www.thaiagj.org Thai Journal of Agricultural Science 2008, 41(3-4): 153-167

Properties and Fertility Capability of Highland Soils in Khao Kho Area, Phetchabun Province, Thailand

B. Samrit[1], I. Kheoruenromne[1,*], A. Suddhiprakarn[1] and S. Swasdiphanich[2]

[1]Department of Soil Science, Faculty of Agriculture, Kasetsart University Bangkok 10900, Thailand
[2]Department of Agronomy, Faculty of Agriculture, Kasetsart University Bangkok 10900, Thailand

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

Abstract

A study on properties and fertility capability of highland soils in Khao Kho area, Phetchabun Province was conducted on six representative soil locations in the elevation range of 724 to 942 meters above mean sea level. Method of study included soil field morphology analysis and laboratory analyses of soil samples on their micromorphological characteristics, physical, chemical and mineralogical properties according to standard methods and assessment of their fertility capability.

Results of the study revealed that these soils are moderately deep to very deep. These soils developed on residuum and colluvium derived from weathered rhyolitic tuff, andesitic tuff and graywacke. All soils have clay coatings on pore walls and as large accumulation spots in their subsoils. They are moderately to well developed. Physical properties of fine earths in these soil do not pose any problem for agricultural uses. Most of them have medium fertility. A major clay mineral in most of these soils is kaolinite and their silt fraction is clearly dominated by quartz. These soils are Paleudults for four areas, Paleudalf and Hapludalf each for one area.

Their fertility capability units include **Chk** for two areas, and **Lh**, **Ch**, **L'hk** and **LCak** each for one area. Their limitation comprised acidity, low phosphorus, low potassium and aluminum toxicity. Selective agricultural uses can be made but measures for soil and water conservation, and good natural forest upkeep are needed to sustain their biophysical system.

Keywords: fertility capability, highland soils, Khao Kho, Thailand

Introduction

The Ministry of Agriculture and Cooperatives reported in 1981 that highland areas in Thailand start from 700 m above mean sea level (Srisuk, 1998; Anongrak, 2003; Samrit et al., 2007). Most highland areas are hilly and mountainous consisting of complex slopes having slope more than 35 percentage and subjected to shifting cultivation. In general, highland areas have a low potential for agricultural uses due to the moderately low soil fertility and high soil erodibility on the areas having steep slope, and shifting cultivation is practiced (Pinthong et al., 1994; Srisuk, 1998; Anongrak, 2003; Samrit, 2008). Shifting cultivation has been condemned as destructive practice that increases the danger of runoff and erosion (Grandstaff, 1981). The degradation of highland soils with the restricted depth by the cultivation seriously impaired soil properties and resulted in significant decreases in the soil organic matter, aggregate stability, mean weight diameter and the hydraulic conductivity (Celik, 2005). Moreover, the deforestation as the trespass that the forest of highland areas may result in a disturbance of the hydrological balance and degradation of the physical and chemical attributes of the soils (Siebert, 1987; Gibson et al., 1988; Saunders et al., 1991; Ojima et al., 1994; Anongrak, 2003). Stoorvogel et al. (1993) reported that in the sub-humid highlands of southern Ethiopia, deforestation of the remnant natural forests and their conversion into low-input agriculture or establishment of plantations has caused extensive soil degradation.

Khao Kho is an area in Phetchabun Province, Central Highlands. This area covers approximately 833,125 rai (133,300 hectares). Most land surface are mainly slope complex and previously covered by forest. Some areas have been converted to agricultural land. More than 70 percent of the total population in the area is directly dependent on farming having a total agricultural land of about 89,829 rai (~14,373 hectares). However, with population increase in the area, it is quite difficult to avoid some expansion of agricultural uses of the lands at least partially. This report is a part of findings of a study carried out to acquire details on highland soils in Khao Kho area aiming at elucidating their characteristics and fertility capability as bases for future agricultural planning.

Materials and Methods

Soil Sampling

The altitude of the study area starts from 700 m above mean sea level. Methods of study comprised field investigation and laboratory analysis. Field investigation emphasized selection of study sites where six sites were selected. Pedon analysis of soil in a soil pit of 1×2×2 m (width×length×depth) was carried out at each site including detailed profile description and collecting samples of soil from each genetic horizon using standard field sampling methods for laboratory analysis (Soil Survey Division Staff, 1993; Kheoruenromne, 2004).

Laboratory Analysis

Bulk samples were air-dried, crushed and then passed through a 2-mm sieve. The resultant <2 mm samples were used for general laboratory analysis. The core samples from all genetic horizons were used for bulk density and hydraulic conductivity measurements. Kubiena samples were used for optical microscopic analysis.

Kubiena samples were transferred to impregnation mould containers, oven dried at 60-70 ºC, and impregnated with resin before slicing to prepare uncovered thin sections on glass slides for optical microscopy. The thin sections were analyzed under a polarizing microscope using standard micromorphological techniques as described by Bullock et al. (1985).

Particle size analysis of bulk soil samples was done by pipette method with pretreatment for removal of carbonate, organic matter and iron oxides (Gee and Bauder, 1986). Bulk density was determined by core method (Blak and Hartge, 1986). For hydraulic conductivity (Ksat), a saturated undisturbed soil (core sample) was installed in a cylinder and supplied with water to the bottom of the sample by variable head method (Klute, 1965).

Soil pH was measured in H_2O and in 1 M KCl (soil:solution, 1:1) by a standardized pH meter (National Soil Survey Center, 1996). Organic carbon was determined according to the Walkley and Black wet oxidation procedure (Nelson and Sommers, 1996) and organic matter content of the soil was taken to be organic carbon content multiplied by 1.724 (Nelson and Sommers, 1996). Total nitrogen was determined by the Kjeldahl method (Jackson, 1965). Available phosphorus was determined by the Bray II method (Bray and Kurtz, 1945) and available potassium was determined by ammonium acetate extraction (1M NH_4OAc) at pH 7.0 (Thomas, 1987). Extractable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+) were determined by ammonium acetate extraction (1M NH_4OAc) at pH 7.0 (Peech, 1945). Extractable acidity was determined by barium chloride-triethanolamine solution buffered at pH 8.2 (Peech, 1965) and extractable aluminum was determined by 1 M KCl extraction (Thomas, 1987). Cation exchange capacity (CEC) was determined by 1M NH_4OAc at pH 7.0 (Chapman, 1965). Aluminum saturation percentages and base saturation percentages were calculated following the methods used by the National Soil Survey Center (1996).

For mineralogical analysis, the clay fraction from sedimentation was deposited as oriented films on ceramic plates and 4 separate treatments were applied prior to X-ray diffraction (XRD) analysis: Mg^{2+} and K^{+} saturation, glycerol for the Mg^{2+} saturated clay, and heated to 550 ºC for the K^{+} saturated clay (Brown and Brindley, 1980). Minerals were determined for all horizons using XRD analysis with a Philips PW-3020 diffractometer with a graphite diffracted beam monochomator (CoKα, 25 kV, 17 mA). Clay and silt fraction samples were scanned respectively from 4 to 40º 2θ and 4 to 70º 2θ, using a step size of 0.02º 2θ and a scan speed of 0.04º 2θ sec^{-1}. Relative proportions of various minerals were calculated by comparing the XRD peak intensities with the intensities of standard minerals (Whittig and Allardice, 1986)

Soil fertility capability classification (Sanchez et al., 1982) was carried out on data obtained from field investigation and laboratory analyses.

Results and Discussion

Environmental Condition and General Characteristics

These soils developed on residuum and colluvium from rhyolitic tuff, andesitic tuff and graywacke in the areas ranging from 724 m to 942 m above mean sea level. Their surrounding landforms are hilly and undulating highlands having 4-30 percent slopes. They are well drained with moderate permeability. Land uses on them include cropping with upland rice, para rubber, coffee, litchie and vegetables (Table 1, Figures 1 and 2). These soils are under semi-humid subtropical climate and having a udic soil moisture regime. Most of the study sites have an annual rainfall of 1,787.6 mm and a mean temperature of 28ºC (Meteorological Department, 2007).

The soils are well drained and with moderate permeability. Though most of them have moderate run off, rapid run off conditions can be found at some sites. These environmental conditions of landscape and drainage can induce variation in their properties and affect land use to some extent.

Field Morphology

Textures of these soils are mostly clay, but some pedons have clay loam and fine sandy clay loam textures (Table 2). They have moderate to strong angular, semi-angular and subangular blocky structures. Their hues are 2.5YR to 10YR. They are moderately deep, deep and very deep soils.

