Research paper

Soil Characteristics and Genesis Processes of a Subtropical Low-Elevation Mountain Forest in Central Taiwan

Shih-Hao Jien,[1)] Chih-Yu Chiu,[1)] Tsai-Huei Chen[2,3)]

【Summary】

Two representative soil pedons under natural broadleaf stands in the Lienhuachih Experiment Forest in central Taiwan were selected to investigate their soil characteristics and evaluate soil genesis processes. The studied soils were acidic (pH 3.80~4.92) with low organic carbon contents (< 4%) and extremely low base saturation (< 5%), which correspond to forest soils in tropical and subtropical regions. Brunification and laterization were found in forest soils where well crystalline iron and aluminum contents are relatively high (> 50%). There was an illuviation phenomenon of clay and free Fe and Al oxides (Fe_d and Al_d) in the studied soils, whereas amorphous Fe and Al oxides (Fe_o and Al_o) and organic Fe and Al complexes (Fe_p and Al_p) were predominant forms in the surface soils of this forest due to effects of the soil organic matter. Well-developed soils were found at the footslope site owing to higher contents of well crystalline Fe and Al oxides compared to those at the backslope site. Soils at the footslope site with bisequences were classified as Typic Hapludults, and those at the backslope site were classified as Typic Dystrudepts. We concluded that the soils have undergone strong weathering under paleoclimatic conditions. These soils had been disturbed in the past and had gone in new genesis directions due to erosion and colluvial conditions resulting from the unstable topography and frequent tectonic episodes.

Key words: aluminum, iron, paleoclimatic, soil genesis, topography.

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研究報告

台灣中部低海拔森林土壤之性質與化育作用

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摘　要

本研究於林業試驗所蓮華池研究中心的天然闊葉林，選取兩代表性之土壤剖面調查其土壤性質與探討土壤化育作用。研究區域土壤皆呈強酸性(3.80~4.92)、低有機質含量(< 4%)及低鹽基飽和度(< 5%)，此些性質乃符合亞熱帶中低海拔森林土壤之特性。高含量及高比例的結晶性游離態鐵與鋁(> 50%總鐵含量)及紅棕色之土壤色彩顯示本研究區域之土壤具有趨向褐色化(brunification)及磚紅壤化(lateralization)之作用。土壤中結晶性良好之游離態鐵和鋁(Fe_d, Al_d)具有隨粘粒共同往下淋洗的趨勢；結晶性較差之無定形(Fe_o, Al_o)與有機態鍵結之鐵和鋁(Fe_p, Al_p)則在土壤表層具有較高含量，顯示逐漸風化釋出的鐵和鋁的結晶性受到土壤表層之有機物質影響而導致結晶性不良。此外，位於麓坡位置上的土壤剖面中具有高含量及高比例的結晶性游離態鐵與鋁，由此可得知此位置上土壤曾經歷高度風化及化育作用。本研究中，位於背坡位置上之土壤可分類為典型低鹽基濕潤弱育土(Typic Dystrudepts)；而位於麓坡位置上具有雙層序的土壤可分類為典型簡育濕潤極育土(Typic Hapludults)。故作者推論此研究區域土壤，在古氣候的影響下，曾受強烈風化及化育作用，而後受不穩定地形影響，例如土壤崩塌或埋入作用，而導致土壤受擾動而重新改變化育的方向。

關鍵詞：鋁、鐵、古氣候、土壤化育、地形。

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INTRODUCTION

In tropical and subtropical montane forests, climate and pedogenic processes are critical factors determining soil properties. Nutrient deficiencies and stronger weathering are dominant features of soils in these regions (Spain 1990, Zinn et al. 2002, Tsui et al. 2004).

To consider various major factors affecting soil properties, certain variables are kept constants, such as climatic conditions and vegetation effects. Pedogenic processes and site-specific effects are therefore major factors affecting soil characteristics. Soil inorganic components, such as the clay fraction, and iron and aluminum oxides, formed from weathering processes are the most important elements for controlling soil properties, the humification process, and nutrient supplies in tropical and subtropical forests (Duchaufour and Souchier 1978). Thus, it is important and necessary to understand soil genesis and the distributions of clay, and iron and aluminum oxides in soils. On the other hand, in montane forests, the topography and parent materials are considered primary important factors in soil development and genesis (Arteaga et al. 2008, Phillips et al. 2008). In some cases, the variable topography in montane forests influences soil properties and pedogenic processes (Chen 1994, Hseu et al. 2001, Wilcke et al. 2003). Scalenghe et al. (2002) also indicated that natural perturbations caused by catastrophic events, such as avalanches and landslides, were mainly disturbances of soils in montane and valley geography. Thus, it is very important to determine soil genesis processes and soil properties for managing forest land uses.

