Research paper

Estimates of Biomass and Carbon Storage in Two Taiwania Plantations of the Liukuei Experimental Forest

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【Summary】

In Taiwania plantations of the Liukuei Experimental Forest managed by the Taiwan Forestry Research Institute, 2 stands aged 20 and 27 yr were selected to estimate the biomass and carbon storage in the ecosystem. According to the allometric equation established by data of 38 harvested trees, the biomass of each component and the total biomass of the trees were highly significantly related to dbh. In addition, the biomass of these 2 stands can be estimated with a set of common equations. The estimated Taiwania biomass was 155 and 169 ton ha^{-1} for the 20- and 27-yr-old stands, respectively, and the major biomass was in the boles. Biomass of the understory vegetation was only 3.2-4.8 ton ha^{-1}, and primarily accumulated in the ground coverage. Biomass in the litter layer was 6.1-10.2 ton ha^{-1}. In the whole stand, 55-62% of carbon storage was in the soil and 36-41% in trees. In soils, 44-50% of the carbon was stored at 0-15-cm depth and in the trees 80% was in the boles. Compared with tropical plantations, the carbon storage of Taiwania trees is slightly lower, but the storage in soils is similar.

Key words: Taiwania, carbon storage, biomass, regression method, understory vegetation, litter layer.

Lin KC, Wang CP, Huang CM, Horng FW, Chiu CM. 2003. Estimates of biomass and carbon storage in two Taiwania plantations of the Liukuei Experimental Forest. Taiwan J For Sci 18(2):85-94.

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Received Sept. 2002, Accepted Feb 2003. 2002年9月送審 2003年2月通過。

*本研究承行政院農業委員會(90農科-1.4.1-森-G9(02)，91農科-1.3.2-森-G1(01))科技計畫補助，特予致謝。

研究報告

六龜試驗林兩台灣杉人工林生物量和碳儲存量之估算

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摘 要

以林試所六龜試驗林的台灣杉人工林為對象，選取20和27年生兩林分，估算其生態系之生物量、碳儲存量。由38株樣木之胸徑所建立之異率迴歸式得知樹體各部位及總生物量皆呈顯著相關，且兩林分可用同一組迴歸式估算。結果顯示，20年生台灣杉林木生物量為155 ton ha^{-1}，27年生則為169 ton ha^{-1}，生物量集中在樹幹。林下植物生物量為3.2-4.8 ton ha^{-1}，大部分集中在地被植物。枝葉層生物量為6.1-10.2 ton ha^{-1}。全林分碳儲存量，土壤佔最大量為55-62%，喬木次之佔36-41%；土壤中約44-50% 集中在0-15 cm處，喬木則約80% 位於樹幹。與熱帶人工林比較，台灣杉全林分碳儲存量，林木部分略為偏低，土壤的量則相近。

關鍵詞：台灣杉、碳儲存量、生物量、迴歸式法、林下植物、枝葉層。

林國銓、王巧萍、黃菊美、洪富文、邱志明。2003。六龜試驗林兩台灣杉人工林生物量和碳儲存量之估算。台灣林業科學 18(2):85-94。

INTRODUCTION

In recent years, the sustainable management of forest ecosystems is assuming greater and greater importance. Estimation of biomass in stands provides the basic data for forest ecosystem management. Research on biomass not only focuses on trees, but also extends to other strata such as understory vegetation, the litter layer, and soils, which can affect nutrient cycling (Long and Turner 1975). Meanwhile, the carbon sequestration function of forests is of great concern due to the global warming phenomenon, where forest plantations will, particularly, play a leading role in the future. Taiwania (*Taiwania cryptomerioides* Hayata) is one of the important economic species in Taiwan. In the Liukuei Experimental Forest of the Taiwan Forestry Research Institute, Taiwania has been intensively planted since 1972. The total area of pure Taiwania plantations over 20-yr-old in the experimental forest is currently around 435 ha (Chen et al. 1997). Basic data on this species need to be established for the sustainable management of this ecosystem. However, most research in the past focused only on the analyses and estimation of timber volume (Hung 1974, Liu et al. 1984, Chen et al. 1997). There are few publications about the biomass and carbon storage in Taiwania stands until now. Thus, 2 stands over 20 yr old in the Taiwania plantations of Liukuei Experimental Forest were selected to estimate the biomass and carbon storage of the whole stands (trees, understory vegetation, litter layer, and soil). These data may provide a good reference for understanding the nutrient cycles as well as for ecosystem management practices in the future.

