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ECOLOGY

Characteristics and pedogenesis of podzolic forest soils along a toposequence near a subalpine lake in northern Taiwan

Shih-Hao JIEN[1], Sen-Po WU[2], Zueng-Sang CHEN[3], Tsai-Huei CHEN[4], and Chih-Yu CHIU[1,*]

[1]*Biodiversity Research Center, Academia Sinica, Taipei 11529, Taiwan*
[2]*Science and Technology Policy Research and Information Center, National Applied Research Laboratories, Taipei 10622, Taiwan*
[3]*Department of Agricultural Chemistry, National Taiwan University, Taipei 10617, Taiwan*
[4]*Taiwan Forestry Research Institute, Taipei 10066, Taiwan*

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ABSTRACT. Podzolic soils are commonly found under cypress forests in the subalpine region of northern Taiwan where the climatic conditions are cold and humid. Toposequential change from summit to lake shore along a subalpine lake (Lake Jialo) was selected to evaluate the influence of high soil moisture conditions on vegetation and pedogenic processes, and to clarify the mechanism of podzolization. Along this toposequence, the podzolization process occurs at all landscape sites except for the one at the lakeshore. Organically-complexed Fe and Al are the dominant forms in the Bs horizons at summit and footslope sites. The fulvic acids complex Fe and Al and translocate the latter downwards into the Bs horizons. The placic horizon in soils at the footslope is dominated by amorphous Fe oxides. Formation of placic horizons is mainly attributed to perched water, which is caused by heavy rainfall and seasonally high lake water level between the AE and Bs horizons. This situation causes Fe reduction and translocation to lower parts of the soil profile, resulting in formation of a placic horizon between E and Bs horizons. The soils towards the lakeshore are characterized by increasing dominance of hydromorphic process over podzolization. However, although the podzolization process occurs, the studied soils cannot be classified as Spodosols. High clay and crystalline Fe oxide contents derived from parent materials retard the mobility of organically-complexed metal cations and thus slow down the podzolization process and formation of spodic horizons in this area.

Keywords: Fulvic acids; Placic horizon; Podzolic soils; Podzolization.

INTRODUCTION

Podzols occur mainly in cool and humid climates under forests of coniferous vegetation with medium to coarse texture (Lundström et al., 2000). The vegetation and climate conditions are critical factors to influence the formation of podzolic soils. These soils are usually found in boreal and temperate regions (Buurman and Jongmans, 2005; Sauer et al., 2007), and podzolization is a major process of soil genesis in these regions. The classical view of podzolization is that Al and Fe are released via weathering in the eluvial E horizon and translocated to the B horizon further down in the soil profile. Podzols typically have three to four major horizons, including a dark-colored, organic surface horizon (O); a bleached eluvial horizon (E); and a reddish, brownish or blackish illuvial horizon enriched in amorphous materials (Bhs), which may be differentiated into an upper Bh (primarily humus-enriched) and lower Bs (primarily sesquioxide enriched) horizon (McKeague et al., 1983). The term "podzolic soil" in this paper is applied to Podzol-like soils with a bleached eluvial horizon and Fe or Al illuviated horizons, which are not expressed well enough to be classified as Spodosols or Podzols.

Some alpine or subalpine areas of tropical and subtropical climatic regions provide similar and suitable environments for podzolization. Hence, small and specific areas with Podzols are also found in some subalpine areas of perhumid tropical and subtropical regions (Hseu et al., 2004; Sauer et al., 2007; Schawe et al., 2007). Taiwan is located in the tropics and subtropics, but cold and humid climatic conditions were prevailing in alpine and subalpine forest areas. These tropical or subtropical forest areas with altitudes higher than 1,900 m, high precipitation (≥ 3,000 mm $year^{-1}$) and dominant coniferous vegetation are suitable for the formation of Ultisols, Spodosols and podzolic soils (Chen et al., 1989, 1995; Liu et al., 1994; Li et al., 1998; Hseu et al., 1999; Liu and Chen, 2004; Wu and Chen, 2005).

*Corresponding author: E-mail: bochiu@gate.sinica.edu.tw.

Published studies on soil genesis in tropical and subtropical mountain forests suggest podzolization and hydromorphism as dominant soil forming processes (Hseu et al., 2004; Wu and Chen, 2005; Schawe et al., 2007). These soil forming processes are affected by different kinds of vegetation, composition of soil organic matter, clay contents, crystalline Fe oxides and different moisture regimes (Wang et al., 1989; Liu and Chen, 1991; Kaiser and Zech, 2000; Lundström et al., 2000; Stutter et al., 2007). Álvarez Arteaga et al. (2008) found Podzol-like soils in montane cloud forests in tropical areas, which resulted from intensive weathering and leaching, spodic material formation, and gleyzation processes, even in heavy-textured soils and hydromorphic soils, but these soils were not typically Spodosols or Podzols. They also indicated that the pedogenesis of Podzols in montane cloud forests is not very stable and might be altered easily by slight modification of soil forming factors. Spodosols or podzolic soils with heavy texture are found in the alpine and subalpine forest regions of central and northern Taiwan (Chen et al., 1989; 1995; Li et al., 1998). Liu and Chen (1991) suggested that the high clay contents in alpine forest regions in central Taiwan slow down the podzolization process because of poor drainage and low mobility of organic matter in soil pedons.

In addition to podzolic soils, soils with placic horizons are found in subalpine forest regions with perhumid climate. A placic horizon is relatively impermeable to water and plant roots. It occurs in some Spodosols as a thin, wavy or convoluted horizon that may transgress several subhorizons (McKeague et al., 1968). In some regions, it occurs within or immediately below the albic E horizon (Soil Survey Staff, 1975). Placic horizons are usually associated with perudic to aquic soil moisture regimes in coastal regions (McKeague et al., 1983). However, in subalpine areas with perhumid conditions in Taiwan Inceptisols with placic horizons are found that result from perched water (Hseu et al., 1999; 2004; Wu and Chen, 2005). Furthermore, the parent materials of the subalpine forest areas of Taiwan are mainly shale and slate, which are easily weathered to a finer soil texture. The fine-textured soils imply that water slowly flows into or out of the soil body and leads to alternation of reduced and oxidized conditions, which is one of the important factors for the genesis of placic horizons in Taiwan (Clayden et al., 1990; Hseu et al., 1999, 2004; Wu and Chen, 2005). The genesis of placic horizons is quite different from the podzolization process (Conry et al., 1996; Hseu et al., 1999). Spodic horizons feature the processes of accumulation of organic carbon, aluminum, with or without Fe, according to the USDA Soil Taxonomy (Soil Survey Staff, 1999).

Recently, the translocation of different extractable Fe, Al and Mn has been studied in alpine or subalpine Spodosols or podzolic soils in subtropical areas (Chen et al., 1989, 1995; Li et al., 1998; Hseu et al., 1999, 2004; Liu and Chen, 2004; Wu and Chen, 2005), but little information is available on associated soils near subalpine lakes and the effects of fluctuating water levels of the lake. In addition, there are no reports on the influence of different fractions of soil organic matter, which would enable understanding the translocation of metal cations in podzolic soils in these alpine and subalpine forests. Therefore, we aim to evaluate the pedogenic processes and podzolization process in podzolic soils along a toposequence near a subalpine lake, and to evaluate the influence of soil forming factors on podzolization process in these soils.

