Ann. For. Sci. 62 (2005) 659–668
© INRA, EDP Sciences, 2005
DOI: 10.1051/forest:2005073

Original article

Conversion of a natural broad-leafed evergreen forest into pure plantation forests in a subtropical area: Effects on carbon storage

Guang-Shui CHEN[a], Yu-Sheng YANG[a*], Jin-Sheng XIE[b], Jian-Fen GUO[a], Ren GAO[a], Wei QIAN[a]

[a] Department of Geography Sciences, Fujian Normal University, Fuzhou 350007, China
[b] Department of Forestry, Fujian Agriculture and Forestry University, Fuzhou 350002, China

(Received 14 February 2005; accepted 27 June 2005)

Abstract – For the last several decades, native broad-leafed forests in many areas of south China have been converted into plantations of more productive forest species for timber use. This paper presents a case study examining how this forest conversion affects ecosystem carbon storage by comparing 33 year-old plantations of two coniferous trees, Chinese fir (*Cunninghamia lanceolata,* CF) and *Fokienia hodginsii* (FH) and two broadleaved trees, *Ormosia xylocarpa* (OX) and *Castanopsis kawakamii* (CK), with an adjacent relict natural forest of *Castanopsis kawakamii* (NF, ~ 150 year old) in Sanming, Fujian, China. Overall estimates of total ecosystem carbon pools ranged from a maximum of 399.1 Mg ha^{-1} in the NF to a minimum of 210.6 Mg ha^{-1} in the FH. The combined tree carbon pool was at a maximum in the NF where it contributed 64% of the total ecosystem pool, while the OX had the lowest contribution by trees at only 49%. Differences were also observed for the carbon pools of undergrowth, forest floor and standing dead wood, but that these pools together represent at the most 5% of the ecosystem C stock. Total C storage in the surface 100 cm soils ranged from 123.9 Mg ha^{-1} in the NF to 102.3 Mg ha^{-1} in the FH. Significant differences ($P < 0.01$) in SOC concentrations and storage between native forest and the plantations were limited to the surface soils (0–10 cm and 10–20 cm), while no significant difference was found among the plantations at any soil depth ($P > 0.05$). Annual aboveground litterfall C ranged from 4.51 Mg ha^{-1} in the CK to 2.15 Mg ha^{-1} in the CF, and annual belowground litterfall (root mortality) C ranged from 4.35 Mg ha^{-1} in the NF to 1.25 Mg ha^{-1} in the CF. When the NF was converted into tree plantations, the vegetation C pool (tree plus undergrowth) was reduced by 27–59%, and the detritus C pool (forest floor, standing dead wood, and soils) reduced by 20–25%, respectively. These differences between the NF and the plantations may be attributed to a combination of factors including more diverse species communities, more C store types, higher quantity and better quality of above- and belowground litter materials under the NF than under the plantations and site disturbance during the establishment of plantations.

carbon storage / carbon input / natural forest / monoculture plantation

Résumé – Conversion d'une forêt naturelle feuillue en plantations forestières pures en zone subtropicale : effets sur le stockage de carbone. Dans les dernières décades, dans beaucoup de zones de la Chine du Sud, des forêts feuillues naturelles ont été transformées en plantations plus productives en bois. Cet article présente une étude de cas examinant comment cette conversion forestière affecte le stockage de carbone dans l'écosystème. L'étude compare des plantations âgées de 33 ans de deux conifères, *Cunninghamia lanceolata* (CF) et *Fokienia hodginsii* (FH) et deux feuillus, *Ormosia xylocarpa* (OX) et *Castanopsis kawakamii* (CK) avec une forêt naturelle relictuelle adjacente de *Castanopsis kawakamii* (NF), âgée d'environ 150 ans, à Sanming, Fujian en Chine. Une estimation générale des pools totaux de carbone permet de les classer depuis un maximum 399.1 Mg ha^{-1} pour NF jusqu'à un minimum de 210.6 Mg ha^{-1} pour FH. Le pool de carbone des arbres était maximum pour NF où il contribue pour 64 % dans le pool total de carbone de l'écosystème, alors que OX présente la contribution des arbres la plus faible, seulement 49 % Des différences ont aussi été observées pour les pools de carbone du sous-bois, de la couverture du sol et des bois morts sur pied, mais ensemble ces pools représentent au maximum 5 % du stock total de carbone de l'écosystème. Le stockage de C dans les 100 cm de sol variait de 123.9 Mg^{-1} pour NF à 102.3 Mg ha^{-1} pour FH. Les différences significatives ($P < 0,01$) dans les concentrations en SOC (carbone organique du sol) et en stockage, entre forêt naturelle et plantations, étaient limitées à la surface du sol (0–10 cm et 10–20 cm), tandis qu'il n'a pas été trouvé de différences significatives parmi les plantations quelle que soit la profondeur de sol ($P > 0,05$). La chute annuelle de litière au-dessus du sol variait de 4.51 Mg ha^{-1} pour CK 0 2.15 mg ha^{-1} pour CF. La litière annuelle souterraine (mortalité racinaire) variait de 4.35 Mg ha^{-1} pour NF 0 1.25 mg ha^{-1} pour CF. Lorsque NF a été transformé en plantations, le pool de carbone de la végétation (arbres + sous-bois) a été réduit de 27 % à 59 % et le pool de carbone de détritus (couverture du sol, arbres morts sur pied, et sols) a été réduit de 20 à 25 % respectivement. Ces différentes entre NF et les plantations peuvent être attribuées à une combinaison de facteurs comprenant davantage de communautés d'espèces, davantage de types de stockage, une quantité plus grande et une meilleure qualité des litières aériennes et souterraines pour NF que pour les plantations et aux perturbations des terrains au moment de la mise en place des plantations.

