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Research paper

Estimation of Soil Organic Carbon Stocks in Plantation Forest Soils of Northern Taiwan

Chen-Chi Tsai,[1)] Ting-En Hu,[2)] Kuo-Chuan Lin,[3)] Zueng-Sang Chen[2,4)]

【Summary】

The possibility of estimating the global carbon pools on the earth has attracted scientists for decades. In Taiwan, among remaining forested areas, 14% (about 420,000 ha) are plantation forests. There are few investigations of the soil organic carbon (SOC) pool of plantation forests in Taiwan. Nine plantation tree species, including 3 broadleaf species and 6 coniferous species were selected to estimate the SOC pools in selected plantation forest soils in northern Taiwan. The uncertainty of the estimates was examined, and strategies to obtain more-precise database for SOC pool management are proposed in this study. The results showed that only 2 Soil Orders, Inceptisols and Ultisols, were found at the study sites, and values of the soil bulk density (Bd) in broadleaf plantation forests were relatively higher than those in coniferous plantation forests. The stone contents were about 17 and 14% (0~30 cm) on average in the broadleaf and coniferous plantations, respectively. The average SOC was about 28 g kg^{-1} (0~30 cm) in the broadleaf plantations and about 48 g kg^{-1} (0~30 cm) in the coniferous plantations. The SOC pool was lowest in the *Aleurites fordii* plantation forest and highest in the *Chamaecyparis obtusa* plantation forest. We calculated that the average values of the SOC pool in the broadleaf plantation forest were about 6.5 (0~30 cm), 8.2 (0~50 cm), and 9.6 kg m^{-2} (0~100 cm). In coniferous plantation forests, they were about 7.4, 9.7, and 12 kg m^{-2}, respectively. Estimation of the SOC pools in this study was potentially compromised by measurement errors of soil Bd, soil volume calculations, C determinations, and the stoniness of the soils. These sources of error might have introduced a bias, when comparing SOC contents among studies in the literature where different methodologies were applied. In conclusion, we suggest that the database of lower taxonomic categories (i.e., greater detail) for Soil Taxonomy and the SOC variability within and among pedons of the same soil type strongly need estimates of soil C stocks in Taiwan.

Key words: soil organic carbon stocks, carbon sequestration, forest soils, plantation forest.

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[1)] Department of Natural Resources, National I-Lan University, 1 Shen-Lung Rd., Sec. 1, Ilan 26047, Taiwan. 國立宜蘭大學自然資源學系，26047宜蘭市神農路一段1號。

[2)] Department of Agricultural Chemistry, National Taiwan University, 1 Roosevelt Rd., Sec. 4, Taipei 10617, Taiwan. 國立台灣大學農業化學系，10617台北市羅斯福路四段1號。

[3)] Division of Silviculture, Taiwan Forestry Research Institute, 53 Nanhai Rd., Taipei 10066, Taiwan. 林業試驗所育林組，10066台北市南海路53號。

[4)] Corresponding author, e-mail:soilchen@ntu.edu.tw 通訊作者。

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研究報告

臺灣北部地區人工林土壤碳存量的估算

蔡呈奇[1)] 胡庭恩[2)] 林國銓[3)] 陳尊賢[2,4)]

摘 要

幾世紀以來，探索地球上全球性碳儲存量的可能性引起科學家的注意。臺灣地區餘留的森林地中，有14% (約420,000 ha)的面積為人工林，但這些人工林下土壤有機碳存量的資料或調查作業很少受到注意與研究。本研究在臺灣北部地區共選取9種人工林樹種，包括3種闊葉樹種與6種針葉樹種，於林下採集土壤樣本進行分析並推估該人工林下土壤之有機碳存量。另外，為了土壤有機碳庫的管理目標，本研究也一併探討推估的不確定性因素與提出獲得更準確資料庫的策略。研究結果指出：研究區的土壤樣體只分類為弱育土(Inceptisols)與極育土(Ultisols)兩種土綱；闊葉樹人工林之土壤總體密度相對較高於針葉樹人工林。在闊葉樹與針葉樹人工林中的平均土壤含石率(0~30 cm)分別約為17與14%。闊葉樹人工林下平均的土壤有機碳含量為28 g kg^{-1} (0~30 cm)，在針葉樹人工林下則為48 g kg^{-1} (0~30 cm)。土壤有機碳存量以油桐人工林存量最低，臺灣扁柏人工林存量最高。經計算推估之後我們得到闊葉樹人工林土壤有機碳存量的平均值為6.5 kg m^{-2} (0~30 cm)、8.2 kg m^{-2} (0~50 cm)與9.6 kg m^{-2} (0~100 cm)，針葉樹人工林土壤有機碳存量的平均值則分別為7.4、9.7與12 kg m^{-2}。由於土壤總體密度、土壤體積的計算、土壤碳存量的測定與土壤含石量等野外採樣及測量上的誤差，本研究之土壤有機碳儲存量的推估受到潛在性的限制。當比較文獻中土壤的碳含量，由於使用不同的方法，這些誤差的來源可能產生偏差性。我們建議在土壤分類系統中較低階(更詳細)的土壤分類等級與相同土壤類型之土壤剖面內部與剖面之間的土壤有機碳的變異，在未來推估臺灣地區土壤碳儲存量時是絕對必要的資料庫。