MATERIALS AND METHOIDS

Soils and environmental conditions

Taiwan is located in the tropics and subtropics, but the climate is cold and humid in the alpine and subalpine forest regions of the island's Central Ridge. The study was conducted in the Jialo Lake area (about 24°28′26″ N, 121°28′42″ E) on Jialo Mountain in northeastern Taiwan (Figure 1). Jialo Mountain belongs to the physiographic region of the Central Ridge in Taiwan. This mountain was formed by tectonic uplift during Miocene and is mainly composed of sandstone, shale and slate (Ho, 1986). At least 18 lakes are distributed in this subalpine region. In the typhoon season, the lakes increase in size, and several small lakes may combine into a few large lakes. The origin of these small lakes is not clear so far. They might be Pleistocene glacial geomorphological features (Cui et al., 2002; Hebenstreit e al., 2006; Carcaillet et al., 2007). Jialo Lake, the largest lake among these subalpine lakes, about 300 m long and 150 m wide, is close to the study area. The elevations of the studied sites from lakeshore to summit are about 2,250-2,300 m above sea level, the mean annual air temperature is 10°C and total annual precipitation is 3,200 mm. The high rainfall in the typhoon season (from July to November) can result in a periodic fluctuation of the lake water level between the footslope and lakeshore sites in the study area. Forests of Taiwan false cypress (*Chamaecyparis formosensis* Matsum) and willow fir (*Cryptomeria japonica* Hassk.) are dominant in the upper parts of the slope and extend to the lower boundary of forest at the footslope site; bushes of yushan cane (*Yushania niitakayamensis*) cover the lower part of the slope, which is the upper line of the lake water level of inundation in the rainy season. Grassland dominated by silver grass (*Miscanthus transmorrisonensis* Hayata) forms the vegetation at the toeslope, followed by aquatic plants (*Schoenoplectus mucronatus*) at the lakeshore and swamp regions. The slope ranges from 0 to 5% on the summit, 5 to 10% at the footslope, and 10 to 15% at the toeslope and in the lakeshore area.

Four soil pedons with clayey texture were selected along the topography from the summit to the lakeshore of Jialo Lake (Figure 1). In each site, a pit was excavated for morphological feature description as well as collection of soil samples according to standard procedures (Soil

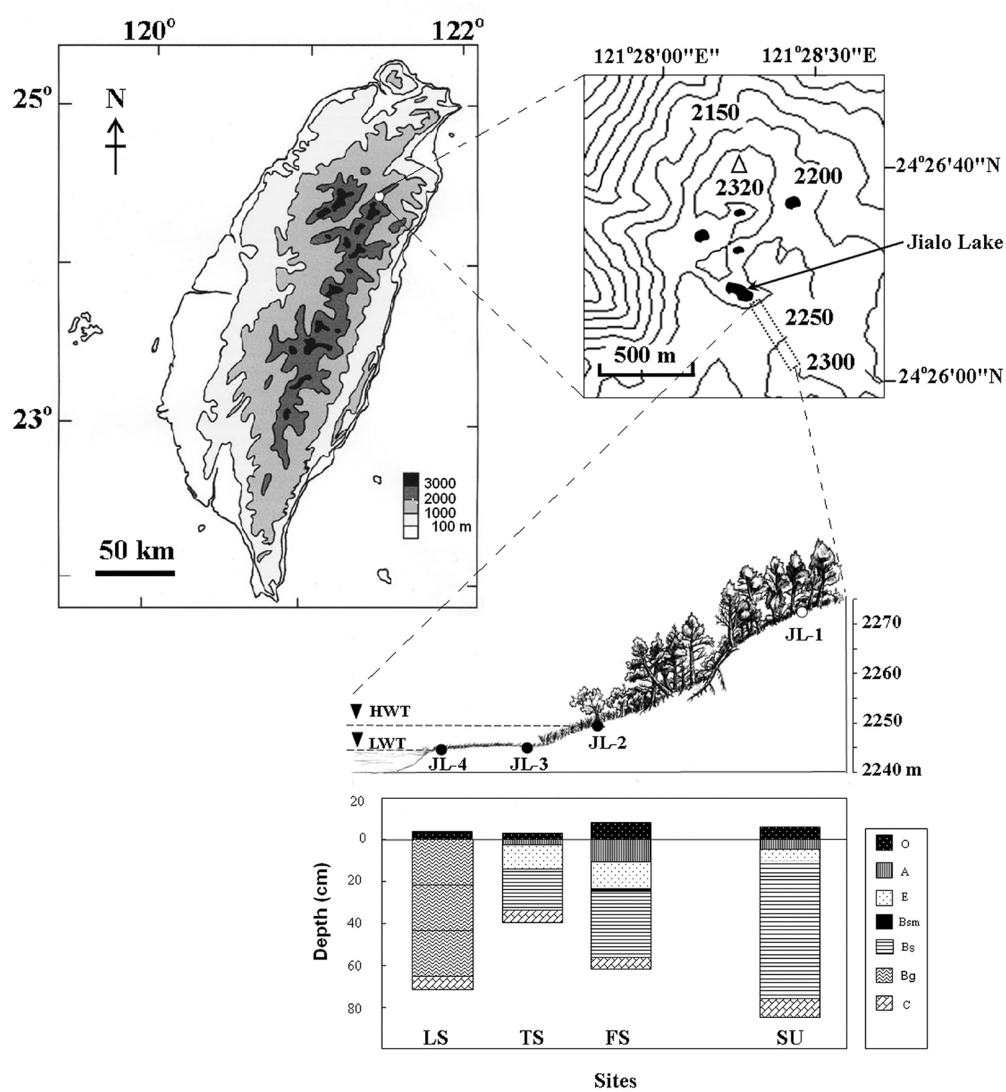

Figure 1. The location of the study area and the four pedons along the toposequence near Jialo Lake in northeastern Taiwan. (LS: lakeshore; TS: toeslope; FS: footslope; SU: summit; HWT: high water table of lake; LWT: low water table of lake).

Survey Staff, 1993). Soil pedons were classified according to the USDA Soil Taxonomy (Soil Survey Staff, 2006) and the World Reference Base for Soil Resources (WRB; IUSS Working Group WRB, 2006).

Laboratory analysis

Soil samples were collected from each horizon of the four pedons for physical and chemical analysis. Soil samples were air dried and ground to pass through a 2-mm sieve. Particle size distribution was determined by the pipette method (Gee and Bauder, 1986). Soil pH was determined at a ratio of soil to water of 1:2.5 (McLean, 1982). Total organic carbon contents were measured by use of a Fisons NA1500 elemental analyzer. Cation exchange capacity (CEC) and exchangeable bases were measured by use of the ammonium acetate method (Thomas, 1982) and elemental analysis by atomic absorption spectrometry (AAS). The dithionite-citrate-bicarbonate method (DCB method) was performed to determine the contents of free Fe and Al oxides (Fe_d and Al_d) (Mehra and Jackson, 1960). The amorphous Fe and Al oxides (Fe_o and Al_o) were estimated by ammonium oxalate (pH 3.0) (McKeague and Day, 1966), and organic Fe and Al compounds (Fe_p and Al_p) were estimated by sodium pyrophosphate (pH 10) (Loveland and Digby, 1984). Fe and Al were analyzed in all extracts by AAS. Calculation of the amounts of crystalline Fe oxide is based on the difference between DCB-extractable Fe and oxalate-extractable Fe (Fe_d-Fe_o).