MATERIALS AND METHODS

Site

The Taiwania plantations are in Fengkangshan District, managed by the

Liukuei Research Center of the Taiwan Forestry Research Institute, located in Liukuei Township, Kaohsiung County, southern Taiwan. The experimental forests lie in a warm temperate climate zone with an annual precipitation of up to 2,280 mm and at elevations of from 1,500 to 2,000 m. The rainy season is from May to September, and the dry season is from October to April (TFRI 1998). Affected by the elevation, the highest temperature on average is less than 25°C (in July), and the lowest temperature on average is less than 10°C (in January). Elevations of the study areas are between 1,550 and 1,695 m.

Methods

1. Taiwania plots and sampling

Two stands 20- and 27-yr-old were selected from among the Taiwania plantations mentioned above, where thinning occurred in 1993, and around 1,000 trees ha^{-1} were left. Three 0.09-ha (30 × 30 m) plots were established for each stand. The characteristics of the studied Taiwania plots are given in Table 1.

By a classification of dbh (diameter at breast height) at an interval of 5 cm, 7 classes were set for dbh from 10 to 40 cm and upward. In each dbh class, 4 to 7 sample trees were selected for biomass estimation. There were 38 sample trees harvested at the end of 1999, 10 trees at 20-yr-old and 28 trees at 27-yr-old.

(1) Sample tree biomass

After cutting down the trees, tree heights, crown lengths, and crown diameters were measured (Table 2). The sample trees were then cut into different sections. The first section was from the ground to 1.3 m in height, and then each 2 m from the 1.3-m height was a section. Each section was further separated into the following components: boles, dead branches, leaves and twigs, and branches (branches without leaves). The fresh weight of each component was recorded in the field. For measuring the biomass of boles, 3 discs were taken from the bole at 1.3 m height, at the height of the lowest branch growth, and halfway between these 2 heights, respectively. Fresh weights of the discs and the sub-samples of dead branches, leaves and twigs, and branches were all recorded in the field, then the samples were taken back to the laboratory to measure the oven dry weight (65°C). The biomass was estimated on

Table 1. Characteristics of 6 plots in 2 Taiwania plantations

Age (yr)	DBH (cm)	Ht (m)	No. of trees (trees ha^{-1})
20	27.3 ± 6.3[1)]	15.3 ± 1.7	800
	24.6 ± 5.5	14.8 ± 1.8	1140
	24.5 ± 4.5	14.9 ± 1.2	950
Mean	25.5	15.0	960 ± 170
27	26.2 ± 7.0	17.6 ± 2.9	760
	25.4 ± 7.0	17.7 ± 2.3	1040
	26.0 ± 6.0	16.7 ± 4.1	1140
Mean	25.9	17.3	980 ± 197

[1)] mean ± standard deviation.

Table 2. Characteristics of 38 sampled trees in Taiwania plantations (mean ± standard deviation)

Item	20 yr old	27 yr old
DBH (cm)	24.7 ± 7.9 (12.7-39.6)[1)]	26.3 ± 9.1 (12.6-42.5)
Tree height (m)	16.1 ± 2.0 (11.9-18.5)	17.5 ± 3.5 (9.7-21.9)
Crown diameter (m)	3.6 ± 1.1 (2.3-5.2)	3.9 ± 1.3 (2.0-6.9)
Crown length (m)	10.1 ± 2.8 (5.7-14.1)	9.3 ± 3.4 (3.9-13.8)

[1)] Numbers in parentheses are the range.

the basis of oven dry and fresh weight ratios of sub-samples and fresh weight of sample trees.