The Lienhuachih Experimental Forest is dominated by natural broadleaf forests, and about 1/2 of the area of this forest has been afforested by coniferous stands since 1978, and altered to grow medicinal plants. King (1986) and Chiang et al. (1993) investigated the soils in this experimental forest in terms of soil classification and clay minerals under the broadleaf forests. They indicated that Typic Dystrochrepts and Typic Hapludults were dominant soils in this experimental forest based on the original parent materials. However, those researchers mainly studied soil classification and the characteristics of Fe nodules in the regolith horizons. No studies have been performed to evaluate the soil properties and genesis processes in natural broadleaf forests of this experimental forest so far. In addition, based on a slightly higher slope in the forest, we hypothesized that collapsed and buried phenomena may have occurred. Therefore, we attempted to (1) evaluate soil properties and soil genesis in the Lienhuachih Experimental Forest with subtropical climatic conditions, and (2) discuss the influence of topography on soil genesis processes in this forest.

MATERIALS AND METHODS

Study area

The study was conducted in the Lienhuachih Experimental Forest (120°54'E and 23°54'N), which belongs to low- to moderate-elevation mountain zones and is adjacent to the Central Range in central Taiwan (Fig. 1). The rocks of our study area are dominated by Tertiary sedimentary sandstone and shale formed in the Miocene to Pliocene (1.8~5.3 Ma). The elevation of this study area ranges from about 600 to 850 m. The climate is warm and humid, and the mean annual precipitation is about 2200 mm, ranging 1100~3400 mm, with 80% occurring in the wet season from May to September. The mean annual temperature is 20.8℃, ranging 15.4~26.0℃ (the lowest in January is 15.4℃ and the highest in July is 26.0℃) (Lu et al. 2008). The dominant vegetation species in this area are natural broadleaf trees, includng *Cinnamomum randaiense* Hay., *Cryptocarya chienesis* (Hance) Hemsl., *Diospyros morrisiana* Hance, *Schefflera octophylla* (Lour.) Harms, *Castanopsis carlesii* (Hemsl.) Hay var. *sessilis* Nakai, *Syzygium buxifolium* Hook. & Arn., *Litsea acuminata* (Blume) Kurata, and *Neolitsea variabillima* (Hay.) Kanehira & Sasaki (Lu and Tang 1995). These broadleaf trees are all mature, and some trees are possibly even older than 200 yr (Horng et al. 1986). Since 1978, some coniferous trees, dominated by *Cunninghamia konishii* Hay. and *Calocedrus formosana* (Florin) Florin, were afforested in certain areas covering about 200 ha in this experimental forest (Chen et al. 2007).

Site selection

The representative soil pedons, HW-1 and HW-2, were selected at different landscape positions, which were a backslope at an elevation of 680 m and a footslope at an elevation of 625 m (Fig. 1, Table 1). At these 2 landscape positions, a 1×1×1.5-m pit was excavated to describe the morphological features as well as to collect soil samples according to standard procedures (Soil Survey Staff 1993). Soil pedons were classified according to USDA Soil Taxonomy (Soil Survey Staff 2006).