The fraction of water soluble organic carbon (WSOC) was extracted three times by use of sequential Millipore Milli-Q H_2O at a soil:water ratio of 1:10 and then shaken at 200 rpm for 16 h at room temperature. The extract was decanted and centrifuged at 10,000 × *g* for 30 min, and the supernatant was filtered through Whatman No. 42 filter paper (Candler et al., 1989). The fulvic acids (FAs) and humic acids (HAs) were extracted with 0.1 M NaOH (using a soil:extractant ratio of 1:20) under N_2 at room temperature for 16 h (Tan, 1985). The alkaline supernatant was separated from the residue by centrifugation (Backman J2-21) at 15,334 × *g* for 20 min, then acidified with 6 M HCl to pH 1 and allowed to stand at room temperature for 24 h. The supernatant (FAs) was separated from the coagulated material (HAs) by centrifugation at 8,000 × *g* for 15 min. The HA fraction was then purified by use of a 0.1M HCl - 0.3M HF mixture (about 50 ml), then the residue was washed thoroughly with distilled water and re-dissolved with 0.1 M NaOH. Each extracted fraction was analyzed for total organic C (O.I. Analytical 1010) by the heat-persulfate oxidation method.

RESULTS AND DISCUSSION

Soil morphological characteristics

Morphological features of the four soil pedons are summarized in Table 1. Pedon JL-1, located on the summit, exhibited a O-A-AE-Bs1-Bs2-BC horizon sequence. A moderately fine granular structure was found in the A horizon. The AE horizon (2-12 cm) with massive structure revealed stagnic conditions. Redoximorphic features (7.5YR 6/8 and 10 YR 7/1 mottles) were also found in the upper part of the Bs1 horizon (12-40 cm), which indicated that perched water regularly occurs in the AE and Bs1 horizons, and reduced conditions probably persist for a long time here. The poor drainage of this pedon was attributed to the fine texture of the AE horizon and texture change between the AE and Bs1 horizons. As this site is located above the influence of lake water, the redoximorphic features could be dominantly attributed to perched water caused by heavy rainfall.

Pedon JL-2 at the footslope exhibited a O-A-AE-Bsm-Bs1-Bs2 horizon sequence. Similar to JL-1 pedon, the stagnic colour pattern of the AE horizon in JL-2 pedon is evidence of long-term reducing conditions. A distinctive placic horizon (Bsm) with an abrupt wavy upper boundary and a clear wavy lower boundary having a soil color of 2.5YR 4/6 was found in this pedon. This placic horizon fulfilled the color requirements of a spodic horizon; however, it was only 3 mm thick and was thus too thin to be classified as a spodic horizon (Table 1). Hseu et al. (1999) found similar conditions in an Inceptisol with a placic horizon in a subalpine forests in northern Taiwan. In JL-2 pedon, surprisingly, redoximorphic features were found in the Bs1 and Bs2 horizons below the placic horizon (Table 1). Such features are unlikely in the Bs horizons beneath the placic horizon because the placic horizon is too hard to be penetrated by roots and percolating water. An explanation for these redoximorphic features could be the periodical fluctuating water level of Jialo Lake, with a high water level in the typhoon season. The inundation caused by high lake water level in JL-2 pedon may also contribute to the formation of the placic horizon, because it prolongs the period of reducing conditions in the surface soil in JL-2 pedon, compared to JL-1 pedon. Similar results were found by Harris et al. (1995; 2000) who proposed that destabilization of Fe was facilitated by fluctuating water table in sandy soils.

Pedon JL-3 exhibited an O-A-BE-Bs-BC horizon sequence with a shallow solum depth at the toeslope. The O and A horizons were thinner than those in JL-1 and JL-2 pedons and could be mainly attributed to differences in vegetation between these pedons. Seasonal inundation and vigorous fluctuating lake water level hamper plant growth. In addition, a warm period in summer, prior to the typhoon season, enhances the decomposition of soil organic matter in this grassland, which results in low soil organic matter content at this seasonally inundated site. In this pedon, no eluvial process was observed; the color of the BE horizon was 10YR 6/3 with 7.5 YR 5/6 mottles, which were identified as redoximorphic features. Minor eluviation from the thin O and A horizons in this site seems possible. In addition, lateral illuviation from the JL-2 pedon may be a major process in this pedon, because high contents of Fe_d were found in the illuvial horizons, but the eluvial horizon was unapparent. Lateral podzolization was also observed by Sommer et al. (2001) who studied Spodosols in a topography with 30% slope in the Black Forest of Germany. Common redoximorphic features in BE and Bs horizons were caused by perched water, caused by heavy rainfall and/or seasonal inundation by lake water.

Pedon of JL-4, located at the lakeshore site, exhibited an O-Bg1-Bg2-Bg3-BC horizon sequence. Depletion colours (chroma ≤ 2) were dominant in all horizons, suggesting that long-term reducing conditions prevailed at this site. Both the grey color and massive structure were enhanced by the long-term reducing conditions, which resulted from permanent saturation with lake water.

Redoximorphic features were found in all studied pedons. The JL-1, JL-2 and JL-3 pedons exhibited these features in the surface soils, eluvial horizons and upper parts of illuvial horizons. Oxidized soil colors in the lower parts of the illuvial horizons, indicated that these features were caused by perched water. However, the influence of seasonal lake water level was inevitable at JL-2 and JL-3 pedons. The seasonal inundation by lake water also caused the perched water in these two pedons. Different from JL-1, JL-2 and JL-3 pedons, grey, reductive colors, prevailed in the JL-4 pedon, indicating endoaquic conditions, caused by persistent inundation of lake water.

Physical and chemical characteristics

The soil physical and chemical properties of the selected pedons are shown in Table 2. Since parent materials predominantly consist of shale and slate, the studied soils are clayey textured with clay contents ranging from 35 to 50%.

In JL-1 pedon, low pH values (≤ 4.0) in the A and AE horizons were due to 10- to 15-fold higher amounts of soil organic matter, compared to the Bs horizons. The surface soils were acidified by organic acids produced from organic matter. The distribution of CEC was consistent

Table 1. Morphological characteristics of four studied soil pedons.

