www.thaiagj.org Thai Journal of Agricultural Science 2013, 46(4): 165-174

Effect of Parent Materials and Organic Carbon on Cation Exchange Capacity of Tropical Red Soils under Different Moisture Regimes

B. Chimchart[1], I. Kheoruenromne[1,*], A. Suddhiprakarn[1] and D.L. Sparks[2]

[1]*Department of Soil Science, Faculty of Agriculture, Kasetsart University, Bangkok 10900, Thailand*
[2]*Department of Plant and Soil Sciences, College of Agriculture & Natural Resources, University of Delaware, Newark, DE, 19716, USA*

**Corresponding author, Email: irbs@ku.ac.th*

Abstract

Eight profiles of highly weathered soils from different parts of Thailand were used as representative soils for the analysis on differential influence of parent materials and organic carbon under ustic and udic moisture regimes on their cation exchange capacity (CEC). These red soils included four Oxisols and four Ultisols. The chemical composition of the clay in the soils derived from basalt, granite and limestone was consistent with kaolinite (Al:Si = 1:1) in both moisture regimes. The amount of elements (O, Ti, Fe, Ni, Na) in these soils were not different. Carbon (C), aluminum (Al) and silicon (Si) in udic soils were 1% higher than that in ustic soils due to low weathering stage and rainfall in ustic moisture regime affecting plant growth and distribution of organic carbon (OC). Difference of parent materials in soil derived from weathered sandstone (Cpg, Kandiustult) and igneous rock (Mt1, Kandiustult) under the same moisture regime did not have any effect on their C content. The OC content of soils derived from basalt and granite is higher than in soils derived from sandstone which OC in udic soils higher than in ustic soils. The OC showed effect on CEC in both ustic and udic soils. The CEC values measured by NH_4OAc at pH 7.0 (CEC_7) of soils in udic moisture regime were higher than that of soils in ustic moisture regime due to more moisture and precipitation in udic moisture regime tending to promote more rapid plant growth and decay of organic materials at a similar range of temperature.

Keywords: organic carbon, moisture regime, parent materials, CEC

Introduction

Red soils have generally been known as highly weathered and highly developed soils of tropical and sub-tropical regions (Fox, 1982; Krishnaswamy and Richter, 2002). They are mainly Oxisols and Ultisols (Buol et al., 2011; Soil Survey Staff, 2010). These soils generally have low cation exchange capacity (CEC). The CEC values of these soils are diverse and having relationships not only with clay and organic matter (OM) content (Manrique et al., 1991; Rashidi and Seilsepour, 2008) but also with climate and parent material (Trakoonyingcharoen et al., 2006). Alvarez and Lavado (1998) found that carbon distribution in soils under udic moisture regime was higher than in soils under ustic moisture regime due to higher plant productivity. Kirschbaum (1995) reported that OC increased with increasing precipitation and decreasing temperature, while Baker et al. (2001) indicated that high mean annual temperature and precipitation influence OM to have high decomposition and less accumulation. Rashidi and Seilsepour (2008) indicated that OC had high affect on CEC of soils. The objective of this study was to evaluate the influence of parent materials and organic carbon on CEC of highly weathered tropical red soils.

Materials and Methods

Sampling Sites

Eight soil profiles used in this study in Northeast Plateau, Southeast Coast, North Continental Highlands and Peninsular Thailand (Figure 1). Four sites are under tropical savanna climate and the soils are in ustic moisture regime and another four sites of soils are under tropical monsoonal climate and the soils are in udic moisture regime. The sites in ustic moisture regime have a range of annual rainfall of 1,200-1,600 mm and a temperature range between 24-26°C, and the sites in udic moisture regime have a range of annual rainfall of 1,600-2,800 mm and a temperature range between 24-28°C (Meteorological Department, 2011).

Physiochemical Analyses

Soil pH was measured in 1:1 soil:H_2O (National Soil Survey Center, 1996). Particle size distribution was analyzed by pipette method (Gee and Bauder, 1986). Organic carbon (OC) was measured by Walkley-Black method (Nelson and Sommers, 1996) and used to calculate the amount of organic matter (OM) as OM = OC × 1.724. Total carbon was measured by CN analyzer (dry combustion) (Elliott et al., 1991). The CEC was measured by NH_4OAc at pH 7.0 (Chapman, 1965). Basic CEC (CEC_B) was determined using the methodology described by the compulsive exchange method (Gillman and Sumpter, 1986). Crystalline Fe and Al were determined by dithionite-citrate-bicarbonate (DCB) (Mehra and Jackson, 1960).

Mineralogical and SEM Analyses

Mineralogy of the soil clay fraction was determined by X-ray diffraction (XRD) using CuK_α radiation with a Philips PW-3020 diffractometer (Cu Kα, 50kV, 20mA) (Brown and Brindley, 1980). For SEM analysis, representative soil samples from each moisture regime were deposited on a AU/PD coated and examined using field emission scanning electron microscope (FE-SEM) Hitachi S4700 with a Gatan Alto 2500 Cryotransfer System and an Oxford INCA energy dispersive spectroscopy (EDS) system operated at 10 kV.