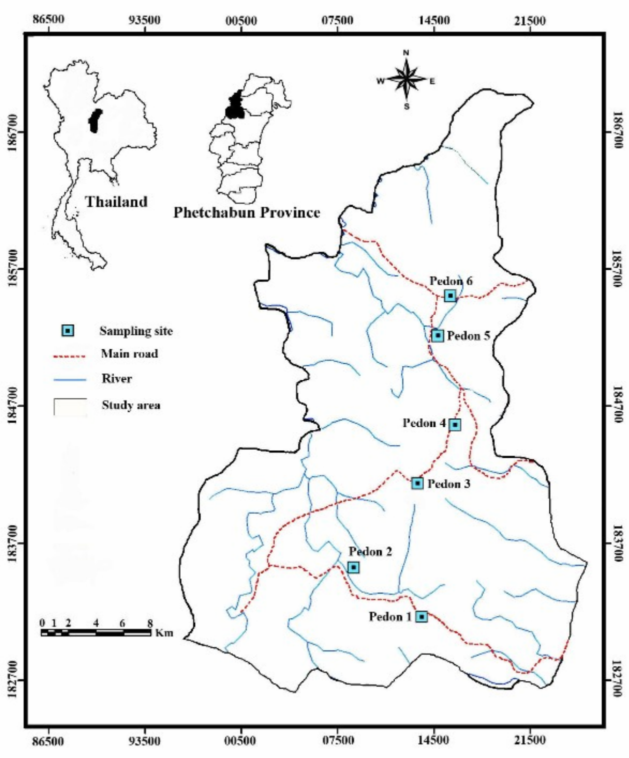

Figure 1 Location map of study sites in Khao Kho area, Phetchabun Province, Thailand.

The profiles as shown in Figure 2 indicate different profile types of these soils. They include Ap-Bt (P1 and P3), Ap-AB-Bt (P2), Ap-AB-Btc-Bt-2Bt-2Crt (P4), Ap-Bt-2Bt (P5) and Ap-Bt-BCrt-Crt-Cr (P6). The difference in their profile types, theoretically, is indicative of their development (Buol et al., 2003). The Ap horizon (topsoil) is relatively rich in organic matter and soil management including tillage has given the topsoil a moderate to strong subangular blocky structure, well drained with brown, dark brown to dark yellowish brown (Samrit, 2008). Most of their Bt horizons have firm, slightly firm and very firm consistence when moist with moderate to strong structures. Almost all of their genetic horizons shows clay coatings on ped faces and pore walls. These features are indicators of the characteristic of the highly developed structure (Srisuk, 1998; Buol et al., 2003). Clay coats can be found sufficiently in their Bt horizons of all pedons to be justified as argillic horizons (Soil Survey staff, 2006). All horizons show very few to common vesicular and tubular pores. The field pH is extremely acid to neutral (pH 4.0-7.0).

Table 1 Environmental setting of sampling sites.

Pedon	Parent Material	Elevation (m MSL)	Slope (%)	Surrounding landform	Physiography	Drainage	Permeability	Run off	Land use
1	Residuum derived from rhyolitic tuff	794	28	Hilly	Lower backslope on highland hilly areas	Well	Moderate	Moderately rapid	Mixed cropping of pararubber and upland rice
2	Residuum derived from rhyolitic tuff	783	4	Undulating	Upper footslope	Well	Moderate	Moderate	Mixed cropping of coffees and evergreen tree species
3	Residuum derived from andesitic tuff	942	7	Hilly	Upper spure valley side slope on highland hilly areas	Well	Moderate	Moderate	Litchie terrace
4	Colluvium over residuum derived from rhyolitic tuff	800	7	Hilly	Lower midslope on highland hilly areas	Well	Moderate	Moderate	Upland rice, left fallow at time of sampling under tall grasses
5	Colluvium over residuum derived from andesitic tuff	740	30	Hilly	Lower blackslope on highland hilly areas	Well	Moderate	Rapid	Chilli, left idle at time of sampling
6	Residuum derived from graywacke	724	4	Undulating	Lower footslope on highland undulating plain	Well	Moderate	Moderate	Vegetable, left fallow at time of sampling

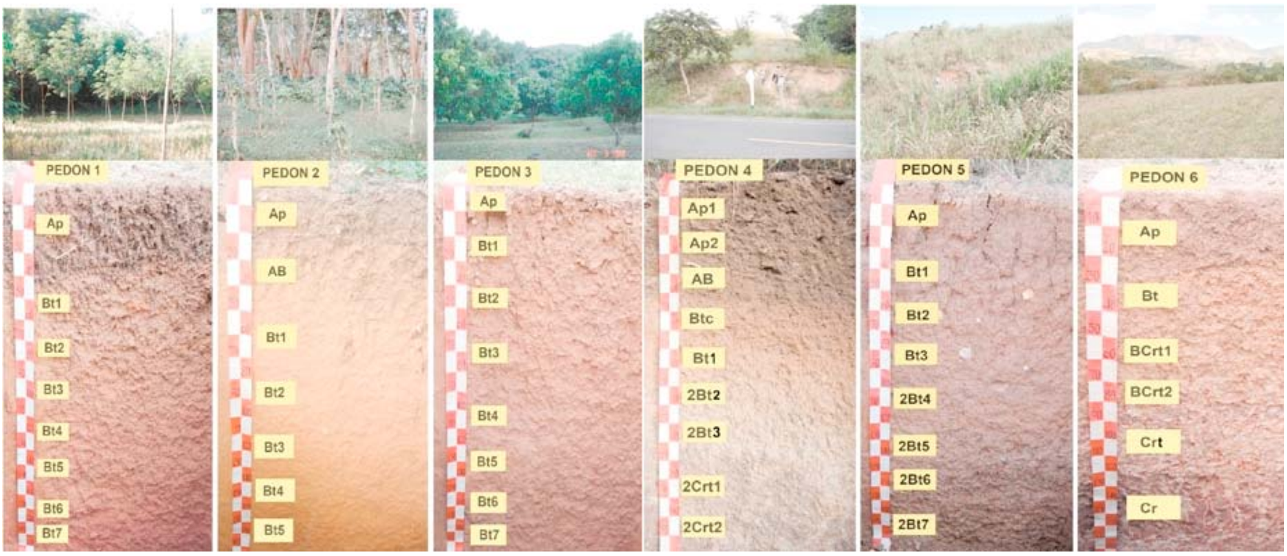

Figure 2 Physiography and soil profiles of Pedons 1, 2, 3, 4, 5 and 6.

Table 2 Morphology of the soils.

Depth (cm)	Horizon	Color	Structure[1/]	Consistence[2/]	Coating	Pore
Pedon 1 Typic Paleudult, very fine, kaolinitic, isohyperthermic						
0-32/40	Ap	7.5YR 3/3	3, f-m, sbk	H, F, VS/VP	Few	Common
40-60	Bt1	5YR 4/6	3, f-m, sbk	H, F, MS/VP	Common	Common
60-81	Bt2	5YR 5/6	3, f-m, sbk	H, VF, MS/VP	Common	Common
81-103	Bt3	Mixed 5YR 5/6, 10YR 6/6, 2.5YR 4/6	3, f-m, sabk	H, F, MS/MP	Common	Common
103-131	Bt4	Mixed 5YR 4/6, 10YR 6/6, 2.5YR 5/6	2, f-m, sabk	SH, SF, MS/MP	Common	Common
131-154	Bt5	Mixed 2.5YR 4/6, 10YR 6/6	2, f-m, sabk	SH, SF, MS/MP	Common	Common
154-179	Bt6	Mixed 2.5 YR 4/8, 10YR 7/4	2, f-m, sabk	SH, SF, MS/MP	Common	Common
179-200+	Bt7	Mixed 2.5 YR 4/8, 10YR 7/4	2, f-m, sabk	SH, SF, MS/MP	Common	Common
Pedon 2 Typic Paleudult, fine, kaolinitic, isohyperthermic						
0-20	Ap	Mixed 7.5YR 4/4, 5YR 6/6	3, f-m, sbk	H, F, SS/MP	-	Common
20-46/51	AB	5YR 4/4	2, f-m, sabk	H,SF, MS/MP	Few	Common
51-72	Bt1	5YR 5/8	2, f-m, abk	SH, SF, MS/MP	Few	Common
72-102	Bt2	Mixed 5YR 5/8, 10YR 7/8, 2.5YR 4/6	2, f-m, sbk	SH, SF, MS/MP	Few	Common
102-130	Bt3	5YR 5/8	2, f-m, sabk	SH, SF, MS/MP	Few	Common
130-160	Bt4	5YR 5/8	2, f-m, sabk	SH, SF, MS/MP	Very few	Common
160-200+	Bt5	5YR 5/8	2, f-m, sabk	SH, SF, MS/MP	Very few	Common
Pedon 3 Typic Paleudult, very fine, kaolinitic, isohyperthermic						
0-10	Ap	7.5YR 4/4	3, f-m, sbk	VH, VF, MS/MP	Few	Common
10-31	Bt1	7.5YR 4/6	3, f-m, sbk	VH, F, MS/VP	Common	Common
31-56	Bt2	Mixed 5YR 4/6, 10YR 5/4	3, f-m, sbk	VH, F, MS/VP	Common	Common
56-81	Bt3	Mixed 5YR 5/6, 10YR 5/4	3, f-m, sbk	H, F, MS/VP	Common	Common
81-112	Bt4	Mixed 5YR 5/6, 10YR 6/6	3, f-m, sbk	H, F, MS/MP	Common	Common
112-142	Bt5	Mixed 5YR 5/6, 10YR 7/4, 10YR 6/6, 2.5YR 4/6	2, f-m, sabk	SH, SF, MS/MP	Common	Common
142-175	Bt6	Mixed 5YR 5/6, 10YR 7/4, 2.5YR 4/6, 10YR 6/8	2, f-m, sabk	SH, SF, MS/MP	Common	Common
175-200+	Bt7	Mixed 5YR 4/6, 10YR 7/4, 2.5YR 4/6, 10YR 6/8	2, f-m, sabk	SH, SF, MS/MP	Common	Common
Pedon 4 Typic Paleudalf, fine-loamy, mixed, active, isohyperthermic						
0-25	Ap1	10YR 4/3	2, f-m, sbk	SH, SF, MS/MP	-	Common
25-45	Ap2	10YR 4/3	2, f-m, sbk	SH, SF, MS/MP	-	Common
45-60	AB	Mixed 10YR 4/3, 7.5YR 4/4	2, f-m, sbk	SH, SF, MS/MP	Few	Common
60-82	Btc	7.5YR 5/4	2, f-m, sbk	SH, SF, MS/MP	Few	Common

