Organic Carbon Storage and Management Strategies of the Forest Soils Based on the Forest Soil Survey Database in Taiwan

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Abstract: Soil organic C (SOC) is a critical component of a terrestrial ecosystem. In Taiwan, forests cover almost 2/3 of the total area of the island, but the detail forest soil survey was conducted from 1993 to 2002 by Taiwan Forestry Research Institute (TFRI). Based on the forest soil survey database and former studies, the aims of this study were (1) to calculate the current forest SOC stocks in the major Soil Orders; (2) to estimate total forest SOC pools in different depths; (3) to examine the regional SOC stocks in andic soil landscape and SOC stocks along an elevation gradient in plantation forest; and (4) to propose the strategies of SOC sequestration in the forest soils. The major Soil Order distributed in the Taiwan forest soils are Inceptisols and Entisols. The mean forest SOC, excluding Histosols and Spodosols, is 18.5 kg m^{-2} (0-100 cm). The total forest SOC pools to the depth of 100 cm calculated from soil surface are about 160 Tg. In addition, in plantation forest in northern Taiwan the SOC stocks increased with elevation increased ($p < 0.01$), and temperature has significantly influences. The study in andic soil landscape in Yangmingshan National Park suggested that the man SOC storage of volcanic ash soils in Taiwan was 15.7 kg m^{-2} (0-100 cm). Based on the regional soil map (1600 ha in Tatunshan and 400 ha in Chishingshan), the SOC pool was 55.2 and 269 Gg/0-100 cm in Tatungshan and 48.5 and 32.5 Gg/0-100 cm in Chishingshan for Andisols and Inceptisols, respectively. The digital soil mapping (DSM) of SOC is important for examining the spatial distribution and stocks of SOC. The case study of DSM in Laoulongshi Forest Working Circles showed that the SOC stock in 0-100 cm soil layer was mostly less than 300 Mg ha^{-1} (ton ha^{-1}) and the estimatied SOC pool was about 10.9 Tg (0-100 cm). A lack of bulk density data is a common problem for estimation of global soil C stocks. We suggested that the database of lower soil taxonomic categories and the SOC variability within and among soil pedons of the same soil type are strong need for estimation of SOC stocks in Taiwan. In order to increase the amount of C sequestration, old growth plantation forests have to thinning. The case study of reforestation at different time after forest fire suggested that reforestation immediately after forest fire could sequestrate more C, especially in the litter layer.
Key Words: Soil organic carbon (SOC), Carbon sequestration, Forest soil, Afforestation

1. Introduction

The greenhouse effect, resulting in the global consequences of climate alterations, has lead scientists to study the global carbon © cycle (Lal et al., 1999; Kondratyev et al., 2003; Lal, 2004; Lal et al., 2004; Lal, 2007). Globally, 1576 Pg (Petagram = 10^{15} g) of C is stored in soils globally, with about 506 Pg of this in soils of the tropics, and with about 40% of the C in soils of the tropics is in the forest soils (Eswaran et al., 1993). In Taiwan, estimates of the stored C in soils of Taiwan are scarce before 1990s. Chen and Hseu (1997) first reported that the estimation of total SOC stocks in Taiwan was about 347 Tg (Teragram =10^{12} g) (123 Tg in cultivated soils and 224 Tg in forest soils, respectively), storing in top one meter of soils in Taiwan. This value was calculated from the database of 100 soil pedons of cultivated soils and 72 soil pedons of forest soils in Taiwan. Tsai and Chen (2002) and Tsai et al. (2007) calculated the SOC stocks of forest soils in Taiwan, according to 101 soil pedons and regression models between SOC content and distribution of major soil groups of forest soil in soil survey area in southern Taiwan, were about 464 Tg in the upper 100 cm depth from soil surface. The results of these two reports have different SOC stocks in the forest soils of Taiwan and indicated that some uncertainties or errors for estimating SOC stocks were existed.

This detail forest soil survey was conducted for 10 years by Taiwan Forestry Research Institute (TFRI) from 1993 to 2002. This soil survey was chaired by Mr. Kuang-Chin Lin, who was working at the Department of Silviculture, Taiwan Forest Research Institute, Council of Agriculture (TFRI). About 16 soil surveyors joined this team for 10 years. The forest soil survey area was > 1,630,000 ha, including 37 Forest Working Circles of 8 Departments of Forest District Offices and 5 Experimental Forests (Fig 1). Until now, six volumes of soil survey reports including four Forest Working Circles (Laoulongshi、Yuching、Pahsianshan and Taanshee) and two Experimental Forest of TFRI) (Liukei and Taimali) and more than 100 soil maps on the scale of 1:25,000 were published. More reports and soil maps will be continuously published in the next few years. The soil classification of this survey was based on *Keys to Soil Taxonomy* (Soil Survey Staff, 1998), and soil mapping unit is soil phase including surface soil textures and slope. This soil survey work was regarded as the most important and great contribution for Taiwan forestry production and development in the next decade. All the published reports and soil maps were combined into the Taiwan National Soil Information System in website of TARI (http://taiwansoil.tari. Gov.tw/Web.Net2008/index_1/main1-1.aspx) (Guo et al., 2005), shown in Chinese, not included English version.

Based on the previous database of SOC in Taiwan before 1997 and new database of SOC in Taiwan after 1997, the objectives of this study were (1) to calculate the current forest SOC stocks in the major Soil Orders; (2) to estimate total forest SOC pools in different depths; (3) to examine the regional SOC stocks in andic soil landscape and SOC stocks along an elevation gradient in plantation forest; and (4) to propose the strategies of SOC sequestration in the forest soils.

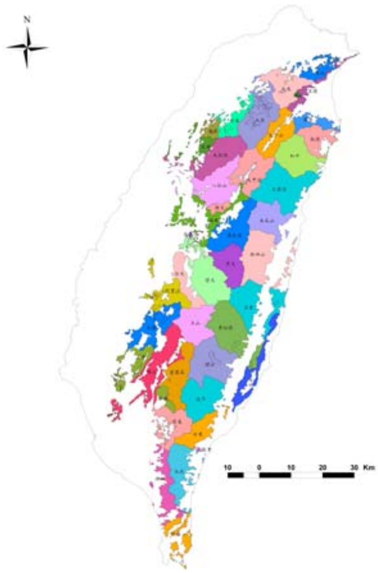

Fig. 1. Map of the detail forest soil survey area in Taiwan conducted by Taiwan Forestry Research Institute (TFRI) from 1993 to 2002. The study area includes 37 Forest Working Circles of 8 Departments of Forest District Offices and 5 Experimental Forests.

2. Materials and methods

2.1 Sources of soil data

The SOC pool in Taiwan was estimated from the database of SOC based on Chen and Hseu (1997), Chen et al. (2001, 2002, 2003, 2004, 2005, and 2006), Tsai and Chen (2002) and Tsai et al. (2007). Totally, 165 soil pedons of forest soils were collected for the total SOC pool estimation in Taiwan.

