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Soil fertility under various types of upland farming in northern Thailand. I. Case study of a village located in a transitional zone of hill evergreen and mixed deciduous forests

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ABSTRACT **Soil fertility status under various types of upland farming was evaluated in a village in Mae Taeng District of Chiang Mai Province in northern Thailand. The farmlands were on sloping land in a transitional zone of hill evergreen and mixed deciduous forests (800-1000 m a.s.l.). Miang tea (*Camellia sinensis var. assamica*), traditionally cultivated as the sole main cash crop, has been replaced by other cash crops. The studied soils originated from granite (n=30), limestone (n=16), and shale (n=6). Clay minerals were composed mainly of kaolin minerals in the granite soils and quartz, chlorite, gibbsite, mica, and kaolin minerals in the limestone and shale soils. Soil texture classes differed among soil types. However, granite and shale soils showed similar chemical properties to each other with an acidic nature and lower levels of exchangeable bases. Irrespective of the parent material, the CEC values were correlated with soil organic matter contents but not with clay contents. The levels of soil organic matter and the resulting CEC as well as ECEC values were higher in the limestone soils than in the granite and shale soils. These results suggest that higher negative charges in the limestone soils were derived from soil organic matter and that these charges developed under higher soil pH conditions. The C/N ratios of the limestone soils were lower than those in the granite soils and shale soils, reflecting the well-decomposed status of soil organic matter. The granite soils were classified into three groups based on their physicochemical properties: forest-type soils (remnant forest, secondary forest, miang tea garden and lychee orchard), soils of annual crop fields, and soils of the home gardens. The forest-type soils were characterized by their strong acidic nature with lower contents of exchangeable bases and available P. Soils of the annual crop fields and those of home gardens showed a less acidic nature and nutrient accumulation occurring as a result of fertilizer application. However, a difference between these soils was that while the annual crop fields possessed preferable soil physical properties for crops caused by tillage management, soils of home gardens were subjected to compaction throughout soil profiles. In contrast to granite soils, the effects of different land uses on soil fertility were not evident in limestone soils. However, the annual crop fields and orange orchards had low total C and total N, engendering lower CEC values. Although the available P of these soils was high because of fertilizer application, fertilizer N in the annual crop fields seemed not to contribute to a buildup of total N and ammonium N. Both in lychee orchards with the granite soils and orange orchards with limestone soils, fertilizer P had accumulated around trees where fertilizer was usually applied. For shale soils, the subsurface soils under the oolong tea gardens (*Camellia sinensis var. sinensis*) were rich in total C and N and less compacted than soils of other land uses. Results show that different farming practices affected soil fertility status depending on soil types with different parent materials.**

Keywords: soil fertility, upland farming, cash crops, miang tea, northern Thailand

INTRODUCTION

Upland agriculture in northern Thailand has been practiced mainly in watershed areas with steep slopes where appropriate conservation measures should be taken. Similarly to the other tropical regions, shifting cultivation was traditionally adopted on such areas, which is regarded as a type of sustainable agricultural system as long as a crop/fallow rotation cycle is adhered to adequately (Grandstaff, 1980). However, shifting cultivation has been transformed to more intensive land use with longer cropping and shorter fallow periods because of the alteration of socioeconomic conditions such as the lack of arable land resulting from increasing population pressure and the enclosure of forest land by the government (Rerkasem et al. 2008). With the rising blame of shifting cultivation practices as the cause of land degradation and deforestation, government officials and other institutes have examined and introduced alternative sustainable farming systems, particularly using agroforestry systems including fruit or timber trees as the key component. At the local farmers' levels, they often prefer to replace shifting cultivation with sedentary farming systems in which commercial crops such as cabbage are planted. Consequently, the landscape of mountainous areas in northern Thailand of today can be characterized as mosaical mixtures of such various agricultural systems as well as protected forests.

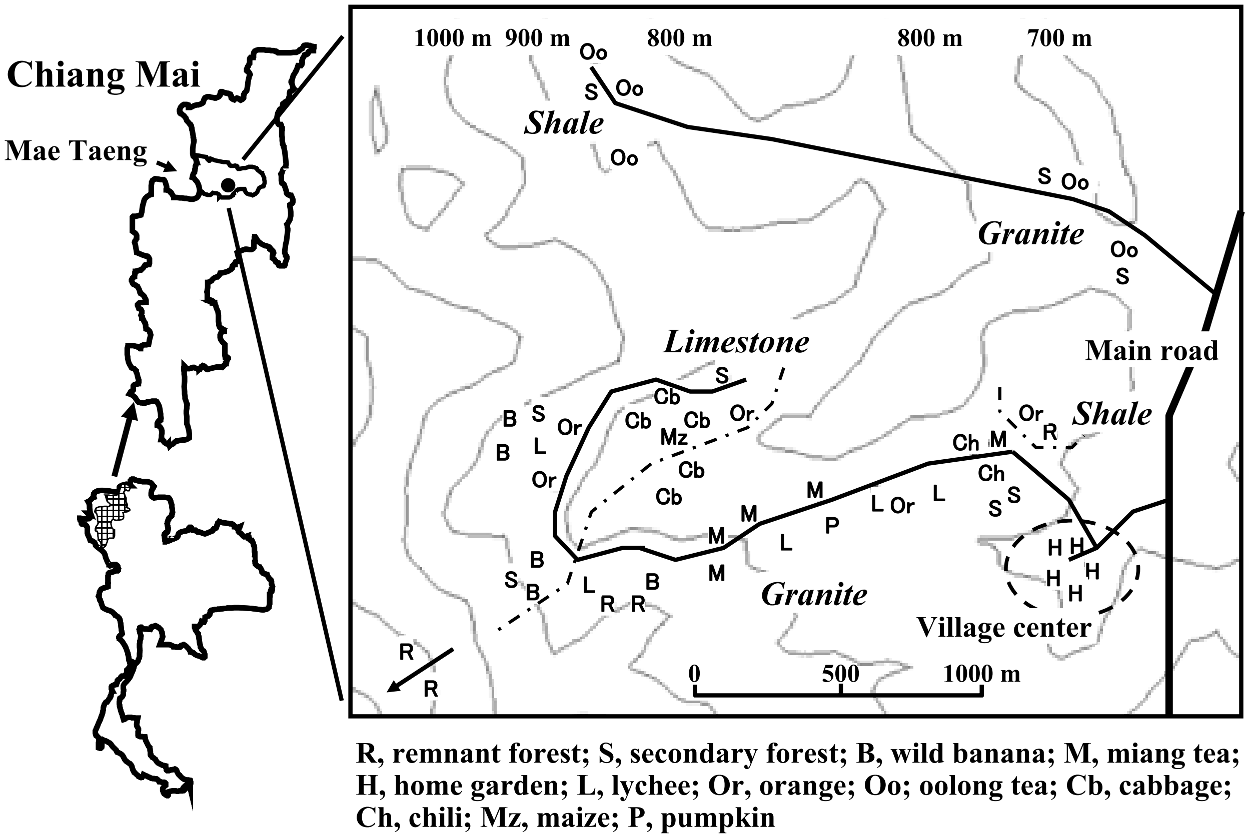
Many studies have been conducted of upland agriculture in northern Thailand, including those examining traditional shifting cultivation and the consequences of its alternation in socioeconomic or agronomic terms (Kunstadter, 1978; Praneetvatakul et al. 2001; Samata and Kawashima, 2004). Land degradation caused by increasing agricultural pressure and its influences on watershed ecosystems have also been studied extensively at a comprehensive watershed level and at a site-specific level (Turkelboom et al. 1997, 1999, 2008; Thanapakpawin et al. 2006). From a soil science perspective, the soil fertility status and nutrient dynamics under each component of upland agriculture have been well-documented, especially for shifting cultivation (Khemnark et al. 1976; Nakano, 1978; Funakawa et al. 1997a, b, 2006; Tanaka et al. 1997, 1998a, b, 2001). In addition, Tanasombat et al. (2005) reported the relation of soil fertility with growth and productivity in the agroforestry system using paper mulberry, while Koonkhunthod et al. (2007) evaluated the effectiveness of teak plantations for forest rehabilitation based on soil properties of the stand. In addition to these field studies, nutrient trials have also been conducted, for example, Roygrong et al. (2007) studied optimum fertilizer application for sustainable production of high-quality lychee fruits, while George et al. (2001) reported the response of upland rice production to phosphorus fertilizer application. However, few studies have elucidated the current situation of upland farming systems in northern Thailand in relation to soil fertility levels as they are affected and altered by diverse farming activities. In their pilot study of a dry evergreen and mixed deciduous forest at altitudes of 280-530 m a.s.l., Boonyanuphap et al. (2006, 2007) compared soil fertility under farming of various crops such as maize (*Zea mays*) and mango (*Mangifera indica*) as well as under remnant and secondary forests. Despite several important findings related to soil characteristics, they presented no rigid conclusion because of the limited number of study sites.