82-100	Bt1	Mixed 5YR 6/6, 7.5YR 7/4, 2.5YR 4/6	2, f-m, sbk	SH, SF, MS/MP	Common	Common
100-122	2Bt2	Mixed 7.5YR 5/6, 10YR 7/4	3, f-m,sabk	H, F, MS/MP	Common	Few
122-146/150	2Bt3	Mixed 7.5YR 6/6, 10YR 7/4	2, f-m, abk	H, F, MS/MP	Common	Few
150-180	2Crt1	Mixed 10YR 7/2, 10YR 3/2, 10YR 5/8, 10YR 6/4, 10YR 7/8	2, m-c, abk	H, F, MS/MP	Few	Common
180-200+	2Crt2	Mixed 10YR 3/2, 10YR 8/2, 10YR 5/8, 10YR 7/8	2, m-c, abk	H, F, MS/MP	Few	Common
Pedon 5 Vertic Hapludalf, very fine, kaolinitic, isohyperthermic						
0-30	Ap	10YR 4/3	3, c, sbk	VH, VF, VS/VP	Few	Few
30-50	Bt1	7.5YR 4/3	3, m-c, sabk	VH, VF, VS/VP	Common	Very few
50-70	Bt2	5YR 4/4	3, m-c, sabk	VH, VF, VS/VP	Common	Few
70-90	Bt3	Mixed 7.5YR 5/4, 7.5YR 4/4	3, m-c, sabk	VH, F, VS/VP	Common	Few
90-115	2Bt4	Mixed 7.5YR 5/4, 2.5YR 4/6, 2.5YR 5/6, 5YR 5/6	2, m-c, sabk	H, F, VS/VP	Many	Few
115-142	2Bt5	Mixed 7.5YR 6/4, 2.5YR 5/6, 5YR 5/6, 5YR 2.5/1	2, f-m, sabk	H, F, VS/VP	Many	Very few
142-165/170	2Bt6	Mixed 7.5YR 6/4, 2.5YR 5/6, 5YR 5/6, 5YR 2.5/1	2, f-m, sabk	H, F, VS/VP	Many	Few
170-200+	2Bt7	Mixed 7.5YR 6/4, 2.5YR 5/6, 5YR 5/6, 5YR 2.5/1	2, f-m, sabk	H, F, VS/VP	Common	Common
Pedon 6 Typic Paleudult, fine, mixed, semiactive, isohyperthermic						
0-25	Ap	10YR 4/4	2, f-m, sbk	SH, SF, MS/VP	-	Common
25-34/50	Bt	Mixed 7.5YR 5/4, 2.5YR 3/6, 2.5YR 5/6	2, f-m, sbk	SH, F, MS/VP	Common	Very few
50-65	BCrt1	Mixed 7.5YR 5/4, 2.5YR 2.5/4, 10YR 5/4, 5YR 5/8	2, f-m, sbk	SH, F, MS/VP	Common	Few
65-85	BCrt2	Mixed 7.5YR 5/4, 2.5YR 3/6, 10YR 5/4, 10YR 6/4, 5YR 5/8	2, f-m, sabk	SH, SF, MS/MP	Common	Few
85-125	Crt	Mixed 10YR 4/3, 2.5YR 3/6, 10YR 6/3	2, f-m, abk	SH, SF, MS/VP	Few	Few
125-200+	Cr	Mixed 10YR 4/3, 2.5YR 3/6, 10YR 6/3	2, f-m, abk	SH, SF, MS/VP	-	Few

1/ Structure; 2 = moderate, 3 = strong, m = medium, f = fine, c = coase, abk = angular blocky, sbk = subangular blocky, sabk = semi-angular blocky

2/ Consistence; SH = slightly hard, H = hard, VH = very hard, SF = slightly firm, F = firm, VF = very firm, SS = slightly sticky, VS = very sticky, VP = very plastic, MS = moderately sticky, MP = moderately plastic

Micromorphology

Results from petrographic analysis of soil fabric (Bullock et al., 1985) showed that general microstructure of the soils ranges from moderately developed to well developed subangular blocky, vughy and granular with some spongy structures (Figure 3). Pores are generally planar voids and vugh and some compound packing voids (Figures 3a, 3b, 3d). The distribution of coarse and fine materials are open and closed porphyric to nearly clay monic, with quartz as the main coarse constituent and with rhyolitic tuff (P4), andesitic tuff (P5) and graywacke rock fragments (P6). Pedological features in the soils are mainly textural pedofeatures as clay coatings (Figure 4a), clay mixed with iron oxide infillings (Figure 4b), microlaminated clay mixed with iron oxide infillings (Figure 4c) on pore walls and some microlaminated clay coatings on cracks of graywacke rock fragments (Figure 4d) for P6. Amorphous pedofeatures in the soils are iron-oxide nodules in limited amount (Samrit, 2008). Illuvial clay in these soils can be identified as mainly kaolinite. Soils formation is however likely to have involved by a combination of processes including migration of clay and sesquioxides from part of topsoil into the subsoil forming argillic horizon (Scolten and Andriesse, 1986). The micromorphological characteristics of these soils correlate well with field morphology and other soil properties.

Physical Properties

Particle size distribution shows these soils to have an increase of clay content in subsoil within a certain depth in the pedon but sand tends to decrease with depth whereas silt fluctuates slightly with depth (Table 3). This condition indicates the presence of an argillic horizon in the subsoil which in turn is the characteristic of well developed soils under tropical forest (Buol et al., 2003). These soils generally have clayey to loamy textures (Soil Survey Staff, 2006). The soils have low bulk density (1.07-1.16 Mg m^{-3}) in topsoil and low to moderately low (1.09-1.63 Mg m^{-3}) in subsoil. Bulk density of most subsoils is higher than that of topsoil and shows no systematic change with increasing clay content with depth and the higher organic matter content of topsoil as compared to that of subsoil. Hydraulic conductivity (Ksat) values of topsoil and subsoil vary from moderately slow to rapid, in a range of 6.71 × 10^{-3} to 16.12 cm h^{-1}. Most of topsoil and immediate subsurface soil have higher hydraulic conductivity than that of subsoil. This is the effect of the higher organic matter content of surface and subsurface soils and the clay accumulation in the subsoils (Srisuk, 1998; Buol et al., 2003; Samrit et al., 2007).

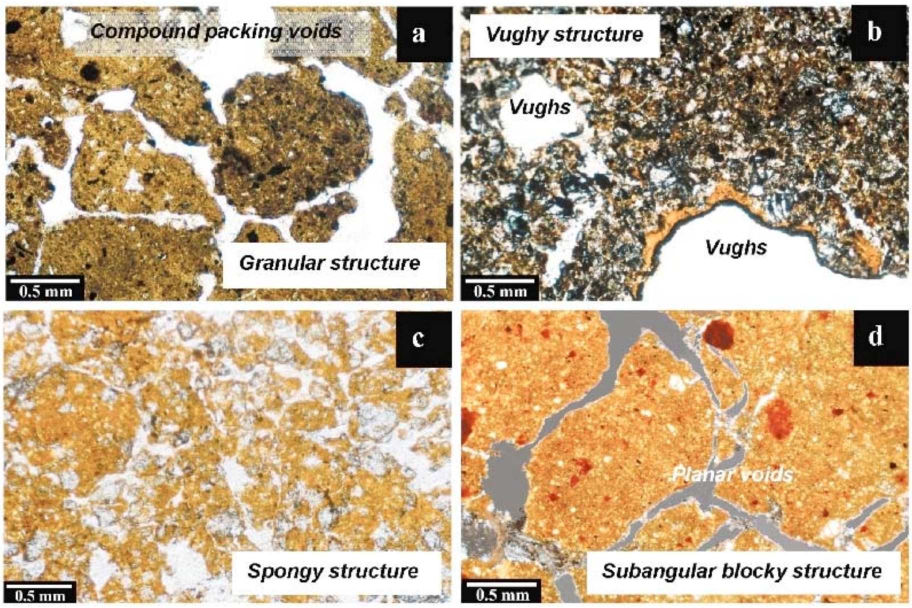

Figure 3 Optical micrographs of microstructure of highland soils showing (a) granular structure and compound packing voids in the P1_Ap horizon, plane polarized light, (b) vughy structure and vugh in the P2_Ap horizon, plane polarized light, (c) spongy structure in the P2_Bt1 horizon, plane polarized light, (d) subangular blocky structure and planar voids in the P3_Bt1 horizon, cross polarized light.