2.2 Calculating SOC stock of individual soil pedon of Taiwan

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

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

where T_d denotes the total amount of organic carbon (Mg m^{-2}) per unit area over depth *d*, ρ_i represents the bulk density (Mg m^{-3}) of layer *i*, P_i is the proportion of organic carbon (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 > 2mm (diameter), particularly when calculated in the forest soils. If there was no field information on the abundance of coarse fragments in the database, the mean value (30% for 0-30 cm, 40% for 30-100 cm) for the forest soil according to the experience of filed observation was applied temporarily. For soil pedons lacking the soil bulk density data, the data reported by Chen and Hseu (1997) were used for this calculation.

2.3 Estimating total SOC stocks in Taiwan

The total SOC stocks, M_d, for the forest soils of study area was calculated as:

$$M_d = \sum_{j=1}^{n} A_j T_{jd} \qquad (2)$$

where M_d denotes the total weight of the SOC (Tg) in the upper *d* cm of the study area, *n* represents the Soil Oders number, A_j is the area (km^2) of the Soil Orders covering forest soils in Taiwan, and T_{jd} denotes the SOC stock (kg m^{-2}) in the upper *d* cm of Soil Orders.

3. Results and Discussion

3.1 SOC of Major Soil Groups in Taiwan

3.1.1 Distribution of major soil groups in Taiwan

Based on the general soil maps and the soil classification of Taiwan soils (Wang et al., 1988; Chen, 1992; Chen and Chiang, 1996) based on Soil Taxonomy (Soil Survey Staff, 2006), the approximate areas of different Soil Orders in soils of Taiwan are shown in Table 1. In forest soils of Taiwan, Inceptisols (44%) and Entisols (35%) are two major Soil Orders, followed by Alfisols (11%), Ultisols (7.5%), Andisols (1.1%), Mollisols (0.7%), Spodosols (0.06%), Histosols (0.01%), and Vertisols (<0.01%).

Table 1. The approximate area of Soil Orders in forest soils of Taiwan

Soil Order	Approximate area (km^2)	Percentage of land use (%)
Inceptisols	7,415	44.2
Entisols	5,923	35.3
Alfisols	1,805	10.8
Ultisols	1,250	7.5
Andisols	184	1.1
Mollisols	120	0.72
Spodosols	10	0.06
Histosols	2	0.01
Vertisols	1	<0.01
Miscellaneous lands	60	0.36
Total area	**16,770**	**100**

Cited from Chen and Hseu (1997)

3.1.2 Distribution of soil bulk density in major soil groups

The mean soil bulk density (Bd) in three soil depth intervals by major Soil Order was shown in Table 2. For forest soils of Taiwan, Vertisols also has highest soil bulk density and Andisols and Histosols also have lower soil bulk density. In general, the mean value of Soil Orders at a depth of 0-30cm for forest soils, excluding Histosols and Andisols, was about 1.33 Mg m^{-3}.

3.1.3 Distribution of soil organic carbon in major soil groups

The soil organic carbon (SOC) content (%) of forest soils at three soil depth intervals are listed in Table 3. Very high SOC content occurred in Histosols (35.1%) and it indicated very slowly decomposed rate of organic matters in poorly drained conditions. Andisols, Inceptisols, and Spodosols have higher SOC contents (> 8%) at a depth of 0-30 cm. Entisols has lowest SOC content (1.11%) in the forest soils. In general, SOC content decreased quickly from 0-30 cm interval to 30-50 cm and 50-100 cm. The SOC content of forest soils also showed the great variation of different Soil Orders or three soil depth intervals. Meanwhile, the mean SOC value of Soil Orders at a depth of 0-30 cm, excluding Histosols, was about 4.50%.

Table 2. The bulk density (Mg m^{-3}) for three soil depth intervals of this study by Soil Order*

	0-30 cm			30-50 cm			50-100 cm		
Soil Orders	Mean	CV	n	Mean	CV	n	Mean	CV	n
				Forest soils (n=72)					
Entisols	1.15	26	10	--#	--	0	--#	--	0
Inceptisols	0.94	18	16	1.04	47	16	1.06	47	16
Alfisols	1.15	25	6	1.50	25	6	1.58	11	6
Ultisols	1.31	5	8	1.18	49	8	1.28	49	8
Mollisols	1.58	34	3	1.56	25	3	1.50	26	3
Vertisols	1.79	35	3	1.75	25	3	1.84	15	3
Andisols	0.48	33	17	0.69	31	17	0.69	34	17
Spodosols	1.42	4	6	1.22	15	6	0.98	52	3
Histosols	0.35	10	3	0.45	10	3	0.50	--	1

*: CV is the coefficient of variation (%); n is the number of observations by depth interval.
#: No data for the 30-50 cm or 50-100 cm depth interval.

Table 3. The soil organic carbon content (%) for three soil depth intervals of this study by Soil Order

	0-30 cm			30-50 cm			50-100 cm		
Soil Orders	Mean	CV*	n¶	Mean	CV	n	Mean	CV	n
				Forest soils (n=72)					
Histosols	35.1	38	3	29.9	37	3	--#	--	0
Andisols	9.51	41	17	3.89	62	17	1.15	44	17
Inceptisols	9.46	60	16	1.71	69	16	1.16	73	16
Spodosols	8.64	59	6	2.21	74	6	0.91	65	3
Mollisols	2.34	35	3	1.54	40	3	0.45	25	3
Ultisols	1.90	47	8	0.72	94	8	0.39	68	8
Vertisols	1.65	28	3	1.54	30	3	0.78	15	3
Alfisols	1.36	44	6	0.62	48	6	0.35	16	6
Entisols	1.11	55	10	--#	--	0	--#	--	0

*: CV is the coefficient f variation (%)
¶: The number of soil pedons by depth interval.
#: No data for the 30-50 cm or 50-100 cm depth interval.

3.1.4 Calculated SOC stock of major Soil Orders

In this article, the SOC stock was calculated using intervals of both 30 cm and 50 cm soil depth for comparison with the results obtained from other countries or regions of the world. In most mineral soils, organic carbon storages (kg m^{-2}) have been calculated to a depth of 100 cm except for Entisols with very shallow soil depth, or Spodosols and Inceptisols located on very steep landscape. The mean

SOC stock of different Soil Orders of forest soils in Taiwan to a depth of 30 cm, 50 cm, and 100 cm was listed in Table 4. The mean SOC stock of Histosols is highest (63.8 kg m^{-2}) in the upper 50 cm depth of forest soils, and Spodosols is highest (41.9 kg m^{-2}) in the upper 100 cm depth. The higher mean values of soil organic carbon of Spodosols is attributed to the large number of complexes of soil organic matter in the soil surface (Chen and Hseu, 1997) or spodic horizon containing higher illuvial humus and iron materials, and thicker organic layer in the soil surface (Vejre et al., 2003). The mean soil carbon stock of forest soils in Taiwan, excluding Histosols and Spodosols, is 10.1 kg m^{-2} (0-30 cm depth), 13.8 kg m^{-2} (0-50 cm depth), and 18.5 kg m^{-2} (0-100 cm depth).