We conducted a series of studies to evaluate soil fertility status under current farming systems in two adjoining villages in northern Thailand. The villages differed in their environmental conditions of forest vegetation and soils as well as traditional farming systems before adoption of the current cash crop farming systems. In this paper, we report results obtained from the village located in a transitional zone of hill evergreen and mixed deciduous forests at altitudes of 800-1,000 m a.s.l. The soils had originated from granite, limestone, or shale. In this village, miang tea (*Camellia sinensis var. assamica*) had been cultivated as the sole main cash crop since the establishment of the village. However, the tea crop had been recently and rapidly replaced by other cash crops. In a paper to follow, we will report the results from another village located in mixed deciduous forest at an altitude of 500-600 m. The parent material of the soils was sandstone. Prior to adoption of fruit tree planting today, upland rice produced by shifting cultivation practices had been the main crop.

MATERIALS AND METHODS

Study village

This study was conducted of farmlands of local farmers in a village, Ban Lao (19°10'-19°11'N, 98°46'-98°47'E) in Mae Taeng District of Chiang Mai Province, northern Thailand during February-April in 2008 (Fig. 1). The average annual precipitation and temperature were around 1,800 mm and 22.8°C, respectively, as recorded in



R, remnant forest; S, secondary forest; B, wild banana; M, miang tea; H, home garden; L, lychee; Or, orange; Oo; oolong tea; Cb, cabbage; Ch, chili; Mz, maize; P, pumpkin

Fig. 1. Map of the study area.

the village by the Mae Taeng Watershed Research Station. The topography was mountainous, with slope gradients commonly exceeding 20-25°, and with an altitude mostly from 800-1,000 m a.s.l. The soil parent materials were mainly of Mesozoic granite with some areas covered by Paleozoic limestone or shale. The original vegetation was a transitional zone of hill evergreen and mixed deciduous forest.

According to the village headman, this village was established approximately 70 years ago and the inhabitants were so-called northern Thai, "Khon muang" . At the time of the present survey, the total population was 442 persons (112 families). Since the village was established, farmers have planted miang tea (*Camellia sinensis var. assamica*) as a main cash crop to purchase rice from other villages. According to Keen (1978), many Khon muang living in upland areas in the Chiang Mai Province were almost wholly dependent on miang tea production for their livelihood. Miang tea is usually planted under the shade of forests and is consumed by chewing or by drinking after fermentation. Lychee (*Litchi chinensis*) and orange (*Citrus reticulate*) were introduced, respectively, as perennial fruit crops by the extension works of the Royal project about 25 years and 10 years ago. Oolong tea (*Camellia sinensis var. sinensis*) and pumpkin (*Cucurbita pepo*) were also introduced about 10 years ago. The local farmers recently started to plant several annual cash crops by themselves. These new cash crops were planted mainly on existing miang tea gardens after slashing and burning, resulting in a rapid reduction in miang tea gardens.

Study sites

The farmlands tended to be concentrated along an unpaved road stretching from the residential area (Fig. 1). A small vehicle would be able pass on this road and some of its branches to carry agricultural materials and harvested produce. The southern part of the road was located on the ridge, but the western and northern parts were on the middle of slopes. Remnant forests were left at higher locations behind farmland areas. Secondary forests were located at surrounding areas of the farmlands, mostly at higher locations behind the farmland areas or on steep slopes between farmlands. Oolong tea gardens were located separate from this farmland center because of the presence of a tea-processing factory. In terms of parent materials of soils, the southern side of the road was covered with granite; the northern side was covered with limestone. Shale areas were scattered in the village territory.

In all, 52 sites were surveyed during the dry season in March 2008 (Table 1). They consisted of remnant forests (hill evergreen forest), secondary forests, wild banana stands, miang tea and oolong tea gardens, lychee and orange orchards, farmlands of annual crops (cabbage, *Brassica oleracea var. capita*; chili, *Capsicum annuum var. acuminatum*; maize; pumpkin), and home gardens within farmer's residences. In terms of parent materials of soils, sites showed compositions of 30 granite, 16 limestone, and 6 shale sites. The studied crops were representative of the village at the time of the field survey, and although some other crops for self-consumption were found planted only in small areas, they were omitted from this study. Irrespective of perennial or annual crops, crop fields were usually watered using self-made sprinkler systems for which water was supplied from the remnant forests. Among annual crop fields, all cabbage fields were harvested in February, immediately before our survey. Information about the land use history and farming practices such as fertilizer application was obtained from interviews of the landowners. Vegetation surveys were conducted at a quadrat ranging from 2 × 2 m^2 to 20 × 20 m^2 size. Numbers of trees or crops were recorded. In remnant and secondary forests, plant specimens were collected and identified at the herbarium of Chiang Mai University.

Soil sampling and physicochemical analysis

Soil samples were collected from surface (0-5 cm depth) and subsurface (20-25 cm depth) layers at the middle points between crops or trees in five replications within each site. They were mixed well into one composite sample for each depth. For lychee and orange orchards, additional samples were collected from 0-5 cm depth under the tree canopy, where fertilizer had been applied. The obtained soil samples were air-dried, crushed, and passed through a sieve with 2-mm mesh. Roots and other plant debris were removed. Soil samples were also collected from the surface and subsurface layers in triplicate using a 100 mL core sampler for determination of the bulk density.