Table 3 Some physical properties of the soils.

Depth	Horizon	Particle size distribution (USDA grading)			Textural class	Bulk density	Hydraulic conductivity
		Sand	Silt	Clay			
(cm)		(---------- g kg^{-1} ---------)				(Mg m^{-3})	(cm h^{-1})
Pedon 1 Typic Paleudult, very fine, kaolinitic, isohyperthermic							
0-30/40	Ap	81	357	562	Clay	1.07	0.71
40-61	Bt1	66	305	629	Clay	1.09	6.33
61-81	Bt2	39	228	733	Clay	1.15	0.27
81-103	Bt3	29	215	757	Clay	1.34	3.74 × 10^{-3}
103-131	Bt4	28	246	726	Clay	1.33	2.67 × 10^{-3}
131-154	Bt5	38	374	588	Clay	1.32	0.14
154-179	Bt6	41	343	617	Clay	1.17	7.88 × 10^{-2}
179-200+	Bt7	63	424	513	Silty Clay	1.23	3.20 × 10^{-3}
Pedon 2 Typic Paleudult, fine, kaolinitic, isohyperthermic							
0-20	Ap	435	288	277	Sandy clay loam	1.08	1.26

20-46/51	AB	377	293	330	Clay loam	1.14	16.12
51-72	Bt1	338	244	417	Clay	1.34	1.60
72-102	Bt2	300	232	468	Clay	1.34	1.04
102-130	Bt3	305	236	460	Clay	1.28	1.85
130-160	Bt4	314	244	441	Clay	1.35	6.34
160-200+	Bt5	337	214	449	Clay	1.32	8.75
Pedon 3 Typic Paleudult, very fine, kaolinitic, isohyperthermic							
0-10	Ap	108	298	594	Clay	1.11	11.25
10-31	Bt1	79	256	665	Clay	1.19	0.89
31-56	Bt2	69	234	697	Clay	1.23	0.25
56-81	Bt3	41	230	729	Clay	1.35	0.16
81-112	Bt4	29	237	734	Clay	1.32	1.88×10^{-2}
112-142	Bt5	35	252	714	Clay	1.33	2.40×10^{-3}
142-175	Bt6	27	275	698	Clay	1.24	3.22×10^{-3}
175-200+	Bt7	26	307	667	Clay	1.29	4.28×10^{-3}
Pedon 4 Typic Paleudalf, fine-loamy, mixed, active, isohyperthermic							
0-25	Ap1	307	397	297	Gravelly clay loam1/	1.12	3.70
25-45	Ap2	330	351	319	Gravelly clay loam1/	1.07	4.16
45-60	AB	340	383	277	Clay loam	1.47	8.60
60-82	Btc	284	377	339	Clay loam	1.21	2.18
82-100	Bt1	229	382	389	Clay	1.45	4.82×10^{-3}
100-122	2Bt2	215	341	444	Clay	1.39	1.20×10^{-2}
122-146/150	2Bt3	230	367	403	Clay	1.37	3.49×10^{-2}
150-180	2Crt1	348	378	274	Clay loam	1.43	5.91×10^{-3}
180-200+	2Crt2	412	362	225	Loam	1.60	1.15×10^{-2}
Pedon 5 Vertic Hapludalf, very fine, kaolinitic, isohyperthermic							
0-30	Ap	85	312	603	Clay	1.07	0.29
30-50	Bt1	105	323	572	Clay	1.29	1.51
50-70	Bt2	79	242	679	Clay	1.35	3.72×10^{-2}
70-90	Bt3	56	219	725	Clay	1.32	4.59×10^{-2}
90-115	2Bt4	76	217	707	Clay	1.35	1.86×10^{-3}
115-142	2Bt5	80	302	618	Clay	1.50	1.06×10^{-3}
142-165/170	2Bt6	82	330	588	Clay	1.42	1.06×10^{-3}
170-200+	2Bt7	151	352	497	Clay	1.22	3.74×10^{-3}
Pedon 6 Typic Paleudult, fine, mixed, semiactive, isohyperthermic							
0-25	Ap	337	376	287	Clay loam	1.16	0.59
25-34/50	Bt	163	272	565	Clay	1.41	0.23
50-65	BCrt1	89	278	634	Clay	1.41	6.71×10^{-3}
65-85	BCrt2	120	315	565	Clay	1.39	0.19
85-125	Crt	167	199	634	Clay	1.37	1.09×10^{-2}
125-200+	Cr	280	408	311	Clay loam	1.63	1.12×10^{-2}

1/ Gravel 15-35%

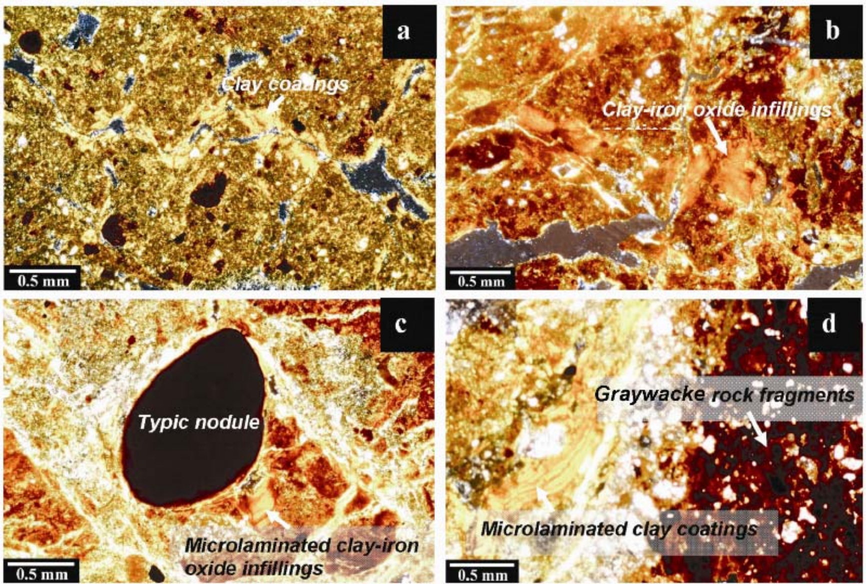

Figure 4 Optical micrographs under cross polarized light of pedofeature of highland soils showing (a) clay coatings on pore walls in the P3_Bt1 horizon, (b) clay mixed with iron oxide infillings on pore walls in the P5_2Bt6 horizon, (c) microlaminated clay mixed with iron oxide infillings on pore walls and typic ferruginous nodules in the P5_2B6 horizon, (d) microlaminated clay coatings on cracks of graywacke rock fragments in the P6_Cr horizon.

Basic Fertility Parameters

The natural fertility status of these soils based on the analytical values is low to medium (Kheoruenromne, 2004). Collectively, these highland soils have pH values in a range of very strongly acid to moderately acid (pH 4.8-5.9) in topsoil and a range of extremely acid to moderately acid (pH 4.2-6.0) in subsoil (Table 4). The low pH values of these soils indicate acid weathering and leaching of basic cations as the important pedogenic processes (Kheoruenromne, 1990; Samrit, 2008). Their delta pH ($\Delta pH = pH_{KCl}-pH_{H_2O}$) values are negative indicating a soil system favoring cation exchange (Sanchez, 1976). Their organic matter contents decrease with depth in a range of very low to high (1.8-42.1 g kg^{-1}) and the trend of total nitrogen with depth relates well with organic matter in these soils. Their available phosphorus have a wide range from very low to moderately low (0.02-9.3 mg kg^{-1}). This low available phosphorus is mainly caused either by the inherent characteristics of the parent material and by the strong sorption of PO_4^{3-} to Al- and Fe-hydroxides, which turns large proportions of total soil P into unavailable forms (Brady and Weil, 2002; Solomon et al., 2002; Havlin et al., 2005). Their available potassium contents range from very low to very high (11-250 mg kg^{-1}) (FAO Project Staff and Land Classification Division, 1973). The soils have relatively high amount of available potassium in the surface horizon (P2 and P3) as a result of fertilizer application for crop production. All soils have available potassium that rapidly decreases with depth. This indicates the loss of potassium by highly leaching condition in their subsoils (West and Beinroth, 2000).

Exchange Properties

In general, most of these soils have low extractable bases, and in most cases calcium is present in higher amount than are the others (Table 4). These soils have relatively low sum of extractable bases (0.48-19.6 cmol kg^{-1}) and the values indicate either a slightly decrease or increase trend with depth in the pedon. These soils have low to high base saturation percentage (4.0-75.2 %), but most of them have low base saturation which decreases with depth, except for Pedons 4 and 5. These soils have moderately high to high extractable acidity (5.2-10.7 cmol kg^{-1}) in topsoil and moderate to high (4.3-14.3 cmol kg^{-1}) in subsoil and fluctuates slightly with depth. The trends with depth in extractable aluminum and acidity follow those of clay percentages which provides the surface sites that retain H^+ and Al^{3+} indicating the high leaching

Table 4 Nutrient status and exchange properties of the soils.