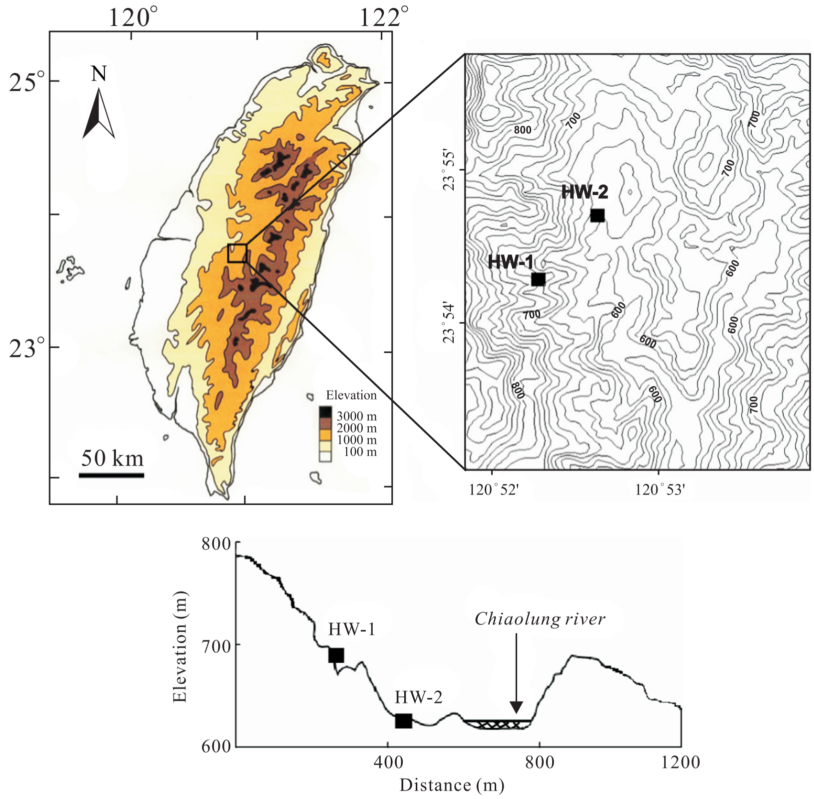

Fig. 1. Location of the study area and sampling sites.

Table 1. Selected characteristics of the studied sites

Pedon	Landscape	Elevation (m)	Slope (%)	Parent materials
HW-1	Backslope	680	25	Sandstone and shale
HW-2	Footslope	625	15	Sandstone and shale; colluvium

Sample preparation and analysis

Soil samples were collected from each horizon of the 2 soil pedons for physical and chemical analyze. Soil samples were air-dried and ground to pass through a 2-mm sieve for analysis. Particle size distribution was determined by the pipette method (Gee and Bauder 1986). Soil pH was determined with a soil/water ratio of 1:2.5 (McLean 1982). Total organic carbon (TOC) and total nitrogen (TN) contents were measured with a elemental analyzer (NA1500, Fisons, Italy). The cation exchange capacity (CEC) and exchangeable bases were measured using the ammonium acetate (pH 7) method (Thomas 1982). Fe and Al were extracted by the dithionite-citrate-bicarbonate (DCB) method (Fe_d and Al_d) (Mehra and Jackson 1960), the ammonium oxalate method (pH 3.0, Fe_o and Al_o) (McKeague and Day 1966), and the sodium pyrophosphate method (pH 10, Fe_p and Al_p) (Loveland and Digby 1984).

DCB-extractable Fe and Al are considered to be the more-crystalline portions of the Fe and Al in soils, and the acid ammonium oxalate-extractable Fe and Al are dominantly the amorphous form, such as ferrihydrite and small proportion of organic forms in soils.

Sodium pyrophosphate-extractable Fe and Al are usually taken to represent the amount of Fe and Al complexed to soil organic matter. The concentrations of total Fe were determined after acid (HNO_3-H_2SO_4-HCl-HF) digestion of 100 mg of finely ground soils in Teflon vessels heated in a microwave oven (MARS 5, CEM, JAPAN). Concentrations of all elements were measured by inductively coupled plasma atomic emission spectroscopy (ICP-AES) (Jobin-Yvon, JY124, JAPAN). Duplicates were made for all samples, and results were accepted when the coefficient of variation was < 5%. A blank and certified material (SRM 2709, National Institute of Standard and Technology, USA) were included in each batch of analyses for quality control of metal measurements. Results were considered satisfactory when recoveries of elements were within a range of ±10% of certified values.