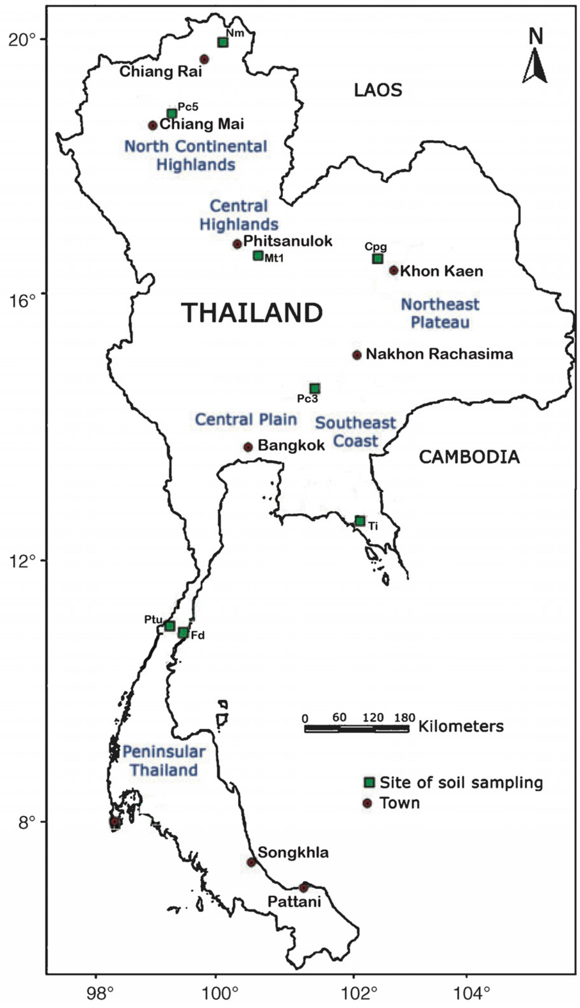

Figure 1 Sampling sites of Oxisols and Ultisoils.

Results and Discussion

Soil Environments and Field Morphology

The soils included four Oxisols and four Ultisols under different land uses. Oxisols have developed on residuum derived from limestone, basalt and clastic rocks (Table 1). The surrounding landforms were undulating to rolling having 3-8% slopes. The genetic horizons of Oxisols generally included A or Ap, Bt, Bto and Bo. These were very deep well drained soils having subangular blocky partially parting to granular and to semi-angular blocky structures with moderate permeability and moderate runoff. The color of

Table 1 The classification and parent materials of the soils.

Soil	Classification	Parent material	Annual rainfall (mm)*	Annual temperature (°C)*	Land use
Ustic					
Pak Chong3 (Pc3)	Rhodic Kandiustox	Residuum derived from weathered limestone	1200	26	Left idle under grasses
Pak Chong5 (Pc5)	Typic Kandiustox	Residuum derived from weathered basalt	1400	24	Mixed Deciduous and Dipterocarp forest
Chum Phuang (Cpg)	Typic Kandiustult	Residuum and wash derived from weathered red sandstone	1400	26	Tree crop plot in experimental field
Mae Taeng1 (Mt1)	Typic Kandiustult	Residuum derived from basic igneous rock	1600	24	Teak forest plantation bordered by cassava field
Udic					
Pathio (Ptu)	Kandiudalfic Eutrudox	Residuum and colluvium derived from fine grained clastic rocks and limestone	2500	28	Rainforest species, para rubber, local weeds and fern
Tha Mai (Ti)	Rhodic Kandiudox	Residuum derived from weathered basalt	2800	26	Tropical fruit tree orchard; banana, durian and rambutan
Nong Mot (Nm)	Typic Paleudult	Mixed colluviums and residuum derived from weathered granite	2000	24	Litchie and Tamarind orchards
Fang Daeng (Fd)	Typic Kandiudult	Residuum derived from clastic sedimentary rock	1600	26	Rainforest species under para rubber

* Thai Meteorological Department (2011)

Oxisols ranges from red to dark yellowish red. The texture ranged from clay to sandy clay. Ultisols have developed on residuum and mixed colluviums derived from sandstone, granite, igneous rock and sedimentary rocks. The surrounding landforms were undulating to rolling having 2-14% slopes. The genetic horizons of Ultisols generally included A or Ap and Bt. These were very deep well drained soils having subangular blocky to semi-angular blocky structure with moderate permeability and moderate runoff. The color of Ultisols ranges from dusky red to dark yellowish red. The texture ranged from clay to sandy loam.

Chemical Properties

The pH of soils in ustic moisture regime ranged from very strongly to slightly acid (pH 5.0-6.1) similar to that of soils in udic moisture regime (pH 4.7-6.4) (Table 2). The cation exchange capacity by NH_4OAc (CEC_7) and cation exchange capacity measured by compulsive exchange method (CEC_{CE}) of soils in ustic moisture regime were lower than that of soils in the udic moisture regime, especially in horizons with low content of organic matter. Organic carbon content of these soils ranged from very low to high (1-24 g kg^{-1}). Total carbon (TC) contents in soils derived from basalt were higher than in soils derived from limestone in both ustic and udic moisture regimes. Crystalline iron oxides estimated by DCB extraction of soils in ustic moisture regime ranged between 3-189 g kg^{-1} and of soils in udic moisture regime ranged between 6-125 g kg^{-1}. Values of crystalline aluminum oxides estimated by DCB of soils in ustic moisture regime ranged between 4-18 g kg^{-1} and of soils in udic moisture regime ranged between 2-21 g kg^{-1}, respectively (Table 2).