關鍵詞：土壤有機碳存量、碳吸存、森林土壤、人工林。

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INTRODUCTION

The possibility of estimating global carbon pools on the earth has attracted scientists for decades. The greenhouse effect, resulting in global consequences of climate alterations, has induced scientists to more-intensely study the global carbon (C) cycle (Lal et al. 1999, 2004, Kondratyev et al. 2003, Lal 2004). Also, global concern has increased over greenhouse gas emissions and their potential impacts on climate change over the past decade. As a result, an international agreement, the *Kyoto Protocol*, was signed to mitigate greenhouse gas concentrations in the atmosphere through improving terrestrial carbon sinks. The soil is important in sequestering atmospheric CO_2 and emitting trace gases (e.g., CO_2, CH_4, and N_2O) that are radiatively active and enhance the 'greenhouse' effect (Batjes 1996). Global C contents in soils have been estimated. Globally, 1576 Pg (petagram = 10^{15} g) of C is stored in soils, with about 506 Pg of this in soils of the tropics, with about 40% of the C in soils of the tropics in forest soils (Eswaran et al. 1993). Batjes (1996) calculated that total soil carbon pools for the entire land area of the world, excluding carbon held in the litter layer and charcoal, amounts to 2157~2293 Pg of C in the upper 100 cm; soil organic carbon (SOC) is estimated to be 684~724 Pg of C in the upper 30 cm, 1462~1548 Pg of C in the upper 100 cm, and 2376~2456 Pg of C in the upper 200 cm.

Estimates of the stored C in soils of Taiwan are scarce before the 1990s. Chen and Hseu (1997) first reported that the estimated total SOC pool was about 347 Tg (teragram = 10^{12} g) (123 Tg for cultivated soil and 224 Tg for forest soil), stored in the top 1 m of soils in Taiwan. This value was calculated from a database of 172 soil pedons of cultivated and forest soils in Taiwan. Tsai and Chen (2002) calculated the SOC pools of forest soils in Taiwan, according to 101 representative soil pedons and a regression model of SOC contents and the distribution of major soil groups of forest soils in a soil survey report in Taiwan, were about 464 Tg in the upper 1 m of soil depth from the soil surface. The results of these 2 reports showed different SOC pools in forest soils of Taiwan and indicated that some uncertainties or errors for estimating SOC pools exist.

In Taiwan, forests cover almost 2/3 of the total area of the island and 1/3 of these lands are monoculture forests planted several decades ago. Among the remaining forested area, 14% (about 420,000 ha) of the area are plantation forests. Most plantations were established about 50 yr ago with *Cryptomeria japonica* (L.F.) D. Don and *Cunninghamia lanceolata*. Also, native species, such as *Chamaecyparis formosensis* Matsum., *Taiwania cryptomerioides* Hayata, *Calocedrus macrolepis* var. *formosana* (Florin) W.C. Cheng & L.K. Fu, *Fraxinus formosana*, and *Zelkova formosana* Hay., were used in plantations since the 1960s. SOC stocks of plantation forests in Taiwan are less studied. The objectives of this article were (1) to estimate SOC stocks in selected plantation forest soils in northern Taiwan (including Taipei, Taoyuan, Hsinchu, Miaoli, and Ilan Counties), and (2) to examine the uncertainty of estimates and propose strategies to obtain a more-precise database for SOC stock management in Taiwan.