Horizon	Depth (cm)	Munsell color	Redoximorphic feature	Texture[a]	Structure[b]	Consistence[c]	Roots[d]	Boundary[e]
JL-1								
O	3-0	7.5YR 2.5/2	-	-	-	-	mvf&f	gw
A	0-2	7.5YR 3/2	-	SiC	2gr, 2vf&fabk	ns&np	mvf&f, sm	ci
AE	2-10	7.5YR 6/1	7.5YR 5/2 (25%)[f]	SiCL	Massive	ss&sp	mvf&f, fm, sc	ci
Bs1	10-40	10YR 5/8	10YR 7/1 (5%) 7.5YR 6/8 (2%)	SiC	3vf&fabk	s&p	fvf&f, fm	d
Bs2	40-70	10YR 5/8		SiC	3vf&fabk	s&p	fvf&f&m, sc	d
BC	>70	-		-	-	-	-	-
JL-2								
O	5-0	7.5YR 2.5/2	-	-	-	-	mvf&f&m, sc	gw
A	0-12	7.5YR 3/2	-	SiC	2gr, 2vf&fabk	ns&np	mvf&f&m	cw
AE	12-25	7.5YR 6/1	7.5YR 4/2 (50%)	SiCL	massive	ss&sp	fvf&f	aw
Bsm	25-25.3	2.5YR 4/6		SCL	platy	-	-	cw
Bs1	25.3-35	10YR 6/8	7.5YR 5/8 (10%) 7.5YR 8/1 (5%)	SiC	3vf&fabk	s&p	fvf&f	gs
Bs2	35-50	10YR 6/8	7.5YR 6/8 (5%)	SiC	3vf&fabk	s&p	fvf&f	d
BC	>50	-	-	-	-	-		-
JL-3								
O	2-0	7.5YR 2.5/2	-	-	-	-	mvf&f	gs
A	0-2	10YR 3/2	-	SiC	1gr	ns&np	mvf&f	cs
BE	2-15	10YR 6/3	7.5YR 5/6 (5%)	SiC	Massive	ss&sp	fvf&f	cs
Bs	15-30	10YR 6/6	7.5YR 5/6 (10%)	SiCL	2vf&fabk	sfm, ss&sp	fvf&f	d
BC	>30	-	-	-	-	-	-	-
JL-4								
O	0-2	7.5YR 3/2	-	-	-	-	-	as
Bg1	2-20	2.5Y 5/2	-	SiCL	Massive	ss&sp	-	d
Bg2	20-40	2.5Y 5/2	-	SiCL	Massive	ss&sp	-	d
Bg3	40-60	2.5Y 5/2	-	SiC	Massive	ss&sp	-	-
BC	>60	-	-	-	-	-	-	-

[a]SiCL=silty clay loam, SiL=silt loam, C=clay, SiC=silty clay.
[b]1=weak, 2=moderate, vf=very fine, f=fine, m=medium, gr=granular, abk=angular blocky, sbk=subangular blocky.
[c]fm=firm, fri=friable, s=sticky, p=plastic, np=non-plastic, ss=slightly sticky, sp=slightly plastic.
[d]c=common, m=many, f=few, c=coarse, m=medium, f=fine, vf=very fine.
[e]a=abrupt, c=clear, s=smooth, g=gradual, d=diffuse, w=wavy, i=irregular.
[f]The value in parentheses is amounts of redoximorphic features.

with organic carbon contents in this pedon, and these values all decreased with depth. Low base saturation (≤ 5%) and extreme acidity probably resulted from heavy rainfall (≥ 3,000 mm per year) in this subalpine area.

In JL-2 pedon, the soil texture was silty clay loam in the horizons above the placic horizon, but the horizons immediately underlying the placic horizon showed finer soil texture (silty clay). Clay contents clearly increased from the AE to the Bs horizons, but clay skins were not found. The clay contents were mainly derived from weathering of parent materials rather then from clay translocation. The O, A and AE horizons of JL-2 pedon have lower pH values (≤ 3.60) than the Bs horizons (≥ 4.30) (Table 2), which may provide a suitable environment for the formation of a placic horizon (Clayden et al., 1990; Lapen and Wang, 1999; Wu and Chen, 2005). In this pedon, the placic horizon has the highest pH value (5.09), compared to all other horizons, which is consistent with previous reports that placic horizons are related to the precipitation of Fe or Mn under oxidizing conditions and high soil pH (Lapen and Wang, 1999; Wu and Chen, 2005). Similar to JL-1 pedon, JL-2 pedon showed low base saturation, probably due to extremely high rainfall. In addition, it is assumed that lateral leaching took place from JL-2 pedon downwards along the toposequence. The data suggest that cations were leached from the JL-2 pedon and then accumulated at the lowest site (JL-4) so that higher pH values were found at the JL-4 pedon, compared to those at other soil pedons.

Except for soil organic matter contents, JL-3 pedon showed a trend in chemical characteristics similar to that of JL-1 and JL-2 pedons. The total contents of soil organic matter in the surface soil in JL-3 pedon were significantly lower than those in JL-1 and JL-2 pedons. It was assumed that this difference was caused by the down slope change of vegetation, and limited plant growth due to seasonal inundation at this site.

Pedon JL-4, influenced by long-term aquic conditions, showed characteristics different from the other soil pedons. Soil horizons showed no significant differences in pH value. The pH values in all horizons were higher than 4.6. In comparison with other soils, slightly higher soil pH in surface soils in this pedon was ascribed to prevailing reduced conditions, because reduction processes consume protons and lead to pH increase. In addition, lateral leaching probably took place in this toposequence, and led to pH increase at the lowest site. The JL-4 pedon received the bases that had been leached from upslope through the lateral pathway, which resulted in slightly higher pH in this pedon, compared to the other pedons. However, pedon JL-4 has still rather low pH values (4.62-4.78). It is assumed that bases can be laterally leached into the lake during times of low lake level, so that pedon JL-4 is also gradually acidified with time.

A low degree of humification and accumulation of soil organic matter was observed in this inundation site, which corresponds well to results of Chen et al. (2000) who studied soils nearby a subalpine lake in Taiwan. CEC showed a similar trend as OC content. Base saturation was also low at this site.

Distribution and translocation of extractable Fe and Al in soil pedons

The extractable Fe and Al contents in all studied pedons are summarized in Table 3. The distribution of different forms of Fe with depth indicated that large amounts of Fe were eluviated from the A/E horizons and accumulated in underlying Bs horizons and placic horizons. The maximum accumulation of DCB-, oxalate- and pyrophosphate-

Table 2. The physical and chemical properties of four studied soil pedons.

Horizon	Depth (cm)	Total %			Texture	pH (H_2O)	OC[a] %	CEC[b] cmol(+)kg^{-1}	BS[c] %
		Clay	Silt	Sand					
JL-1									
O	3-0	-[d]	-	-	-	3.41	46.7	124	4.18
A	0-2	42.8	55.5	1.70	SiC	3.82	32.7	65.8	3.13
AE	2-10	36.6	62.1	1.30	SiCL	4.05	3.91	17.0	2.11
Bs1	10-40	46.3	50.9	2.80	SiC	4.60	2.54	23.4	0.71
Bs2	40-70	49.6	47.1	3.20	SiC	4.89	2.42	18.9	0.77
JL-2									
O	5-0	-	-	-	-	3.61	24.3	51.4	5.72
A	0-12	44.9	52.7	2.40	SiC	3.58	28.8	67.0	2.33
AE	12-25	38.1	58.9	3.00	SiCL	3.91	5.65	23.0	1.42
Bsm	25-25.3	-	-	-	SCL	5.09	3.86	42.1	0.73
Bs1	25.3-35	46.9	50.2	2.80	SiC	4.36	1.99	18.9	0.88
Bs2	35-50	44.4	46.0	9.70	SiC	4.65	2.19	18.3	0.64
JL-3									
O	2-0	-	-	-	-	3.62	20.8	43.8	3.30
A	0-2	42.7	53.3	4.00	SiC	3.80	26.9	42.8	2.33
BE	2-15	46.1	50.9	3.10	SiC	4.81	2.87	17.3	1.48
Bs	15-30	38.6	50.3	11.1	SiCL	4.64	2.24	14.8	0.83
JL-4									
O	0-2	-	-	-	-	4.62	32.1	85.3	11.0
Bg1	2-20	35.7	60.4	3.90	SiCL	4.65	4.22	13.8	2.36
Bg2	20-40	38.8	58.1	3.10	SiCL	4.71	3.89	14.1	3.95
Bg3	40-60	41.2	54.6	4.10	SiC	4.78	3.64	14.3	3.64

[a]Organic carbon; [b]Cation exchange capacity; [c]Base saturation percentage; [d]Not determined.