RESULTS AND DISCUSSION

Morphological characteristics of the studied soils

The morphological characteristics of the studied soil pedons are shown in Table 2. At the soil surface, there were a thin litterfall (< 2 cm) and a dark organic layer (< 15 cm), followed by slight development and more-reddish soils than in the C horizon in both studied pedons. The HW-1 pedon was overlaid by consolidated sandstone rocks and had a depth of 70 cm. In contrast, the HW-2 pedon was

Table 2. Morphological characteristics of the studied soil pedons

Horizon	Depth (cm)	Munsell Color	Texture[1)]	Structure[2)]	Consistency[3)]	Roots[4)]	Boundary[5)]
HW-1							
Oi	0~2	-	-	-	-	-	-
A	2~10	10YR 3/3	SCL	2fg, 2f sbk	ms&mp	mvf&f, fm	cw
AB	10~19	10YR 3/6	SCL	2f&m sbk	ms&mp	cvf&f, fm	gw
Bw1	19~35	10YR 4/8	SCL	2f&m sbk	ms&mp	cvf&f, fm	gs
Bw2	35~51	7.5YR 5/8	SCL	2f&m sbk	ms&vp	cm	gs
Bw3	51~70	7.5YR 5/8	SCL	2f&m sbk	ms&vp	cm	gs
BC	70~95	7.5YR 5/8	SCL	3m sbk	ms&vp	cm	ci
C	> 90	10YR 6/8	SCL	platy	-	-	-
HW-2							
O/A	0~14	10YR 3/4	C	3vf&f g	vs&vp	cvf&f, cm	cw
Bt1	14~31	10YR 6/8	C	2 f&m sbk	vs&vp	fvf&f, fm	gs
Bt2	31~53	7.5YR 5/8	C	3 f sbk	vs&vp	fvf&f	gs
Bt3	53~67	7.5YR 5/8	C	2 f&m sbk	vs&vp	fvf&f	gs
2Bt1	67~96	5YR 5/8	C	2 f sbk	vs&vp	fvf&f	gs
2Bt1	96~113	2.5YR 4/8	C	2 f sbk	vs&vp	fvf&f	gs
2Bt2	113~140	10R 4/8	C	2 f abk	vs&vp	fvf&f	gs

1) SCL, sandy clay loam; C, clay.
2) 2, moderate; 3, strong; vf, very fine; f, fine; m, medium; g, granular; abk, angular blocky; sbk, subangular blocky.
3) s, sticky; p, plastic; ms, moderately sticky; mp, moderately plastic; vs, very sticky; vp, very plastic.
4) f, few; m, many; c, common; vf, very fine; f, fine; m, medium.
5) c, clear; g, gradual; s, smooth; w, wave; i, irregular.

overlaid by relatively red soils which had a soil color of 5YR or redder, and the soil depth was ≥ 150 cm. The distinct difference in the soil color found between the upper and lower parts of the HW-2 soil pedon reflected colluvial events at this site, and this was further evidenced by physical and chemical analyses of the soils. 10 YR and 7.5 YR were dominant soil colors in the HW-1 pedon and upper parts of the HW-2 pedon. The more-reddish color in the Bw (7.5 YR) than C horizons (10 YR) and good soil structure (subangular blocky) in the Bw horizon suggested in situ soil weathering from parent materials in the HW-1pedon. Soil textures varied from loamy sand to clay, reflecting weathering sequences along this transect. Pedon HW-1 with a sandy clay loam texture was considered to have been weathered to a lesser degree than the HW-2 pedon with its clayey texture, which might have undergone stronger weathering.

Soil physical and chemical characteristics

In this area, warm and humid subtropical climatic conditions characterized by a slightly high mean annual temperature (20.8℃) and annual precipitation (2200 mm) have resulted in moderate to strong development of soils. With the exception of the observed brunification process of these soils, significantly higher clay fraction contents (≥ 60%) and lower sand fraction contents (≤ 10%) were found in the HW-2 pedon (Table 3). Additionally, clay skins were also found in the HW-2 pedon. These characteristics indicated that the HW-2 pedon had undergone greater development than the HW-1 pedon. As shown in Table 4, both soils were characterized by a pronounced acidic reaction (pH ≤ 5.0), and this resulted from the original siliceous parent materials. This agrees with results of Arteaga et al. (2008) who proposed that extreme acidity in montane cloud forest soils in Mexico could be attributed to parent materials with poor bases. Imaya et al. (2007) also indicated the same situation in brown forest soils in Japan, and they indicated that lower pH values (≤ 5.5) were found in soils derived from sandstone and mudstone. Additionally, due to heavy rainfall in this area and the moderate to strong