MATERIALS AND METHODS

Description of the study sites

The locations of the study sites are shown in Figure 1, and include Gandaoshan (GDS), Jiouhuashan (JHS), Sihmashan (SMS), Fushan (FS), Pinglin (PL), Taipingshan (TPS),

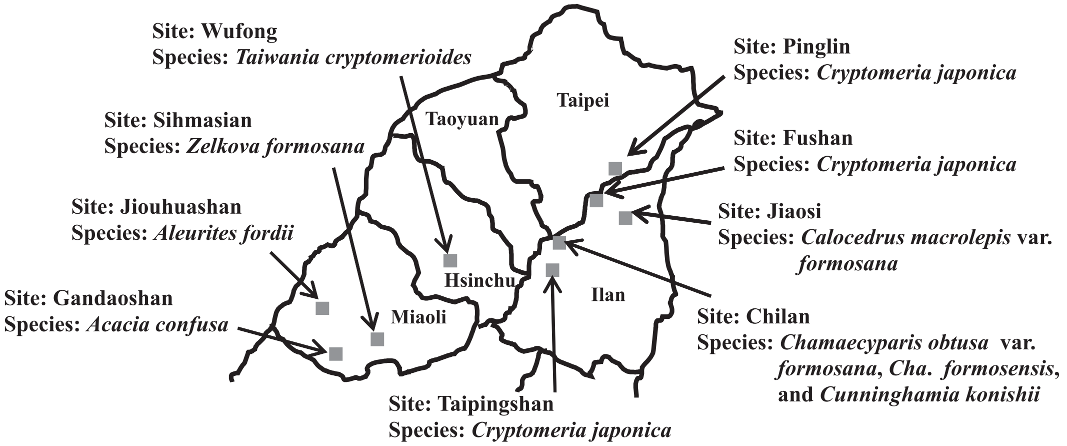

Fig. 1. The location of sampling sites in 9 species in plantation forests of northern Taiwan.

Wufong (WF), Cilan (CL), and Jiaosi (JS). Of the 9 study sites, GDS, JHS, SMS, and WF are located in northwestern Taiwan, and the others (FS, PL, TPS, CL, and JS) are located in the northeastern part. Nine plantation tree species, including 3 broadleaf species (*Acacia confusa* Merr. (aged 50 yr) in GDS, *Aleurites fordii* (20 yr) in JHS, and *Z. formosana* (27 yr) in SMS) and 6 coniferous vegetation species (*Cry. japonica* (20 yr in FS, 40 yr in PL, and 51 yr in TPS), *T. cryptomerioides* (10 yr) in WF, *Cha. obtusa* Siebold & Zucc. var. *formosana* (Hayata) Rehder (37 yr) in CL1, *Cunninghamia konishii* Hayata (16 yr) in CL2, *Cha. formosensis* (16 yr) in CL3, and *Cal. macrolepis* var. *formosana* (Florin) W.C. Cheng & L.K. Fu (30 yr) in JS were selected at the 9 study sites (Fig. 1) (Table 1). The elevations of the study site ranged 195 (JHS) to 1950 m (TPS). According to the database of the Central Weather Bureau, Taiwan, the lowest mean annual temperature (MAT) was found at TPS (13.5℃), and the highest was at JHS (21.8℃). The mean annual precipitation

Table 1. Locations and climatic characteristics of selected plantation tree species

Tree species	Stand age	Sampling site1)	Longitude, Latitude	MAT2)	MAP3)
	(yr)			(℃)	(mm yr^{-1})
Broadleaf trees					
Acacia confusa	50	GDS	23°29’56”N, 120°49’43”E	20.2	2300
Aleurites fordii	20	JHS	24°27’32”N, 120°44’32”E	21.8	1850
Zelkova formosana	27	SMS	24°24’22”N, 120°18’23”E	17.1	2700
Coniferous trees					
Cryptomeria japonica	20	FS	24°45’13”N, 121°37’03”E	20.7	3200
Cryptomeria japonica	40	PL	24°52’25”N, 121°46’09”E	19.5	3250
Cryptomeria japonica	51	TPS	24°25’12”N, 121°37’13”E	13.5	2700
Taiwania cryptomerioides	10	WF	24°32’11”N, 121°49’17”E	18.6	2500
Chamaecyparis obtusa var. *formosana*	37	CL1		14.0	2800
Cunninghamia konishii	16	CL2	24°37’10”N, 121°29’40”E	16.3	3250
Chamaecyparis formosensis	16	CL3	24°37’10”N, 121°29’40”E	16.3	3250
Calocedrus formosana	30	JS		19.8	2800

1) GDS, Gandaoshan (關刀山); JHS, Jiouhuashan (九華山); SMS, Sihmasian (司馬限); FS, Fushan (福山); PL, Pinglin (坪林); TPS, Taipingshan (太平山); WF, Wufong (五峰); CL, Chilan (棲蘭); JS, Jiaosi (礁溪).

2) MAT, Mean annual temperature (Central Weather Bureau, Taiwan).

3) MAP, Mean annual precipitation (Central Weather Bureau, Taiwan).