Batjes and Dijkshoorn (1999) has reported that the mean soil carbon density in 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 for the mineral soils, excluding Arenosols and Andosols (30.5 kg m^{-2}), is 9.8 kg m^{-2}. Tan et al. (2004) estimated the SOC stocks in Ohio and proposed the the mean soil carbon density (0-100 cm depth) for the mineral soils is 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, respectively. In Danish forest soils, Vejre et al. (2003) examined 140 forest soil pedons and calculated the average total soil organic C contents was 12.5 kg m^{-2}, in which, Spodosols has greatest soil C stock (14.6 kg m^{-2}), and Alfisols is the least content (8.8 kg m^{-2}). The calculated results of this study are higher than those of literature reported, and are also associated with the differences on the sampling sizes and analytical methods of the original studies (Eswaran et al., 1995).

Table 4. The SOC storages (kg m^{-2}) for three soil depth intervals by soil order

	0-30 cm[1]			0-50 cm			0-100 cm			Ratio[2]	
Soil Orders	Mean	CV	n[3]	Mean	CV	n	Mean	CV	n	A	B
Forest soils (n=165)											
Histosols	36.9	38	3	63.8	37	3	--[4]	--	--	--	--
Spodosols	29.5	49	10	38.3	50	10	41.9	42	7	70	91
Andisols	14.0	47	24	19.5	46	24	27.7	43	24	51	70
Mollisols	11.1	65	3	15.9	35	3	19.3	42	3	58	82
Inceptisols	12.5	46	60	16.8	43	60	22.4	48	60	56	75
Ultisols	12.3	55	29	15.3	56	29	21.0	58	29	58	73
Vertisols	8.86	50	3	14.3	35	3	21.4	24	3	41	67
Entisols	7.12	59	27	8.32	77	17	8.47	77	17	84	98
Alfisols	4.67	69	6	6.53	61	6	9.30	42	6	50	70
Average										***59***	***78***

[1]: CV is the coefficient f variation (%); n is the number of observations by depth interval.
[2]: A stand for the ratio of the soil organic carbon stock of 0-30cm divided by that in the 0-100cm zone, and B stand for the ratio of the soil organic carbon stock of 0-50cm divided by that in the 0-100cm zone.
[3]: soil pedon numbers collected in this article.
[4]: No data for the 50-100cm depth interval.

Cumulatively, 41-84% (59% in average) of the total SOC to a depth of 100 cm is stored in the upper 30 cm and 67-98% (78% in average) in the upper 50 cm from the surface if the soil depth is only 50 cm (Table 4). For a global average (n=2,640), Batjes (1996) indicated that 39-70% of the total soil organic carbon in the upper 100 cm of mineral soils is in the first 30 cm depth, and 58-81% is in the first 50 cm depth. The result of Batjes and Dijkshoorn (1999) also suggested that about 52% of soil carbon stock in the Amazon region is held in the top 30 cm of the soil. Nearly the same trends appear for soil organic carbon distributed in different soil depths around the world. 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 owing to adverse human activity or environmental degradation (Detwiler, 1986; Batjes, 1996).

3.1.5 Estimation the SOC stocks in Taiwan

The estimated total SOC stocks of Taiwan in forest soils to depths of 30 cm, 50 cm, and 100 cm are shown in Table 5. The SOC stocks in miscellaneous lands are not included in this estimation. Higher than 50% of total SOC stocks was found to be stored in Inceptisols. The summation of SOC stocks in

Inceptisols, Alfisols, Ultisols, and Entisols were higher than 90% of total SOC stocks. The total SOC stocks in forest soils in 100 cm depth are estimated about 160 Tg (Tg, teragram, 10^{12} g).

Table 5. The estimated total forest soil organic carbon stocks in different soil depths

	Organic carbon stock (**Tg,** Teragram, 10^{12} g)		
Soil Orders	0-30 cm	0-50 cm	0-100 cm
Inceptisols	64.9	74.7	99.4
Entisols	29.5	29.5	30.1
Ultisols	10.7	11.5	15.8
Alfisols	5.90	7.07	10.1
Andisols	1.80	2.15	3.06
Mollisols	0.93	1.14	1.39
Spodosols	0.21	0.23	0.25
Histosols	0.05	0.08	--
Vertisols	0.01	0.01	0.01
Miscellaneous lands	--#	--	--
Subtotal	**114**	**126**	**160**

#: No organic carbon was included in the miscellaneous lands.

3.2 SOC Stocks along an Elevation Gradient

In the plantation forest of northern Taiwan, nine plantation tree species distributed in nine plantation forest sites, including three broadleaf vegetation speciesand six coniferous vegetation specieswere selected to study the carbon pool (Tasi et al., 2009) **(**Fig. 2**).** The elevation of 9 study sites ranged from 200 to 2000 m above sea level (Table 6). The climate condition also changed with increasing the elevation from subtropical to temperate zone. The lowest mean annual temperature (MAT) was found in TPS site (13.5 ℃), and the highest was in JHS site (21.8℃) (Table 7). The mean annual precipitation (MAP) ranged from 1850 mm (JHS site) to 3250 mm (PL and CL sites). Three soil profiles were dug in each plantation forest at least to 1 m from the soil surface or to the bed rock if the soil profile was less than 1 m. Totally 33 soil profiles were sampled. Five layers of each soil profile were collected, including 0-15 cm, 15-30 cm, 30-50 cm, 50-75 cm, and 75-100 cm depth. The soil particle size distribution, soil bulk density, soil pH, soil total organic carbon (SOC) content was analyzed. For an individual soil pedon with k layers, the total soil organic carbon content by volume basis was calculated.

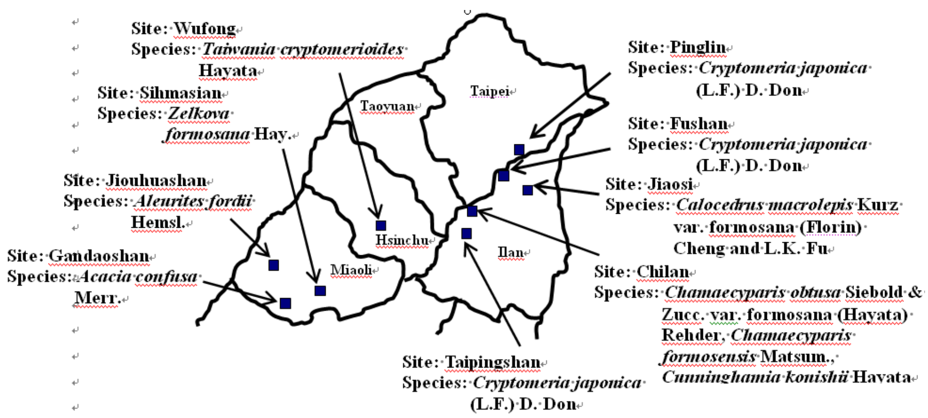

Fig. 2. The position of sampling sites in 9 species of plantation forest in northern Taiwan

Table 6. Environmental characteristics of soils and soil classifications at sample sites

Sample site[1)]	Elevation (m)	Slope(°)	Aspect(°)	SMR[2)]	STR[2)]	Parent material[3)]	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)] GDS = Gandaoshan; JHS = Jiouhuashan; SMS = Sihmasian; FS = Fushan; PL = Pinglin; TPS = Taipingshan; WF = Wufong; CL = Chilan; JS = Jiaosi.
[2)] SMR, soil moisture regime; STR, soil temperature regime (Soil Survey Staff, 2006).
[3)] SS, sandstone.