(2)Stand biomass

The most commonly used natural logarithmic equation, ln(Y) = a + b ln(dbh), was selected as the regression model (Dudley and Fownes 1992). In the equation, the dependent variable Y stands for biomass (kg) of each component, total biomass, and tree height, while dbh (cm) stands for the independent variable, and a and b are constants. Also, a correction factor needs to be applied to the constant a (cf = $S_{y \cdot x}^2/2$, where $S_{y \cdot x}$ stands for standard error of the estimate), and a is equal to c + cf, where c stands for the constant in the equation $Y = c(dbh)^b$. The sample tree biomass at the ages of 20- and 27-yr were respectively estimated by different regression equations. Then, the slope (b) and intercept (a) from these 2 sets of regression equations were tested by the general linear model (GLM) to see if they were identical, and this decides whether the same set of equations is suitable for use with sample trees from both stands.

The biomass of the different components of each tree in the study plot was estimated using the regression equations obtained from the sample trees. And then the mean biomass of the replicate plots was converted into biomass per unit area.

2.Bushes and ground vegetation

In the Taiwania plantations, three 5 × 5-m subplots were randomly established for each stand. The composition of bushes (understory plants taller than 1.3 m) and ground vegetation (plants shorter than 1.3 m) in the subplots were investigated, and then all of the bushes and ground vegetation were harvested. The main species of bushes or small trees were *Ficus formosana* Maxim, *Ardisia sieboldii* Miq., *Eurya* spp., and *Machilus japonica* Sieb. & Zucc. in the 20-yr-old stand and *Ardisia sieboldii*, *Lasianthus* spp., and *Machilus thunbergii* Sieb. & Zucc. in the 27-yr-old stand. *Elatostema herbaceifolium* Hayata was the main species of ground vegetation in both stands, and its coverage exceeded 80% in most plots.

The bush biomass was measured in the same way as the biomass of Taiwania. Harvested bushes were mixed together instead of analyzing single bushes and then categorized into 3 components (boles, branches, and leaves). But the ground vegetation was considered 1 component. After the fresh weights of the components of bushes and the ground vegetation were recorded in the field, subsamples were weighed and brought back to laboratory to measure the oven dry weight and carbon contents.

3.Litter layer and forest soils

In the Taiwania plantations, 5 litter samples (0.5 × 0.5 m) and soils for each stand were collected and brought back to the laboratory. Litter samples were dried at 65℃ and weighed to determine oven dry weight, then finely ground. Soils were divided into 3 compartments: 0-15, 15-30, and 30-45 cm. Soil bulk density was measured by the excavation method (Lal and Kimble 2001).

4.Carbon storage

For estimating the carbon storage of the Taiwania stands, carbon concentrations of different components were analyzed. For Taiwania, 9 trees (4 aged 20 and 5 for aged 27 yr old) from the sample trees of different dbh classes were selected. Samples from different components of the selected trees, bushes, ground vegetation, and litter layers were finely ground (< 0.5 mm). Following the dry combustion method (Sollins et al. 1999), 2-4 mg of ground sample was used for carbon concentration analysis in a CN elemental analyzer (EA, Thermo Finnigan NA1500). For soil organic carbon determinations, soils at the same depths from each plot were mixed and milled to < 0.5 mm, then analyzed by the Walkley-Black method (Nelson and Sommers 1996).

The Taiwania biomass of each component obtained by the regression method was multiplied by its own average carbon concentration to estimate the total carbon storage of trees per unit area. And the total carbon storage of the Taiwania plantations was estimated by adding the total carbon storage of trees, bushes, ground vegetation, litter layer, and soils together.

RESULTS

1. Regression equation

Two groups of natural logarithmic regression equations were established with the sample trees aged 20- and 27-yr-old, respectively. Leaves and twigs, branches, dead branches, boles, total biomass, and tree height were all highly related to dbh ($p < 0.01$). By comparing the regression equations of both stands with the GLM, all slopes and intercepts of the 2 sets of equations were determined to be statistically non-significant ($p > 0.05$). This means that the slopes and intercepts of the 2 sets of equations derived from the stands aged 20- and 27-yr-old were the same. Thus, a set of common regression equations was suitable for both stands (Table 3).

2. Stand biomass

The stand biomass was 154.9 ton ha^{-1} in the 20-yr-old Taiwania stand and increased to 169.1 ton ha^{-1} in the 27-yr-old one (Table 4). The major biomass was in boles, comprising 78-79% of the total biomass. The total biomass of understory vegetation was much lower than that of trees. It was only 2-3% of the Taiwania tree biomass, and was primarily in the ground vegetation. The biomass of bushes and ground vegetation in the 27-yr-old stand was higher than that of the 20-yr-old stand, however, the difference was not statistically significant. The standard deviation was extremely large among the plots, especially for bushes.