Table 3. Particle size distribution of the studied soil pedons

Pedon	Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)
HW-1	Oi	0~2	-[1)]	-	-
	A	2~12	62.8	16.0	21.2
	AB	12~19	61.3	15.8	22.9
	Bw1	19~35	63.2	16.8	20.0
	Bw2	35~51	64.0	14.0	22.0
	Bw3	51~70	60.2	17.7	22.1
	BC	70~95	58.1	17.9	24.0
HW-2	O/A	0~14	6.8	34.5	58.7
	Bt1	14~31	4.4	32.4	63.2
	Bt2	31~53	4.0	27.1	68.9
	Bt3	53~67	1.3	28.3	70.4
	2Bt1	67~96	3.9	30.7	65.4
	2Bt2	96~113	3.1	24.5	72.4
	2Bt3	113~140	3.5	30.1	66.4

[1)] Data not available.

Table 4. Chemical properties of the studied soil pedons

Horizon	Depth	pH		OC[1)]	C/N	CEC[2)]	Ca	Mg	K	Na	Sum	BSP[3)]
	(cm)	(H_2O)	($CaCl_2$)	(%)		(cmol (+) kg^{-1})						(%)
HW-1												
Oi	0~2	-[4)]	-	-	-	-	-	-	-	-	-	-
A	2~10	4.10	3.65	2.30	11.03	11.54	0.07	0.09	0.15	0.02	0.31	2.86
AB	10~19	4.13	3.80	1.36	10.27	6.50	0.02	0.03	0.09	0.03	0.17	2.45
Bw1	19~35	3.80	3.92	0.88	12.41	4.62	0.02	0.02	0.07	0.02	0.13	2.75
Bw2	35~51	4.41	3.95	0.46	9.35	4.49	0.02	0.01	0.08	0.02	0.13	3.08
Bw3	51~70	4.37	3.96	0.35	8.54	4.83	0.01	0.01	0.08	0.03	0.13	2.80
BC	70~95	4.23	3.96	0.34	8.02	5.00	0.01	0.01	0.08	0.02	0.12	2.50
HW-2												
O/A	0~14	4.24	3.69	3.66	29.9	19.6	0.03	0.02	0.14	0.07	0.26	1.32
Bt1	14~31	4.61	3.81	1.68	24.2	15.5	0.01	0.01	0.06	0.02	0.10	0.64
Bt2	31~53	4.70	3.84	1.14	26.1	14.2	0.01	0.01	0.06	0.02	0.10	0.72
Bt3	53~67	4.56	3.83	0.66	29.6	14.1	0.01	0.01	0.04	0.02	0.07	0.52
2Bt1	67~96	4.57	3.83	0.59	23.5	16.5	0.01	0.01	0.05	0.01	0.08	0.50
2Bt2	96~113	4.90	3.80	0.50	25.8	18.0	0.02	0.01	0.06	0.05	0.13	0.72
2Bt3	113~140	4.92	3.77	0.37	20.8	15.7	0.02	0.01	0.06	0.03	0.12	0.76

1) Organic carbon.
2) Cation exchangeable capacity.
3) Base saturation percentage.
4) Not detectable.

weathering degree of the soils, most of base cations had been leached out and lost, and that would have led to the relatively low pH values in these studied soils. In Table 4, concentrations of carbon and nitrogen in surface soils were slightly high (C, 2.30~3.66%; N, 0.12~0.21%) but all decreased with increasing depth in both studied soils. The concentrations of carbon and nitrogen in the studied soils are consistent with those of other natural broadleaf forest soils of the world with similar climates and elevations (Brown and Lugo 1982, Spain 1990, Hirai et al. 1991, Ohta et al. 1992, Wilcke et al. 2003). In addition, similar C and N concentrations were found compared to other soils under natural broadleaf forests with similar environmental settings and climatic conditions in Taiwan (Tsui et al. 2004, Liao 2006, Tsai et al. 2007a). The C/N ratio was higher at the footslope site than at the backslope one. This was attributed to the accumulation of organic matter at the footslope site where the slope was flatter than at the backslope site. Tsui et al. (2004) indicated that more C contents would accumulate at flatter-slope sites. The CEC values ranged 6.32~18.0 cmol(+) kg^{-1}. Higher CEC values are usually found in surface soils which have higher contents of organic matter. In addition, a high clay contents contribute to high CEC values. The values of both clay contents and organic matter were higher in the HW-2 soil, resulting in the higher CEC values. This trend was consistent with results of Skyllberg et al. (2001), Arteaga et al. (2008), and Bonifacio et al. (2008) who suggested that organic matter and clay contents contribute to the CEC in soils. Extremely low exchangeable base cations, ranging 0.26~0.53 cmol(+) kg^{-1}, were found in the studied soils, and base saturation percentages were also found. Soils being derived from the poor-base origin was the major reason for the low levels of exchangeable base cations in this area, and this concept agrees with findings of Arteaga et al. (2008) and Schawe et al. (2007).