Table 7. Locations and climatic characteristics of selected plantation tree species

Tree species	Stand age (yr)	Sampling site[1)]	MAT(°C)[2)]	MAP(mm yr^{-1})[2)]
Broadleaf trees				
Acacia confusa	50	GDS	20.2	2300
Aleurites fordii	20	JHS	21.8	1850
Zelkova formosana	27	SMS	17.1	2700
Coniferous trees				
Cryptomeria japonica	20	FS	20.7	3200
Cryptomeria japonica	40	PL	19.5	3250
Cryptomeria japonica	51	TPS	13.5	2700
Taiwania cryptomerioides	10	WF	18.6	2500
Chamaecyparis obtusa var. *formosana*	37	CL1	14.0	2800
Cunninghamia konishii	16	CL2	16.3	3250
Chamaecyparis formosensis	16	CL3	16.3	3250
Calocedrus formosana	30	JS	19.8	2800

[1)] Sample sites are defined in the footnotes of Table 6.
[2)] MAT, Mean annual temperature; MAP, Mean annual precipitation (Central Weather Bureau, Taiwan).

This study indicated that the SOC pool have significant differences among nine plant species ($p < 0.05$), but there are no significant differences among different plantation time of same species **(**Table 8**).**

Table 8. The organic carbon storage (kg m^{-2}) of plantation tree species for three soil depth intervals in this study.

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

*: Means followed by same letter within each column are not significantly different based on the Duncan's multiple test (p<0.05).

The soil carbon pool is lowest in *Aleurites fordii* Hemsl. Plantation forest (only 4.0 kg m^{-2} at 0-100cm depth from soil surface) and highest in *Chamaecyparis obtusa* Siebold & Zucc. var. plantation forest (21.1 kg m^{-2}). The soil carbon pool of other plantation species is between these two species. In general, the average value of SOC pool to the depth of 30cm, 50cm, and 100cm in broadleaf plantation forest is about 6.5, 8.2, and 9.6 kg m^{-2}, respectively. In coniferous plantation forest, it is about 7.4, 9.7, and 12 kg m^{-2}, respectively. After the analysis of SOC data, about 50% of C pool was stored in upper 30cm of 1m soil pedon and about 70% of C pool was stored in upper 50cm of 1m pedon of different plant species. This study also indicate that other environmental factors including air temperature and precipitation, also have significant effects on the accumulation of soil organic carbon storage, except the tree species of plantation in northern Taiwan. Linear regression model was calculated between mean SOC stocks (Y, kg m^{-2}) of plantations and elevation (X, m), and the results showed significantly positive correlation (Fig. 3). Besides, mean SOC stocks (Y, kg m^{-2}) of 0-30 cm depth also showed significantly but negative correlation with annual mean air temperature, but no correlation with annual precipitation (Fig. 4). As indicated by Garten et al. (1999), the changes of air temperature along an elevation gradient affect the dynamic changes of soil organic matters. Soil organic carbon was accumulated at higher elevation because of the lower air temperature reducing the microbial activity for decomposing soil organic matters.

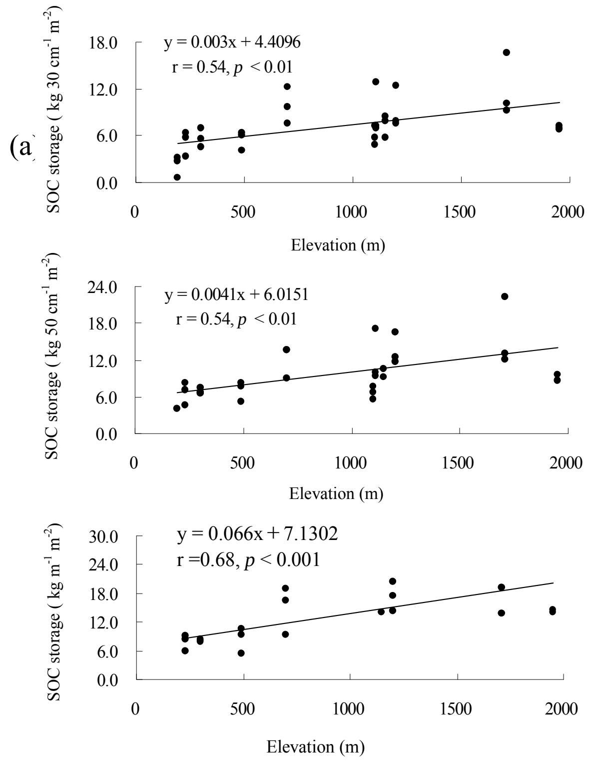

Fig. 3. The relationship between soil organic carbon storage and elevation in 0-30 cm (n = 33), 0-50 cm (n = 29), and 0-100 cm soil depth (n = 21).

(a) SOC storage vs. Temperature (b) SOC storage vs. precipitation

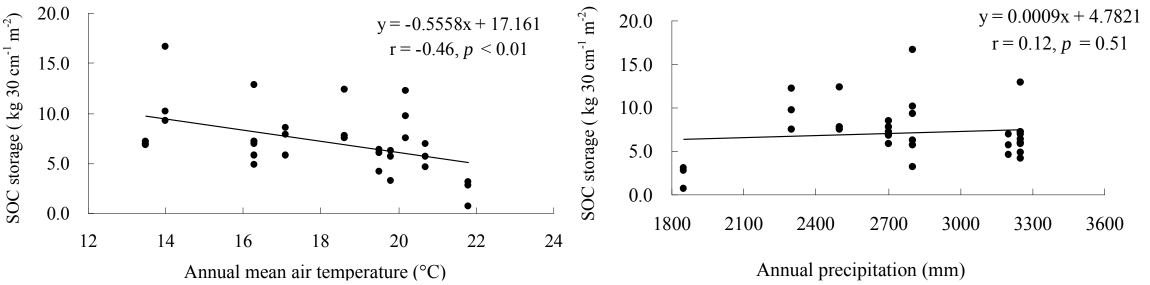

Fig. 4. The relationship between (a) annual mean air temperature (n = 33) and (b) annual precipitation (n =33) and soil organic carbon storage in 0-30 cm soil depth.