(MAP) ranged 1850 (JHS) to 3250 mm (PL and CL).

Environmental characteristics of the study sites

As shown in Table 2, elevations of study site ranged from a lowland (elevation < 200 m) site to a temperate site (elevation about 2000 m). At the 11 sampling sites, 4 sites (JHS, FS, PL, and JS) were at < 500 m, 5 sites (GDS, SMS, WF, CL2, and CL3) were at 500~1500 m, and 2 sites (TPS and CL3) were at > 1500 m. The site slopes ranged from 5° to 25° (about 10~48%). The slope distribution of studied sites indicated one of the characteristics of forests in Taiwan, that is, steep slope (16°~25°) were evident.

According to the MAT and MAP in Table 1, the soil moisture regime (SMR) of the sampling sites was udic or perudic, and the soil temperature regime (STR) was mostly thermic, but was mesic at TPS and CL1 based on the USDA Soil Taxonomy System (Soil Survey Staff 2006). Parent materials are sandstone-shale, shale, and slate. Based on the soil morphological, physical, and chemical characteristics, such as soil color, soil structure, clay fraction distribution, and base saturation percentage, only 2 Soil Orders, Inceptisols (at GDS, SMS, FS, WF, CL2, CL3, and JS) and Ultisols (at JHS, PL, TPS, and CL1) were classified.

Collection of soil samples

Three soil profiles were examined in each plantation forest to at least to 1 m from the soil surface, or to the bed rock if the soil profile was < 1 m. Totally, 33 soil profiles were sampled. Five layers of each soil profile were collected, including 0~15, 15~30, 30~50, 50~75, and 75~100 cm. The stone content (%) of each soil layer was estimated according to the occupied volume percentage of fragments > 2 mm in about 2 kg of collected soil (v/w). Also the soil core (7.6 cm in diameter and 7.6 cm in height) was carefully collected to avoid soils with stones and coarser roots in each soil layer for estimating soil Bd. About

Table 2. Environmental characteristics of soils and soil classifications at each sample site

Sample site[1]	Elevation (m)	Slope (°)	Aspect (°)	SMR[2]	STR[3]	Parent material[4]	Soil Order
GDS	700	25	250	udic	thermic	SS-shale	Inceptisols
JHS	195	10	270	udic	thermic	SS-shale	Ultisols
SMS	1150	25	20	udic	thermic	SS-shale	Inceptisols
FS	300	20	60	perudic	thermic	Shale	Inceptisols
PL	490	25	0	perudic	thermic	SS-shale	Ultisols
TPS	1950	25	0	perudic	mesic	Slate	Ultisols
WF	1200	15	280	udic	thermic	Slate	Inceptisols
CL1	1710	5~25	40	perudic	mesic	Slate	Ultisols
CL2	1110	5	350	perudic	thermic	Slate	Inceptisols
CL3	1100	10	10	perudic	thermic	Slate	Inceptisols
JS	230	15	220	perudic	thermic	Slate	Inceptisols

[1] Sample sites are defined in the footnotes of Table 1.

[2] SMR, soil moisture regime (Soil Survey Staff, 2006).

[3] STR, soil temperature regime (Soil Survey Staff, 2006).

[4] SS, sandstone.

2 kg soil in each soil layer was collected, air-dried, passed through a 2-mm sieve, and stored in the laboratory for soil analysis, after exclusion of the litter layer. Environmental characteristics, including slope and aspect around each soil profile, were also recorded.

Soil analysis

The physical and chemical analyses of the air-dried soil are briefly described as follows. The pipette method was used to determine the particle size distribution (Gee and Bauder 1986), and the soil texture was classified according the USDA system (Soil Survey Staff 2006). The core method was used to determine the Bd (Blake and Hartge 1986). The pH was measured using a mixture of soil and deionized water (1:1, w/v) and 1 M KCl (1:1, w/v) with a glass electrode (McLean 1982). The total SOC content was determined by the Walkley-Black wet oxidation method (Nelson and Sommer 1982).

Calculating the SOC pool of individual soil pedons

For an individual soil pedon with k layers, the total SOC content by volume basis can be expressed as follows:

$$T_d = \sum_{i=1}^{k} \rho_i P_i D_i (1 - S_i); \qquad (1)$$

where T_d denotes the total amount of organic carbon (Mg m^{-2}) per unit area over depth d, ρ_i represents the Bd (Mg m^{-3}) of layer i, P_i is the proportion of OC (g C g^{-1} soil) in layer i, D_i denotes the thickness of this layer (m), and S_i represents the volume of the fraction of fragments > 2 mm (in diameter), particularly for calculating the soil carbon of forest soils.