Furthermore, topographic effects could not be excluded in this study, and these effects seem to have contributed to the variances of some soil characteristics, such as OC concentrations, the C/N ratio, and CEC values. Slightly lower OC concentrations were found in surface soils in the HW-1 pedon, and this can probably be ascribed to erosion due to the slightly steeper slope (≥ 25%).

Distribution of iron and aluminum oxides in the soil profiles

The concentrations of different forms of selective extractable Fe and Al are shown in Table 5. Fe_d was the dominant extractable form of Fe and comprised > 50% of Fe_t, suggesting moderate to strong weathering of these soils. In general, the Fe_d concentration is considered a major index for evaluating soil age and development degree (Blume and Schwertmann 1969). Amundson et al. (1989) studied alluvial soils in Nevada, USA and indicated that Fe_d and clay contents increased with increasing soil age. Richardson and Hole (1979) also suggested that Fe_d/Fe_t ratio is a good index to determine the degree of soil weathering. In addition, Fe_d contents tended to increase with increasing depth, and these

Table 5. Contents of selective extractable Fe and Al, activity, and crystallinity ratios of the studied soil pedons

Horizon	Depth (cm)	Free iron oxides						Fe_t	Fe_o/Fe_d	Fe_d/Fe_t
		Fe_d	Al_d	Fe_o	Al_o	Fe_p	Al_p			
		($g\ kg^{-1}$)								
HW-1										
Oi	0~2	-[1)]	-	-	-	-	-	-	-	-
A	2~10	6.90	2.15	3.19	1.58	5.18	1.12	11.7	0.46	0.59
AB	10~19	6.85	1.87	3.17	1.34	5.03	0.89	10.7	0.46	0.64
Bw1	19~35	6.32	1.75	2.76	1.16	4.78	0.85	12.0	0.44	0.53
Bw2	35~51	7.13	2.01	2.34	1.09	4.53	0.76	12.6	0.33	0.57
Bw3	51~70	7.91	2.35	2.08	1.21	4.32	0.71	13.1	0.26	0.60
BC	70~95	8.18	2.47	1.72	1.07	3.98	0.66	13.6	0.21	0.60
HW-2										
O/A	0~14	36.52	8.02	6.65	2.97	15.22	4.89	35.7	0.18	1.00
Bt1	14~31	35.82	7.68	5.70	2.70	16.41	4.93	41.8	0.16	0.86
Bt2	31~53	38.43	7.82	4.64	2.31	14.64	4.36	40.9	0.12	0.94
Bt3	53~67	41.36	7.96	3.20	2.15	11.57	3.65	43.7	0.08	0.95
2Bt1	67~96	47.61	8.06	2.65	2.24	10.12	3.38	48.7	0.06	0.98
2Bt2	96~113	64.23	7.81	2.75	2.37	6.00	2.70	65.0	0.04	0.99
2Bt3	113~140	36.55	8.02	6.65	2.97	15.25	4.89	35.7	0.18	1.00

The subscripted d, o, p, and t are dithionite-citrate-bicarbonate-, oxalate- pyrophosphate-extractable and total amounts, respectively.

[1)] Not available.

were associated with clay contents in the soil profile (r = 0.95, p < 0.01) (Fig. 2), indicating a colluviation of Fe oxides and clay minerals (Maejima et al. 2002). Similar to Fe_d, Al_d contents had a similar vertical trend to the clay contents and also tended to be correlated with clay contents (r = 0.99, p < 0.01). This also indicates that Al oxides were translocated downward concomitantly with the clay. Additionally, obvious differences were found between the studied soil pedons. The Fe_d and Al_d contents in the HW-2 pedon were significant higher than those in the HW-1 pedon, revealing the higher soil development degree of the HW-2pedon. However, the Fe_d and Al_d contents seemed to have irregular distributions in the lower parts of the HW-2 soil at depths below 70 cm. This further supports our hypothesis that the upper parts of soils in the HW-2 pedon were colluvial materials collapsed form upper slope sites based on observations of morphological features.