3.3 Regional SOC Stocks in Andic Soil Landscape

Taiwan is located at the convergent boundary between the Eurasian plate and the Philippine Sea plate. The Yangmingshan Volcanic National Park (YMS-NP) is formed by the Pleistocene island-arc volcanic activities related to the Ryukyu arc-trench system, and with its eruptive products covering an area of ca. 200 km^2 in the northern tip of Taiwan. According to the results of soil classification of 121 soil pedons collected in the region, three Soil Orders (Andisols, Inceptisols, and Ultisols), three Soil Suborders (Udands, Udepts, and Udults), and five Soil Great Groups (Melanudands, Fulvudands, Hapludands, Dystrudepts, and Hapludults) were formed in YMS-NP area.

The soil organic carbon (SOC) storage for Andisols (mean value, n=43) was 8.57 kg m^{-2} (0-30 cm), 10.8 kg m^{-2} (0-50 cm), and 14.9 kg m^{-2} (0-100 cm); for Inceptisols (n=19) it was 10.1 kg m^{-2}, 13.4 kg m^{-2}, and 18.2 kg m^{-2}, respectively; for Ultisols (n=3) it was 5.86 kg m^{-2}, 8.31 kg m^{-2}, and 10.4 kg m^{-2}, respectively (Table 9). The less SOC storage in Andisols than in Inceptisols could be attributed to the slowly decomposed organic matters in high elevation with cold and wet climate condition. In general, the man SOC storage of volcanic ash soils in Taiwan is 15.7 kg m^{-2} (0-100 cm). Cumulatively, 56.7 % of the total SOC to a depth of 100 cm is stored in the upper 30 cm and 72.9 % in the upper 50 cm from the surface. Relatively high SOC storage was accumulated in volcanic ash soils and this suggested that these soils with less than 0.6% of the Taiwan's land surface are important in soil carbon sequestration in Taiwan.

Table 9. Bulk density and soil organic carbon content (mean±SD) of three Soil Orders*

Soil Order	Depth (cm)	Bulk density Mg m^{-3}	Organic Carbon g kg^{-1}	Organic Carbon kg m^{-2}
Andisols	0-30	0.57±0.14 (43)	67.9±34.6 (43)	8.57±3.36 (43)
	30-50	0.71±0.16 (42)	31.6±19.9 (43)	2.26±1.25 (43)
	50-100	0.77±0.16 (38)	23.3±14.9 (43)	4.11±2.58 (43)
	100-150	0.82±0.14 (16)	14.8±10.3 (21)	2.12±2.28 (21)
	150-200	0.82±0.19 (3)	17.9±12.2 (3)	4.27±3.26 (3)
	200-250	0.61 (1)	16.8±18.2 (2)	5.13±5.56 (2)
Inceptisols	0-30	0.67±0.18 (19)	69.2±34.6 (19)	10.1±3.27 (19)
	30-50	0.89±0.18 (19)	30.3±23.4 (19)	3.33±1.86 (19)
	50-100	0.87±0.22 (18)	23.8±21.4 (18)	4.79±3.43 (18)
	100-150	0.93±0.21 (7)	12.6±13.3 (7)	2.09±1.41 (7)
	150-200	0.90 (1)	10.1 (1)	1.68 (1)
	200-250	0.88 (1)	9.49 (1)	1.54 (1)
Ultisols	0-30	0.89±0.06 (3)	25.2±8.54 (3)	5.86±1.68 (3)
	30-50	1.10±0.09 (3)	15.5±11.3 (3)	2.45±1.83 (3)
	50-100	1.17±0.16 (3)	6.65±4.09 (3)	2.09±1.35 (3)
	100-150	1.24±0.10 (2)	2.82±0.71 (2)	0.81±0.39 (2)
	150-200	1.45 (1)	3.71 (1)	0.81 (1)
	200-250	--	--	--

*: The number in the parenthesis is the number of soil pedon included; -- = no data.

Traditional soil survey map (TSS map) of the Tatung Mountain area (1600 ha, 4 km x 4 km) and the Chishing Mountain area (400 ha, 2 km x 2 km) (Fig. 5) was prepared using traditional soil survey procedures, and was based on the distribution of 86 legend pedons collected over two study areas. From the preliminary soil survey based on the traditional soil survey method (Soil Survey Staff, 1993), 86 pedons were collected from theYangmingshan Volcanic National Park, 80 pedons were located in two study areas and 6 pedons were not. The 86 soils are classified into Andisols (37%) and Inceptisols (63%) (Soil Survey Staff, 2006). Furthermore, Andisols is classified into Melanudand, Fulvudand, and Hapludand Soil Great Groups, but Inceptisols only classified as Dystrudept soil Great Group. The Dystrudept great group occupied greatest areas (65%) in Tatung area, but it was Hapludand great group in Chishing area (Table 10). The miscellaneous area (ML) also occupied great areas in these two study areas.

Except for the ML, according to the soil carbon stock (kg m^{-2}) and occupied area of two Soil Orders in Tatung and Chishing area, we examined the SOC pool in this two area (Table 11). The SOC pool in Tatungshan was 55.2 and 269 Gg/0-100 cm for Andisols and Inceptisols, respectively. In Chishingshan, it was 48.5 and 32.5 Gg/0-100 cm for Andisols and Inceptisols, respectively.

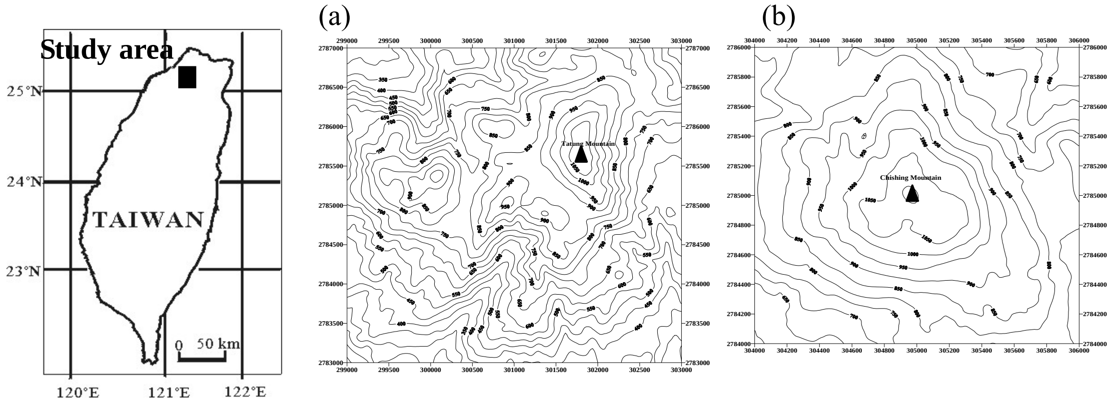

Fig. 5. The location and contour map of two study area (a) Tatung Mountain area (1600 ha); (b) Chishing Mountain area (400 ha).