RESULTS AND DISCUSSION

Characteristics of selected soils

The soil pH (H_2O) ranged from 3.6 to 4.8, being classified as extremely acidic (pH 3.5~4.4) and very strongly acidic (pH 4.5~5.0) (Table 3). No trends were found between soil pH and tree species, or soil pH and the elevation of the sampled soils. Total contents of sand, silt, and clay suggested the influence of parent material on soil formation. Higher total sand contents were found at the GDS, JHS, SMS, and PL sites, the soils of which formed on sandstone-shale parent materials. On the contrary, soils formed on slate parent material had lower sand contents but higher clay contents. Both GDH and JHS sites had a coarse soil texture (sandy clay loam or sandy loam), and soils sampled from TPS, WF, CL, and JS all had a clayey soil texture.

The soil Bd gradually increased from the surface layer to the subsurface layer in all soils (Table 3), and this could be attributed to the higher organic matter accumulation in the surface soil. We also found that the Bd in the broadleaf plantations, including GDS, JHS, and SMS, sites were all relatively higher than those of coniferous plantations. The average Bd in the broadleaf and coniferous plantations were respectively 0.97 and 0.73 Mg m^{-3} at 0~30 cm in depth. In addition, the correlation between the Bd of the surface soil (0~30 cm) and the elevation of a study site was significantly negative ($r = -0.5338$, $p < 0.05$). For different Soil Orders, the average Bd at 0~30 cm in depth was 0.77 Mg m^{-3} in Inceptisols, and 0.87 Mg m^{-3} in Ultisols. The results of this study are lower than previous studies in Taiwan. Chen and Hesu (1997) proposed that the average Bd values of Inceptisols and Ultisols at 0~30 cm in depth of forest soils were 0.94 and 1.31 Mg m^{-3}, respectively. Tsai and Chen (2002) and Tsai et al. (2007) both found similar values. Different forest types, sampling sites, numbers of samples, and environmental characteristics can explain difference in soil Bd between these study and previous

Table 3. Selected soil characteristics under different tree species

Depth	pH		Total			Soil	Bd2)	O.C3)	Stone
(cm)	H_2O	KCl	Sand	Silt	Clay	texture1)			content
			------------	(%)	------------		(Mg m^{-3})	(g kg^{-1})	(%)
				Acacia confusa. (GDS)					
0~15	3.6	3.0	56	18	26	SCL	0.65	62.4	0
15~30	4.1	3.4	53	21	26	SCL	0.90	20.6	10
30~50	4.3	3.4	53	19	28	SCL	1.07	12.6	20
50~75	4.4	3.5	51	21	28	SCL	1.17	7.23	32
75~100	4.6	3.7	49	21	30	SCL	0.80	6.35	8
				Aleurites fordii. (JHS)					
0~15	4.5	3.6	66	17	17	SL	1.19	12.1	27
15~30	4.5	3.5	56	21	23	SCL	1.41	4.75	10
30~50	4.6	3.4	51	29	20	SL	1.55	4.20	0
				Zelkova formosana. (SMS)					
0~15	4.5	3.6	37	29	34	CL	0.82	45.2	10
15~30	4.6	3.6	21	36	43	C	1.09	23.8	37
30~50	4.7	3.7	26	48	26	L	1.31	14.3	45
50~75	4.6	3.7	24	49	27	L	1.15	11.3	40
75~100	4.6	3.7	30	44	27	L	1.30	10.8	60
				Cryptomeria japonica (FS)					
0~15	4.4	3.7	12	42	47	SiC	0.75	43.0	7
15~30	4.5	3.8	13	47	40	SiC	0.81	20.6	43
30~50	4.6	3.8	10	55	35	SCL	1.04	11.8	50
50~75	4.6	3.8	25	40	35	CL	1.08	9.30	70
75~100	4.7	3.8	35	32	32	CL	1.03	9.90	70
				Cryptomeria japonica (PL)					
0~15	4.1	3.5	40	26	33	CL	0.71	34.8	0
15~30	4.4	3.7	42	18	40	CL	1.03	11.9	0
30~50	4.5	3.7	42	24	33	CL	1.17	7.27	12
50~75	4.5	3.8	32	27	42	C	1.17	4.70	22
75~100	4.6	3.8	35	23	42	C	1.20	6.40	70
				Cryptomeria japonica (TPS)					
0~15	4.5	3.3	22	48	30	CL	0.31	118	0
15~30	4.5	3.5	13	47	40	SiC	0.65	33.8	23
30~50	4.6	3.6	4	39	57	SiC	0.78	19.2	25
50~75	4.8	3.7	3	43	54	SiC	0.72	22.8	13
75~100	4.7	3.8	4	45	51	SiC	0.73	17.8	40
				Taiwania cryptomerioides. (WF)					
0~15	4.5	3.6	6	37	57	C	0.70	59.6	0
15~30	4.5	3.6	12	34	54	C	0.76	26.0	3
30~50	4.4	3.6	15	35	49	C	0.89	26.2	7
50~75	4.5	3.7	11	43	45	SiC	1.04	15.9	7