3. Carbon storage

The highest concentration of carbon was in the boles and the lowest in the leaves and twigs in both stands (Table 5). Differences in carbon concentrations of Taiwania components at different ages did not reach statistical significance ($p > 0.05$), and differences for the components of bushes were slight ($0.05 > p > 0.01$).

The soil bulk density and the soil organic carbon concentrations at different

Table 3. Regression coefficients and statistics of allometric equations ($\ln(Y) = a + b\ln(dbh)$) estimating aboveground biomass and height of trees

Y	a	b	Adjusted R^2	SEE[1)]
Leaves and twigs	-5.5522	2.4901	0.896	0.292
Branches	-5.9272	2.6988	0.861	0.375
Dead branches	-7.2400	2.5671	0.624	0.684
Boles	-2.3294	2.1992	0.967	0.141
Total biomass	-2.3707	2.2847	0.968	0.144
Tree height	1.2633	0.4889	0.727	0.103

[1)] Standard error of estimates.

depths are listed in Table 6. The soil bulk density did not change much with depth in the 20-yr-old stand, while in the 27-yr-old stand it increased with depth. Although the

Table 4. Estimate of aboveground biomass (ton ha^{-1}) among strata and litter layer for 2 Taiwania plantations

Stratum	20 yr old		27 yr old	
Taiwania				
Regression method				
Leaves and twigs	12.70 ± 1.35[1)]	(8.2)[2)]	14.01 ± 2.49	(8.3)
Branches	17.46 ± 1.91	(11.3)	19.47 ± 3.36	(11.5)
Dead branches	3.03 ± 0.33	(2.0)	3.36 ± 0.59	(2.0)
Boles	121.70 ± 12.81	(78.5)	132.26 ± 24.24	(78.2)
Total	154.89 ± 16.30	(100)	169.10 ± 30.72	(100)
Understory vegetation				
Bushes	0.30 ± 0.16	(9.2)	1.00 ± 1.50	(20.9)
Ground vegetation	2.94 ± 0.77	(90.8)	3.79 ± 1.27	(79.1)
Total	3.24 ± 0.77	(100)	4.79 ± 1.50	(100)
Litter layer	6.10 ± 1.63		10.24 ± 2.38	

1) mean ± standard deviation.
2) Numbers in parentheses are the percentage of the total.

Table 5. Carbon concentration (%) among components of the sample trees, understory vegetation, and litter layer (mean ± standard deviation)

Component	20 yr old	27 yr old
Taiwania		
Leaves and twigs	41.92 ± 0.87	43.52 ± 0.92
Branches	44.31 ± 4.34	46.56 ± 4.12
Dead branches	46.38 ± 0.51	46.66 ± 0.74
Boles	47.51 ± 0.44	47.25 ± 0.62
Understory vegetation		
Bushes		
Leaves	50.02 ± 1.48	49.14 ± 1.75
Branches	47.78 ± 1.27	47.14 ± 0.88
Boles	47.57 ± 0.88	46.85 ± 0.59
Ground vegetation	47.22 ± 1.40	47.77 ± 2.01
Litter layer	43.54 ± 6.23	46.38 ± 1.55

Table 6. Bulk density (g cm^{-3}) and organic carbon (%) among depths of soil (mean ± standard deviation)

Depth	20 yr old		27 yr old	
	Bulk density	C	Bulk density	C
0-15 cm	0.37	11.33 ± 6.27	0.31	10.04 ± 6.49
15-30 cm	0.33	7.19 ± 0.48	0.42	6.27 ± 3.38
30-45 cm	0.37	4.77 ± 1.47	0.44	3.16 ± 1.86

Table 7. Estimates of carbon storage (ton ha^{-1}) among components with respect to strata in 2 Taiwania plantations