Table 10. The occupied areas of soil great groups in Tatung and Chishing Mountain area

Study Area	Soil Great Group	Area (ha)	Area (%)
Tatung	Dystrudept	1034	64.6
	Hapludand	187	11.7
	Fulvudand	53	3.3
	ML	326	20.4
Chishing	Hapludand	199	49.7
	Dystrudept	125	31.3
	Fulvudand	12	3.0
	ML	63	16.0

*: ML = miscellaneous, Including road, parking area etc.

Table 11. SOC pool (Gg) estimation in Tatun and Chishing area

	Tatungshan		Chishing	
Soil layer (cm)	Andisols	Inceptisols	Andisols	Inceptisols
0-30 cm	25.6	127	22.5	15.3
0-50 cm	35.6	176	31.3	21.3
0-100 cm	55.2	269	48.5	32.5
0-150 cm	68.8	319	60.5	38.6
0-200 cm	85.0	366	74.7	44.3
0-250 cm	97.3	409	85.5	49.5

3.4 Digital Soil Mapping of SOC: Case Study in Laoulongshi Forest Working Circles

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Digital Soil Mapping (DSM) attempts to translate our existing scientific understanding of how soils are formed into predictions of soil properties and features based on factors such as parent material, climate, slope or aspect. It can be used to create maps of indicative properties of agricultural or environmental interest, such as soil nutrient status, hydrological response, pH or carbon content.

As described in Introduction paragraph, the detail forest soil survey has accomplished and six volumes of soil survey reports and more than 100 soil maps on the scale of 1:25,000 have been published. In order to recognize the spatial distribution of SOC in Taiwan forest, one volume of soil survey reports (Laoulongshi Forest Working Circles, LLS-FWC) was selected for examining SOC distribution by DSM. Laoulongshi Forest Working Circles, with area 47,648.68 ha, located at the southern Taiwan (TFRI, 1996) (Fig. 6). The elevation ranged from 400 m a.s.l. to 3666 m a.s.l. Twenty-three soil series were classified and those soil series were classified into Inceptisols (9 soil series), Ultisols (7), Entisols (6), and Spodosols (1). Finally, the soil series map of LLS-FWC was composed of 68 soil mapping unit.

SOC examination in LLS-FWC was based on the raw data of soil chemical and physical analysisof previously soil survey samples by TFRI. The missing value of soil bulk density was based on the Table 2 (The bulk density (Mg m^{-3}) for three soil depth intervals of this study by Soil Order). The SOC content (Mg ha^{-1}) of soil mapping unit was the basic unit for examining SOC pool in this study area. The miscellaneous (ML) or ML-associated mapping unit were both not included in SOC pool examination. The spatial distribution of SOC was calculated by ordinary Kriging method and the DSM of SOC was produced by ArcGIS.

The DSM of SOC stocks in Laoulongshi Forest Working Circles was showed in Figure 7. The SOC stock in 0-30 cm soil layer was mostly less than 300 Mg ha^{-1} (ton ha^{-1}). Even in 0-100 cm soil layer, it still has more than 50% of total area with SOC stocks less than 300 Mg ha^{-1}. Moreover, the estimation of SOC pool in LLS-FWC was about 7.30 (0-30 cm), 8.94 (0-50 cm), and 10.9 (0-100 cm) Tg.

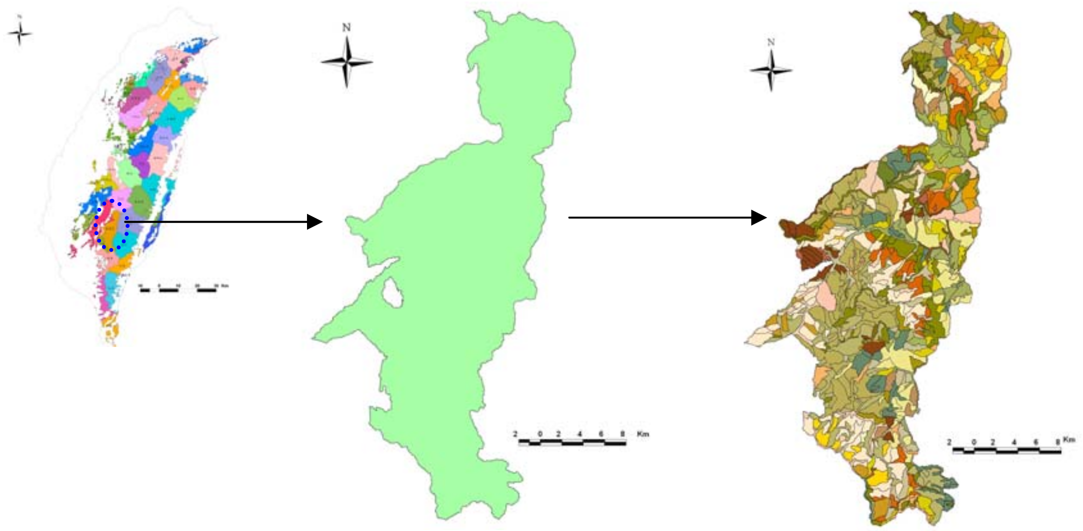

Fig. 6. Location, base map and soil series map of Laoulongshi Forest Working Circles

3.5 Uncertainty for the estimation and strategies to get more precision data

Batjes (1996) have proposed four main uncertainty factors that complicate the SOC stock calculations, including (1) the limited knowledge of the distribution of different major soil groups, (2) the limited availability of reliable, complete and uniform data for these soils, (3) the considerable spatial variation in soil carbon content, stoniness and bulk density of soils that have been classified similarly, and (4) the combined effects of climate, relief, parent material, vegetation types, and land use projects. Methodological factors may also increase the uncertainty of the estimates (Corti et a1., 2002).

Moreover, accurate estimate of SOC distribution are further complicated by several factors including high spatial variability in SOC content, poor spatial coverage of areas with reliable estimates of SOC content, and temporal variation in vegetation types (Eswaran et al., 1995; Homann et al., 1998). Hagedorn et al. (2001) also suggested that soil type was the greatest determining factor in SOC dynamics. Davis et al. (2004) also had the conclusions and recommendations drawn from a number of studies in estimating SOC stocks, including (1) soil group is the best approach to estimate soil C stock, (2) lower soil taxonomic categories (more detail) in Soil Taxonomy are more reliable predictions of SOC stocks than that of higher categories; and (3) there is a strong need for estimates of SOC variability within and among soil pedons of the same soil type.