Soil pH was determined in water or 1 mol L^{-1} KCl in a soil-to-solution ratio of 1:5 using a glass electrode method. Total C and N contents were analyzed using an NC analyzer (JM 1000 CN; J-Science, Kyoto, Japan). The contents of exchangeable bases (Ca, Mg, K, and Na) and the cation exchange capacity (CEC) were measured, respectively, after successive extraction using 1 mol L^{-1} ammonium acetate adjusted to pH 7.0 and 10% NaCl. The amount of NH_4 replaced by Na was determined for CEC using steam distillation and titration, whereas the contents of exchangeable bases were determined using atomic absorption spectrophotometry for Ca, Mg, and K, and by flame photometry for Na (AA-6800; Shimadzu Corp., Kyoto, Japan). Exchangeable Al, H, and NH_4 were extracted with 1 mol L^{-1} KCl. The exchange acidity (Al + H) was determined by titration with 0.01 mol L^{-1} NaOH, and the content of the exchangeable Al was determined with 0.01 mol L^{-1} HCl. The content of exchangeable H was calculated as the difference between the values of the exchange acidity and exchangeable Al. The content of exchangeable NH_4 was measured using the indophenol blue method (Mulvaney, 1996). Available phosphorus was quantified using the Bray II method (Kuo, 1996). The particle size distribution was determined using the pipette method. For the three selected subsurface soils originating from each parent material, the clay mineral composition was identified by X-ray diffraction analysis using CuKα radiation (XD-D1w; Shimadzu Corp., Kyoto, Japan). Soil hardness was examined at depths of 0-5 and 20-25 cm using a Yamanaka-type push cone penetrometer.

RESULTS

Land uses and crop management in the study village

Basic information related to the land uses and crop management of the study sites is provided in Table 1. The allocation of the study sites is presented in Fig. 1. Remnant forests were conserved at higher altitudes behind farmlands as water sources to supply to crops. Secondary forests were results of wild fires, and probably shifting cultivation activities, in the past and had remained unused at least for 10 years. The recorded major woody species were *Castanopsis diversifolia*, *Schima wallichii*, *Colona floribunda* and *Symplocos racemosa* in the remnant forests and *Schima wallichii* and *Ficus tinctoria* in the secondary forests. Some of these forests were occasionally damaged by accidental fires and logging for domestic uses including charcoal production to process miang tea. Wild banana stands were formed as a result of fire. They were almost entirely of one species, *Musa acuminata*. In the granite area, the banana stand was the only one existing with a large area: the others were located along the bottoms of ravines with steep slopes. Local farmers maintain the banana stand to use its leaves to wrap the miang tea at harvest. According to local farmers' perception, wild banana stands occurred on

Table 1. Land use and crop management of study sites.

Land use	No. sites1)				Years of cropping	Altitude	Area	Tree density2)	No. of tree spp2)	Crop spacing	Fertilizer3)	N	P	K
	Total	G	L	S		m	ha	plant 100 m^{-2}	spp. 100 m^{-2}	m × m		kg ha^{-1} y^{-1}		
Remnant forest	5	3	1	1		900–1300		4–8	7–12					
Secondary forest	8	4	3	1		730–1040		2–14	2–8					
Wild banana	5	1	4	0		940–100		16–44						
Miang tea	5	5	0	0	60–80	830–960	1.0–6.4	8–22						
Home garden	5	5	0	0	14–65	780–840	0.2–1.3	4–15	5–26		NPK	2–20	1–11	2–18
Lychee	5	4	1	0	10–25	880–910	0.3–6.6	1–3		8 × 8	NPK	9–34	4–15	8–34
Orange	5	3	1	1	4–11	850–990	0.3–8.0	4–9		4 × 4	NPK	70–422	31–184	75–350
Oolong tea	5	2	0	3	3–11	650–900	0.2–0.5			0.5 × 1.0	Urea	86–216	0	0
											Urea+NPK in 1 case	133	6	11
Cabbage	5	2	3	0	2–3	820–850	0.1–0.3			0.3 × 0.4	NP+NPK (granite)4)	181	90	109
											NP (limestone)	200–300	109–164	0
Chili	2	2	0	0	14)	850–880	0.24)			0.5 × 0.5	NPK+Urea4)	191	20	39
Maize	1	0	1	0	1	840	0.04			0.5 × 0.5	NP	100	55	0
Pumpkin	1	1	0	0	2	860	0.3			2 × 2	NPK+Urea	117	41	78

1) Number of study sites: G, granite; L, limestone; S, shale. 2) Plant density and numbers of species were recorded for tree species with a DBH more than 5 cm in a 10×10 or 20×20 m^2 quadrat. 3) NPK fertilizer of several types was used such as 13-13-21, 15-15-15, 8-24-24, and 25-7-7, whereas NP and urea were 16-20-0 and 46-0-0. In cases of two home gardens, 150 and 300 kg ha^{-1} of cow dung manure were used with NPK fertilizer. 4) No difference in data was found for two sites according to the interviews of landowners.

moist soils.

Miang tea gardens were located under forests, with shading similar to that of remnant forests (Keen, 1978; Sasaki, 2008), but which had been logged considerably for charcoal production. The gardens were large, 1-6 ha, although some parts might no longer be used. No fertilizer was applied for miang tea planting. Home gardens were found in the residence area on gentle slopes of 11-29°. The vegetation included various plants with various uses, including plants reported by Lattirasuvan et al. (2010). The number of species was comparable to that in the remnant forests. A small amount of NPK fertilizer was applied at an annual rate of 10-20 kg ha^{-1}.

All farmlands were converted directly from miang tea gardens except for the cases of two chili fields after six years of orange tree planting and a maize field after two years of cabbage cropping. Only lychee and orange were planted as fruit tree crops. As described earlier, they were introduced respectively as extension works of the Royal project about 25 years and 10 years ago. A smaller amount of NPK fertilizer was applied twice a year in lychee orchards than for other crops. In contrast, fertilizer application rates for orange orchards were high, with split doses applied 2-6 times a year, irrespective of their stand ages. Corresponding to a better market price of orange during this several years, farmers preferentially converted their farmlands into orange orchards, creating a landscape dominated by rather young orange orchards. The oolong tea trees were planted on terraces with width of 1.5 m constructed along counter lines of the slope. The main fertilizer was urea with split doses applied four times a year. Cabbage, chili, and pumpkin were cropped twice a year with tillage all over the field, whereas maize was cropped once a year on a small mound. Considerable amounts of fertilizer were applied: NPK fertilizer along with NP or urea fertilizer was applied for the fields in the granite area, but only NP fertilizer was used for fields in the limestone area. Nevertheless, no interesting information was obtained that this difference resulted from the results of farmers' selection recognizing soil properties and fertility levels. In addition to fertilizers, insecticides and herbicides were commonly used in cash crop farming.

Differences in soil physicochemical properties in terms of parent materials

Table 2 presents a comparison of soil physicochemical properties under forests (remnant and secondary forests) in terms of parent materials. Because of the limited quantities of the study sites for each parent materials, the average values of granite and limestone soils are calculated and compared using statistical methods by mixing the data of the remnant and secondary forests. According to Table 2, the granite and shale soils under the forests showed similar physicochemical properties. These soils were clayey, but only for the granite soils, the clay contents increased from the surface layer to the subsurface layer. The sand contents were high in the granite soils, although the silt contents were high in the shale soils. They were acidic and poor in exchangeable bases and high in exchangeable Al, resulting in high levels of Al saturation, especially in the subsurface soils. The available P contents were low. On the other hand, the limestone soils under the forests were clayey with higher silt contents than the granite soils. The clay contents were lower in the subsurface soils than in the surface soils, probably because of the increasing contribution of strongly weathered coarser fractions to sand contents in deeper layers. Compared with the granite and shale soils,

Table 2. Comparison of soil physicochemical properties under remnant and secondary forests in terms of parent materials.