Component	20 yr old	27 yr old
Taiwania		
Leaves and twigs	5.32 ± 0.57[1)] (7.4)[2)]	6.10 ± 1.08 (7.7)
Branches	7.74 ± 0.85 (10.7)	9.07 ± 1.56 (11.4)
Dead branches	1.41 ± 0.15 (1.9)	1.57 ± 0.28 (2.0)
Boles	57.82 ± 6.09 (80.0)	62.49 ± 11.46 (78.9)
Subtotal	72.29 ± 7.60 (100)	79.23 ± 14.38 (100)
	(36.0)[3)]	(40.9)
Understory vegetation		
Bushes	0.14 ± 0.08	0.48 ± 0.71
Ground vegetation	1.40 ± 0.37	1.80 ± 0.61
Subtotal	1.54 ± 0.37	2.28 ± 0.71
	(0.8)	(1.2)
Litter layer	2.64 ± 0.78	4.77 ± 1.28
	(1.3)	(2.5)
Soil		
0-15 cm	62.90 (50.3)	46.72 (43.6)
15-30 cm	35.58 (28.5)	39.50 (36.9)
30-45 cm	26.47 (21.2)	20.89 (19.5)
Subtotal	124.95 (100)	107.11 (100)
	(61.9)	(55.4)
Total	201.42 (100)	193.39 (100)

1) mean ± standard deviation.
2) Numbers in parentheses are the percentage of the subtotal.
3) Underlined numbers in parentheses are the percentage of the total.

concentration of organic carbon decreased with depth, the difference was not statistically significant ($p > 0.05$). Also, the carbon concentrations did not significantly differ ($p > 0.05$) between the 2 ages of stands.

As shown in Table 7, the major biomass of Taiwania accumulates in the boles, as does the carbon storage. In soils, 44-50% of carbon was stored in the first 0-15-cm depth, and the carbon storage decreases with soil depth. The carbon storage of Taiwania, understory vegetation, and the litter layer in stands all increased with stand age. But carbon concentrations and its contents in soils both decreased with stand age (Tables 6, 7). The carbon storage in understory vegetation and the litter layer was extremely low, with each portion being less than 3%. And soil was the main place where carbon was stored in Taiwania plantations.

DISCUSSION

Generally, the total biomass of trees increases with age (Turner and Long 1975, Ponette et al. 2001). In this study, biomass increased with the age due to the increase in bole size, since boles comprise the major part of a tree's biomass (Table 4). However, not only the total biomass but also all of the tree's components increase with stand age. This result is similar to that for a loblolly pine (*Pinus taeda* L.) stand before 20-yr-old (Switzer and Nelson 1972) and some Douglas-fir

(*Pseudotsuga menzieii* (Mirb.) Franco.) stands before 73-yr-old (Long and Turner 1975).

In order to avoid harvesting too many sample trees, the regression method is most commonly used to estimate biomass these days. In this research, tree biomass was significantly correlated with the dbh parameter (Table 3). As to these 2 Taiwania stands, the age and site characteristics did not affect the slope or intercept of the regression model; however, in France, Douglas-fir of 5 different ages needed 5 sets of regression equations (Ponette et al. 2001). On the contrary, Rayachhetry et al. (2001) found that there was no effect of habitat on the regression model, and Bartelink (1996) found that the relationship between dbh and stem biomass in a Douglas-fir stand was independent of stand characteristics. The result in this research seems to show that a set of common equations may be suitable for estimating the biomass of these 2 stands.

Since most publications about Taiwania have estimated timber volume only (Hung 1974, Liu et al. 1984, Chen et al. 1997), we can only compare our biomass data with those of some other conifers, such as Cryptomeria (*Cryptomeria japonica* (L.F.) D. Don) and China fir (*Cunninghamia lanceolate* (Lamb) Hook). Cryptomeria biomass varied strongly among sites, ranging from 125 to 268 ton ha^{-1} at ages 18 or 21 yr old (Wang 1978, Chang 1986) and ranged from 151 to 255 ton ha^{-1} at ages 30 to 32 yr old (Hsu 1981, Chang 1986). These great differences among sites may have mainly been due to site characteristics and tree density. The biomass of China fir approached its approximate maximum, 161 ton ha^{-1}, at 20 yr old (Horng et al. 1985). The biomass of Taiwania at age 20 yr in our research (Table 4) was similar to that of China fir (Horng et al. 1985), but slightly lower than that of Cryptomeria (Wang 1978, Chang 1986). However, the biomass of the Cryptomeria stand (151 ton ha^{-1}) in the Chitou area with a similar density (980 trees ha^{-1}, Yu 1981) to that of our study site was similar to our estimations. The Taiwania biomass at age 27 yr (Table 4) was higher than that of Cryptomeria in Chitou, and even much higher than that of China fir at 30 yr old (140 ton ha^{-1}) (Horng et al. 1985).