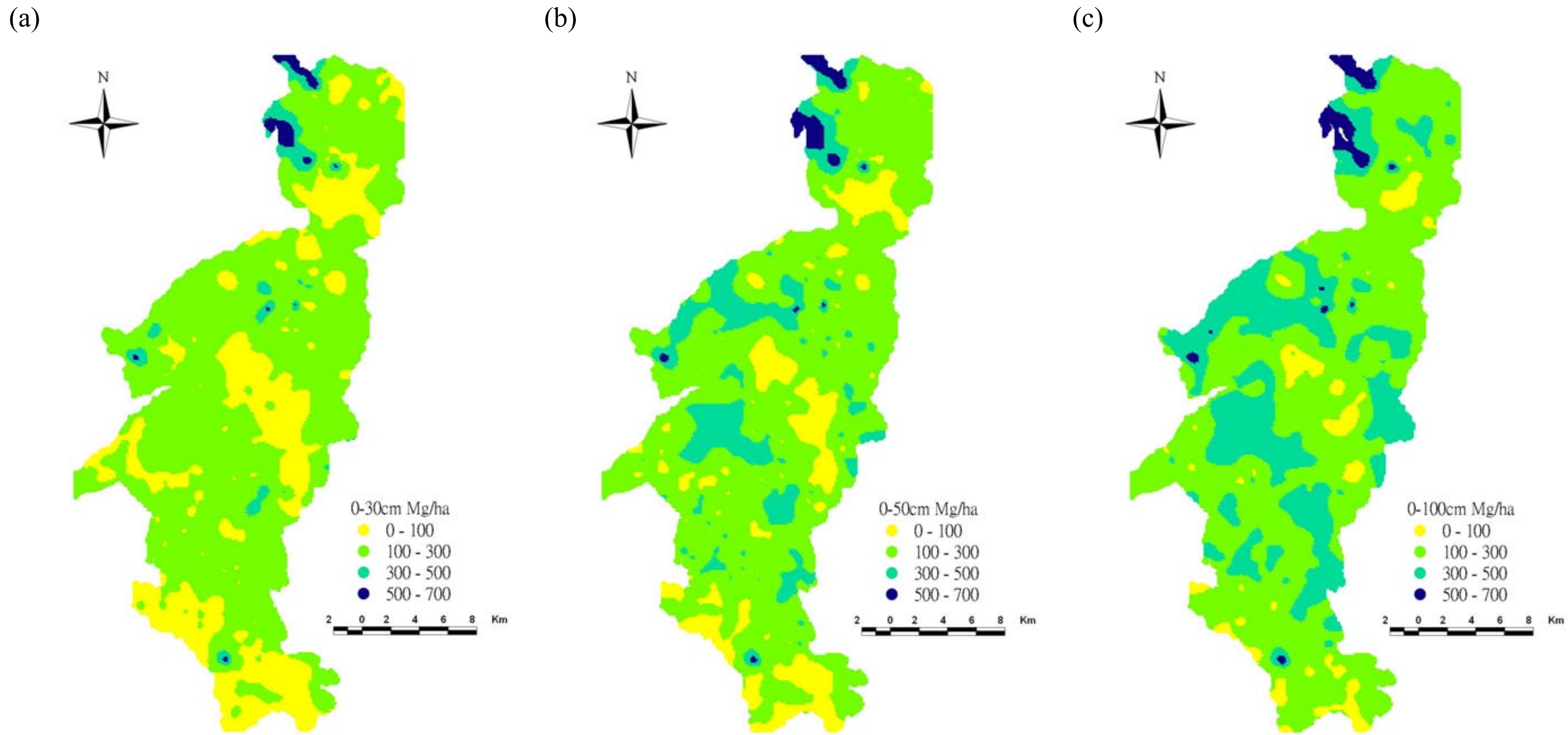

Fig. 7. The DSM of SOC stocks in Laoulongshi Forest Working Circles (a) 0-30 cm; (b) 0-50 cm; (c) 0-100 cm.

3.6 Strategies of SOC Sequestration in the Forest Soils

The increase in greenhouse gases (GHG) in the atmosphere and the climatic change will have major effects on the environmental quality and crop production in the 21st century. Although current scenarios are still fraught with uncertainty, serious negative effects are expected although some positive effects are also expected and it is essential that a number of actions be undertaken in order to reduce GHG emissions and to increase their sequestration in soils and biomass. In this connection, new strategies and appropriate policies for agricultural and forestry management must be developed. One option concerns carbon sequestration in soils or in terrestrial biomass, especially on lands used for agriculture or forestry. Since the Kyoto Protocol, this is referred to as "Land Use, Land-Use Change and Forestry (LULUCF)" and concerns articles 3.3 and 3.4 of the Protocol of IPCC (IPCC, 2000). Taking action on C sequestration under the Kyoto Protocol or any post-Kyoto treaty will not only stimulate important changes in land management but will also, through the increase in organic matter content, have significant direct effects on soil properties and a positive impact on environmental or agricultural qualities and biodiversity. The consequences will include increased soil fertility, land productivity for food production and food security. This economic tool will also make agricultural practices more sustainable and help prevent or mitigate the land resource degradation. Lal (2007) indicated that we need develop more restoration techniques for the degraded soils and ecosystem and also develop the land-saving technologies to enhance our soil fertility including using the techniques of integrated nutrient management, soil and water conservation, cropping system and water harvesting and recycling.

In the present time, sustainable forest practices must aim to maintain long-term forest ecosystem structure and function, as well as relate to the socio-economic values of the forest (Blanco et al., 2005, 2008). Taiwan, with 36,000 km^2 in area, is an offshore island situated between 24 N to 22 N in the subtropical region. Over 50 percent of the island area is covered by lush and diverse forests. Among the remaining forested area, 14 percent, that is, 420,000 ha of the area are plantation forests (Forestry Bureau, 1995). Most plantations in Taiwan were established 50 years ago, with introduced species such as Sugi (*Cryptomeria japonica)* and China-fir (*Cunninghania lanceolata)* planted for further harvest. As the plantation forests in Taiwan enter the maturation stage at this moment, policies for harvesting timbers nonetheless become a challenge for several reasons (Sun, 2007): First of all, many of the plantations located in the proximities of unstable geology area in which harvest timber may further endanger this area. Second challenge comes from the public opinion on biodiversity conservation. Also yield decline and soil degradation may occur in monospecific plantations. Thus, how to increase biodiversity and ecosystem function in these forests become a major challenge. The third challenge of timber harvesting in Taiwan is an economic one, it is not economically viable to harvest our own timber. The fourth challenge comes from international pressure, especially after the implementation of Kyoto protocol. In the near future, Taiwan has to come up with strategies to compensate carbon emission or face international sanctions on carbon tax. One simple and easy way is to increase tree growth and to increase its carbon storage. With sound management strategies, plantation forests can provide timber for local consumption as well as carbon storage for carbon tax. Thus finding a good way to efficiently manage the 420,000 ha of plantation forests becomes an important task foresters must accomplish. A new management strategy which incorporates the need of timber production, public opinion, biodiversity conservation, carbon sequestration and long-term sustainability of plantation forest is urgently needed.