		Surface 0–5 cm soils			Subsurface 20–25 cm soils		
Parent material		Granite	Limestone	Shale	Granite	Limestone	Shale
No. sites (remnant/secondary)		7(3/4)	4(1/3)	2(1/1)	7(3/4)	4(1/3)	2(1/1)
pH(H_2O)		5.23	7.12**	5.33	5.23	6.36*	4.97
pH(KCl)		4.22	6.46**	4.49	4.13	5.34*	4.14
EC	(mS m^{-1})	3.9	8.5**	3.0	1.3	2.7	1.0
Total C	(g kg^{-1})	34.4	56.9**	38.3	15.0	24.1	16.4
Total N	(g kg^{-1})	2.4	4.2*	2.8	1.1	2.2	1.0
C/N ratio	(cmol$_c$ kg^{-1})	14.5	13.8	13.9	14.0**	11.0	20.4
CEC	(cmol$_c$ kg^{-1})	11.9	26.3**	11.6	6.9	15.4*	6.2
Exch. Ca	(cmol$_c$ kg^{-1})	0.77	10.6**	0.90	0.30	4.16*	0.10
Exch. Mg	(cmol$_c$ kg^{-1})	1.39	4.53**	0.50	0.28	2.49*	0.03
Exch. K	(cmol$_c$ kg^{-1})	0.55	1.13**	0.27	0.29	0.49	0.08
Exch. Na	(cmol$_c$ kg^{-1})	0.01	0.01	0.01	0.01	0.01*	0.01
Exch. Al	(cmol$_c$ kg^{-1})	1.04*	0.01	0.81	1.62**	0.44	1.12
Exch. H	(cmol$_c$ kg^{-1})	0.38*	0.07	0.32	0.40**	0.07	0.20
Exch. NH_4-N	(cmol$_c$ kg^{-1})	0.09	0.07	0.07	0.04	0.04	0.03
Al saturation	(%)	32.5*	0.0	34.1	64.8**	17.1	81.9
Available P	(mg kg^{-1})	1	5	1	1	1	1
Clay	(%)	33	31	26	40**	20	20
Silt	(%)	15	48*	31	15	37**	31
Sand	(%)	52**	21	43	46	42	48
Bulk density	(Mg m^{-3})	1.0	0.9	1.0	1.3**	1.0	1.2
Soil hardness	(mm)	10	13	11	25	22	19

Al saturation, percentage of exchangeable Al to the sum of exchangeable bases and Al. Soil hardness was measured using a Yamanaka-type penetrometer. * and ** indicate a significant difference between granite soils and limestone soils for each depth at $P < 0.05$ and $P < 0.01$ (*t*-test).

Table 3. Physicochemical properties of soils derived from granite.

		Average	Remnant forest	Secondary forest	Miang tea	Home garden	Lychee	Annual crops	Wild banana	Oolong tea	Orange
No. sites		30	3	4	5	5	4	5	1	2	1
					Surface 0–5 cm soils						
pH(H$_2$O)		6.05	5.43a	5.09a	5.68a	6.39ab	5.72a	7.45b	5.83	5.87	6.88
pH(KCl)		5.12	4.21a	4.23a	4.47ab	5.47ab	4.54a	7.12c	4.93	4.79	6.09
EC	(mS m^{-1})	10.4	2.9a	4.7a	3.9a	5.8a	3.1a	39.3b	4.1	4.4	13.5
Total C	(g kg^{-1})	29.5	29.6	38.1	30.4	28.5	27.7	26.0	31.5	25.7	24.9
Total N	(g kg^{-1})	2.2	1.9	2.8	2.4	2.0	2.1	2.3	2.4	2.0	2.0
C/N ratio	(cmol$_c$ kg^{-1})	13.3	15.8b	13.6ab	12.5ab	14.2ab	13.4ab	11.5a	13.1	12.8	12.5
CEC	(cmol$_c$ kg^{-1})	11.0	11.3	12.4	10.2	9.9	10.0	11.8	14.1	11.0	9.8
Exch. Ca	(cmol$_c$ kg^{-1})	2.72	0.75b	0.78b	1.13b	2.43b	1.99b	7.53a	4.18	2.31	4.08
Exch. Mg	(cmol$_c$ kg^{-1})	1.75	1.24	1.50	1.49	1.54	1.31	3.07	2.53	1.32	1.99
Exch. K	(cmol$_c$ kg^{-1})	0.68	0.52	0.57	0.56	0.97	0.48	0.96	0.37	0.43	1.05
Exch. Na	(cmol$_c$ kg^{-1})	0.10	0.01	0.01	0.01	0.02	0.02	0.54	0.01	0.04	0.05
Exch. Al	(cmol$_c$ kg^{-1})	0.46	0.73b	1.27b	0.74b	0.06a	0.28b	0.00a	0.00	0.69	0.00
Exch. H	(cmol$_c$ kg^{-1})	0.21	0.30	0.44	0.22	0.12	0.19	0.07	0.13	0.30	0.05
Exch. NH$_4$-N	(cmol$_c$ kg^{-1})	0.08	0.07	0.10	0.09	0.04	0.06	0.15	0.05	0.05	0.04
Al saturation	(%)	14.9	23.3b	39.4b	25.5b	1.6ab	8.1ab	0.0a	0.0	25.6	0.0
Available P	(mg kg^{-1})	7	1a	1a	1a	12a	2a	21b	1	3	5
Clay	(%)	30	27	37	34	24	33	22	30	35	29
Silt	(%)	17	15	15	17	12	15	24	17	19	22
Sand	(%)	53	58ab	48a	49ab	63b	51ab	54ab	53	45	49
Bulk density	(Mg m^{-3})	1.1	1.1a	1.0a	1.1a	1.3b	1.1ab	1.1ab	1.0	1.1	1.3
Soil hardness	(mm)	12	10a	10a	10a	17b	11a	10a	9	15	11
					Subsurface 20–25 cm soils						
pH(H$_2$O)		5.59	5.47	5.06	5.44	6.10	5.34	6.09	5.33	5.47	5.43
pH(KCl)		4.47	4.13	4.13	4.25	4.79	4.22	5.19	4.17	4.35	4.36
EC	(mS m^{-1})	2.4	1.2a	1.3a	1.4a	2.0a	1.4a	6.8b	1.3	2.1	2.6
Total C	(g kg^{-1})	16.7	12.0	17.3	17.4	15.9	16.9	16.9	18.5	21.8	15.6
Total N	(g kg^{-1})	1.3	0.9a	1.2ab	1.3ab	1.1a	1.3ab	1.5b	1.4	1.7	1.2
C/N ratio	(cmol$_c$ kg^{-1})	13.3	14.0	13.9	13.4	14.8	12.8	11.4	13.2	12.7	13.0
CEC	(cmol$_c$ kg^{-1})	7.5	7.4	6.4	7.4	7.5	7.6	7.8	8.8	8.5	5.9
Exch. Ca	(cmol$_c$ kg^{-1})	0.93	0.38	0.25	0.18	1.18	0.67	2.63	0.70	0.90	0.63
Exch. Mg	(cmol$_c$ kg^{-1})	0.66	0.34a	0.24a	0.34a	1.04ab	0.45a	1.25b	1.04	0.65	0.48
Exch. K	(cmol$_c$ kg^{-1})	0.31	0.32ab	0.27ab	0.27a	0.57b	0.19a	0.36ab	0.12	0.12	0.17
Exch. Na	(cmol$_c$ kg^{-1})	0.01	0.01ab	0.01ab	0.01a	0.01b	0.01ab	0.02ab	0.01	0.02	0.01
Exch. Al	(cmol$_c$ kg^{-1})	0.95	1.65	1.60	1.12	0.33	1.18	0.36	0.92	1.02	0.57
Exch. H	(cmol$_c$ kg^{-1})	0.29	0.40	0.39	0.38	0.17	0.30	0.16	0.29	0.33	0.27
Exch. NH$_4$-N	(cmol$_c$ kg^{-1})	0.04	0.04ab	0.04ab	0.04ab	0.02a	0.04ab	0.06b	0.04	0.04	0.05
Al saturation	(%)	41.5	60.6	67.9	59.2	13.3	52.6	12.6	32.6	45.7	29.8
Available P	(mg kg^{-1})	3	1	1	1	4	1	12	1	1	1
Clay	(%)	36	34	44	35	31	36	34	34	39	40
Silt	(%)	16	15	15	17	11	16	22	14	17	16
Sand	(%)	48	51ab	41a	48ab	58b	48ab	44ab	52	44	43
Bulk density	(Mg m^{-3})	1.2	1.3ab	1.2ab	1.2ab	1.4ab	1.2b	1.1a	1.3	1.1	1.3
Soil hardness	(mm)	23	24b	25b	24b	27b	23ab	16a	22	22	24