Clay Mineralogy

The clay fraction of both Oxisols and Ultisols was dominated by kaolinite. A small amount of goethite present in some Oxisols under udic moisture regime and in trace amounts in both Oxisols and Ultisols under udic and ustic moisture

Table 2 The values for physical and chemical properties of soils in this study.

Soil sample	Depth	pH H_2O	CEC_7	CEC_{CE}	OC	TC	Fe_d	Al_d	Particle size distribution		
									Sand	Silt	Clay
	(cm)		(-- $cmol_c$ kg^{-1} --)		(-------------------------- g kg^{-1} --------------------------)						
Ustic											
Pc3-Ap	0-28	5.4	23.0	7.8	20	19	78	11	64	98	838
Pc3-Bt3	80-100	5.0	12.0	6.7	36	4	73	10	16	9	975
Pc3-Bt5	123-147	5.0	11.0	5.5	24	4	77	14	19	6	975
Pc5-A	0-20	5.2	17.0	3.4	7	7	178	10	33	41	926
Pc5-Bo	20-50	5.8	9.0	3.2	5	4	189	10	34	30	937
Pc5-Bto1	50-80	5.7	8.0	2.7	2	2	180	11	28	37	936
Cpg-Ap	0-20	5.7	1.5	1.1	3	3	3	16	813	104	83
Cpg-Bt3	75-100	5.4	1.7	1.2	1	1	7	15	702	111	187
Cpg-Bt5	130-160	5.2	2.5	1.3	1	1	7	18	690	135	174
Mt1-Ap1	0-10	5.4	4.2	3.8	10	10	57	4	267	205	528
Mt1-A	30-50	5.5	7.5	3.0	7	7	58	4	237	218	545
Mt1-Bt2	80-110	6.1	5.2	2.3	4	4	48	4	91	167	741
Udic											
Ptu-Ap	0-20	5.6	5.1	3.0	4	5	39	5	545	195	260
Ptu-Bto2	46-75	5.5	8.6	4.0	3	3	85	4	296	108	596
Ptu-Bto3	75-104	5.5	9.6	4.1	3	3	82	5	291	137	572
Ti-Ap	0-20	5.7	35.0	5.3	24	25	97	17	81	389	531
Ti-Bo1	15-42	5.2	31.0	5.2	11	12	114	21	43	421	535
Ti-Bto1	67-100	4.8	27.0	5.5	3	4	125	20	33	188	780
Nm-Ap	0-20	5.0	23.0	6.5	21	20	50	9	283	189	29
Nm-Bt1	20-50	4.8	23.0	4.1	7	8	58	10	87	92	721
Nm-Bt3	80-110	5.2	14.0	3.9	4	4	69	11	180	68	753
Fd-Ap	0-10	6.4	2.4	2.2	3	4	6	2	702	86	212
Fd-Bt1	10-30	5.3	2.7	2.3	2	2	8	3	634	122	244
Fd-Bt4	78-103	4.7	3.4	1.9	1	2	12	3	563	137	300

regime (Table 3). Jenkins and Jones (1980); Trakoonyingcharoen et al. (2006) reported that different of type and amounts of minerals depended on parent materials and climate. Small amount of hematite was also present in Oxisols under both ustic and udic moisture regimes. Boero and Schwertmann (1989); Singer et al. (1998) and Trakoonyingcharoen et al. (2006) reported that hematite dominated in soils developed on limestone under high temperature and high turnover rate of OM, and goethite dominated over hematite in soils under moist conditions and large amounts of organic matter. Gibbsite and maghemite were present in clay fractions of soils derived from basalt and granite under udic moisture regime similar with results reported by Goulart et al. (1998).

Factors Affecting the Variability of the Chemical Composition

Scanning electron microscopy results on the chemical composition of the fine fractions in soils by the EDS system were consistent with kaolinite (Al:Si = 1:1) both in ustic and udic moisture regime (Figures 2a and 2b). The amount of elements (O, C, Al, Si, Ti, Fe, Ni and Na) were not different for both Typic Kandiustox (Pc5) and Typic Paleudult (Nm). Carbon contents in Typic Paleudult were 1% higher than in Typic Kandiustox due to rainfall effect plant growth and distribution of OC in soils (Figure 2c) (Jobbágy and Jackson, 2000). Aluminum (Al) and silicon (Si) content in Typic Paleudult (Nm) were higher than in Typic Kandiustox (Pc5) due to Al contained

Table 3 Clay mineralogy of Oxisols and Ultisols.

Soil sample	Abundant (>60%)	Moderate (20-60%)	Little (5-20%)	Trace (<5%)
Ustic				
Pak Chong3	kao	-	hem, qtz	goe, HIV
Pak Chong5	kao	-	hem	goe, HIV, qtz, ant
Chum Phuang	kao	-	qtz	hem
Mae Taeng1	kao	-	goe	-
Udic	-	-	-	-
Pathio	kao	-	hem, qtz, HIV	goe, ant
Tha Mai	kao	-	goe	hem, qtz, HIV, ant, gib, mh
Nong Mot	kao	-		goe, hem, gib
Fang Daeng	kao	-		goe, hem, qtz, HIV, ant

Kao = kaolinite, qtz = quartz, goe = goethite, gib = gibbsite, HIV = hydroxyl Al interlayered vermiculite, ill = illite, hem = hematite, ant = anatase, mh = maghemite.