Thinning has been used widely in forest management strategy, and is a prerequisite activity adopted in the plantation management. Thinning allows forest managers to choose the trees to which the additional growth will be allocated and to harvest growth that would otherwise be lost due to mortality (Della Binanca and Dils, 1960; Smith ,1986). Slodick et al. (2005) indicated that thinning is generally considered beneficial for stand microclimate, litter decomposition and biogeochemical cycling of nutrients in temperate forests, in contrast to the possible negative effects or increasing production risks; and thinning is also a key variable for managing accumulation of organic matter and rates of nutrient cycling (Roig et al., 2005). Nowadays, to be consistent with the forest ecosystem management, how to apply thinning practice on existing plantations to enhance the heterogeneity of stand composition and structure to meet the goal of biodiversity conservation, land productivity promotion, and stability of ecosystem becomes a quite important issue for the sustainable forest management in Taiwan. Afforestation, that is, converting land from other land uses to forestry, is expected to contribute to the mitigation of increasing CO_2 concentrations in the atmosphere by sequestrating atmospheric C in tree biomass (Nabuurs et al., 2007). In addition to tree biomass, the C stock in the soil also gradually increases following afforestation (Paul et al., 2002). Besides, in northeastern Taiwan a study was conducted for examining the C sequestration of reforestation at different time after forest fire (control-91 plot, one year-92 plot, and six years-97 plot). The preliminary results of this study suggested that reforestation immediately after forest fire could sequestrate much more C, especially in the litter fall layer (Fig 8).

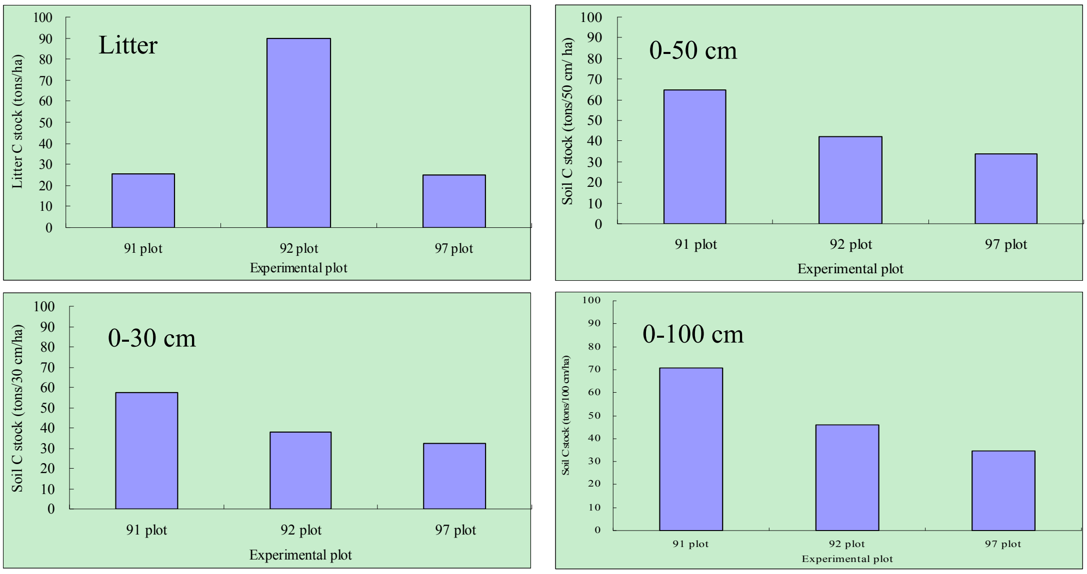

Fig. 8. Litter and soil carbon stocks between three treatments of reforestation at different time after forest fire (control-91 plot, one year-92 plot, and six years-97 plot).

4. Conclusion

Soil organic C (SOC) is a critical component of a terrestrial ecosystem. In Taiwan, forests cover almost 2/3 of the total area of the island, but the detail forest soil survey was conducted for 10 years by Taiwan Forestry Research Institute (TFRI) from 1993 to 2002. The estimates of the stored C in forest soils of Taiwan are scarce before the 1990s. Based on the forest soil survey database and former studies, the result of this study indicated that the major Soil Order distributed in the Taiwan forest soils are Inceptisols (44.2%), Entisols (35.3%), Alfisols (10.8%), and Ultisols (7.50%). The mean forest SOC, excluding Histosols and Spodosols, is 10.1 kg m^{-2} (0-30 cm), 13.8 kg m^{-2} (0-50 cm), and 18.5 kg m^{-2} (0-100 cm). Cumulatively, 59% and 78% (on average) of the total forest SOC to a depth of 100 cm is stored in the upper 30 cm and 50 cm, respectively. The total forest SOC pools to the depth of 30 cm, 50 cm, and 100 cm calculated from soil surface are about 114, 126, and 160 Tg, respectively. In addition, the results of SOC stocks along an elevation gradient (200 m~2000 m a.s.l.) in plantation forest in northern Taiwan showed that the SOC stocks increased with elevation increased ($p < 0.01$), and temperature has significantly influences on SOC stocks than precipitation. The values of calculated average SOC stocks to the depth of 100 cm were 9.6 kg m^{-2} and 12 kg m^{-2} for the broadleaf and coniferous plantation forests, respectively. Besides, the examination of the regional SOC stocks in andic soil landscape in Yangmingshan National Park suggested that Andisols and Inceptisols are major soils in this area, and the man SOC storage of volcanic ash soils in Taiwan is 15.7 kg m^{-2} (0-100 cm). Based on the soil map derived from a small scale soil survey (1600 ha in Tatunshan and 400 ha in Chishingshan), the SOC pool in Tatungshan was 55.2 and 269 Gg/0-100 cm for Andisols and Inceptisols, respectively. In Chishingshan, it was 48.5 and 32.5 Gg/0-100 cm for Andisols and Inceptisols, respectively. The digital soil mapping (DSM) of SOC is important for examining the spatial distribution and stocks of SOC. The case study of DSM in Laoulongshi Forest Working Circles showed that the SOC stock in 0-100 cm soil layer was mostly less than 300 Mg ha^{-1} (ton ha^{-1}). The estimation of SOC pool in LLS-FWC was about 10.9 (0-100 cm) Tg.

A concern in many SOC studies is depending on the soil database of previous studies. Estimation of SOC stocks in this study are potentially compromised by the measurement errors on soil bulk density, soil volume calculations, C determination, and stoniness of soils. A lack of bulk density data is a common problem for estimation of global soil C stocks, and our prediction of missing bulk densities may produce the errors of this estimation. The sources of database error may produce a bias, when comparing SOC content among studies in the literature where different methodologies have been applied. In conclusions, we suggested that the database of lower soil taxonomic categories (more detail soil survey and classification) and the SOC variability within and among soil pedons of the same soil type are strong need for estimation of SOC stocks in Taiwan. Furthermore, in order to increase the amount of C sequestration, old growth plantation forests have to thinning, but it is conditionally for preventing frequently typhoon and moon soon disturbance. Steeply slope, stony and clayey soil texture within soils are both obviously characteristics of forest soil in Taiwan. Recently studies suggested reforestation immediately after forest fire could sequestrate much more C, especially in the litter fall layer.

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