Depth	Horizon	pH (1:1)		OM	Total N	Available		Extractable					Sum bases	EA	CEC		Al sat.	BS
		H_2O	KCl			P	K	Ca	Mg	K	Na	Al			by sum	NH_4OAc		
(cm)				(----g kg^{-1}----)		(----mg kg^{-1}---)		(-------------------------------------cmol kg^{-1}----------------------------------)									(-----%-------)	
Pedon 1 Typic Paleudult, very fine, kaolinitic, isohyperthermic																		
0-30/40	Ap	5.0	4.1	42.1	1.87	1.44	73	5.48	1.99	0.19	0.26	0.28	7.91	8.05	16.0	17.9	3.4	49.6
40-61	Bt1	5.3	3.4	18.4	0.82	0.75	21	1.68	1.37	0.05	0.22	2.13	3.31	9.23	12.5	13.4	39.1	26.4
61-81	Bt2	5.6	3.6	11.7	0.70	1.43	12	0.72	0.81	0.03	0.29	2.02	1.84	9.07	10.9	14.4	52.2	16.9
81-103	Bt3	5.4	3.5	7.4	0.50	0.56	19	0.52	0.43	0.05	0.24	1.94	1.23	8.22	9.5	15.5	61.2	13.0
103-131	Bt4	5.8	3.5	5.4	0.47	0.46	17	0.62	0.39	0.04	0.27	1.82	1.32	9.41	10.7	14.7	58.0	12.3
131-154	Bt5	5.6	3.5	7.1	0.54	0.46	13	0.56	0.26	0.03	0.26	1.95	1.11	9.54	10.6	14.5	63.8	10.4
154-179	Bt6	5.5	3.4	5.2	0.41	0.45	14	0.62	0.23	0.03	0.26	2.67	1.14	8.51	9.7	13.2	70.0	11.9
179-200+	Bt7	5.4	3.3	2.8	0.44	0.74	15	0.47	0.17	0.04	0.24	3.36	0.92	8.04	9.0	12.7	78.4	10.3
Pedon 2 Typic Paleudult, fine, kaolinitic, isohyperthermic																		
0-20	Ap	5.7	4.1	26.4	1.78	9.31	166	3.13	0.95	0.42	0.29	0.06	4.79	5.31	10.1	9.1	1.2	47.4
20-46/51	AB	5.9	4.1	11.5	0.86	0.72	123	2.62	0.70	0.31	0.24	0.05	3.86	5.06	8.9	7.4	1.4	43.3
51-72	Bt1	5.7	3.7	6.1	0.58	1.39	100	2.38	0.88	0.25	0.24	0.27	3.74	4.30	8.0	9.4	6.6	46.6
72-102	Bt2	5.0	3.3	7.2	0.69	7.35	26	0.69	0.56	0.07	0.22	1.25	1.53	6.39	7.9	10.5	45.0	19.3
102-130	Bt3	4.7	3.4	4.2	0.47	0.10	10	0.21	0.36	0.03	0.20	1.34	0.80	6.56	7.4	8.1	62.5	10.9
130-160	Bt4	4.8	3.4	3.4	0.51	0.11	12	0.14	0.32	0.03	0.20	1.10	0.69	4.78	5.5	9.2	61.6	12.6
160-200+	Bt5	4.6	3.3	3.8	0.48	0.11	15	0.17	0.24	0.04	0.22	1.25	0.66	5.77	6.4	7.4	65.5	10.2
Pedon 3 Typic Paleudult, very fine, kaolinitic, isohyperthermic																		
0-10	Ap	5.3	3.7	37.9	2.38	0.85	249	3.84	1.55	0.62	0.29	0.29	6.30	10.66	17.0	16.6	4.5	37.2
10-31	Bt1	5.1	3.4	25.8	1.73	0.02	110	1.35	0.59	0.28	0.28	1.48	2.49	10.54	13.0	14.6	37.3	19.1
31-56	Bt2	5.2	3.3	17.7	0.81	0.02	38	0.45	0.26	0.10	0.24	2.27	1.04	10.69	11.7	14.9	68.6	8.9
56-81	Bt3	5.4	3.3	13.3	0.84	0.02	23	0.28	0.42	0.06	0.25	2.06	1.00	9.29	10.3	13.3	67.4	9.7
81-112	Bt4	5.5	3.4	7.3	0.63	0.02	14	0.14	0.41	0.04	0.20	1.86	0.78	8.21	9.0	13.7	70.4	8.7
112-142	Bt5	5.5	3.5	5.7	0.53	0.02	19	0.20	0.48	0.05	0.20	2.06	0.93	8.75	9.7	12.7	68.8	9.6
142-175	Bt6	5.6	3.4	3.9	0.49	1.45	16	0.09	0.31	0.04	0.16	2.21	0.60	9.01	9.6	13.3	78.7	6.2
175-200+	Bt7	5.6	3.4	2.8	0.52	0.20	27	0.07	0.26	0.07	0.25	2.08	0.66	8.83	9.5	14.3	75.9	6.9
Pedon 4 Typic Paleudalf, fine-loamy, mixed, active, isohyperthermic																		
0-25	Ap1	5.9	4.1	27.3	1.96	1.77	78	9.19	3.03	0.20	0.27	0.06	12.7	5.15	17.8	18.5	0.45	71.1
25-45	Ap2	6.0	4.2	18.1	1.33	0.11	40	8.73	2.49	0.10	0.28	0.11	11.6	5.61	17.2	17.9	0.95	67.4
45-60	AB	5.9	4.1	17.7	1.41	3.51	22	8.80	2.35	0.06	0.24	0.14	11.4	6.72	18.2	16.9	1.22	63.0
60-82	Btc	6.0	3.8	9.7	0.70	0.11	16	8.71	2.71	0.04	0.25	0.17	11.7	5.40	17.1	16.0	1.46	68.5
82-100	Bt1	6.0	3.1	7.3	0.55	0.73	21	9.46	4.04	0.05	0.35	0.72	13.9	7.25	21.2	20.8	4.93	65.7
100-122	2Bt2	5.8	3.1	5.8	0.57	0.11	35	10.62	5.20	0.09	0.40	2.36	16.3	9.63	25.9	26.9	12.63	62.9
122-146/150	2Bt3	6.0	3.0	4.3	0.46	0.11	33	9.78	5.79	0.08	0.73	3.31	16.4	10.70	27.1	28.7	16.81	60.5
150-180	2Crt1	5.9	3.0	3.4	0.42	0.11	32	8.98	5.63	0.08	1.09	1.91	15.8	8.50	24.3	24.3	10.78	65.0
180-200+	2Crt2	5.9	3.0	1.8	0.25	0.02	22	11.25	6.53	0.06	1.71	0.88	19.6	6.46	26.0	24.3	4.30	75.2
Pedon 5 Vertic Hapludalf, very fine, kaolinitic, isohyperthermic																		
0-30	Ap	5.4	4.0	24.5	1.44	1.10	32	9.69	2.70	0.08	0.26	0.18	12.7	7.51	20.2	19.7	1.36	62.9
30-50	Bt1	5.6	4.0	16.3	0.87	0.11	22	10.41	2.75	0.06	0.27	0.21	13.5	6.71	20.2	20.3	1.50	66.8
50-70	Bt2	5.5	3.9	13.3	0.65	0.75	12	9.86	2.72	0.03	0.20	0.25	12.8	7.29	20.1	21.6	1.90	63.7
70-90	Bt3	5.5	3.9	12.1	1.00	0.11	23	9.72	3.02	0.06	0.28	0.30	13.1	7.07	20.1	20.2	2.22	64.9
90-115	2Bt4	5.7	3.9	10.6	0.84	0.11	13	9.97	3.10	0.03	0.23	0.36	13.3	7.56	20.9	20.6	2.66	63.8
115-142	2Bt5	5.7	4.1	7.3	0.54	0.02	27	9.31	3.10	0.07	0.27	0.38	12.8	6.50	19.2	25.2	2.88	66.2
142-165/170	2Bt6	5.9	4.0	5.6	0.36	0.02	43	12.48	4.36	0.11	0.26	0.51	17.2	6.52	23.7	23.5	2.88	72.5
170-200+	2Bt7	5.9	3.9	4.3	0.48	0.02	31	11.43	4.27	0.08	0.30	0.17	16.1	6.56	22.6	24.7	1.08	71.0
Pedon 6 Typic Paleudult, fine, mixed, semiactive, isohyperthermic																		
0-25	Ap	4.8	3.3	32.5	1.67	6.61	51	2.23	1.05	0.13	0.19	1.06	3.60	8.30	11.9	25.7	22.8	30.3
25-34/50	Bt	4.5	3.2	16.6	1.10	0.39	34	2.01	0.98	0.09	0.28	4.21	3.35	12.71	16.1	18.4	55.7	20.9
50-65	BCrt1	4.5	3.1	12.6	0.93	0.75	35	0.80	0.70	0.09	0.26	5.91	1.85	14.32	16.2	28.5	76.1	11.5
65-85	BCrt2	4.3	3.2	7.6	0.54	0.22	25	0.39	0.48	0.06	0.28	6.28	1.21	14.06	15.3	23.8	83.8	8.0
85-125	Crt	4.2	3.1	7.2	0.57	0.04	15	0.18	0.35	0.04	0.26	6.50	0.83	13.91	14.7	25.0	88.7	5.6
125-200+	Cr	4.2	3.2	1.8	0.39	0.38	16	0.01	0.15	0.04	0.28	5.84	0.48	11.52	12.0	19.2	92.5	4.0

condition (Sanchez, 1976). Pedon 6 is very strongly acidic with high aluminum toxicity (aluminum saturation percentage > 60%). This is possible for calcium, magnesium and phosphorus imbalance (Havlin et al., 2005). These soils have moderately low to high cation exchang capacity (7.4-28.7 cmol kg^{-1}). Variation in CEC with depth is related to the soil organic matter content but there is not a systematic relationship between organic carbon and CEC in these soils. Based on their exchange properties these soils are highly leached and highly developed soils (Buol et al., 2003; Samrit et al., 2007).

