and some chemical properties to aggregate properties including strength.

MATERIALS AND METHODS

Site description

Two contrasting types of land use were chosen for this study, i.e., perennial crops for 4 sites and annual crops for 6 sites. The perennial land use is the culture of durian (*Durio zibethinus*) and rubber (*Hevea brasiliensis*) trees, while the annual crops are maize (*Zea mays*), sugarcane (*Saccharum officinarum*), and cassava (*Manihot esculenta*). Soils of the study areas are Oxisols, i.e., acidic, clayey, deep, and well drained with dark reddish brown (5YR3/4) to dark red (2.5YR3/6) of B horizon. The boundaries between epipedon and sub-soil range from abrupt to clear, while boundaries between subsurface horizons range from clear to diffuse. The subsoils have strong fine granular structure. The perennial crops were located in the south-east coast region of Thailand. The climate is tropical monsoon with an average temperature of 28–30 °C, and annual rainfall of 3000–4000 mm. The soils are not dry in any part for as long as 90 cumulative days. The soils are Kandiudox with a udic soil moisture regime. The sites have continually produced either durian or rubber latex for more than 30 years. This type of land use has received no cultivation, a single lime application at the rate of 12.5 t/ha annually and the soil has been mulched with crop residue after annual harvesting. Farmers had also applied 15–15–15, 8–24–24, and 13–13–21 fertilizers at the annual rates, respectively, of 125, 250, and 125 kg/ha for durian plantations, and 18–4–5 and 46–0–0 fertilizers at the annual rates, respectively, of 142.5 and 250 kg/ha for rubber plantations. The annual crops, in contrast, were located on the north-east plateau of Thailand with a tropical savannah climate with an annual average temperature of 26–30 °C, and rainfall of 1000–1500 mm. The soils are dry in some or all parts for 90 or more cumulative days. The Oxisols under annual crops are Kandiustox with a ustic soil moisture regime. These sites have continually produced monocrops without any rotation or mulching for more than 30 years. The soil has received continuously tillage, normally to 25–30 cm depth, twice a year for maize production, once a year for sugarcane and cassava production. Litter was tilled into the soil and no lime was applied. Three hundred kg/ha of 15–15–15 fertilizer was applied 2–3 times a year for maize and sugarcane production, but once annually for cassava production.

Soil sampling

Two replicate sites were sampled for each land use type. All sites had less than 2% slope. Soil samples were collected from surface (0–5 cm) and subsurface (5–20 cm) layers. Litter was removed before sampling. Three positions in the middle of each unit, at least 20 m apart, were randomly selected and soil samples were then mixed to form composite samples for analysis. At every point sampled, a 40 cm-wide by 40 cm-depth soil profile was excavated. Undisturbed soil samples for 0–5 and 5–20 cm layers were obtained by core samplers. Disturbed soil samples ($\sim$ 1 kg) were also collected. Disturbed samples were air dried under shade then passed through an 8 mm sieve after gentle crushing. The sieved soil fractions were composited per plot per depth for aggregate distribution analysis. Some air-dried soil was also crushed and passed through a 2-mm sieve for determining physical and chemical properties.

Soil properties

Soil pH was determined with a pH electrode at a 1:1 (w/w) soil/water ratio[27]. Carbon concentration and total N for whole soil and sand free aggregate size fractions were determined by a dry combustion method using a CN analyser (Vario Max CN Macro Elemental Analyser). Cation exchange capacity (CEC) was determined by the NH_4OAc method[28]. Crystalline, non-crystalline, and organic forms of Fe, Al, and Mn were extracted respectively by dithionite-citrate-bicarbonate solution, 0.2 M ammonium oxalate solution at pH 3.0, and sodium pyrophosphate[29–31]. Dissolved Fe, Al, and Mn were measured using atomic absorption spectrophotometry. Total Fe and Al (Fe_t and Al_t) was determined by X-ray fluorescence spectrometry of fused samples[32].