Acid oxalate-extractable forms of Fe and Al are considered the dominant amorphous forms (Kodama and Hayashi 1985),

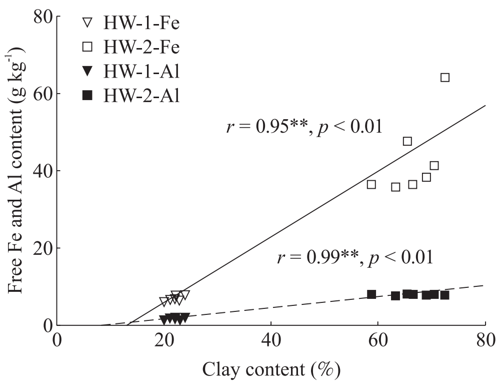

Fig. 2. Relationships between free Fe and Al and clay contents in the studied soils. The open symbols are Fe and solid ones are Al. The solid line is the regression line for Fe, and the dashed line is the regression line for Al.

such as ferrihydrite and small proportion of the organic forms in soils (Mckeague et al. 1971). In contrast to Fe_d and Al_d, Fe_o and Al_o contents were relatively low (0.10~0.70%) and decreased with increasing soil depth in both studied soils. This was consistent with a report by Hirai et al. (1991) who studied weakly to moderately developed forest soils derived from sandstone which had 0.18~0.56% Fe_o concentrations. In our study, the higher Fe_o and Al_o concentrations in surface soils than in the deeper subsoils could be attributed to higher SOM contents in the surface soils. Schwertmann (1985) indicated that higher SOM contents in surface soils will retard the crystallization degree of Fe. Brahy et al. (2000) studied soils along a transect in a forest in Belgium; they indicated that the Fe_o/Fe_t ratio was higher in the A and AB horizons, and this resulted from the higher amounts of SOM in surface soils. Fe_p and Al_p concentrations in the studied soils were also similar to those reported by Hirai et al. (1991) in warm forest soils situated at middle elevations (400~700 m), and these concentrations decreased with increasing soil depths. Similar to the contents of Fe_o and Al_o, higher contents of Fe_p and Al_p in surface soils were attributed to higher SOM contents there, which corresponds with results of Zanelli et al. (2007). Additionally, we found that the Fe_p and Al_p contents were higher than the Fe_o and Al_o contents in both studied soils; this probably represents a fraction of sesquioxides protected by SOM from extractable Fe and Al by oxalate (Jongkind et al. 2007). Kleber et al. (2004) also indicated that the alkaline pyrophosphate extractant attacks hydroxyl-like Al (e.g., Al interlayers or poorly ordered gibbsite) that may be resistant to the acid oxalate procedure. Furthermore, no trend of downward translocation of Fe_p and Al_p was found in these 2 soils, despite the Fe_p and Al_p

contents being higher than the Fe_o and Al_o contents, suggesting that no any podzolization process was found in our study.