stockage de carbone / apport de carbone / forêt naturelle / monoculture en plantation

* Corresponding author: geoyys@fjnu.edu.cn

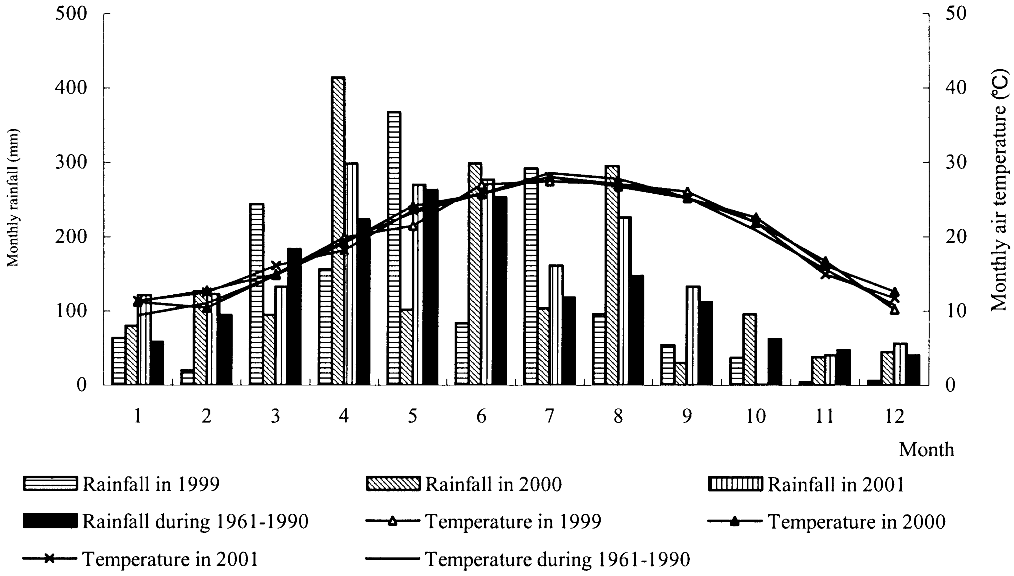

Figure 1. Monthly changes of rainfall and air temperature in the study sites.

1. INTRODUCTION

The effects of land use change on carbon storage are of concern in the context of international policy agendas on greenhouse gas emissions mitigation, and the first of all are those associating with the conversion of native forest to agricultural systems, especially in the tropical zone. However, the effects of conversion of natural forest to tree plantation have less been assessed. Carbon stocks of both natural and plantation forests are well documented [5, 9, 11, 19, 21, 23, 29, 43, 47], in terms of carbon sequestration, however, the relative importance of each is often confused.