The carbon concentration in soil generally decreases with soil depth. For example, the carbon concentration decreased from 46 to 17 mg g^{-1} in the soil from 0-9 to 38-49 cm in a red spruce (*Picea rubens* Sarg.) stand in the Great Smoky Mountains, USA (Johnson et al. 1991). Similarly, carbon concentrations of soil in a pure Norway spruce stand of Austria decreased dramatically with depth as well (Berger et al. 2002). The soil organic carbon content of the Taiwania stands also decreased with soil depth. However, the difference was not statistically significant.

Since the biomass of each component of trees of the 27-yr-old stand was greater than that of the 20-yr-old stand (Table 7), the total carbon storage in all components of the 27-yr-old Taiwania stand was higher than that of the 20-yr-old one. It is well known that most of the organic carbon in a forest ecosystem usually accumulates in the soil. The soil organic carbon of Taiwania stands comprises 55-62% of the total carbon in the ecosystem (Table 7), which is higher than the 45% reported for some tropical forests (Malhi et al. 1999).

The average aboveground biomass of trees in tropical plantations is 65-224 ton ha^{-1} at the ages of 16-20 yr and 108-303 ton ha^{-1} at the ages of 21-30 yr (Brown et al. 1986). The biomass of Taiwania stands in this study fell within this range (Table 4). As to carbon storage, the vegetation and soils contained

137-200 and 104 ton ha^{-1}, respectively, in a tropical rain forest in Brazil (Schroeder and Winjum 1995). Malhi et al. (1999) found that the aboveground carbon storage was 180 ton ha^{-1}, and in the soil was 162 ton ha^{-1} in a highly dense tropical rain forest in Amazonia, Brazil. In comparison to those estimations in tropical forests, the aboveground carbon storage in the Taiwania stand of Liukuei was much smaller, but the soil carbon storage fell within the ranges (Table 7).

In the Taiwania stands, the average carbon sequestration rate of the trees, which was 3.6 and 2.9 ton ha^{-1} yr^{-1} at the ages of 20 and 27 yr, respectively, decreased beyond 20 yr of age. Hung (1974) concluded that the mean annual basal area increment of Taiwania in Liukuei also decreased significantly from ages 20 to 28 yr. However, for the entire ecosystem, the data on carbon sequestration in this study do not include the amount in roots, snags, and fallen trees, which may have a great or little influence on the carbon sequestration in a Taiwania ecosystem.

Lee et al. (2000) used timber volume equations and volume and carbon conversion coefficients to estimate the carbon storage for Taiwania stands at Liukuei. The carbon storages of trees in the stands at ages 19 and 23 yr were 77 and 133 ton ha^{-1}, respectively, both higher than the result in our research (Table 7). After the analysis, the coefficient of timber volume conversion from bole to whole tree selected in their research was 1.65, the mean of all species. The coefficients of biomass conversion from bole to whole tree estimated for the 2 stands in this research were 1.27 and 1.28, respectively, much lower than that of all species. In addition, all carbon concentrations of all Taiwania components in our research were lower than 50% as hypothesized by that research. This may be the reason that data in our research are lower.

LITERATURE CITED

Bartelink HH. 1996. Allometric relationships on biomass and needle area of Douglas-fir. For Ecol Mgmt 86:193-203.

Berger TW, Neubauer C, Glatzel G. 2002. Factors controlling soil carbon and nitrogen stores in pure stands of Norway spruce (*Picea abies*) and mixed species stands in Austria. For Ecol Mgmt 159:3-14.

Brown S, Lugo AE, Chapman J. 1986. Biomass of tropical tree plantations and its implications for the global carbon budget. Can J For Res 16: 390-4.

Chang CT. 1986. Biomass productivity of *Cryptomeria japonica* stand in central and northern Taiwan. Q J Chin For 19(4):45-85. [in Chinese with English summary].