Table 3. The selected extractable Fe and Al of four studied soil pedons.

Horizon	Depth (cm)	Dithionite (g kg^{-1})		Oxalate (g kg^{-1})		Pyrophosphate (g kg^{-1})		Al_o+1/2Fe_o (%)	Fe_o/Fe_d	Fe_p/Fe_d	Fe_p/Fe_o	Al_o/Al_d	Al_p/Al_d	Al_p/Al_o	Fe_d-Fe_o	(Fe_p+Al_p)/(Fe_d+Al_d)
		Fed	Ald	Feo	Alo	Fep	Alp									
JL-1																
O	3-0	1.50	1.10	0.80	1.10	0.30	0.50	0.15	0.53	0.20	0.38	1.00	0.45	0.45	0.70	0.31
A	0-2	4.90	2.20	2.40	2.10	2.10	1.10	0.33	0.49	0.43	0.88	0.95	0.50	0.52	2.50	0.45
AE	2-10	11.9	1.30	3.80	1.80	2.60	0.60	0.36	0.32	0.22	0.68	1.38	0.46	0.33	8.10	0.24
Bs1	10-40	59.3	7.40	27.4	5.60	30.7	3.10	1.93	0.46	0.52	1.12	0.76	0.42	0.55	31.9	0.51
Bs2	40-70	52.3	9.50	27.2	5.70	27.9	3.70	1.93	0.52	0.53	1.03	0.60	0.39	0.65	25.1	0.51
JL-2																
O	5-0	17.3	2.00	10.4	1.90	9.00	0.80	0.72	0.60	0.52	0.87	0.95	0.40	0.42	6.90	0.51
A	0-12	10.3	3.60	7.90	2.60	7.10	1.70	0.66	0.77	0.69	0.90	0.72	0.47	0.65	2.40	0.63
AE	12-25	12.1	1.70	8.40	1.50	6.10	0.90	0.57	0.69	0.50	0.73	0.88	0.53	0.60	3.70	0.51
Bsm	25-25.3	167	10.9	111	5.20	23.9	3.60	6.09	0.66	0.14	0.22	0.48	0.33	0.64	56.0	0.15
Bs1	25.3-35	57.1	4.60	22.0	2.20	16.1	1.40	1.31	0.39	0.28	0.73	0.48	0.30	0.69	35.1	0.28
Bs2	35-50	45.2	7.50	20.5	3.40	19.9	2.40	1.36	0.45	0.44	0.97	0.45	0.32	0.71	24.7	0.42
JL-3																
O	2-0	2.90	4.20	1.80	3.70	1.70	1.20	0.46	0.62	0.59	0.94	0.88	0.29	0.32	1.10	0.41
A	0-2	2.90	4.30	1.70	3.00	1.60	2.40	0.38	0.59	0.55	0.94	0.70	0.56	0.80	1.20	0.56
BE	2-15	9.90	2.30	4.70	2.10	2.80	1.50	0.44	0.47	0.28	0.60	0.91	0.65	0.71	5.20	0.35
Bs	15-30	75.8	5.90	20.2	2.60	9.40	3.60	1.27	0.27	0.12	0.47	0.44	0.61	1.38	55.6	0.16
JL-4																
O	0-2	8.80	3.90	7.50	1.80	6.30	1.60	0.56	0.85	0.72	0.84	0.46	0.41	0.89	1.30	0.62
Bg1	2-20	6.80	4.20	3.80	1.90	2.50	1.00	0.38	0.56	0.37	0.66	0.45	0.24	0.53	3.00	0.32
Bg2	20-40	7.60	3.90	4.20	1.60	2.90	1.40	0.37	0.55	0.38	0.69	0.41	0.36	0.88	3.40	0.37
Bg3	40-60	7.40	3.60	4.00	1.50	3.00	1.50	0.35	0.54	0.41	0.75	0.42	0.42	1.00	3.40	0.41

Subscripted d, o, and p are dithionite-citrate-bicarbonate, oxalate and pyrophosphate extractable.

extractable Fe (Fe_d, Fe_o, and Fe_p) and Al (Al_d, Al_o, and Al_p) was found in the Bs horizon of JL-1 pedon and in the placic horizon of JL-2 pedon. A similar trend of all extractable Fe forms was also found in the Bs horizon of JL-3 pedon. Additionally, DCB-extractable Al (Al_d) and pyrophosphate-extractable Al (Al_p) were accumulated in the Bs horizon in JL-3 pedon. Overall, the distribution of extractable Al forms was similar to extractable Fe forms, but the amounts of these Al forms were much lower than those of Fe in all studied soil pedons.

Albic characteristics of the E horizon and high contents of all extractable Fe and Al forms in the Bs1 and Bs2 horizons suggested eluviation and illuviation processes in JL-1 pedon. High ratio of Fe_p/Fe_d (≥ 0.50) in the Bs horizons indicated that more than half of the amounts of extractable Fe were organically-complexed Fe forms. In addition, the ratio of pyrophosphate-extractable Fe (Fe_p) and Al (Al_p) to oxalate-extractable Fe (Fe_o) and Al (Al_o) can be used to indicate the proportion of organically-complexed Fe or Al in amorphous Fe or Al translocated from surface soils (Child et al., 1983). High ratios of Fe_p/Fe_o (≥ 1.00) and Al_p/Al_o (≥ 0.55) in the Bs horizons of the studied soils indicated that most of the non-crystalline Fe and Al was present in organically-complexed forms, suggesting that most of the organically-complexed Fe and Al was formed in surface soils, and then translocated downwards into the lower parts of the pedons. Similar phenomena in clayey soils were also found in Ultic Spodosols in Oregon (Bockheim et al., 1996) and in subtropical subalpine forests in central Taiwan (Hseu et al., 2004). Additionally, the ratio of $(Fe_p+Al_p)/(Fe_d+Al_d)$, which can be used as a criteria for podzolization, was higher than 0.50 in the Bs horizons with medium contents of crystalline Fe oxides (Fe_d-Fe_o = 25-30 g kg^{-1}) in JL-1 pedon, as suggested by Wang et al. (1989). This further supports that podzolization has taken place in this clayey soil pedon.