Annual crops include two cabbage, two chili, and one pumpkin sites. Al saturation is the percentage of exchangeable Al to the sum of exchangeable bases and Al. Soil hardness was measured using a Yamanaka-type penetrometer. Values in the same row followed by different letters are significantly different at $P < 0.05$ (Scheffe's multiple comparison test).

the limestone soils were high in the contents of total C and N and the levels of CEC, although the C/N ratios were low in the subsurface soils. The soil reaction was almost neutral, with higher contents of exchangeable bases. However, the levels of available P resembled those in other soils.

According to semi-quantification based on peak heights of the X-ray diffraction analysis, the clay mineral composition of the granite soils was dominated by kaolin minerals followed by quartz. Mica minerals and chlorite were also detected as accessory components. In contrast to the simple composition of the granite soils, the limestone and shale soils possessed mutually similar clay mineral composition. The composition was rather complicated with quartz, chlorite, gibbsite, mica minerals, and kaolin minerals as major components.

Irrespective of parent materials and land uses, soils studied were composed of A and B and their transitional horizons at least down to 50-60 cm in depth, to which soil pits had been dug for sampling.

Consequently, as a whole, limestone soils possessed higher soil fertility than granite and shale soils. Granite soils and shale soils differed in soil texture and clay mineralogy. These results imply that fertility levels of the soils originating from different parent materials must be evaluated separately in terms of the effects of various land uses. The shale soils will be omitted from further detailed discussion herein because of the limited number of samples available for them.

The soils were classified mainly as Typic Haplustults for granite soils, Typic or Dystric Haplustepts for limestone soils, and Typic Dystrustepts for shale soils according to the USDA soil classification system (Soil Survey Staff, 2006).

Physicochemical properties of granite soils

Table 3 presents a compilation of the physicochemical properties of the granite soils in terms of land use types. No significant differences were found in soil properties between remnant forests, secondary forests, miang tea gardens, and lychee orchards. Among granite soils, these soils were characterized as having a more acidic nature, with lower contents of exchangeable bases and higher contents of exchangeable Al. The Al saturation of the subsurface soils reached 50-60%. However, the soil acidity under lychee orchards tended to be weak, with higher exchangeable Ca contents than those of the remnant forests, secondary forests, and miang tea gardens. The levels of available P were commonly low in these four soils.

On the other hand, the soils under annual crops (two cabbage, two chili, and one pumpkin site) were less acidic and contained higher amounts of exchangeable bases, especially Ca and Mg. The Al saturation was very low in both the surface and subsurface soils. The levels of available P were higher than those of the other land uses. These tendencies of the acidity and soil nutrient levels were more apparent in the surface soils than in the subsurface soils. The total C contents of the surface soils and the total N contents of the subsurface soils tended to be low and high, respectively, engendering lower C/N ratios in both layers. The subsurface soils were less compacted than the other land uses, as reflected in lower levels of bulk density and soil hardness.

Under home gardens, the most conspicuous characteristics of the soils were significantly higher bulk density and hardness than those of the other land uses. Other properties of the soils were intermediate between the two land use groups described above: the levels of total C, total N, and the C/N ratio tended to be more similar to those of the remnant and secondary forests, miang tea gardens, and lychee orchards, although the levels of acidity, exchangeable bases, and available P resembled those of the annual crop fields. Despite the lack of replication for statistical analyses, the soil properties under the oolong tea gardens, orange orchard, and wild banana stand more closely resembled those under the lychee orchards than to those of the remnant forests, secondary forests, or miang tea gardens.

Physicochemical properties of limestone and shale soils

Among limestone soils, no significant difference was found between soil properties under secondary forests and wild banana stands (Table 4). These soils showed almost neutral conditions, with higher levels of exchangeable bases. The level of available P was low. The soil properties under the orange orchards and annual crop fields also resembled those under the secondary forests, except for several properties. These soils tended to be low in the levels of total C, total N, and the C/N ratio in both layers and high in the levels of available P in the surface layer. A significant difference was found in pH values between the soils under the orange orchards and annual crop fields. The soil properties of the lychee orchard were almost identical to those under the orange orchards. In contrast to the roughly similar soil properties found for these five land uses, the soils under the remnant forest tended to be acidic, especially in the subsurface layer. Because only one site was surveyed for

Table 4. Physicochemical properties of soils derived from limestone.