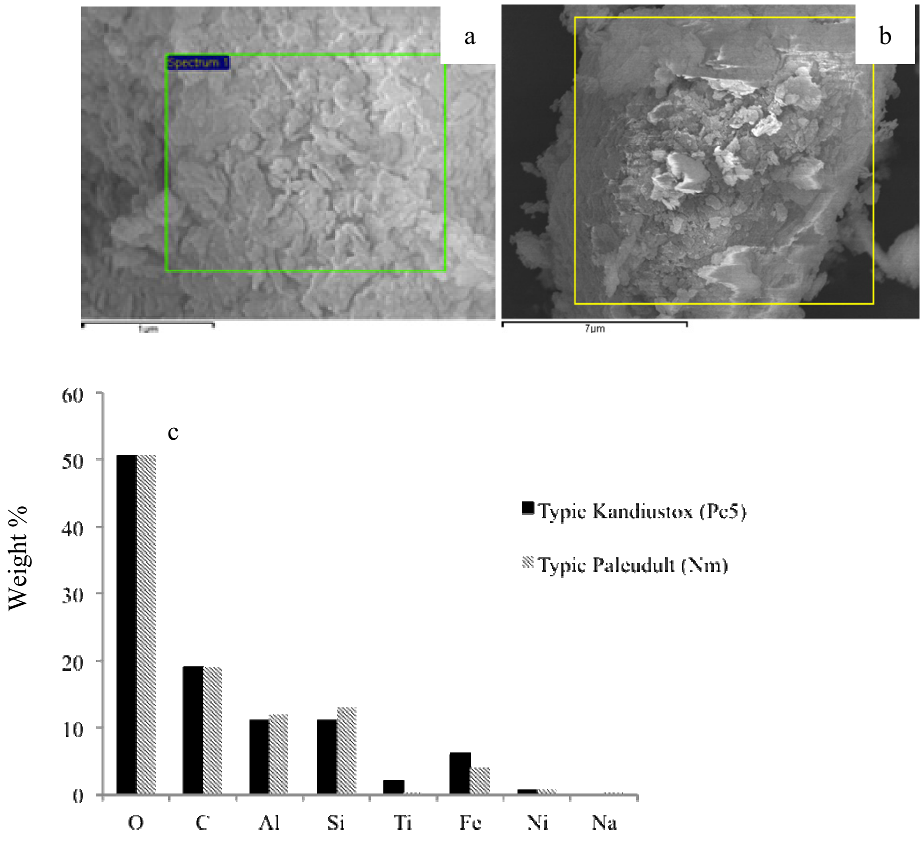

Figure 2 SEM images showing chemical composition of the soil fine fractions in (a) ustic (Pc5) and (b) udic moisture regimes (Nm) and (c) graph show weight % of chemical composition.

in gibbsite derived from granite and gneiss and Si was contained in quartz derived from granite of low weathering stage (Watanabe et al., 2000; Herrmann et al., 2007; Hausrath et al., 2009).

Chemical compositions of soil derived from different parent materials in ustic moisture regime are shown in Figures 3a and 3b. The elements (O, C, Al, Si, Ti, Fe and Ni) found in soils were not different between Typic Kandiustult (Cpg) derived from weathered sandstone and Typic Kandiustult (Mt1) derived from igneous rock. Potassium (K) was found only in Cpg due to its sandstone parent rock contains some feldspar similar to what reported by Wilkinson et al. (2001) and Jafarzadeh and Hosseini-Barzi (2008) (Figure 3c). Silicon (Si) content was higher in soil derived from weathered sandstone than in soils derived from igneous rock due to sandstone have higher content of quartz (Ahmed, 2008; Jafarzadeh and Hosseini-Barzi, 2008).

Effect of Moisture Regimes on OC

Temperature and precipitation are the most important factors regulating soil organic matter (SOM) (Jenny, 1980). Relationships of OC in these soils with precipitation and temperature are shown in Figures 4a and 4b (n=4). The OC increased with annual rainfall increase as what reported by Alvarez and Lavado (1998) but OC were not different with annual temperature since the mean temperature ranges were not much different. Raich et al. (2006) reported temperature had no effect on total carbon storage among moist tropical evergreen forests. Jenny (1980) and Burke et al. (1989) reported that the SOM levels commonly increased as mean annual precipitation increased and temperature decreased. Alvarez and Lavado (1998) also reported that SOM content in the top 0-50 cm soil layer was positively correlated with the precipitation/temperature ratio in the Pampa and Chaco soils in Argentina. Moreover, parent material also effect on OC. According to Table 1 and Table 2, OC content in soils derived from weathered basalt and granite are higher than in soils derived from sandstone which OC in udic soils higher than in ustic soils. Except for Pc3 soil derived from limestone under grass cover have high OC similar to what reported by Hassink (1997). Jobbágy and Jackson (2000) reported that total SOC content increased with precipitation and clay content. Torn et al. (1997) reported soils formed from volcanic ash have high OC and abundance of