Soil texture was determined using the sieve and pipette method[33]. Soil bulk density (BD) was determined by the core method[34]. The aggregate size distribution was measured by wet sieving through a series of three sieves (2000, 250, and 53 µm) according to Ref. 35. A 100 g subsample was submerged in deionized water for 5 min at room temperature, on the top of the 2000 µm sieve. Aggregate separation was made by moving sieves up and down with a 3 cm stroke with 50 repetitions during a period of 2 min. The stable aggregates ($>$ 2000 µm) were then gently backwashed off the sieve into an aluminium pan. Floating organic material ($>$ 2000 µm) was decanted and discarded because this large size organic material is not considered to be soil organic matter. Water plus soil that went through the sieve into the collector was poured onto the next sieve and the sieving was repeated. Consequently, four size fractions were produced: (i) large macroaggregates, LMA ($>$ 2000 µm); (ii) small macroaggregates, SMA (250–2000 µm); (iii) microaggregates, µA (53–250 µm); and (iv) silt and clay ($<$ 53 µm) particles. The three aggregate fractions were oven-dried (50 °C), weighed, and stored at room temperature. A correction for the sand content of each size fraction was determined by weighing the material that was retained on a 53 µm screen sieve after dispersion of aggregates[36]. The weight data were used to compute the abundance of water stable aggregates (WSA)[37]. Mean weight diameter (MWD) was used as an index of aggregate stability and was calculated by summing the mass weighted proportions of each aggregate fraction[38]. Aggregate strength refers to the force required to break an aggregate. In this work, it is expressed as the total force at the point of failure exerted on a single aggregate of a uniform size by parallel flat plates. The strength of air dry aggregates was measured using a compact digital force gauge. Since microaggregates are very small, we could not determine their strength using our parallel plate crushing procedure, the strength of only LMA and SMA was measured.

Mineralogical composition

X-ray diffraction (XRD) analyses of the clay fraction were carried out using a computer driven Philips PW-3020 diffractometer with a graphite diffracted beam monochromator and Cu Kα radiation obtained at 50 kV and 20 mA. The proportions of minerals were estimated by comparison of integrated areas of reflections with XRD patterns of standard minerals. Coherently scattering domain (CSD) size of kaolin

Table 1 Mean values of soil properties for the various types of land use.

Land use	pH 1:1 H_2O	CEC (cmol/kg)	C_{ws} (%)	Total N (%)	Fe_t (%)	Al_t (%)	Fe_c (%)	Al_c (%)	Mn_c (%)	Fe_n (%)	Al_n (%)	Mn_n (%)	Fe_o (%)	Al_o (%)	Mn_o (%)	Clay (%)	BD (g/cm^3)
Topsoil (0–5 cm)																	
Durian†	4.93	13.4^{a}	4.09^{a}	0.37^{a}	18.11	22.10^{b}	7.06	1.07^{a}	0.44^{a}	0.55^{a}	0.69^{a}	0.41^{ab}	0.263^{ab}	0.376^{a}	0.051	41	0.93^{c}
Rubber†	4.88	11.0^{ab}	4.18^{a}	0.39^{a}	18.09	21.71^{b}	8.83	1.37^{a}	0.61^{a}	0.57^{a}	0.70^{a}	0.50^{a}	0.365^{a}	0.416^{a}	0.054	43	0.95^{bc}
Maize‡	5.33	7.1^{cde}	1.36^{c}	0.16^{c}	10.09	26.45^{a}	5.87	0.12^{b}	0.09^{b}	0.09^{b}	0.06^{b}	0.06^{c}	0.016^{c}	0.028^{b}	0.025	68	1.25^{ab}
Sugarcane‡	5.48	6.0^{cde}	1.40^{c}	0.14^{c}	12.60	23.95^{ab}	7.62	0.17^{b}	0.14^{b}	0.10^{b}	0.07^{b}	0.08^{c}	0.014^{c}	0.025^{b}	0.023	71	1.16^{abc}
Cassava‡	3.95	4.9^{de}	1.15^{c}	0.12^{c}	12.45	26.90^{a}	9.99	0.24^{b}	0.07^{b}	0.08^{b}	0.07^{b}	0.02^{c}	0.014^{c}	0.063^{b}	0.020	51	1.06^{abc}
Subsoil (5–20 cm)																	
Durian†	4.88	8.1^{bcd}	2.37^{bc}	0.23^{a}	18.94	23.62^{ab}	9.46	1.38^{a}	0.50^{a}	0.53^{a}	0.62^{a}	0.38^{b}	0.320^{a}	0.394^{a}	0.026	59	0.94^{bc}
Rubber†	5.00	9.0^{bc}	2.62^{b}	0.25^{ab}	18.85	21.79^{b}	9.62	1.39^{a}	0.55^{a}	0.53^{a}	0.67^{a}	0.50^{a}	0.312^{a}	0.326^{a}	0.026	57	1.01^{abc}
Maize‡	5.19	5.8^{cde}	1.25^{c}	0.14^{c}	10.09	26.39^{a}	5.90	0.25^{b}	0.12^{b}	0.10^{b}	0.08^{b}	0.07^{c}	0.018^{c}	0.026^{b}	0.022	73	1.27^{a}
Sugarcane‡	5.49	5.4^{cde}	1.29^{c}	0.13^{c}	12.85	25.01^{ab}	7.54	0.21^{b}	0.17^{b}	0.11^{b}	0.07^{b}	0.08^{c}	0.018^{c}	0.027^{b}	0.020	79	1.29^{a}
Cassava‡	3.93	3.9^{e}	1.16^{c}	0.13^{c}	11.95	25.75^{a}	8.04	0.19^{b}	0.07^{b}	0.07^{b}	0.07^{b}	0.02^{c}	0.017^{c}	0.071^{b}	0.019	60	1.19^{abc}
P-value	0.515	<0.001	<0.001	<0.001	0.121	0.017	0.57	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.265	0.144	0.008