		Average	Secondary forest	Wild banana	Orange	Annual crops	Remnant forest	Lychee
No. sites		16	3	4	3	4	1	1
				Surface 0–5 cm soils				
pH(H_2O)		7.24	7.35ab	7.26ab	6.85a	7.76b	6.44	6.73
pH(KCl)		6.79	6.77a	6.65a	6.38a	7.82b	5.51	5.77
EC	(mS m^{-1})	14.4	10.0	10.7	12.0	27.6	4.2	7.3
Total C	(g kg^{-1})	45.0	58.4	55.6	36.6	32.0	52.4	32.2
Total N	(g kg^{-1})	3.6	4.4	4.5	3.0	2.8	3.7	3.0
C/N ratio	(cmol$_c$ kg^{-1})	12.4	13.7b	12.4ab	12.1ab	11.5a	14.2	10.7
CEC	(cmol$_c$ kg^{-1})	21.5	27.8ab	27.8b	17.5ab	14.8a	21.7	15.6
Exch. Ca	(cmol$_c$ kg^{-1})	10.81	12.7	13.8	8.12	11.0	4.28	7.31
Exch. Mg	(cmol$_c$ kg^{-1})	3.72	5.02	4.10	2.86	3.44	3.04	2.69
Exch. K	(cmol$_c$ kg^{-1})	1.16	1.14	0.98	1.36	1.26	1.11	1.11
Exch. Na	(cmol$_c$ kg^{-1})	0.10	0.01	0.01	0.03	0.35	0.01	0.01
Exch. Al	(cmol$_c$ kg^{-1})	0.01	0.01	0.01	0.02	0.01	0.00	0.00
Exch. H	(cmol$_c$ kg^{-1})	0.06	0.05	0.05	0.05	0.05	0.13	0.03
Exch. NH_4-N	(cmol$_c$ kg^{-1})	0.07	0.07	0.06	0.07	0.09	0.07	0.06
Al saturation	(%)	0.1	0.0	0.0	0.2	0.0	0.0	0.0
Available P	(mg kg^{-1})	10	6	3	16	18	2	8
Clay	(%)	27	30	28	27	23	37	28
Silt	(%)	40	50	44	37	29	42	38
Sand	(%)	33	21	29	36	48	22	34
Bulk density	(Mg m^{-3})	1.0	0.9	0.9	1.1	1.1	1.0	1.3
Soil hardness	(mm)	13	13	11	14	14	13	12
				Subsurface 20–25 cm soils				
pH(H_2O)		6.90	6.76	7.01	6.59	7.57	5.17	6.91
pH(KCl)		5.91	5.73	5.84	5.70	6.76	4.19	5.71
EC	(mS m^{-1})	3.1	3.2	2.5	2.9	4.5	1.4	2.5
Total C	(g kg^{-1})	19.9	25.1	23.2	18.9	14.8	21.1	13.1
Total N	(g kg^{-1})	1.8	2.3	2.2	1.6	1.4	1.9	1.5
C/N ratio	(cmol$_c$ kg^{-1})	10.7	11.0	10.7	11.5	10.4	11.1	8.7
CEC	(cmol$_c$ kg^{-1})	12.2	16.3	14.3	13.1	8.5	12.6	12.7
Exch. Ca	(cmol$_c$ kg^{-1})	5.13	5.43	6.91	4.35	5.03	0.35	4.54
Exch. Mg	(cmol$_c$ kg^{-1})	2.05	3.19	2.38	1.91	1.58	0.39	1.21
Exch. K	(cmol$_c$ kg^{-1})	0.50	0.54	0.35	0.66	0.57	0.32	0.32
Exch. Na	(cmol$_c$ kg^{-1})	0.02	0.01	0.01	0.01	0.04	0.01	0.01
Exch. Al	(cmol$_c$ kg^{-1})	0.13	0.15	0.04	0.05	0.00	1.29	0.00
Exch. H	(cmol$_c$ kg^{-1})	0.09	0.07	0.06	0.08	0.08	0.36	0.09
Exch. NH_4-N	(cmol$_c$ kg^{-1})	0.04	0.04	0.04	0.05	0.04	0.04	0.03
Al saturation	(%)	4.5	4.9	0.4	1.0	0.0	53.7	0.0
Available P	(mg kg^{-1})	1	1	1	1	1	1	3
Clay	(%)	19	21	17	22	17	18	17
Silt	(%)	37	40	45	41	25	29	36
Sand	(%)	45	39	38	38	58	52	46
Bulk density	(Mg m^{-3})	1.1	1.0	1.0	1.1	1.2	1.0	1.2
Soil hardness	(mm)	21	21	21	22	21	23	20

Annual crops include three cabbage and one maize sites. Al saturation, percentage of exchangeable Al to the sum of exchangeable bases and Al. Soil hardness was measured using a Yamanaka-type penetrometer. Values in the same row followed by different letters are significantly different at $P < 0.05$ (Scheffe's multiple comparison test).

Table 5. Comparison of selected soil properties between sampling points.

		Lychee (granite soils, *n*=4)			Orange (limestone soils, *n*=3)		
Sampling point		Middle	Fertilizer	Ratio	Middle	Fertilizer	Ratio
Total N	(g kg^{-1})	2.1	2.0	0.9	3.0	2.7	0.9
Exch. Ca	($cmol_c$ kg^{-1})	1.99	3.54	1.8	8.12	6.34	0.8
Exch.Mg	($cmol_c$ kg^{-1})	1.31	1.45	1.1	2.86	1.87	0.7
Exch.K	($cmol_c$ kg^{-1})	0.48	0.61*	1.3	1.36	2.11*	1.6
Exch. NH_4-N	($cmol_c$ kg^{-1})	0.06	0.06	0.9	0.07	0.17	2.3
Available P	(mg kg^{-1})	2	15*	9.8	16	189**	11.6

Middle, middle points between fruit trees; Fertilizer, fertilizer applied circles around fruit trees; Ratio, the ratio of a property at the fertilizer to that of the middle. * and ** indicate a significant difference between the middle point and fertilizer applied circle at $P < 0.05$ (paired *t*-test).

remnant forest within the limestone area, further investigations cannot be conducted. However, judging from a comparison of the data presented in Tables 2 and 4 and a comparison of the clay mineral composition determined for the subsurface soil from this site with the other sites, the soil properties of the remnant forest are thought to be in limestone soils.

For shale soils, although the sites were few, the relation of the soil properties between the forests and orange orchard was similar to that of the granite and limestone soils. The subsurface soils under the oolong tea gardens (9-11 years old) were rich in total C and N and less compacted than those under the forests and orange orchard, probably because of the contribution of the dense root distribution under densely planted trees.

Soil properties at fertilizer applied points in lychee and orange orchards

Table 5 respectively compares selected soil properties between the sampling points with and without fertilizer application for the lychee orchards with granite soils and orange orchards with limestone soils. Among the soil nutrients, only the levels of exchangeable K and available P were significantly higher at the points where fertilizer had been applied than at the middle points between the fruit trees. The accumulation of available P at the points where fertilizer had been applied was conspicuous in comparison with exchangeable K.

DISCUSSION

General characteristics of soils studied

Turkelboom et al. (2008) compiled soil erosion processes and severities caused by land use intensification in northern Thailand. Based on our field observations, however, the studied soils seemed sufficiently deep to provide a sufficient rooting zone for crops. The evidence of rill and gully erosion and landslide was not found even in annual crop fields with tillage management, which might be ascribable partially to the short history of adoption of cash crop farming and conversion directly from miang tea planting under forest shading.

Soil texture classes and clay mineral compositions differed between those of soils originating from granite and those from limestone and shale. Similar compositions of clay minerals were reported in results from earlier studies in Thailand (limestone in Ogawa et al. 1981; granite in Yoshinaga et al. 1989; limestone in Yoothong et al. 1997; granite and shale in Watanabe et al. 2006). In the present study, in addition to the dominance of kaolin minerals and quartz, mica minerals and chlorite were detected as accessory components in the granite soils, suggesting that the weathering status of the soils were not very strong, probably because of their locations on steep slopes. This view of the weathering status of granite soils coincided with that of Funakawa et al. (1997a) who studied granite soils under fallow forests in the Mae Hong Song Province. On the other hand, the almost identical clay mineral composition of the limestone and shale soils suggested that similar weathering processes of these sedimentary rocks occurred under almost identical environmental conditions.