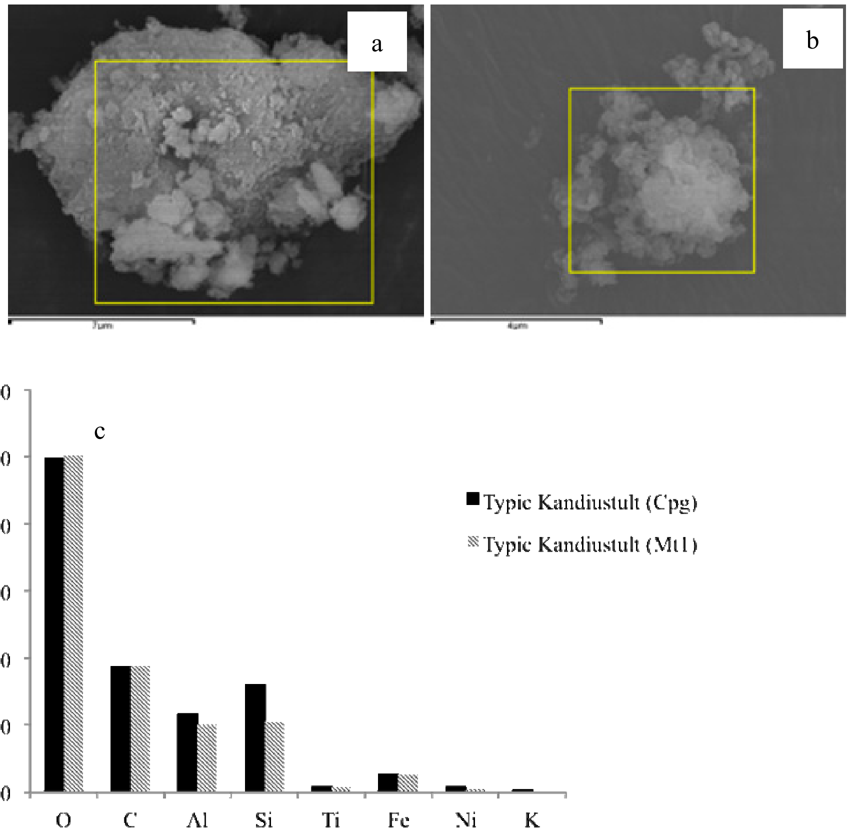

Figure 3 SEM images showing chemical composition in (a) soil derived from weathered sandstone (Cpg), (b) soils derived from igneous rock (Mt1) and (c) graph showing weight % of chemical composition.

non-crystalline minerals that can form stable organic-mineral complexes under humid conditions. Wagai et al. (2008) reported that soils developed on basic parent materials accumulated more OC than those on acid parent materials under humid condition, due to the difference in weathering rate. The OC values of the studied soils in udic moisture regime had higher relationships with rainfall and had lower relationships with temperature than that of soils in ustic moisture regime due to rainfall affected plant growth to contribute OC in soils and the rates of decomposition increased with temperature increase (Robert and Wim, 1996; Craswell and Lefroy, 2001).

The OM was reported to be the most important contributor to the CEC in highly weathered soils (Gallez et al., 1976; Duxbury et al., 1989). The CEC$_7$ values of soils in udic moisture regime were higher than that of soils in ustic moisture regime for both Oxisols and Ultisols (Figure 5). This was due to the high moisture and precipitation in udic moisture regime promoting plant growth and decay of organic materials (Craswell and Lefroy, 2001). This was also supported by result reported by Schmitt and Glaser (2011) that OC decreased with decreasing precipitation. The CEC$_7$ values in Oxisols were higher than in Ultisols both in ustic and udic moisture regime due to the higher clay content in Oxisols similar to what reported by Sahrawat (1983). However some soils in udic moisture regime had high CEC even with low clay content. This was due to the effect of OM content (Skinner et al., 2001). These results indicated that both OC and clay content affected the CEC$_7$ of these soils as reported by several studies (Manrique et al., 1991; Caravaca and Albaladejo, 1999; Rashidi and Seilsepour, 2008). Figure 6 showed relationships of OC with CEC$_7$ (n = 11) and CEC$_{CE}$ (n= 11) for soils in ustic and udic moisture regimes. The OC had high relationships with both CEC$_7$ and CEC$_{CE}$. The OC did not show any different relationships either with CEC$_7$ or CEC$_{CE}$ for both udic and ustic soils. These results indicated that tropical soils have low OC content, the CEC values by two methods were not different.as Medeira et al. (2003) reported that the difference between CEC by NH$_4$OAc and CEC$_{CE}$ increases with increasing content of OC.