Chen LC, Huang GM, Lin JS, Chiou CR. 1997. Growing stock and growth estimation of Taiwania plantations in the Liukuei area. Taiwan J For Sci 12(3):319-27. [in Chinese with English summary].

Dudley NS, Fownes JH. 1992. Preliminary biomass equations for eight species of fast-growing tropical trees. J Trop For Sci 5(1):68-73.

Horng FW, Sun JC, Hwang SG. 1985. Aboveground biomass distribution of China-fir plantations with respect to age at Lien-Hua-Chi. Bull TFRI No. 444. 12 p. [in Chinese with English summary].

Hsu CC. 1981. Studies on the seasonal variation of litter-fall and its nutrient contents of Cryptomeria and China-fir [Thesis]. Taiwan: National Chung Hsing University. 41 p. [in Chinese with English summary].

Hung LP. 1974. Study on the stands' growth of Taiwania plantation established by test of planting on different forest districts in Taiwan. Bull TFRI No. 375. 20 p. [in Chinese with English summary].

Johnson DW, Van Miegroet H, Lindberg SE, Todd DE, Harrison RB. 1991. Nutrient cycling in red spruce forests of the Great Smoky Mountains. Can J For Res 21:769-87.

Lal R, Kimble JM. 2001. Importance of soil bulk density and methods of its importance. In: Lal R, Kimble JM, Follett RF, Stewart BA, editors. Assessment methods for soil carbon. New York: Lewis Publishers. p 31-44.

Lee KJ, Lin JC, Chen LC. 2000. The potential of carbon sequestration and its cost-benefit analysis for *Taiwania* plantations. Taiwan J For Sci 15(1):115-23. [in Chinese with English summary].

Liu SC, Lin KC, Tang JL. 1984. Growth and wood properties of planted *Taiwania cryptomerioides* at Liu-Kuei. Bull TFRI No. 408. 25 p. [in Chinese with English summary].

Long JN, Turner J. 1975. Aboveground biomass of understorey and overstorey in an age sequence of four Douglas-fir stands. J Appl Ecol 12:179-88.

Malhi Y, Baldocchi DD, Jarvis PG. 1999. The carbon balance of tropical, temperate and boreal forests. Plant Cell Environ 22:715-40.

Nelson DW, Sommers LE. 1996. Total carbon, organic carbon, and organic matter. Methods of soil analysis. Part 3. Chemical methods–SSSA Book Series no. 5. Madison, WI: Soil Science Society of America. p 961-1010.

Ponette Q, Ranger J, Ottorini JM, Ulrich E. 2001. Aboveground biomass and nutrient content of five Douglas-fir stands in France. For Ecol Mgmt 142:109-27.

Rayachhetry MB, Van TK, Center TD, Laroche F. 2001. Dry weight estimation of the aboveground components of *Melaleuca quinquenervia* trees in southern Florida. For Ecol Mgmt 142:281-90.

Schroeder PE, Winjum JK. 1995. Assessing Brazil's carbon budget: I. Biotic carbon pools. For Ecol Mgmt 75:77-86.

Sollins P, Glassman C, Paul EA, Swanston C, Lajtha K, Heil JW, Elliott ET. 1999. Soil carbon and nitrogen: pools and fractions. In: Robertson GP, Coleman DC, Bledsoe CS, Sollins P, editors. Standard soil methods for long-term ecological research. New York: Oxford University Press. p 89-105.

Switzer GL, Nelson LE. 1972. Nutrient accumulation and cycling in loblolly pine (*Pinus taeda* L.) plantation ecosystems: the first twenty years. Soil Sci Soc Am Proc 36:143-7.

TFRI 1998. Climate data of Liu Kuei station, TFRI. TFRI Extension Series No. 89. 517 p. [in Chinese].

Turner J, Long JN. 1975. Accumulation of organic matter in a series of Douglas-fir stands. Can J For Res 5:681-90.

Wang TT. 1978. Tree biomass production in Cryptomeria stands of different age classes. J Agric Assoc China New Series 102:59-76. [in Chinese with English summary].

Yu HM. 1981. Aboveground biomass and net production in Cryptomeria stands of different age classes [Thesis]. Taipei, Taiwan: National Taiwan University. [in Chinese with English summary].