Figure 2 portrays the relation between total N and CEC. Total N was used to represent soil organic matter because total C determined in this study might include inorganic C under high soil pH conditions. As this figure shows, the CEC were highly correlated with total N in both soil layers. The correlation was also valid when the relation was assessed within soils originating from each parent material (data not shown). This figure also clearly depicts that the levels of total N and CEC were higher in both layers of the limestone soils than in those of granite

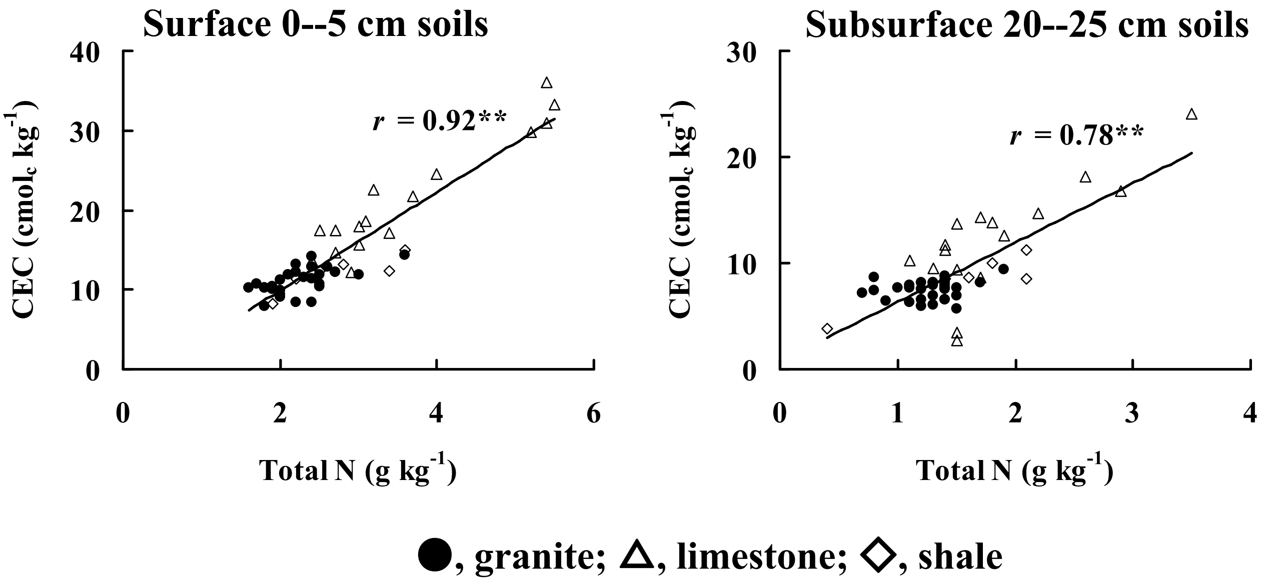


Fig. 2. Relation between total N contents and CEC values.

and shale soils. In addition, the effective CEC (ECEC; the sum of exchangeable bases and Al) was markedly higher in limestone soils: 5.8, 15.9, and 6.0 $\mathrm{cmol_c\ kg^{-1}}$ on average in the surface layers and 2.9, 7.9, and 3.8 $\mathrm{cmol_c\ kg^{-1}}$ in the subsurface layers of granite soils, limestone soils and shale soils, respectively. In contrast, no correlation was found between clay contents and CEC. Therefore, higher CEC and ECEC values of the limestone soils might be ascribed to higher amounts of variable negative charges derived from soil organic matter and their development under higher soil pH conditions. In contrast to the results for subsurface soils obtained in this study, Funakawa et al. (1997a) found the positive correlation between clay contents and CEC values for subsurface 30-40 cm soils, including those originating in fine-textured sedimentary rocks and granites. This discrepancy might be explained by soil characteristics in their study, which included a wider range of clay contents, from 13-66%, and the depth of 30-40 cm, which was less affected by soil organic matter. The latter might present a clear relation of CEC with increasing clay contents. For surface soils (0-10 cm depth), in agreement with the present study, they found a highly positive correlation between total C contents and CEC values and inferred that soil organic matter contents primarily determine the capacity of the soils to retain basic cations, irrespective of the variation in soil texture and clay mineralogy. Although the higher organic matter contents in the limestone soils remains unexplained, favorable soil fertility condition without toxicity of Al on plant roots might enhance the primary production of plants to supply more fresh organic matter to soils. However, it is noteworthy that the C/N ratio in the subsurface layer of the limestone soils was lower than those of the granite and shale soils, indicating the well-decomposed status of soil organic matter in the limestone soils. Because few studies related to limestone soils and comparative studies of soil properties from different parent materials have been done, additional investigation is necessary to elucidate the effects of different soil texture and clay mineralogy on CEC values and the presumed difference in soil organic matter decomposition process between limestone soils and granite soils.

Soil fertility status under different land uses in the granite area

A principal component analysis (PCA) was performed of the physicochemical properties of granite soils (Excel Statistics ver. 2008 for Windows; SRI, Tokyo, Japan; Table 6, Fig. 3) to grasp the overall tendencies under different land uses. The cumulative contribution of the first and second principal components (PC1 and PC2) was about 60% for each layer. The contribution of the third component (PC3) was about 10%. However, because no tendency related to land use was found, the PC 3 is omitted from further discussion. As presented in Table 6, each PC 1 and PC2 showed similar factor loadings in the surface soils to those in the subsurface soils. The PC1 showed high positive factor loadings for pH, exchangeable Ca, Mg, and K and available P and high negative factor loadings to exchangeable Al and H and clay content, except for exchangeable K and clay content in the subsurface soils. Consequently, the PC1 of both soil layers represented soil acidity and nutrient status affected by fertilizer application. On the other hand, in the PC2, the factor loadings of the surface soils were positive and high for total N, CEC and exchangeable NH_4-N and negative and high for bulk density, although those in the subsurface soils were positive and high for total N and exchangeable NH_4-N and negative and high for exchangeable K, sand content, bulk density and soil hardness. The PC2 seemed to reflect mainly the soil condition related to organic matter and physical properties as a result of field managements such as tillage. The site scores of the PCA analysis show the distinctive allocation of the study sites depending on the land use type and the management practices (Fig. 3). Based on the allocation along the PC1 and PC2, the granite soils are classifiable into three groups: forest-type soils (remnant forest, secondary forest, miang tea garden and lychee orchard), soils of annual crop fields, and soils of home gardens.

Table 6. Factor loadings of physicochemical properties of granite soils in PCA analysis.

	PC1		PC2	
	Surface	Subsurface	Surface	Subsurface
Contribution	39%	35%	22%	23%
pH(H_2O)	0.90	0.85	0.02	-0.34
pH(KCl)	0.88	0.88	0.23	-0.08
EC	0.61	0.78	0.63	0.46
Total C	-0.66	0.04	0.43	0.53
Total N	-0.42	0.30	0.70	0.71
C/N ratio	-0.44	-0.37	-0.44	-0.32
CEC	-0.12	0.41	0.77	0.06
Exch. Ca	0.80	0.91	0.31	0.06
Exch. Mg	0.76	0.91	0.32	-0.24
Exch. K	0.72	0.52	0.16	-0.63
Exch. Na	0.44	0.35	0.55	0.29
Exch. Al	-0.83	-0.81	0.25	0.31
Exch. H	-0.84	-0.82	0.26	0.35
Exch. NH_4-N	0.18	0.11	0.77	0.66
Available P	0.64	0.71	0.31	0.17
Clay	-0.71	-0.49	0.27	0.36
Silt	0.33	0.40	0.30	0.57
Sand	0.52	0.13	-0.51	-0.78
Bulk density	0.55	-0.11	-0.63	-0.84
Soil hardness	0.35	-0.51	-0.55	-0.62

The forest-type soils can be characterized by a strongly acidic nature with lower contents of exchangeable bases and available P. The plots of the secondary forests and miang tea gardens differed greatly. Ash and charcoal deposition observed over the soil surface at some of these sites, reflecting the influences of fires and resultant ash addition, might explain the large variation. Compared with the results presented for this study, granite soils under fallow forests in shifting cultivation cycles, reported by other researchers, showed higher pH values with higher contents of exchangeable Ca and Mg (Nakano, 1978; Funakawa et al. 1997a). This might be ascribed to the effects of periodic ash input from burning in shifting cultivation practices to alleviate soil acidity and increase the contents of exchangeable Ca and Mg in the surface layer (Funakawa et al. 1997a; Tanaka et al. 1997; Boonyanuphap et al. 2007).