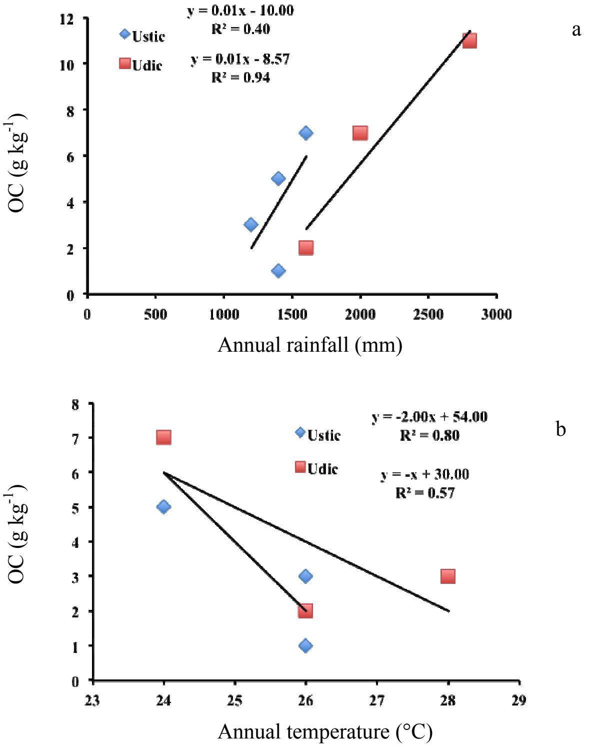

Figure 4 Relationships of OC with (a) precipitation and (b) temperature.

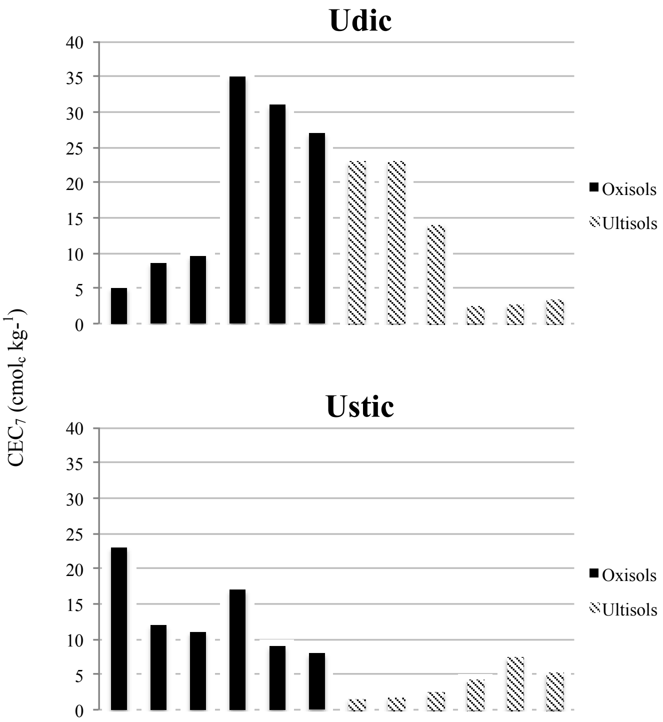

Figure 5 Values of CEC$_7$ of Oxisols and Ultisols in udic and ustic moisture regimes.

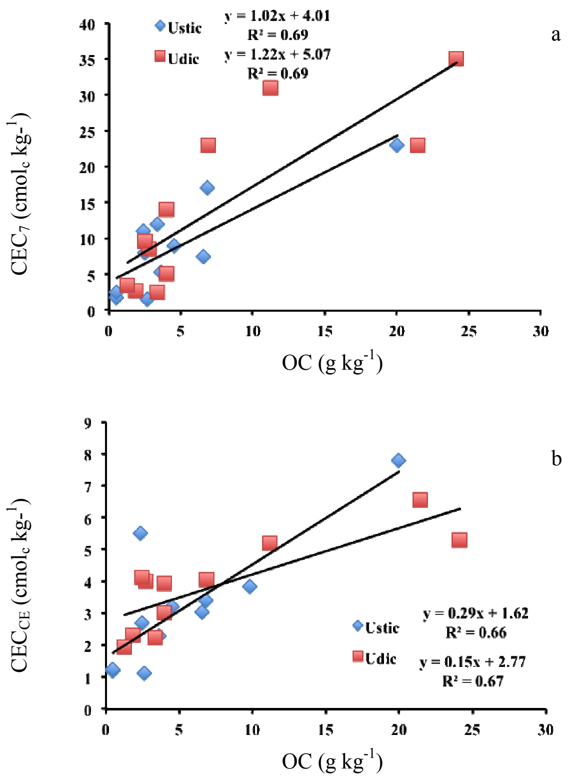

Figure 6 Values of CEC_7 of Oxisols and Ultisols in udic and ustic moisture regimes.

Conclusions

Tropical red soils derived from weathered basalt, granite and limestone was dominated by kaolinite, goethite was present in small amounts in soils under udic moisture regime (Ti) and in trace amounts in soils under ustic moisture regime (Pc5), and hematite was present in small amounts in soils in both udic and ustic moisture regimes (Ptu, Pc5).

The content of C, Al and Si in soils derived from weathered granite under udic moisture regime (Nm) were higher than that of soils derived from weathered basalt in ustic moisture regime (Pc5). While, the content of O, C, Al, Si, Ti, Fe and Ni were not different in soil derived from sandstone and igneous rock except K and Si was found in soil derived from sandstone. The content of OC in soils derived from weathered basalt and granite are higher than in soils derived from sandstone which OC increased with the annual rainfall increase. The OC content in soils under udic moisture regime were more contributor CEC than soils under ustic moisture regime due to the high moisture and precipitation promoting plant growth and decay of organic materials. This partially the effect of OM content induced the higher CEC in udic soils as compared to that in the ustic soils. These results indicate that climate affect plant productivity and rate of weathering of parent materials which they regulate contents of the elements, OC and CEC as in these soils.