Soil genesis and classification

Several studies have successfully evaluated the soil development index using extractable Fe and Al (Blume and Schwertmann 1969, Nagatsuka 1972, Richardson and Hole 1979, Hirai et al. 1991, Ohta et al. 1992, Devaux et al. 2004). The active ratio (Fe_o/Fe_d) and crystallinity ratio (Fe_d/Fe_t) are considered common and effective indices to evaluate soil development. McFadden and Hendricks (1985) showed that Fe_o/Fe_d in the chronosequence of southern California ranged from 0.22 to 0.58 in Middle Holocene to Late Pleistocene soils and progressively decreased to < 0.10 in older soils. In this study, we also used these 2 indices to evaluate soil development. As shown in Table 5, the Fe_o/Fe_d ratio ranged 0.04~0.46, indicating a low to moderate degree of pedogenic Fe activity; however, the Fe_d/Fe_t ratio ranged 0.53~1.00, indicating moderate to strong development of the studied soils. These results suggest that the studied soils have undergone moderate to strong weathering. Hirai et al. (1991) indicated that an Fe_o/Fe_d ratio of < 0.40 usually occurs in warm temperate or humid subtropical forest regions in their study in Japan. Tsai et al. (2007b) used these soil development indices to discuss soil ages and weathering degree of Pakua tablelands in central Taiwan, which have similar climatic conditions with our studied areas. They indicated that the Fe_d/Fe_t ratio was > 0.60 and < 0.20 for the Fe_o/Fe_d ratio for Ultisols with a high weathering degree. In addition, higher Fe_d/Fe_t ratios were found in the HW-2 pedon than in the HW-1 pedon, indicating that the HW-2 pedon has reached a more-advanced weathered stage than the HW-1 pedon. Additionally, we suggest that the studied soils could have undergone moderate to strong weathering in this area after erosion events occurred. The soils in our study were classified as Typic Dystrudepts at the backslope site and Typic Hapludults at the footslope site according to US Soil Taxonomy (Soil Survey Staff 2006). One reasonable explanation is that soil erosion and collapse occurred in the past in this study area. As a whole, the following geogenetic and pedogenetic processes are likely to have occurred in the study forest. First of all, soils exhibit strong weathering and soil development due to paleoclimatic conditions in this area. At the same time, brunification and laterization processes occurred in these soils under paleoclimatic conditions. Second, the higher slope percentage (15~30%) of the different landscape positions and unstable topographic situation controlled clay illuviation and soil genesis in this study area. Both studied soils under broadleaf forests in this area have moderate to strong soil development and with an extremely low base saturation after the topography stabilized in the late Pleistocene. Furthermore, our findings suggested that unstable topographic situations such as a high slope and microrelief were critical factors determining the direction of soil genesis.

Implications of pedogenesis in study area

In tropical and subtropical forest regions, the warm and humid climate causes high weathering of most soils. The strongly developed soils with gradual formation of more Fe and Al oxides will influence SOC storage in forests in these regions. In general, Fe and Al oxides are important factors stabilizing the SOC of tropical and subtropical forest regions, especially for highly weathered and low-fertility soils (Zinn et al. 2002). Mikutta et al. (2006) indicated that poorly crystalline Fe and Al phases explained 86% of the mineral-protected SOC in tropical rain forests and temperate mixed broadleaf and coniferous forests where climatic conditions, SOC contents (1.0~4.0%), and Fe and Al oxide contents (Fe_d, 2.0~10%; Fe_o, 0.1~2.0%; Al_o, 0~0.2%) were similar to those in our study area.

Furthermore, the highly weathered soils resulting from high temperatures and heavy precipitation in tropical and subtropical forest soils exhibit decreased amounts and bioavailability of soil nutrients for plant growth. The basic cations are leached during pedogenesis, and there are relative accumulations of free Fe and Al oxides, which can combine with SOC, humic substances, and phosphorous to form metallic-organic complexes or Fe-P and Al-P compounds (Smeck 1985, Agbenin and Tiessen 1994). Therefore, the poor fertility of forest soils due to pedogenic processes must be considered when land uses change or these areas are afforested in the future.

CONCLUSIONS

Low levels of SOC (2~4%), the C/N ratio (10~30), CEC (≤ 20 cmol(+) kg^{-1}), and base saturation (≤ 3%) were found in soils in this forest, and these are typical of warm, subtropical humid climate regions characterized by high precipitation (≥ 2200 mm) and temperatures (≥ 20℃). In addition, rapid mineralization of SOM resulting from these climatic conditions led to a thin depth of accumulation of soil humic substances (≤ 5 cm).

Furthermore, Fe and Al oxides and clay contents also dominate the soil characteristics in these moderately to strongly weathered soils. Free Fe and Al (Fe_d and Al_d) contents and clay fractions were higher in the B horizons than in surface soils, especially for pedon HW-2 at the footslope site, whereas amorphous and organic Fe and Al (Fe_o, Al_o, Fe_p and Al_p) were predominant forms in surface soils in this experimental forest. Soils with unapparent illuviation of Fe_d and the clay fraction were found on steeper slopes (≥ 20%) at the upper slope site; however, strongly developed soils were generally found on the lower slope site with a gentler slope (10%). The soils in our study were classified as Typic Dystrudepts at the backslope site and Typic Hapludults at the footslope site. We deduced that the unstable topography caused new soil genesis directions of the studied forest soils in this area, which originally had strongly weathered red soils, such as Ultisols.

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