The annual crop field soils showed the highest PC1 scores, followed by soils of the home gardens, reflecting the less acidic nature and nutrient accumulation as a result of fertilizer application. The levels of available P of these two soil groups also tended to be high (Table 3). In dry evergreen and mixed deciduous forests at altitudes of 280-530 m a.s.l. in northern Thailand, Boonyanuphap et

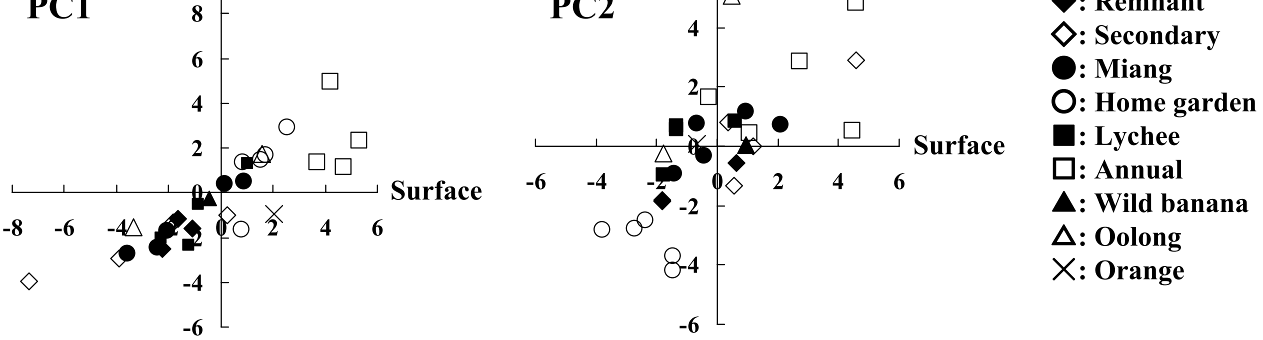


Fig. 3. Site scores of PC1 and PC2 for granite soils.

al. (2007) were not able to detect the influences of cash crop farming on soil fertility well in comparison with remnant and secondary forests because of the effects of fire invasion occurring every year, which seemed to conceal the effects of fertilizer application. Compared with severe dry conditions and the resultant frequent occurrence of fires at the lower altitudes, the area in this study, which was at a higher altitude, might be less susceptible to fire influences. Plots of subsurface soils in home garden soils were allocated similarly to those of the surface soils in spite of the small amounts of applied fertilizer. Lattirasuvan et al. (2010) examined soil properties of home gardens located at about 200 m a.s.l. in the Phrae Province of northern Thailand and reported that soil nutrient status was high down to deeper soil layers, although their home garden showed even higher soil fertility, probably because of higher fertilizer application rates. Their results suggested several mutually interacting factors to interpret their findings: 1) location of home gardens on almost flat land, which prevents soils from nutrient loss caused by erosion or runoff water and which allows nutrients to move to deeper soil layers; 2) higher bulk density values, resulting in lower water permeability to prevent the excess losses of nutrients resulting from leaching downward; and 3) nutrient sources aside from fertilizers such as direct drainage of wastewater from bathrooms or laundry areas and ash input derived from burning fuel wood and garbage and producing charcoal.

In contrast to their similarity in the site scores of the PC1, the site scores of the annual crop fields and the home gardens were shown oppositely along the PC2. The forest-type soils showed intermediate PC2 scores between them. Higher PC2 scores were obtained for the surface and subsurface soils of the annual crop fields, indicating better soil physical properties for crops by tillage management. In addition, in the annual crop fields, the total C contents of the surface soils and the total N contents of the subsurface soils tended to be low and high, respectively, resulting in lower C/N ratios in both layers (Table 3), which might be ascribed to interaction of mixing surface and subsurface soils by tillage and stimulating soil organic matter decomposition because of improved aeration. In contrast, the surface and subsurface soils of home gardens showed lower PC2 scores, reflecting soil compaction throughout soil profiles. Other land uses, one wild banana stand, two oolong tea gardens and one orange orchard were apparently classified in either the forest-type group or the annual crop group.

Soil fertility status under different land uses in the limestone area

In contrast to the granite soils, the effects of different land uses on soil fertility were not evident in limestone soils. However, the annual crop fields and orange orchards tended to be low in total C and total N in both layers, resulting in lower CEC values. The C/N ratio of the surface soils was lower in the annual crop fields than in soils related to other land uses. Funakawa et al. (1997b) investigated soil organic matter under shifting cultivation on sedimentary rocks (Paleozoic shale) and found that the levels of soil organic C under continuous cropping were lower, with a lower C/N ratio, than fallow forests because of rapid decomposition of soil organic matter and less organic matter input from plants to soils. Although appreciable amounts of NP fertilizer were applied in the annual crop fields, the levels of total N and exchangeable NH_4 were not different from those at the middle points (no fertilizer application) of the orange fields. In annual crop fields, at least on limestone soils, fertilizer N seemed not to contribute effectively to the build up of total N and ammonium N.

The Hmong people, one ethnic group in northern Thailand, who had been notorious for opium production on limestone soils by shifting cultivation practices, reportedly used their lands for cropping until soil fertility was 'exhausted' (Kunstadter and Chapman, 1978). Knowing that the level of exchangeable K was not lowered in the annual crop fields without fertilizer K input, N, or P depletion might be one reason for such exhaustion under conditions without fertilizer application.

Although the soil pH level was significantly higher in annual crop fields than in orange orchards, we were unable to find any explanation for this difference.

Effects of fertilizer application in fruits orchards

The fertilizer application rates for orange orchards were comparable to those for annual crop fields on the site scale basis, whereas those for lychee orchards were low (Table 1). However, it is noteworthy that in case of fruit tree orchards (orange and lychee) fertilizer application was concentrated around trees, resulting in several times higher rates on the fertilizer application point basis.

When comparing soil properties in terms of sampling points, fertilizer P, and K to a lesser extent, was accumulated to the soils at points where fertilizer had been applied, irrespective of parent materials (Table 5). In addition to P and K, exchangeable Ca and exchangeable NH_4 were each high at the points where fertilizer had been applied in the lychee orchards and the orange orchards. For granite soils, soil pH and exchangeable Ca at the middle points between the trees tended to be higher under the fruit orchards (orange and lychee) than in the other forest-type soils (Table 3). However, in limestone soils, only available P tended to be higher under the orchards than in soils associated with other land uses (Table 4). These differences suggest respectively different fates of fertilizer nutrients in granite soils and limestone soils. Additional studies should be made of the movement of fertilizer nutrients in relation to soil parent materials. In cases of orange orchards, where the application rates were considerably higher than in the lychee orchards, efficient and effective methods of fertilizer application are necessary to prevent loss of nutrients and to avoid unnecessary accumulation of P in the soils.

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