Acknowledgments

The authors are thankful to the Royal Golden Jubilee Ph.D. Program under the Thailand Research Fund, Kasetsart University and Kasetsart University Research and Development Institute (KURDI) for financial support. We also would like to thank the Delaware Biotechnology Institute, and Deborah Powell for assistance.

References

Ahmed, W., 2008. Contrast in clay mineralogy and their effect on reservoir properties in sandstone formations. Bull. Chem. Soc. Ethiop. 22: 41-65.

Alvarez, R. and R.S. Lavado. 1998. Climate, organic matter and clay content relationships in the Pampa and Chaco soils, Argentina. Geoderma 83: 127-141.

Baker III, T., G. Lockaby, W.H. Conner, C.E. Meier, J.A. Stanturf, and M.K. Burke. 2001. Leaf litter decomposition and nutrient dynamics in four southern forested floodplain communities. Soil Sci. Soc. Am. J. 65: 1334-347.

Boero, V. and U. Schwermann. 1989. Iron oxide mineralogy of terra rossa and its genetic implications. Geoderma 44: 319–327.

Brown, G. and G.W. Brindley. 1980. X-ray diffraction procedures for clay mineral identification, pp. 305-359. In G.W. Brindley and G. Brown, eds. Crystal Structures of Clay Minerals and Their X-ray Identification. Mineralogical Society Monograph. No. 5. Spottiswoode Ballantyne Ltd., London.

Buol, S.W., R.J. Southard, R.C. Graham and P.A. McDaniel. 2011. Soil Genesis and Classification. 6th ed. The Iowa State Press., A Blackwell Publishing Company, Iowa.

Burke, I.C., C. M. Yonker, W. J. Parton, C. V. Cole and D. S. Schimel. 1989. Texture, climate, and cultivation effects on soil organic matter content in U.S. grassland. Soil Sci. Soc. Am. J. 53: 800-805.

Caravaca, F., A. Lax and J. Albaladejo. 1999. Organic matter, nutrient contents and cation exchange capacity in fine fractions from semiarid calcareous soils. Geoderma 93:161–176.

Chapman, H.D. 1965. Cation Exchange Capacity, pp. 891-901. In C.A. Black, ed. Methods of Soil Analysis, Past 2. Chemical and Microbiological Properties. 2nd ed. Amer. Soc. Of Agron. Inc., Madison, WI.

Craswell, E.T. and R.B.D. Lefroy. 2001. The role and function of organic matter in tropical soils. Nut. Cyc. Agroeco. 61: 7-18.

Duxbury, J.M., M.S. Smith and J.W. Doran. 1989. Soil organic matter as a source and a sink of plant nutrients, pp. 33-67. *In:* D.C. Coleman, J.M. Oades, G. Uehara, (Eds.), Dynamics of Soil Organic Matter in Tropical Ecosystems. NifTAL Project, University of Hawaii.

Elliott, E.T., C.A. Palm, D.E. Reuss and C.A. Monz. 1991. Organic matter contained in soil aggregates from a tropical chronosequence: correction for sand and light fraction. Agr. Ecosyst. Environ. 34: 443-451.

Evans, D.M., F.M. Barrett, H.M. Prichard and P.C. Fisher. 2012. Platinum-palladium-gold mineralization in the Nkenja mafic-ultramafic body, Ubendian metamorphic belt, Tanzania. Miner. Deposita 47: 175-196.

Fox, R.L. 1982. Some highly weathered soils of Puerto Rico 3: Chemical properties. Geoderma 27: 139-176.

Gallez, A., A.S.R. Juo and A.J. Herbillon. 1976. Surface and charge characteristics of selected soils in the tropics. Soil Sci. Soc. Am. J. 40: 601-608.

Gee, G.W. and J.W. Bauder. 1986. Particle-size analysis, pp. 961-1010. In A. Klute, ed. Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods. Amer. Soc. Agron. Inc., Madison, Wisconsin, USA.

Gillman, G.P. and E.A. Sumpter. 1986. Surface charge characteristics and lime requirements of soil derived from basaltic, granitic and metamorphic rocks in high rainfall tropical Queensland. Aust. J. Soil Res. 24: 173-192.

Goulart, A.T., J.D. Fabris, M.F. De Jesus Filho, J.M.D. Coey, G.M. Da Costa, and E. De Grave. 1998. Iron oxides in a soil developed from basalt. Clays Clay Miner. 46: 369-378.

Hassink, J. 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. Plant & Soil 191: 77-87.

Hausrath, E.M., A. Neaman and S.L. Brantley. 2009. Elemental release rates from dissolving basalt and granite with and without organic ligands. Am. J. Sci. 309: 633–660.

Herrmann, L., N. Anongrak, M. Zarei, U. Schuler and K. Spohrer. 2007. Factors and processes of gibbsite formation in Northern Thailand. Catena 71: 279-291.