Table 3. Selected soil characteristics under different tree species (con't)

Depth	pH		Total			Soil	$Bd^{2)}$	$O.C^{3)}$	Stone
(cm)	H_2O	KCl	Sand	Silt	Clay	texture[1)]			content
			------------	(%)	------------		($Mg\ m^{-3}$)	($g\ kg^{-1}$)	(%)
				Chamaecyparis obtusa var. *formosana*. (CL1)					
0~15	3.7	3.0	29	43	28	CL	0.60	107	13
15~30	3.9	3.1	22	40	38	CL	1.17	24.3	17
30~50	4.3	3.3	38	29	34	CL	1.27	19.3	20
50~75	4.5	3.3	25	34	41	C	1.27	16.2	33
75~100	4.7	3.5	14	41	46	C	0.73	14.7	30
				Cunninghamia konishii. (CL2)					
0~15	4.0	3.6	8	39	53	C	0.33	111	10
15~30	4.3	3.9	3	47	50	SiC	0.76	48.0	17
30~50	4.6	4.1	7	51	41	SiC	1.02	24.5	27
				Chamaecyparis formosensis. (CL3)					
0~15	4.5	3.9	7	41	52	C	0.68	47.5	10
15~30	4.6	4.2	17	33	50	C	0.88	23.5	50
30~50	4.8	4.2	21	32	47	C	1.11	16.1	80
				Calocedrus formosana (JS)					
0~15	4.2	3.8	4	38	58	C	0.72	30.1	5
15~30	4.2	3.9	4	38	59	C	0.90	16.5	13
30~50	4.3	3.9	5	39	56	C	1.01	13.7	43
50~75	4.3	3.9	17	34	49	C	1.02	9.70	73
75~100	4.4	3.9	17	35	48	C	1.15	9.13	80

1) C, clay; L, loam; CL, clay loam; SCL, sandy clay loam; SiC, silty clay; SL, sandy loam.

2) Bd, bulk density.

3) OC, organic carbon.

(Sample sites are defined in the footnotes of Table 1).

research sites.

In northeastern Taiwan, Chang et al. (2006) reported that the coarse fragment (> 2 mm) content was about 36% (on averaged) at 0~30 cm in depth in a mixed coniferous-broadleaf forest soil. In this study, the stone contents at 0~30 cm in depth in broadleaf and coniferous plantations were about 17±23 and 14±13% (on average), which are lower than the results of Chang et al. (2006). On the other hand, higher stone contents existed in the subsurface soil at all study sites, and this phenomenon is common in forest soils of Taiwan.

In general, the SOC content decreased with soil depth (Table 3). The average SOC content at 0~30 cm in depth was about 28 g kg^{-1} in the broadleaf plantations and 48 g kg^{-1} in the coniferous plantations. The highest soil organic carbon content was found in the coniferous plantations, especially at TPS and CL2 with more than 75 g kg^{-1} at 0~30 cm in depth, which indicates the slow decomposition rate of organic matter in temperate and humid conditions. On the contrary, high temperature and relatively dry conditions at JHS accelerated the decomposition of organic matter and resulted in the lowest SOC. In mixed coniferous-broadleaf forests of northeastern Taiwan, Chang et al. (2006) calculated the average SOC content at 0~10, 10~20, and 20~30 cm to be 298, 90, and 49 g kg^{-1}, respectively. The average SOC content in Inceptisols was about 41 g kg^{-1} for 0~30 cm in depth. In Ultisols, it was 44 g kg^{-1}. Compared to the results of Chen and Hesu (1997), 95 and 19 g kg^{-1} at 0~30 cm in depth for Inceptisols and Ultisols of Taiwan forest soils, much lower SOC contents in Inceptisols and much higher SOC contents in Ultisols were found in this study. Differences were attributed to the different database on soil sampling number and spatial variations in soil properties.