Mineralogical Characteristics

Results of the mineralogical analysis (Table 5, Figures 5 and 6) reveal that minerals in their clay fraction are kaolinite, vermiculite, chlorite, smectite, illite, quartz, goethite and 1.4 nm clay minerals. Kaolinite and quartz are present in every pedons, but vermiculite, chlorite, smectite, illite, goethite, feldspar and 1.4 nm clay minerals are present only in some pedons.

Kaolinite is the dominant silicate clay mineral conforming with typical situation of the soils in the Tropics (Hart et al., 2003; Kanket et al., 2005; Trakoonyingcharoen et al., 2006) and this reflects

Table 5 Mineralogy characteristics of the soils.

Depth	Horizon	Clay fraction[1/]							Silt fraction[1/]			
(cm)		Kao	Ver	Chl	Smec	Ill	Qtz	Others	Qtz	Kao	Mica	Feld
Pedon 1 Typic Paleudult, very fine, kaolinitic, isohyperthermic												
0-30/40	Ap	xxxx	tr	-	-	-	tr	-	xxxx	tr	tr	-
81-103	Bt3	xxxx	tr	-	-	-	tr	-	xxxx	tr	tr	-
131-154	Bt5	xxxx	tr	-	-	-	tr	-	xxxx	tr	tr	-
179-200+	Bt7	xxxx	tr	-	-	-	tr	-	xxxx	tr	tr	-
Pedon 2 Typic Paleudult, fine, kaolinitic, isohyperthermic												
0-20	Ap	xxx	x	-	-	tr	tr	-	xxxx	tr	tr	-
51-72	Bt1	xxx	x	-	-	tr	tr	-	xxxx	tr	tr	-
102-130	Bt3	xxx	x	-	-	tr	tr	-	xxxx	tr	tr	-
160-200+	Bt5	xxx	x	-	-	tr	tr	-	xxxx	tr	tr	-
Pedon 3 Typic Paleudult, very fine, kaolinitic, isohyperthermic												
0-10	Ap	xxxx	-	-	-	tr	tr	tr	xxxx	tr	tr	-
56-81	Bt3	xxxx	-	-	-	tr	tr	tr	xxxx	tr	tr	-
112-142	Bt5	xxxx	-	-	-	tr	tr	tr	xxxx	tr	tr	-
175-200+	Bt7	xxxx	-	-	-	tr	tr	tr	xxxx	tr	tr	-
Pedon 4 Typic Paleudalf, fine-loamy, mixed, active, isohyperthermic												
0-25	Ap1	xx	-	-	x	-	x	tr	xxxx	tr	tr	tr
45-60	AB	xx	-	-	x	-	x	tr	xxxx	tr	tr	tr
60-82	Btc	xx	-	-	x	-	x	tr	xxxx	tr	tr	tr
82-100	Bt1	xx	-	-	x	-	x	tr	xxxx	tr	tr	tr
100-122	2Bt2	xx	-	-	x	-	x	tr	xxxx	-	tr	tr
150-180	2Crt1	xx	x	-	-	-	x	tr	xxxx	-	tr	tr
Pedon 5 Vertic Hapludalf, very fine, kaolinitic, isohyperthermic												
0-30	Ap	xxxx	-	-	-	tr	tr	tr	xxxx	tr	tr	-
70-90	Bt3	xxxx	-	-	-	tr	tr	tr	xxxx	tr	tr	-
90-115	2Bt4	xxxx	-	-	-	tr	tr	tr	xxxx	tr	tr	-
142-165/170	2Bt6	xxxx	-	-	-	tr	tr	tr	xxxx	tr	tr	-
Pedon 6 Typic Paleudult, fine, mixed, semiactive, isohyperthermic												
0-25	Ap	xxx	-	xxx	-	tr	tr	-	xxxx	-	-	-
25-39/50	Bt	xxx	-	xxx	-	tr	tr	-	xxxx	tr	tr	-
65-85	BCrt2	xx	-	xx	-	tr	tr	-	xxxx	tr	tr	-
125-200+	Cr	xxx	-	xxx	-	tr	tr	-	xxxx	tr	tr	-

[1/] Kao = kaolinite, Ver = vermiculite, Chl = chlorite, Smec = smectite, Ill = illite, Qtz = quartz, Feld = feldspar, others = mainly 1.4 nm clay minerals; tr = trace (<5%), x = few (5-20%), xx = moderate (20-40%), xxx = large (40-60%), xxxx = dominant (>60%).

the well drained condition in the soils (Goss and Allew, 1968;) The presence of kaolinite is consistent with the quite highly weathered condition of most of these soils (Dixon, 1989; Trakoonying-charoen et al., 2006; Samrit, 2008) in highland areas and similar conditions have been reported for highly weathered soils from other parts of the Tropics (Juo, 1980; Fox, 1982; Krishnaswamy and Richter, 2002; Srisuk, 1998). Quartz is present in clay fraction of all pedons in trace to some amounts indicates the quite highly weatherd condition of these soils (Dixon, 1989). This condition does not promote their exchange properties. Nevertheless, the presence of illite, smectite and some other minerals in their clay fraction still indicates a condition within these soils to favor cation exchange (Uehara and Gillman, 1981).

The mineralogy of silt fractions is dominated by quartz which can be ascribed to the selective accumulation due to its relative resistance to weathering (Kabata-Pendias and Pendias, 2001). All soils have a trace amount kaolinite and mica (muscovite). Nevertheless, a trace amount of feldspar is present every genetic horizon of Pedon 4 correlate well with field morphology and weathered rhyolitic tuff parent material.

Classification

Based on their morphology, physical and chemical properties and mineralogical characteristics of these soils can be placed into taxonomic classes of two orders including Alfisols and Ultisols (Soil Survey Staff, 2006). All soils have clay accumulations in the subsoil justifying an argillic horizon. They have developed under udic condition, so their suborders are Udalfs and Udults. Most of these soils are in "Typic" subgroup, except for Pedon 5 that shows cracks within 125 cm that are 5 mm or wider and slickensides in a layer thicker than 15 cm and mixed mineralogy, so it belongs to the "Vertic" subgroup. Pedons 1 and 3 are Typic Paleudults, very fine, kaolinitic, isohyper-thermic. Pedon 2 is a Typic Paleudult, fine, kaolinitic, isohyperthermic. Pedon 4 is a Typic Paleudalf, fine-loamy, mixed, active, isohyperthermic. Pedon 5 is a Vertic Hapludalf, very fine, kaolinitic, isohyper-thermic. Pedon 6 is a Typic Paleudult, fine, mixed, semiactive, isohyperthermic (Soil Survey Staff, 2006).

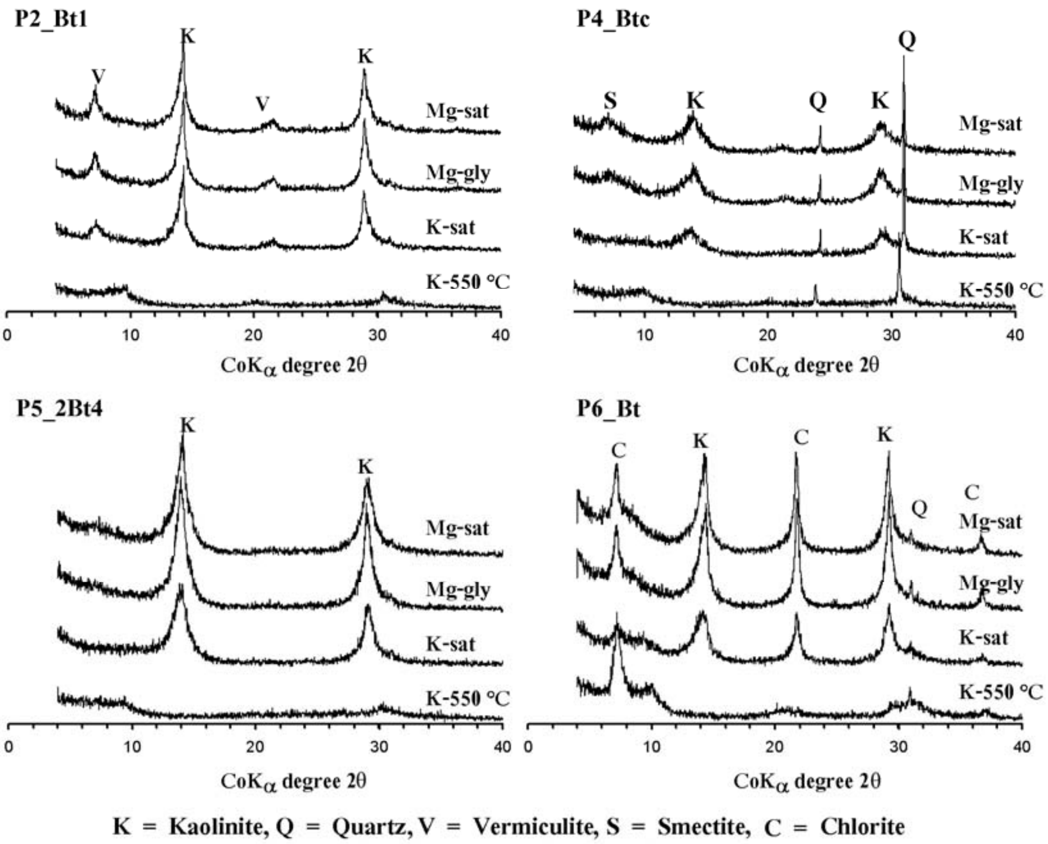

Figure 5 Some X-ray diffraction patterns of clay minerals of the studied highland soils.