Jafarzadeh, M. and M. Hosseini-Barzi. 2008. Petrography and geochemistry of Ahwaz Sandstone Member of Asmari Formation, Zagros, Iran: implications on provenance and tectonic setting. Rev. Mex. Cien. Geol. 25: 247-260.

Jenkins, D.A. and R.G.W. Jones. 1980. Trace elements in rock, soil, plant and animal: introduction, pp. 1–20. *In:* B.E Davies, (Ed.), Applied Soil Trace Elements. John Wiley and Son Ltd.

Jenny, H. 1980. The Soil Resource: Origin and Behavior, Ecological Studies. Vol. 37. Springer-Verlag, New York.

Jobbágy, E.G. and R.B. Jackson. 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol. Appl. 10: 423-436.

Kirschbaum, M.U.F. 1995. The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic carbon storage. Soil Biol. Biochem. 27: 753–760.

Krishnaswamy, J. and D.D. Richter. 2002. Properties of advanced weathering-stage soils in tropical forests and pasture. Soil Sci. Soc. Am. J. 66: 244-253.

Manrique, L.A., C.A. Jones, and P.T. Dyke. 1991. Predicting cation-exchange capacity from soil physical and chemical properties. Soil Sci. Soc. Am. J. 55: 787-794.

Medeira, M., E. Auxtero, and E. Sousa. 2003. Cation and anion exchange properties of Andisols from the Azores, Portugal, as determined by the compulsive exchange and the ammonium acetate methods. Geoderma 117: 225-241.

Mehra, O.P., M.L. Jackson. 1960. Iron oxide removal from soils and clay by a dithionite-citrate system buffered with sodium bicarbonate. Clays Clay Miner. 7: 317-327.

Meteorological Department. 2011. Annual Weather Summary of Thailand in 2011. Meteorological Department, Thailand.

National Soil Survey Center. 1996. Soil Survey Laboratory Methods Manual. United States Department of Agriculture, Natl. Soil Surv. Cent., Soil Surv. Lab., Soil Survey Investigation No. 42, Version 3.

Nelson, D.W. and L.E. Sommers. 1996. Total carbon, and organic matter, pp. 961-1010. *In:* D.L. Sparks, A.L. Page, P.A. Helmke, R.H. Loeppert, (Eds.), Methods of Soil Analysis. Part III. Chemical Method. Amer. Soc. Agron. Inc., Madison, Wisconsin.

Raich, J.W., A.E. Russel, K. Kitayama, W.J. Parton and P.M. Vitousek. 2006. Temperature influences carbon accumulation in moist tropical forest. Ecology 87: 76-87.

Rashidi M. and M. Seilsepour. 2008. Modeling of soil cation exchange capacity based on soil organic carbon. ARPN J. Agri. Biol. Sci. 3: 41-45.

Robert, B. and G.S. Wim. 1996. The effects of global change on soil conditions, pp. 49-64. In B. Fakhri, S. Wim, eds. Relation to plant growth and food production, in Global climate change and agricultural production. Direct and indirect effects of changing hydrological, pedological and plant physiological processes. FAO, Rome, Italy.

Sahrawat, K.L. 1983. An analysis of the contribution of organic matter and clay to cation exchange capacity of some Philippine soils. Commun. Soil Sci. Plant Anal. 14: 803-809.

Schmitt, A., and B. Glaser. 2011. Organic matter dynamics in a temperate forest as influenced by soil frost. J. Plant Nutr. Soil Sci. 174: 754–764.

Singer, A., U. Schwertmann and J. Friedl. 1998. Iron oxide mineralogy of Terre Rosse and Rendzineas in relation to their moisture and temperature regimes. Eur. J. Soil Sci. 49: 385-395.

Skinner, M.F., D. Zabowski, R. Harrison, A. Lowe and D. Xue. 2001. Measuring the cation exchange capacity of forest soils. Commun. Soil Sci. Plant Anal. 32: 1751-1764.

Soil Survey Staff. 2010. Key to Soil Taxonomy. United States Department of Agriculture, Washington, DC.

Torn, M.S., S.E. Trumbore, O.A. Chadwick, P.M. Vitousek and D.M. Hendricks. 1997. Mineral control of soil organic carbon storage and turnover. Nature 389: 170-173.

Trakoonyingcharoen, P., I. Kheoruenromne, A. Suddhiprakarn, and R.J. Gilkes. 2006. Properties of kaolins in red Oxisols and red Ultisols in Thailand. Appl. Clay Sci. 32: 25-39.

Wagai, R., L.M. Mayer, K. Kitayama and H. Knicker. 2008. Climate and parent material controls on organic matter storage in surface soils: A three-pool density-separation approach. Geoderma 147: 23-33.

Watanabe, T., S. Funakawa and T. Kosaki. 2000. Distribution and formation conditions of gibbsite in the upland soils of humid Asia: Japan, Thailand and Indonesia. 19th World Congress of Soil Science, Soil Solutions for a Changing World.

Wilkinson, M., K.L. Milliken and R.S. Haszeldine. 2001. Systematic destruction of K-feldspar in deeply buried rift and passive margin sandstones. J. Geol. Soc. 158: 675-683.

Manuscript received 03 January 2014, accepted 09 February 2014