Similar accumulation trends of all extractable Fe and Al forms were found in the Bs horizons of JL-2 pedon. The organically-complexed Fe and Al compounds were predominant among all extractable Fe and Al forms in the Bs horizons in this pedon ($Fe_p/Fe_o \geq 0.70$; $Al_p/Al_o \geq 0.69$) (Table 3). However, the contents of organically-complexed Fe and Al and the ratio of $(Fe_p+Al_p)/(Fe_d+Al_d)$ in the Bs horizons of JL-2 pedon were lower than those of the Bs horizons in the JL-1 pedon, indicating that the illuviation process was less expressed than in the JL-1 pedon. A possible explanation may be that the illuviation of organically-complexed Fe and Al compounds into the lower parts of the soil was progressively retarded by the formation of the placic horizon in this pedon. In the placic horizon of JL-2 pedon, amorphous Fe oxides were the predominant form (Fe_o/Fe_d = 0.66). This value is similar to the values of placic horizons in other soils described in the literature, which ranged from 0.60 to 0.80 (McKeague et al., 1967; De Coninck, 1980; Righi et al., 1982; Hseu et al., 1999; Wu and Chen, 2005). These results imply that different genetic processes occur in the Bs horizons of JL-1 pedon and the placic horizon of JL-2 pedon.

Unlike the organically-complexed Fe of the Bs horizons in JL-1 and JL-2 pedons, the well-crystallized Fe oxides are the predominant forms in the Bs horizon in JL-3 pedon ($(Fe_d$-$Fe_o)/Fe_d$ = 0.73), whereas the activity of Fe is low in this horizon ($Fe_o/Fe_d \leq 0.27$). On the other hand, high ratios of Al_p/Al_d (0.61) and Al_p/Al_o (1.38) were found in the Bs horizon in JL-3 pedon, indicating that illuviation of organically-complexed Al still occurred in this pedon. However, the weakly expressed eluvial horizon (BE horizon) and significantly lower contents of organically-complexed Fe in the Bs horizon, compared to those in Bs horizons of JL-1 and JL-2 pedons, indicated a relatively slower podzolization process at this site than that at the upper slope sites.

JL-4 pedon is the wettest soil pedon in this study. Extractable Fe and Al contents were low in all horizons, with no trend of Fe and Al accumulation (Table 3). The A and B horizons in this pedon are depleted of Fe due to long-term inundation and prevailing reduced conditions. A matrix color with chroma ≤ 2 is associated with saturation duration of more than 50-70% of the year (West et al., 1998; Jacobs et al., 2002; Jien et al., 2004).

Distribution and translocation of different fractions of humic substances

The amounts of FAs ranged from 2.80 to 27.3 g kg^{-1} in all soil pedons. FAs showed a trend of downward leaching in all studied soil pedons except JL-4 (Figure 2a and Table 4). The FAs made up the largest fraction of organic carbon in the B horizons of the soil pedons at all sites (32.7-52.6% of total organic carbon) (Table 4). The retention of the FAs in mineral soil horizons could have resulted from high clay contents and formation of clay-organic complexes in these horizons (Schnitzer and Kodama, 1966; Schnitzer and Khan, 1972). Such mechanism is suggested by a significant positive correlation between FAs and clay contents ($r = 0.63$, $p < 0.05$) in eluviated and illuviated horizons (Table 5). It is assumed that FAs could be trapped by expanded clay minerals in the interlayer, because at pH < 5, acidic functional groups of FAs become undissociated, and the negative charge in FAs is reduced under acid conditions, which leads to higher affinity between FAs and negatively charged clay (Schnitzer and Kodama, 1966). Moreover, FAs are assumed to play a major role in complexing Fe ($r = 0.68$, $p < 0.01$) and being translocated downwards into lower parts of the soil pedons. This finding suggests that Fe has a higher affinity to form complexes with FAs than Al (MacDowell and Wod, 1984; Jansen et al., 2004). In JL-4 pedon, located at the lakeshore and under dominantly reducing conditions, FAs were mainly found in the O/A horizon and relatively few amounts (< 4 g kg^{-1}) were found in the Bg horizons. This finding is consistent with results of Kaiser and Zech (1997), who found that the amounts of dissolved organic carbon content adsorbed to clay and sesquioxides in subsoils decreased significantly under anaerobic conditions. This situation explains why the amount of FAs was relatively low in mineral soil horizons at the lakeshore site. Additionally, the poor vegetation around JL-4 pedon produces little biomass, resulting in lower amounts of FAs than under dense vegetation at the upslope sites. The importance of FAs for podzolization (translocation of Fe and Al) has been confirmed in this study, in agreement with previous studies (Schnitzer and Kodama, 1966; Schnitzer and Khan, 1972; MacDowell and Wod, 1984; Jansen et al., 2004).

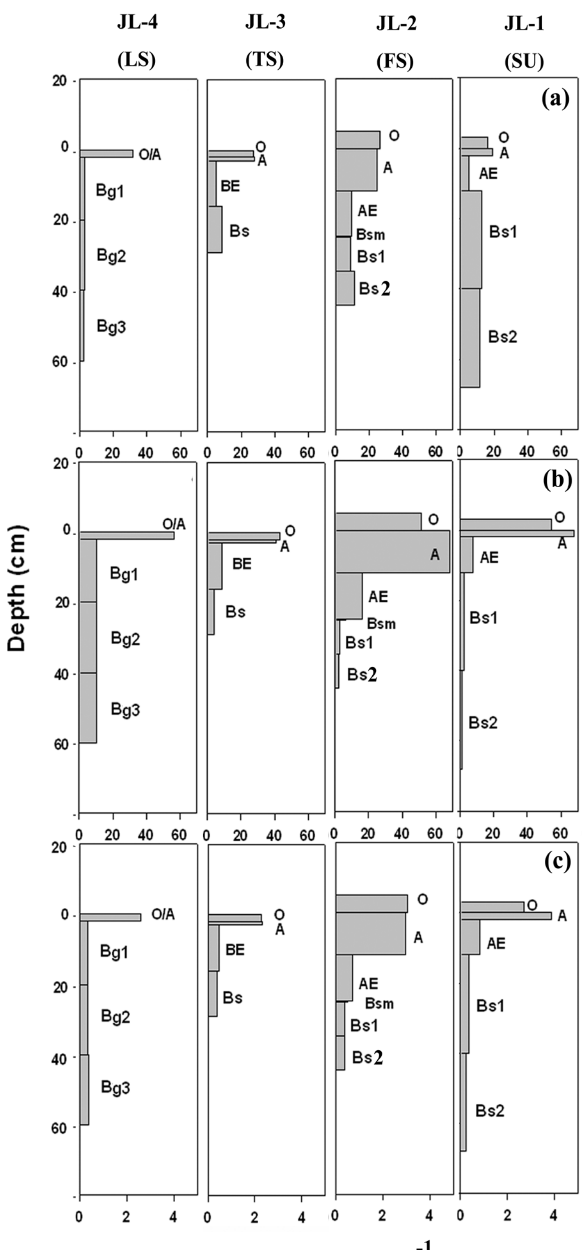

Figure 2. Distribution of C contents of different fractions of organic substances in the four pedons along a toposequence near Jialo Lake in northeastern Taiwan: (a) fulvic acids; (b) humic acids; and (c) water soluble organic C. The four sites are SU: summit; FS: footslope; TS: toeslope; LS: lakeshore.

Table 4. The percentage of different fraction of soil organic matter in total organic carbon of four studied soil pedons.