SOC stocks

Table 4 shows that SOC stocks exhibited significant differences among the 9 plant species ($p < 0.05$), but there were no significant differences among different plantation ages of the same species. The soil carbon stock was lowest in the *A. fordii* plantation forest (only 4.0 kg m^{-2} at 0~100 cm depth from soil surface) and highest in the *Cha. obtusa* plantation forest (21 kg m^{-2} at 0~100 cm depth). The soil carbon stocks of the other plantation species were between these 2 species. In general, without regarding the conditions of climate, parent materials, or landscape position effect, average values of SOC stocks at depths of 30, 50, and 100 cm in broadleaf plantation forest were about 6.5, 8.2, and 9.6 kg m^{-2}, respectively. In coniferous plantation forests, they were about 7.4, 9.7, and 12 kg m^{-2}, respectively. The coefficient of variation (CV%) was relatively lower in coniferous forests than in broadleaf forests.

Cumulatively, 55~76% (66% on average) and 54~89% (67% on average) of the total SOC to a depth of 100 cm in the broadleaf and coniferous forest soils were stored in the upper 30 cm, and 80~100% (90% on average) and 70~100% (85% on average), respectively,

Table 4. Organic carbon stocks (kg m^{-2}) of plantation tree species for 3 soil depth intervals in this study

Tree species	Stand age (yr)	*n*	0~30 cm		0~50 cm		0~100 cm	
			Mean	CV%	Mean	CV%	Mean	CV%
			Broadleaf trees					
Acacia confusa (Aca)	50	3	9.8 ab[1]	24[2]	12 abc	23	15 abc	33
Aleurites fordii (Ale)	20	3	2.2 d	61	4.0 e	67	4.0 e	67
Zelkova formosana (Zel)	27	3	7.4 bc	19	8.6 bcd	9	9.7 cde	42
			Coniferous trees					
Cryptomeria japonica (Cry I)	20	3	5.7 bcd	21	6.9 de	8	8.1 cde	2
Cryptomeria japonica (Cry II)	40	3	5.5 cd	21	7.0 de	23	8.4 cde	33
Cryptomeria japonica (Cry III)	51	3	7.0 bc	3	8.4 cd	16	12 bcd	36
Taiwania cryptomerioides (Tai)	10	3	9.2 abc	30	14 ab	19	17 ab	17
Chamaecyparis obtusa var. *formosana* (ChO)	37	3	12 a	33	16 a	35	21 a	40
Cunninghamia konishii (Cun)	16	3	9.0 abc	37	12 abc	35	12 bcd	35
Chamaecyparis formosensis (ChF)	16	3	5.9 bcd	30	6.6 de	16	6.6 de	16
Calocedrus macrolepis var. *formosana* (Cal)	30	3	5.1 cd	23	6.6 de	29	7.8 cde	23

[1] Means followed by same letter within a column do not significantly differ based on Duncan's multiple tests ($p < 0.05$).

[2] CV%, coefficient of variation.

in the upper 50 cm from the surface if the soil depth was only 50 cm. For a global average (*n* = 2640), Batjes (1996) indicated that 39~70% of the TOC in the upper 100 cm of mineral soils is in the first 30 cm depth, and 58~81% is in the first 50 cm of depth. In Taiwan, Tsai et al. (2007) reported that cumulative averages of 59 and 78% of the total SOC to a depth of 100 cm in the forest soils (*n* = 165) are stored in the upper 30 and 50 cm, respectively. In addition, these results also indicate that, potentially, a large amount of carbon dioxide can be released from the soil surface to a depth of 30 cm as a result of adverse human activities or environmental degradation (Detwiler 1986, Batjes 1996).

Furthermore, the mean carbon stocks of the soil pedons in this study were 7.4 (0~30 cm in depth), 9.5 (0~50 cm in depth), and 10.9 kg m^{-2} (0~100 cm in depth) in Inceptisols, and were 6.7, 8.9, and 11.4 kg m^{-2} in Ultisols, respectively. Tsai et al. (2007) proposed that the mean carbon stocks of soil pedons in forest soils of Taiwan were 12.5 (0~30 cm), 16.8 (0~50 cm), and 22.4 kg m^{-2} (0~100 cm) in Inceptisols, and were 12.3, 15.3, and 21.0 kg m^{-2} in Ultisols, respectively. Batjes and Dijkshoorn (1999) reported that the mean soil carbon densities in the Amazon region, to a depth of 100 cm, range from 4.0 kg m^{-2} for Arenosols to 72.4 kg m^{-2} for Histosols, and the mean carbon density of mineral soils, excluding Arenosols and Andosols (30.5 kg m^{-2}), is 9.8 kg m^{-2}. Tan et al. (2004) estimated the SOC pools in Ohio and proposed the mean carbon density (0~100 cm in depth) for the mineral soils to be about 10.2 kg m^{-2}, ranging from 7.1 kg m^{-2} in Ultisols to 8.8 kg m^{-2} in Alfisols, 11.3 kg m^{-2} in Inceptisols, 12.7 kg m^{-2} in Entisols, and 16.9 kg m^{-2} in Mollisols. In Danish forest soils, Vejre et al. (2003) examined 140 forest soil profiles and calculated the average total SOC contents to be 12.5 kg m^{-2}. The calculated results of this study were relative lower than those reported in the literature (Eswaran et al. 1993), which may be associated with different sample sizes, sample numbers, and analytical methods, or different climatic conditions, parent materials, and vegetation types. Moreover, accurate estimates of SOC distributions are further complicated by several factors including a high spatial variability in SOC contents, poor spatial coverage of areas with reliable estimates of SOC contents, and temporal variations in vegetation types (Eswaran et al. 1993, Homann et al. 1998).