† Perennial crop land use; ‡ annual crop land use.
C_{ws} stand for carbon concentration in whole soil;
Fe_c, Al_c, and Mn_c = crystalline forms of Fe, Al, and Mn; Fe_n, Al_n, and Mn_n = non-crystalline forms of Fe, Al, and Mn; Fe_o, Al_o, and Mn_o = organic forms of Fe, Al, and Mn; Fe_t, Al_t stand for Total Fe and Al, respectively.
Values followed by the same letter in a column are not significant at 5% level by the Duncan Multiple Range Test.

particles was calculated from the width at half height of XRD reflections using the Scherrer equation[39].

Calculations and statistical analysis

Amount of LMA, SMA, and μA were expressed as percentages of the total sample. Their values together with soil carbon concentrations (C_{WS}), total N, WSA, MWD, strengths, and all forms of Fe, Al, and Mn data were analysed using SPSS software. The effects of land use and crop types on soil parameters were determined using a general linear model. Multiple comparisons of means for each parameter were performed using Duncan's Multiple Range Test at the significance level (α) = 0.05. Correlation analysis of soil and aggregate parameters were performed using Pearson's correlation procedure. Stepwise regression was also performed to identify parameters affecting the strength of soil aggregates.

RESULTS AND DISCUSSION

Soil properties

All soils used in this study were clays. Clay contents of soil layers in any profile were not significantly different regardless of land use type and for all depths ranged from 41–79%. The soils were extremely to strongly acidic with mean pH ranging 3.95–5.48 and 3.99–5.49 for surface and subsurface layers, respectively, (Table 1). CEC values for the surface layer were higher than those of the subsurface layer for all types of land use (Table 1). Annual crop soils had lower CEC values than perennial crop soils, which may reflect differences in carbon concentration and the nature of clay minerals between sites. Thai Oxisols contain kaolin as the sole or major clay mineral. Under ustic conditions, kaolin has a larger crystal size with higher crystallinity and lower specific surface area when compared to the kaolin under udic conditions[26]. Soils under perennial crops had high values of C_{ws} for the topsoil (4.09–4.18%), but values sharply decreased with depth (Table 1). Values were higher than those for annual crops. This might be caused by the large amount of fine roots and litter left after harvesting. Soil BD was higher for annual crops than for perennial crops for both surface and subsurface layers (Table 1). The high BD for soil under annual crops is a common situation for continuous cultivation[40]. BD has a negative relationship with carbon concentration for all aggregate size fractions (Table 2). Soils under perennial crops had more total N than under annual crops. The surface soil under perennial crops had higher total N than for the subsurface layer. Total N of both layers for the annual crops was not significantly different. Furthermore, different crops under the same land use had no significant difference in total soil N. Contents of all free forms of Al and Mn, i.e., crystalline (c subscript), non-crystalline (n subscript), and organic (o subscript), for both the surface and subsurface layers were significantly higher for perennial crop land use than for annual crops (Table 1). Contents of non-crystalline and organic forms of Fe, Al, and Mn for both types

Table 2 Correlation matrix (r values) for some whole soil properties and the carbon concentration of aggregates versus properties of various size aggregates for Thai Oxisols.