Horizon	Depth (cm)	Fraction of total organic carbon (%)			TOC[d]
		FAs[a]	HAs[b]	WSOC[c]	
JL-1					
O	3-0	3.49	11.6	0.58	46.8
A	0-2	5.89	20.6	1.17	32.8
A/E	2-10	13.3	19.6	2.07	3.91
Bs1	10-40	50.5	8.91	1.50	2.54
Bs2	40-70	47.4	4.74	0.95	2.42
JL-2					
O	5-0	11.0	21.0	1.25	24.4
A	0-12	8.65	23.6	1.03	28.8
AE	12-25	17.3	29.0	1.31	5.65
Bsm	25-25.3	8.77	16.9	1.30	3.86
Bs1	25.3-35	46.3	13.5	1.91	1.99
Bs2	35-50	52.6	9.19	1.78	2.19
JL-3					
O	2-0	13.1	20.7	1.10	20.8
A	0-2	10.3	15.3	0.86	26.9
BE	2-15	18.5	30.7	1.71	2.87
Bs	15-30	37.2	17.7	1.79	2.24
JL-4					
O	0-2	9.85	17.6	0.81	32.1
Bg1	2-20	7.67	24.6	0.85	4.22
Bg2	20-40	7.78	27.2	0.90	3.89
Bg3	40-60	7.68	27.7	1.07	3.64

[a]Fulvic acids; [b]Humic acids; [c]Water soluble organic carbon; [d]Total organic carbon.

In this study, HAs accumulated in O and A horizons of all soils (Figure 2b). In JL-1 and JL-2 pedons, which were not (JL-1) and little (JL-2) affected, respectively, by the fluctuating water level of the lake, the HAs mainly accumulated in the A horizon. HAs might be rapidly adsorbed by clay minerals in the A horizon when they are eluted by percolating water from the O horizon. In contrast, in JL-3 and JL-4 pedons, HAs were mainly found in O and O/A horizons. It is suggested that, before the summer monsoon season, when soil temperature is high and lake water level is low, soil organic matter is decomposed quickly in this position, as reflected by the low amounts of HAs and total soil organic matter in this landscape position. In JL-4 pedon, persistently saturated by lake water, soil organic matter continuously accumulates in the O horizon. Therefore, high amounts of organic matter (32.1%) were found in the surface horizon of this pedon which is considered a thin peat layer.

In comparison with total soil organic carbon, a high proportion of total organic carbon above the E horizon

Table 5. The correlation coefficient of soil properties, selected Fe and Al and different fractions of soil organic matter from eluviated and illuviated horizons in four studied pedons.

	Clay	OC[a]	Fe_d	Al_d	Fe_o	Al_o	Fe_p	Al_p	FAs[b]	HAs[c]	WSOC[d]	Al_o+1/2Fe_o	Fe_o/Fe_d	Fe_d-Fe_o
Clay	1.00													
OC	-0.61*	1.00												
Fe_d	-0.38	-0.27	1.00											
Al_d	-0.04	-0.45	0.81**	1.00										
Fe_o	-0.49	-0.07	0.96**	0.77**	1.00									
Al_o	0.15	-0.42	0.68**	0.88**	0.66*	1.00								
Fe_p	0.28	-0.51	0.66*	0.85**	0.60*	0.94**	1.00							
Al_p	0.07	-0.54	0.75**	0.89**	0.64*	0.84**	0.77**	1.00						
FAs	0.63*	-0.46	0.12	0.31	-0.03	0.51	0.68**	0.40	1.00					
HAs	-0.47	0.92**	-0.46	-0.66*	-0.29	-0.68**	-0.74**	-0.67*	-0.55*	1.00				
WSOC	-0.43	0.60*	-0.14	-0.57*	-0.07	-0.40	-0.40	-0.52	-0.14	0.54	1.00			
Al_o+1/2Fe_o	-0.44	-0.11	0.96**	0.81**	1.00	0.71**	0.66*	0.68**	0.02	-0.34	-0.10	1.00		
Fe_o/Fe_d	-0.34	0.66*	0.09	0.15	0.32	0.10	0.05	-0.07	-0.23	0.56*	0.03	0.31	1.00	
Fe_d-Fe_o	-0.16	-0.52	0.90**	0.73**	0.73**	0.61*	0.64*	0.80**	0.32	-0.64*	-0.24	0.74	-0.28	1.00

Subscripted d, o, and p are dithionite-citrate-bicarbonate, oxalate and pyrophosphate extractable.
[a]Total organic carbon; [b]Fulvic acids; [c]Humic acids; [d]Water soluble organic carbon. *$p < 0.05$; **$p < 0.01$.

consisted of HAs, and this phenomenon was explained by the fact that HAs could have been precipitated rather than adsorbed by clay minerals at very low pH (≤ 4) (Chaney and Swift, 1986). Furthermore, HAs seem not to be involved in translocation of Fe and Al in podzolization processes, because significant negative correlations were found between HAs and Fe_p (r = -0.74, $p < 0.01$) and Al_p (r = -0.67*, $p < 0.05$). A significant positive correlation was found between HAs contents and Fe_o contents in soil pedons (r = 0.56*, $p < 0.05$), indicating that the presence of HAs resulted in poor crystallization of Fe oxides.

The highest amounts of WSOC were found in surface soil horizons (O and A horizons) of all soil pedons, ranging from 2.30 to 3.85 g kg^{-1} (Figure 2c). The amounts of WSOC decreased with increasing soil depth, which is consistent with results of Huang and Schoenau (1996). In JL-1, JL-2 and JL-3 pedons, WSOC was accumulated slightly above Bs and placic horizons. The difference of texture and structure between AE and Bs horizons in JL-1 and JL-3 pedons, and the hardness and low permeability of the placic horizon in JL-2 pedon retarded the percolation of WSOC. No obvious trend was found in different landscape positions.

Pedogenic processes and classification of soils

Due to environmental conditions favoring podzolization in this subalpine forest, such as high annual precipitation and very acid surface soils, podzolization occurred in the JL-1, JL-2 and JL-3 pedons. Nevertheless, they could not be classified as Spodosols because the Bs horizons in these pedons did not meet the criteria for spodic horizons (Soil Survey Staff, 2006). JL-1 pedon was classified as Typic Epiaquept according to the US Soil Taxonomy (Soil Survey Staff, 2006) and Stagnic Cambisol according to the WRB system (IUSS Working Group WRB, 2006). JL-2 pedon was classified as Typic Epiaquept with placic horizon according to the US Soil Taxonomy and Stagnosol (Dystric, Placic) according WRB. The reasons are as follows: (1) high clay contents, (2) medium to high crystalline Fe oxide contents, and (3) existence of a placic horizon retarded Fe and Al translocation down into the lower part of the soils and hampered formation of spodic horizons. As for the first reason, high clay contents prevent the mobility of organic matter within the soil pedon, which was evidenced by a significant negative correlation between organic carbon and clay contents (r = -0.61, $p < 0.05$) (Table 5). Liu and Chen (1991) also indicated that high clay contents derived from parent materials decrease the mobility of organically-complexed Fe and Al compounds in forest soils in central Taiwan. Moreover, a clayey texture is less suitable for podzolization than a sandy one. Additionally, high clay contents probably facilitated lateral leaching along the toposequence. Therefore, the formation of spodic horizons was unapparent in these clayey soils.

The second reason was proposed by Wang et al.

(1989) who demonstrated that high amounts of crystalline Fe oxides ($\geq$ 50 g kg^{-1}) could slow down podzolization processes. This was further supported by significant positive correlations between well crystalline Fe oxide contents (Fe_d-Fe_o) and organically-complexed Fe (Fe_p) and Al (Al_p) contents (r = 0.64, $p < 0.05$ for Fe and r = 0.80, $p < 0.01$ for Al) in this study, indicating that more contents of well crystalline Fe oxides would adsorb more organically-complexed Fe and Al.