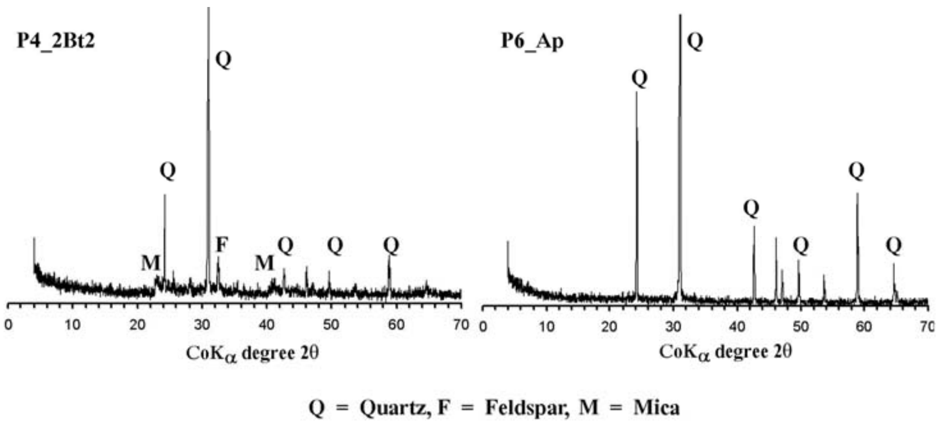

Figure 6 Some X-ray patterns diffraction of silt minerals of the studied highland soils.

Fertility Capability and Management

To evaluate soil fertility capability, a defined set of physical, chemical and mineralogical properties of soils within a depth of 50/60 centimeters from surface soil is used (Sanchez et al., 1982; Kheoruenromne, 2004). This set of soil parameters includes broad-grouped texture of surface (Ap) and subsurface soils, critical analytical values of soils, and some distinct soil morphological characteristics indicative of particular soil environment (Table 6). Based on soil data in Tables 2 to 4, only some of parameters indicated in Table 6 are relevant for determining fertility capability of these highland soils. The data analysis results on fertility capability for each soil and relavant basic suggestions are summarized in Table 7.

These six soils can be grouped into five fertility capability classification (FCC) units. Pedons 1 and 5 are in **Chk** of which their clayey texture, low pH and K reserve status are major constraints for cropping. Pedons 2 and 3 can be classed into **Lh** and **Ch** respectively. These two soils have loam and clay textures with low pH. Pedon 4 is in **L'hk** with loamy texture and with 18.4% of gravels by volume in subsurface soil and low pH and K reserve status. Pedon 6 is in **LCak** with loamy textured topsoil and clayey textured of subsoil. This has a more serious condition of acidity and Al-toxicity with low K reserve.

Managements of these soils should depend on the tolerance to the negative effects at the particular acidity levels and nutrient requirement of the crops. Most suitable economic crops are tree crops, fruit crops and selected non-flooded annual crops (Samrit et al., 2007). Selective agricultural uses can be made but plant nutrients management practice and the combining use of green manure, barn manure, mineral fertilizer and liming to improve soil fertility are needed. The most suitable land use on these highland soils is forest cover, being under natural vegetation cover or agroforestry (Yamoah et al., 1999; Samrit, 2008). The natural conservation of organic matter in these soils indicates low degree of agricultural use. A strict conservation measure and restrictive agricultural uses are recommended for management of these Khao Kho highland soils.

Conclusions

Result of this study revealed that highland soils in Khao Kho Area, Phetchabun Province, Thailand include Typic Paleudults (P1, 2, 3, 6), a Vertic Hapludalf (P5) and a Typic Paleudalf (P4). Most of these soils have kaolinitic mineralogy class. Their fertility capability units include Chk for two areas, and Lh, Ch, L'hk and LCak each for one area. These results indicate that they are highly leached and highly weathered to moderately weathered soils. The soils have good general physical properties. Their general limitation for crop practices comprises acidity, low phosphorus, low potassium and aluminum toxicity in some pedons. Recommendations for their basic fertility management generally include the combining use of green manure, barn manure, mineral fertilizer and liming along with soil surface organic matter management. The most suitable land use on these highland soils is forest cover, being under natural vegetation cover or agroforestry.

Table 6 Indicative soil parameters used in determination of soil fertility capability (from surface 50-60 cm depth).

Parameters	Soil characteristics/Properties	Symbols[1/]
Type	Broad group of surface soil texture	S, L, C, O
Substratra Type	Broad group of subsurface soil texture	S, L, C, R
Modifiers	1. Aluminum toxicity (pH in 1:1 H_2O <5.0)	a
	2. Basic reaction (pH in 1:1 H_2O >7.3)	b
	3. Cat clay (presence of jarosite with pH in 1:1 H_2O <3.5)	c
	4. Dry (soil has ustic, aridic or xeric moisture regime)	d
	5. Low cation exchange capacity (sum of bases extracted by NH_4OAc <7 cmol kg^{-1})	e
	6. Gleying (soil color with low chroma ($\leq$ 2))	g
	7. Acid (pH in 1:1 H_2O = 5.0-6.0)	h
	8. High-P fixation with iron (soil has more than 35% clay and has a color of 7.5 YR or redder, with granular structure)	i
	9. Low K reserve (soil has weatherable minerals <10% in silt fraction)	k
	10. Natric (exchangeable sodium percentage 15%)	n
	11. Salinity (EC $\geq$ 4 dSm^{-1})	s
	12. Vertisols (soil has > 35 % clay and more than 50% of clay is smectite)	v
	13. X-ray amorphous (used only when soil has pH >10 in 1N NaF or soil developed on volcanic ash)	x
	14. Slope (slope limitation indicated by slope range)	%
	15. Prime (-') (indicates amount of gravels by volume in subsurface soil, (-') gravel 15-35%, (-'') gravel >35%)	-' -''

[1/] S = sandy, L = loamy, C = clayey, O = organic, R = rock

Table 7 Fertility capability of the soils.

Site	Horizon[1/] (cm)	Texture	2:1 expending clay	pH 1:1 H_2O	K reserved cmol kg^{-1}	Gravel (%)	Al sat. (%)	FCC[2/]
Pedon 1	Topsoil	Clayey	<50%	5.0	0.19	-	3.43	Chk
	Subsoil	Clayey	<50%	5.1	0.14	-	15.33	
Pedon 2	Topsoil	Loamy	<50%	5.7	0.42	-	1.21	Lh
	Subsoil	Loamy	<50%	5.9	0.31	-	1.38	
Pedon 3	Topsoil	Clayey	<50%	5.3	0.62	-	4.47	Ch
	Subsoil	Clayey	<50%	5.1	0.20	-	52.15	
Pedon 4	Topsoil	Loamy	<50%	5.9	0.20	18.4	0.45	L'hk
	Subsoil	Loamy	<50%	6.0	0.11	18.3	0.92	
Pedon 5	Topsoil	Clayey	<50%	5.4	0.08	-	1.36	Chk
	Subsoil	Clayey	<50%	5.5	0.06	-	1.46	
Pedon 6	Topsoil	Loamy	<50%	4.8	0.13	-	22.80	LCak
	Subsoil	Clayey	<50%	4.6	0.09	-	61.12	

[1/] Topsoil = Ap or 0-20 cm, Subsoil = horizon under Ap or 20-50/60 cm depth interval
[2/] L = loamy, C = clayey, a = pH < 5.0 and Al saturation >60%, h = pH range 5.0-6.0, k = K reserve $\leq$0.2 cmol kg^{-1}, _' = gravel 15-35%

Acknowledgments

This research was financially supported partly by the Graduate School, Kasetsart University. We would like to thank the Office of Science for Land Development, Land Development Department for the facility and kind assistance on optical analysis and XRD analysis.

References

Anongrak, N., 2003. Highland Soil Catena as Affected by Land Uses and Land covers in Doi Inthanon Area, Chiang Mai Province. Ph.D. Thesis, Kasetsart University.

Brady, N.C. and R.R. Weil. 2002. The Nature and Properties of Soils. 13th ed. Prentice-Hall, Inc., New Jersey, USA.