	C_{ws}	C_{LMA}	C_{SMA}	$C_{\mu A}$	Fe_c	Al_c	Mn_c	Fe_n	Al_n	Mn_n	Fe_o	Al_o	Mn_o	CSD	CEC
CEC	0.91	0.93	0.92	0.90	–	0.73	0.77	0.83	0.83	0.80	0.72	0.79	–	−0.84	1.00
MWD	0.94	0.90	0.92	0.93	–	0.77	0.84	0.80	0.82	0.86	0.84	0.80	0.70	−0.73	0.89
BD	−0.69	−0.73	−0.72	−0.70	–	−0.79	–	−0.82	−0.84	−0.73	–	−0.85	–	0.70	–
$Strength_{LMA}$	0.92	0.88	0.90	0.91	–	0.77	0.83	0.78	0.80	0.84	0.89	0.84	0.76	−0.74	0.83
$Strength_{SMA}$	0.89	0.88	0.89	0.88	–	–	–	–	–	–	0.70	–	0.73	−0.71	0.83
$Amount_{LMA}$	0.96	0.91	0.94	0.94	–	0.81	0.87	0.84	0.85	0.88	0.84	0.83	0.69	−0.74	0.87
$Amount_{SMA}$	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
$Amount_{\mu A}$	−0.94	−0.91	−0.92	−0.92	–	−0.78	−0.85	0.82	−0.83	−0.87	−0.82	−0.79	−0.68	0.76	−0.91
CSD	−0.81	−0.85	−0.81	−0.81	–	−0.75	−0.73	−0.82	−0.83	−0.75	−0.75	−0.82	−0.70	1.00	−0.84

C_{ws} = carbon concentration in whole soil; C_{LMA} = carbon concentration in large macroaggregate; C_{SMA} = carbon concentration in small macroaggregate; $C_{\mu A}$ = carbon concentration in microaggregate;
CSD = coherently scattering domain;
Fe_c, Al_c, and Mn_c = crystalline forms of Fe, Al, and Mn; Fe_n, Al_n, and Mn_n = non-crystalline forms of Fe, Al, and Mn; Fe_o, Al_o, and Mn_o = organic forms of Fe, Al, and Mn.
– = r was not statistically significant at 5% level.

Table 3 Land use as a function of some soil aggregate characteristics and carbon concentration in various size of aggregate of Thai Oxisols.

Land use	Aggregate size distribution (%)			MWD	WSA	CSD	Strength (N)		Carbon concentration (%)		
	LMA	SMA	μA	(mm)	(%)	(nm)	LMA	SMA	LMA	SMA	μA
					Topsoil (0–5 cm)						
Durian	29.7^{ab}	52.6	5.68^{c}	1.20^{ab}	88	82.0^{c}	6.7^{ab}	3.2^{a}	4.67^{a}	4.00^{a}	3.90^{a}
Rubber	41.2^{a}	41.6	6.12^{c}	1.31^{a}	89	114.5^{bc}	9.0^{a}	3.2^{a}	4.17^{ab}	3.98^{a}	3.92^{a}
Maize	7.63^{c}	53.4	28.8^{abc}	0.80^{cd}	86	144.5^{bc}	4.2^{bc}	1.8^{ab}	1.35^{de}	1.26^{b}	1.33^{c}
Sugarcane	7.83^{c}	45.1	30.5^{ab}	0.72^{cd}	83	149.5^{ab}	4.3^{bc}	2.3^{ab}	1.43^{de}	1.29^{b}	1.29^{c}
Cassava	2.68^{e}	43.8	36.2^{a}	0.61^{d}	83	140.0^{ab}	3.2^{bc}	1.6^{b}	1.30^{de}	1.16^{b}	1.11^{c}
					Subsoil (5–20 cm)						
Durian	17.0^{bc}	48.8	21.0^{bc}	0.93^{bcd}	87	112.0^{bc}	5.8^{abc}	2.2^{ab}	2.97^{bc}	2.31^{b}	2.20^{bc}
Rubber	24.4^{b}	46.1	16.7^{c}	1.04^{abc}	87	111.0^{bc}	6.4^{ab}	2.4^{ab}	2.61^{cd}	2.42^{b}	2.50^{b}
Maize	7.71^{c}	49.1	28.2^{abc}	0.76^{cd}	85	163.0^{a}	2.8^{c}	1.6^{b}	1.32^{de}	1.19^{b}	1.18^{c}
Sugarcane	6.52^{c}	45.9	30.2^{abc}	0.70^{cd}	83	158.0^{a}	3.3^{bc}	2.1^{ab}	1.36^{de}	1.23^{b}	1.14^{c}
Cassava	1.60^{e}	41.3	39.2^{a}	0.57^{d}	82	161.5^{a}	2.7^{c}	1.8^{b}	1.21^{e}	1.17^{b}	1.09^{c}
P-value	< 0.001	0.399	< 0.001	< 0.001	0.424	0.009	0.001	0.015	< 0.001	< 0.001	< 0.001