In comparison with the soil genesis of JL-1 pedon, that of JL-2 pedon is relatively different except for the podzolization process. In addition to perched water caused by heavy rainfall, high lake water level also reaches this pedon during the monsoon season, as indicated by the demarcation of high lake water level, which could be identified by the difference of the predominant vegetation (Figure 1). This site with Yushan cane bushes is located in a transitional zone between coniferous forest and aquatic plants. Alternating reducing and oxidizing conditions were dominantly caused by a perched water table which was due to heavy rainfall and seasonal inundation by high seasonal lake water level at this site. The duration of reducing conditions in this pedon was therefore longer than in JL-1 pedon. Due to this pedogenic environment, a thin placic horizon (3 mm) was formed in JL-2 pedon. The formation of the placic horizon could be attributed to alternation of oxidizing and reducing conditions in surface soils (Clayden et al., 1990; Conry et al., 1996; Hseu et al., 1999). Reduced Fe is leached from the AE horizon and accumulates in the upper part of the Bs1 horizon, where the pH value is higher than in the AE horizon (Table 2), which also corresponds with the results of Lapen and Wang (1999). Accordingly, we suggest that podzolization and formation of a placic horizon occurred simultaneously in this pedon.

Dominant coniferous forest and absence of lake water favored podzolization at the upper slope sites, particularly in the JL-1 pedon. Along the toposequence, vegetation changes as a result of increasing influence of the lake water level, especially at the lower slope sites (JL-3 and JL-4 pedons). The prevailing silver grass and aquatic plants at the lower slope are occasionally influenced by lake water level change. Under these conditions, hydromorphic processes predominate in these soils.

JL-3 pedon, located at the toeslope, was strongly influenced by the fluctuating lake water level (Figure 1). This pedon was frequently inundated by lake water. As lake water level fell, some water was perched in the clayey BE horizon and led to reduction of most of the Fe oxides in the BE horizon, followed by translocation and oxidation in the Bs horizon. The remaining Al-bearing minerals, such as gibbsite or kaolinite, released Al ion to form organically-complexed compounds with humic substances. Locally, spodic material (5-10%) was found in the BE and in the upper part of the Bs horizon with high contents of crystalline Fe oxides. Although spodic material was found in these pedons, the amounts were too low to classify this pedon as Haplorthod or Spodic Dystudept according to US Soil Taxonomy. Therefore, JL-3 pedon was classified as Typic Epiaquept according to US Soil Taxonomy and as Stagnosol (Dystric) according to WRB. On the other hand, vegetation is obviously different between this site and upper slope sites. Silver grass (*Miscanthus transmorrisonensis* Hayata) is the predominant vegetation in this site. The fast turnover rate and decomposition of organic matter in grassland could lead to a thin organic horizon and low humic substance contents in surface soils (Table 1 and Figure 2). These conditions also slow down the translocation of organically-complexed Fe and Al. At this site, we believe that hydromorphic processes were the predominant pedogenic processes rather than podzolization.

In the JL-4 pedon, in a prevailing reduced condition due to long-term inundation of lake water, most of the Fe oxides in the soil was reduced and lost. JL-4 pedon was classified as Typic Endoaquept according to US Soil Taxonomy and Dystric Gleysol according to WRB.

On the basis of the present US Soil Taxonomy system, we found no suitable Soil Great Group and Subgroup in the US Soil Taxonomy for JL-2 pedon with a placic horizon. This result was consistent with those of Wu and Chen (2005). Therefore, we suggest that a Placic Epiaquept should be added in the Subgroup of Epiaquepts in the US Soil Taxonomy.

CONCLUSIONS

This investigation of soil transect nearby subalpine lake contributed to the understanding of soil genesis and relationships between podzolization and soil properties in clayey soils in subtropical mountain forest.

Podzolization and hydromorphic processes are dominant soil forming processes in the investigated catena. Towards the lakeshore, the soils are characterized by increasing dominance of hydromorphic processes over podzolization, particularly in the locations which are reached by the lake water level for some time of the year. Hydromophic processes become less important about 35 to 40 m away from the lakeshore. The fluctuating lake water level influences vegetation pattern and soil genesis. In the area below the lake water maximum (about 3 m above average lake water level), the importance of hydromorphic processes gradually increases towards the lakeshore.

FAs have been confirmed as playing a major role in forming organic complexes with Fe and moving downwards to deeper parts of the pedons during podzolization. The HAs are the group of organic substances that predominantly hinder the crystallization of Fe oxides in surface soils.

The Podzol-like soils in this area could not be classified as Spodosols or Podzols, because the soil colors of the Bs horizons did not meet the criteria for spodic horizons. Three reasons are suggested: (1) high clay contents, (2) high well crystalline Fe oxides contents, and (3) the formation of a placic horizon. All of these soil properties slow down the podzolization process. In addition, we suggest that the Placic Epiaquept should be included in the US Soil Taxonomy.

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北臺灣高山湖畔之地形序列下淋澱化森林土壤之化育與特性

簡士濠[1] 吳森博[2] 陳尊賢[3] 陳財輝[4] 邱志郁[1]

[1] 中央研究院 生物多樣性研究中心

[2] 國家實驗研究院 科技政策研究與資訊中心

[3] 國立台灣大學 農業化學系

[4] 行政院農業委員會林業試驗所 育林組

台灣北部冷涼潮濕的亞高山檜木林下，經常可發現淋澱化土壤。本項研究乃針對高山湖泊 (太平山加羅湖) 旁，由山頂至湖畔的地形序列上的淋澱化土壤，探討土壤高濕度狀態對植物和土壤化育的影響，並釐清土壤中淋澱化作用的機制。研究結果顯示：除湖邊位置外，其餘各地形位置上之土壤皆具淋澱化作用。山頂與麓坡位置上土壤中的鐵鋁聚積土層 (Bs 層) 中，以有機結合態的鐵和鋁為主。和腐植成份的黃酸所結合的鐵與鋁，由表層往下淋洗並聚積於 Bs 層。至於麓坡位置的土壤，鐵與鋁所蓄積形成之薄膠層 (Bsm 層)，鐵和鋁的成份是以無定形態為主。根據此等結果可推論薄膠層的形成，主要是受到高雨量與季節性湖水位影響，導致水份長期滯留於麓坡位置上之土壤洗出層 (AE 層) 和鐵鋁聚積層 (Bs 層) 間，致使鐵還原並往下移動，經由反覆的氧化－還原作用，在土壤剖面洗出層與洗入層交界處形成一鐵磐層 (薄膠層)。就地形效應而言，趨向湖邊位置，土壤水成特徵愈趨明顯，淋澱化作用則愈趨減弱。研究區域之土壤皆具淋澱化作用，但依目前美國土壤分類標準，卻未能將之歸類為淋澱土。主要的癥結，在於土壤中含有高量的黏粒及鐵鋁氧化物，使得有機物質或是和有機結合態的鐵鋁成份，皆未能順利往下洗入，以至於無法形成淋澱層。

關鍵詞：黃酸；薄膠層；淋澱化土壤；淋澱化作用。