Bray, R.H. and L.T. Kurtz. 1945. Determination of total, organic, and available forms of phosphorus in soils. Soil Sci. 59: 39-45.

Brewer, R. 1964. Fabric and Mineral Analysis of Soils. John Wiley and Sons, Inc., New York.

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

Bullock, P., N. Fedoroff, A. Jongerius, G. Stoops, T. Turisna, U. Bablel, J. Agrilar, H.J. Altemuller, E.A. Fitzpatrick, S.T. Kowalinski, G.K. Rutherford and E.A. Yarilova. 1985. Handbook for Thin Section Description. Waine Research, Albrighton, United Kingdom.

Buol, S.W., R.J. Southard, R.C. Graham and P.A. McDaniel. 2003. Soil Genesis and Classification. 5th ed. Iowa State Press. A Blackwell Pub. Co., Ames.

Blake, G.R. and K.H. Hartge. 1986. Bulk density, pp. 363-382. *In* A. Kulte et al., eds., Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods, 2nd ed. Agronomy, No. 9. Amer. Soc. Agron. Inc., Madison, WI.

Celik, I. 2005. Land-use effects on organic matter and physical properties of soil in a southern Mediterranean highland of Turkey. Soil & Tillage Research 83: 270-277

Chapman, N. 1965. Cation exchange capacity, pp. 891-901. *In* C.A. Black, ed., Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties, 2nd ed. Amer. Soc. of Agron. Inc., Madison, Wisconsin.

Dixon, J.B. 1989. kaolin and serpentine group minerals. pp. 467-525. *In* J.B. Dixon and S.B. Weed, eds., Minerals in Soils Environments. 2nd ed. Soil Science Society of America. Book Series No.1.

FAO Project Staff and Land Classification Division. 1973. Soil Interpretation Handbook for Thailand. Land Classification Division, Department of Land Development, Bangkok.

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

Gee, G.W. and J.W. Bauder. 1986. Particle-size analysis, pp. 383-411. *In* A. Klute, ed., Methods of Soil Analysis, Part I. Physical and Mineralogical Methods. Agronomy, No.9. Amer. Soc. Agron. Inc., Madison, WI.

Gibson, J.D., S.L. Collins and R.E. Good. 1988. Ecosystem fragmentation of oak–pine forest in the New Jersey pineland. Forest Ecology and Management 25: 105-122.

Goldberg, S. and H.S. Foster. 1990. Flocculation of reference clays and arid-zone soil clay. Soil Sci. Soc. Am. J. 54: 714-718.

Goss, D.W. and B.L. Allew. 1968. A genetic study of two soils developed on granite in Liano Country, Texas. Soil Sci. Soc. Amer. Proc. 32: 409-413.

Grandstaff, T.B. 1981. Shifting cultivation. Ceres 4: 28-30.

Havlin, J.L., J.D. Beaton, S.L. Tisdale and W.L. Nelson. 2005. Soil Fertility and Fertilizer: an Introduction to Nutrient Management. 7th ed., Prince-Hall Inc., Upper Saddle River, New Jersey.

Hart, R.D., W. Wiriyakitnateekul and R.J. Gilkes. 2003. Properties of soil kaolins from Thailand. Clay Minerals 38: 71-94.

Jackson, M.L. 1965. Soil Chemical Analysis-Advanced Course. Department of Soils, University of Wisconsin.

Juo, A.S.R. 1980. Mineralogical characteristics of Alfisols and Ultisols, pp. 69-86. *In* B.K.G. Theng, ed., Soils with Variable Charge. New Zealand Society of Soil Science, Lower Hutt, New Zealand.

Kabata-Pendias, A. and H. Pendias. 2001. Trace Elements in Soil and Plants. CRC Press, Beca Roton, Florida.

Kanket, W., A. Suddhiprakarn, I. Kheoruenromne and R.J. Gilkes. 2005. Chemical and crystallographic properties of kaolin from Ultisols in Thailand. Clay and Clay Minerals 53: 478-489

Kheoruenromne, I. 1990. Soils of Thailand: Characteristics, Distribution and Uses. Department of Soil Science, Faculty of Agriculture, Kasetsart University, Bangkok. (in Thai).

Kheoruenromne, I. 2004. Soil Survey Laboratory Manual. Department of Soil Science, Faculty of Agriculture, Kasetsart University, Bangkok. (in Thai).

Klute, A. 1965. Laboratory measurement of hydraulic conductivity of saturated soil, pp. 210-220. *In* A. Kulte et al., eds., Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods, 2nd ed. Agronomy, No. 9. Amer. Soc. Agron. Inc., Madison, WI.

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

Meteorological Department. 2007. Climatological Data of Thailand for 10 Year Period 1997-2006. Bangkok, Thailand.

National Soil Survey Center. 1996. Soil Survey Laboratory Method Manual. Soil Survey Investigation. Report No. 42, Version 3.0, National Resources Conservation Service, United States Department of Agriculture.

Nelson, D.W. and L.E. Sommers. 1996. Total carbon, organic carbon, and organic matter, pp. 961-1010. *In* D.L. Sparks *et al.,* eds., Methods of Soil Analysis, Part 3. Chemical Methods. Agronomy No. 5. SSSA Book Series., Madison, WI.

Ojima, D.S., K.A. Galvin and B.L. Turner. 1994. The global impact of land-use change. BioScience 44: 300-304.

Peech, M. 1945. Determinations of exchangeable cations and exchange capacity of soils-rapid micromethods utilizing centrifuge and spectrophotometer. Soil Sci. 59: 25-28.

Pinthong, J., T. Kunaporn, T. Klodpeng, N. Anongrak, A. Ramlee and S. Tuntikiat. 1994**.** Vetiver Grass as Hedges Against Soil Erosion in the Shifting Cultivation Area of Northern Thailand. Final Report Submitted to Forestry Research Support Programme for Asia and Pacific.

Samrit, B., I. Kheoruenromne, A. Suddhiprakarn. 2007. Properties and agricultural potential of highland soils in Khao Kho area, Phetchabun Province. The 33rd Congress on Science and Technology of Thailand. Science and Technology for Global Sustainability. Walailuk University, Nakhon Si Thammarat, Thailand.

Samrit, B., 2008. Characteristics and Fertility Capability of Highland Soils in Khao Kho Area, Phetchabun Province. M.S. Thesis, Kasetsart University. (in Thai).

Sanchez, P.A. 1976. Properties and Managementof Soils in the Tropic. John Wiley and Sons, Inc., New York.

Sanchez, P.A., W. Couto and S.W. Buol. 1982. The fertility capability soil classification system; interpretation, applicability and modification. Geoderma 27: 283-309.

Saunders, D.A., R.J. Hobbs and C.R. Margules. 1991. Biological consequences of ecosystem fragmentation: a review. Conservation Biology 5: 18-32.

Scholten, J.J. and W. Andriesse. 1986. Morphology, genesis and classification of three soils over limestone, Jamica. Geoderma 39: 1-40.

Siebert, S.F. 1987. Land use intensification in tropical uplands: effects on vegetation, soil fertility and erosion. Forest Ecology and Management 21: 37-56.

Solomon, D., J. Lehmann, T. Mamo, F. Fritzsche and W. Zech. 2002. Phosphorus forms and dynamics as influenced by land use changes in the sub-humid Ethiopian highlands. Geoderma 105: 21-48.

Soil Survey Division Staff. 1993. Soil Survey Manual. Handbook No. 18. United States Dept. of Agr., United States Government Printing Office, Washington, D.C.

Soil Survey Staff. 2006. Key to Soil Taxonomy. 10th ed. Natural Resources Conservation Service. United States Department of Agriculture, Washington, D.C.

Srisuk, P. 1998. Characteristics of Highland Soils in Mae Taeng Watershed, Chiang Mai. M.S. Thesis, Kasetsart University. (in Thai).

Stoorvogel, J.J., E.M.A. Smaling and B.H. Janssen. 1993. Calculating soil nutrient balances in Africa at different scales: II. District scale. Fert. Res. 35: 227-235.

Thomus, G.W. 1987. Exchange cations, pp. 159-161. *In* C.A. Black, ed., Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties, 2nd ed. Amer. Soc. of Agron. Inc., Madison, Wisconsin.

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.

Uehara, G. and G. Gillman. 1981. The Mineralogy, Chemistry and Physics of Tropical Soils with Variable Charge Clay. Westview Press, Inc., Colorado.

West, L.T. and F.H. Beinroth. 2000. Ultisols, pp. 358-372, *In* Wilding, L.P., ed., Handbook of Soil Science, Vol. E. CRC Press, Boca, Raton, London, New York, Washington, DC.

Whittig, L.D. and W.R. Allardice. 1986. X-ray diffraction technique, pp. 671-698. *In* A. Kulte et al., eds., Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods, 2nd ed. Agronomy, No. 9. Amer. Soc. Agron. Inc., Madison, WI.

Yamoah, C.F., J.R. Burleigh and M.R. Malcolm. 1999. Application of expert systems to study of acid soils in Rwanda. Agriculture, Ecosystems and Environment 30: 203-218.

Manuscript received 23 September 2008, accepted 30 November 2008