Values followed by the same letter in a column are not significant at 5% level by the Duncan Multiple Range Test.

of land use behaved in the same manner for both soil layers, while contents of total and the crystalline form of Fe were not statistically different regardless of land uses and soil depths (Table 1). Contents of total Al (Al_t) of the perennial land use ranged from 21.71–23.62% were significantly lower than those for annual land use which ranged from 23.95–26.45% (Table 1). These data were collected primarily to investigate the influence of these elements on aggregate abundance and strength as is discussed below.

Mineralogical properties

The clay samples consist almost entirely of kaolin and iron oxides for all samples. Coherently scattering domain (CSD) size of kaolin particles was 72–127 nm for soils under udic moisture regime and 131–188 nm for soils under ustic moisture regime. CSD data in Table 3 showed a significant difference between land uses for both depths.

Aggregate size distribution, MWD, and aggregate strength

Land use had a significant influence on the aggregate size distribution, MWD, and aggregate strength, although the abundance of WSA remained high for all land uses (82–89%, Table 3). Perennial crop soils had more LMA than μA, while the opposite trend existed for annual crop soils (Table 3). Amount of LMA in surface soils for perennial crops was significant higher than in subsurface whereas annual crops had no significant difference between depths. Carbon concentrations of aggregates in the surface soil for perennial land use ranged from 3.90–4.67%, while those of the subsurface layer ranged from 2.20–2.97% (Table 3). These concentrations were significantly different. In contrast, carbon concentrations for aggregates in the annual crop soils were not statistically different for either soil layer. Values range 1.09–1.43% and are significantly less than those for perennial crop soils. Whole soil CEC was highly positively correlated with the amount of LMA ($r = 0.87$, Table 2) presumably both properties reflecting the higher contents of organic matter in the soil. Large amounts of MWD were present under perennial crops, smaller amounts under annual crops (Table 3). We can therefore propose that the structure of soils under perennial crops is more stable than for soils under annual crops.

Significant differences in aggregate strength occur for different land uses. The strength of aggregates under perennial crops was higher for both surface and subsurface soil layers than for soils under annual crops (Table 3). Regardless of land use type and crop, LMA were stronger than SMA which is presumably the consequence of the larger size providing greater resistance to fracture at an equivalent applied force. Topsoil aggregates were significantly stronger than the subsoil aggregates. Highly significant stepwise regression relationships relating the strength of LMA and SMA to soil properties were found:

$$\text{Strength}_{\text{LMA}} = 0.51\,\text{Fe}_\text{o} + 0.44\,\text{C}_{\text{LMA}} + 2.26 \quad (1)$$

$$\text{Strength}_{\text{SMA}} = 1.23\,\text{C}_{\text{SMA}} - 0.86\,\text{Al}_\text{o} - 0.23\,\text{Al}_\text{t} + 0.41\,\text{Fe}_\text{o} + 2.79 \quad (2)$$

with $R^2 = 0.85$ and 0.96, respectively.