Uncertainty of the estimates and strategies to obtain more-precise data

The estimates of total SOC are approximate considering the current state of the art. Batjes (1996) proposed 4 main factors that complicate SOC calculations, including (1) limited knowledge of the distributions of different major soil groups; (2) the limited availability of reliable, complete, and uniform data for these soils; (3) considerable spatial variations in soil carbon contents, stoniness, and bulk densities of soils that are classified similarly; and (4) the combined effects of climate, relief, parent material, vegetation types, and land use projects.

In addition, methodological factors may also increase the uncertainty of the estimates (Corti et al. 2002). Hagedorn et al. (2001) suggested that soil type was the greatest determining factor in carbon dynamics. Davis et al. (2004) also summarized the conclusions, and recommendations drawn from a number of studies in estimating SOC pools were: (1) the soil group is the best approach to estimate soils C pools; (2) lower taxonomic categories (i.e., greater detail) of soil taxonomy are more-reliable predictors of SOC pools than are higher categories; and (3) there is a strong need for estimates of SOC variability within and among soil pedons of the same soil type. In this study, fewer soil samples in each plantation forest could have resulted in great uncertainties in estimating SOC stocks in northern Taiwan. As mentioned by Davis et al. (2004), lower taxonomic categories in Soil Taxonomy (i.e., Soil Great Group or Soil Family) and SOC variabilities within and among soil pedons of the same soil type need to be estimated in future studies.

CONCLUSIONS

Nine plantation tree species, including 3 broadleaf species and 6 coniferous species were selected to estimate the SOC pools in selected plantation forest soils in northern Taiwan. The uncertainty of estimation and proposed strategies to obtain more-precise databases for SOC pool management were also examined in this study. Elevations at the study sites ranged from a lowland (elevation < 200 m) site to a temperate site (elevation about 2000 m). Only 2 Soil Orders, Inceptisols and Ultisols, were classified. The soil bulk density in the broadleaf plantation forests was relatively higher than that in the coniferous plantation forests, and correlations between Bd of surface soil (0~30 cm) and elevation of the study site were negative ($r = -0.5338$, $p < 0.05$). In this study, the stone contents at 0~30 cm in depth in the broadleaf and coniferous plantations were about 17% and 14% (on average), which are lower than the results of previous studies. The average SOC was about 28 g kg^{-1} (0~30 cm) in the broadleaf plantations and was about 48 g kg^{-1} (0~30 cm) in the coniferous plantations.

The soil carbon stocks were lowest in the *Aleurites fordii* plantation forest and highest in the *Chamaecyparis obtusa* plantation forest. We calculated the average values of SOC stocks in the broadleaf plantation forests to be about 6.5 (0~30 cm), 8.2 (0~50 cm), and 9.6 kg m^{-2} (0~100 cm). In the coniferous plantation forests, they were about 7.4, 9.7, and 12 kg m^{-2}, respectively. Moreover, cumulatively 66 and 67% (on average) of the total SOC to a depth of 100 cm in the broadleaf and coniferous forest soils were stored in the upper 30 cm, and 90 and 85% (on average) in the upper 50 cm from the surface if the soil depth was only 50 cm. A concern in many SOC studies is the dependence on soil databases of previous studies. The estimation of SOC pools in this study was potentially compromised by measurement errors of soil bulk density, soil volume calculations, C determination, stoniness of the soils, and fewer soil samples in each plantation forest. In conclusion, we suggest that a database of lower taxonomic categories (i.e., greater detail) in Soil Taxonomy and SOC variability within and among pedons of the same soil type are strongly needed for estimates of soil C stocks in Taiwan.

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