Equations (1) and (2) indicate that C concentration and Fe_o content of LMA and SMA made an important contributions to macroaggregate strength (Fig. 1). This result was consistent with the effectiveness of binding agents for different aggregate classes reported by Ref. 41. Al compounds were not effective binding agents for macroaggregates but they were most effective for microaggregates[42].

Beside land use, environmental conditions might also affect the soil aggregation and carbon concentration. Drying of annual crop soils causes unequal strains to arise throughout the soil mass, which results in crack development and aggregate size reduction[43]. The more uniform soil moisture of perennial crop and no removal harvest of perennial crop soils may reduce cracking and enhances aggregate stability. Longer moisture of udic soils also induces higher weathering and releasing content of Fe, Al, and Mn in soils than prolonged dry of ustic soils[44]. At low pH, these cations (especially in amorphous form) can form complexes with dissolved organic compounds which precipitate in soils[21]. These complexes decrease microbial accession to SOC[44], thus more C_ws persists in soils. The smaller crystal size of kaolin crystals for the udic soil moisture regime was another factor to induce aggregation by increasing interaction between clay crystals and organic compounds[40].

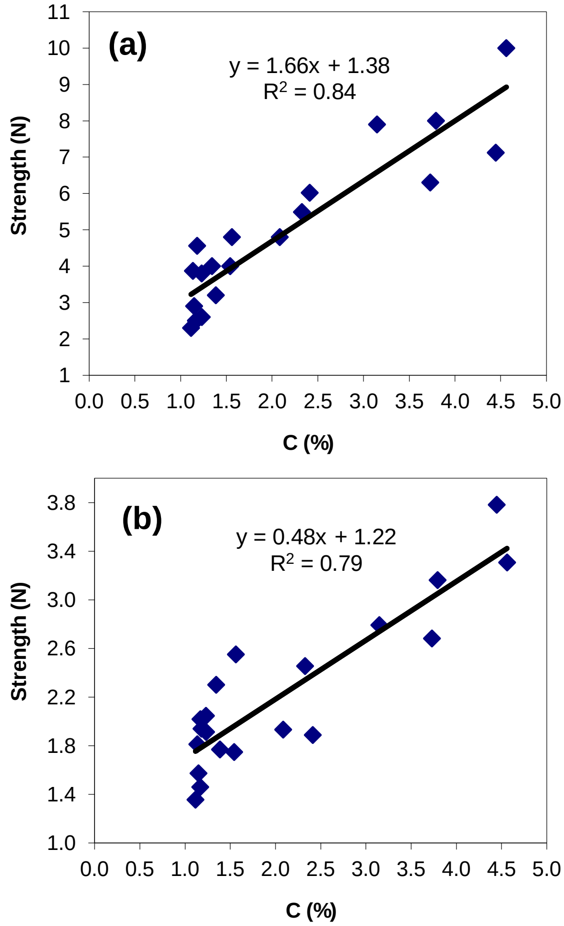

Fig. 1 Relationships between strength and carbon concentration in whole soil for (a) large macroaggregate and (b) small macroaggregate.

CONCLUSIONS

Thai Oxisols under perennial crop land use with a udic soil moisture regime held larger MWD, higher contents of LMA, carbon concentration, CEC, Fe, Al, Mn, and more strength than did Oxisols under annual crop land use with a ustic soil moisture regime. Oxisols attributes such as carbon concentration, CEC, and content of Fe, Al, and Mn, especially amorphous and organic forms, significantly related to aggregation. Carbon concentration and Fe_o played important roles to strength the large and small macroaggregates. These results indicated that soils under perennial land use with longer humid conditions hold the better attributes than those under annual land use. CEC for perennial was at least 2 folds higher than that for annual crops. Amount of macroaggregate was at least 6 folds higher. MWD was almost 2 folds higher. Carbon and nitrogen concentrations were more than 2 fold higher for all aggregate sizes. Content of all Fe, Al, and Mn forms were clearly significantly higher. Carbon concentration, soil aggregation, and aggregate strength of perennial crop land use made soils to resist erosion thereby providing a basis for improved land management and implications for accounting of carbon stocks in tropical soils.

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