Due to rapid human population growth, demand for timber, fuel material, and other forest products is increasing. In many areas of South China, native broad-leafed forests have been cleared for the last several decades, and subsequent development has involved the plantation of more productive forest species. Following timber extraction, the forest land is slashed, burned, and planted with economical conifer species, especially Chinese fir (*Cunninghamia lanceolata*) [50]. As an important native conifer, Chinese fir has been widely planted for more than 1000 years and used for a variety of wood products. Planting area has reached 6 million ha and accounted for 24% of all forested land in China [53]. Currently, it is thought that this conifer will be able to bring great profit of carbon sequestration in addition to timber production. However, there is little known about the effects of forest conversion to tree plantations on C stores in subtropical China.

The establishment of tree species trials during the 1960s at the Xinkou Experimental Station in Sanming, Fujian, which include a variety of tree plantations such as *Cunninghamia lanceolata* (Chinese fir, CF), *Fokienia hodginsii* (FH), *Ormosia xylocarpa* (OX) and *Castanopsis kawakamii* (CK) that grown on a same soil and with the same former forest, natural forest of *Castanopsis kawakamii*, and an adjacent relict natural forest of *Castanopsis kawakamii* (NF) that as a control, provided a unique opportunity to examine how changes occur following converting a natural forest to tree plantations. We had reported litterfall and fine-root dynamics and soil biological changes on these forests [8, 49, 51]. The primary objective of this study was to determine if plantations consisting of broadleaved and coniferous species altered the ecosystem C stocks. To address this question, we measured carbon storage in trees, undergrowths, forest floor, standing dead woods and mineral soils, and above- and belowground litterfall C changes at these forests.

2. MATERIALS AND METHODS

2.1. Site description

The study was carried out in the Xiaohu work-area of the Xinkou Experimental Forestry Centre of Fujian Agricultural and Forestry University, Sanming, Fujian, China (26° 11' 30'' N, 117° 26' 00'' E). It borders the Daiyun Mountain on the southeast, and the Wuyi Mountain on the northwest. The region has a middle sub-tropical monsoonal climate, with a mean annual temperature of 19.1 ºC and a relative humidity of 81%. The mean annual precipitation is 1749 mm, mainly occurring from March to August (Fig. 1). Mean annual potential evapotranspiration is 1585 mm (Penman-Monteith equation). The growing season is relatively long with an annual frost-free period of around 330 days. The parent material of the soil is sandy shale and soils are classified as red soils (humic Planosols in FAO system). Thickness of the soil exceeds 1.0 m.

Selected forest characteristics and some properties of the surface soil (0–20 cm) of the five sites are described in Table I. NF represents the evergreen, broadleaved *C. kawakamii* forest in mid-subtropical China with high purity (85% of total stand basal area for *C. kawakamii*), old age (~ 150 year), and large area (~ 700 ha). In addition to *C. kawakamii*, the overstorey also contained other tree species, such as *Pinus massoniana*, *Schima superba*, *Lithocarpus glaber*, *Symplocos caudate*, *Machilus velatina*, *Randia cochinchinensis*, and *Symplocos*

Table I. Forest characteristics and soil properties of the NF, CK, FH, CF, and OX stands.

Parameters	Forest type[1]				
	NF[2]	CK	OX	FH	CF
Mean tree age (year)	~ 150	33	33	33	33
Mean tree height (m)	24.3	18.9	18.4	21.4	21.9
Mean tree diameter at breast height (cm)	42.2	24.2	17.2	21.6	23.3
Stand density (stem ha^{-1})	255	875	1109	975	1117
Stand volume (m^3 ha^{-1})	398.31	412.43	209.01	379.57	425.91
Canopy coverage (%)	80	90	70	70	65
Soil (A horizon, 0–20 cm depth, mean ± sd[3])					
Total N (mg g^{-1})	1.88 ± 0.20	1.12 ± 0.23	1.29 ± 0.19	1.37 ± 0.22	1.12 ± 0.28
C/N ratio	14.0 ± 2.5	15.3 ± 2.2	13.6 ± 2.3	12.9 ± 1.8	15.1 ± 2.1
Hydrolyzable N (mg g^{-1})	0.14 ± 0.03	0.12 ± 0.02	0.13 ± 0.01	0.12 ± 0.02	0.11 ± 0.02
Available P (mg kg^{-1})	7.6 ± 1.4	5.9 ± 1.1	6.8 ± 1.3	5.6 ± 0.9	4.7 ± 0.8
Available K (mg kg^{-1})	140 ± 15	121 ± 9	109 ± 11	108 ± 9	100 ± 7
CEC (cmol kg^{-1})	13.5 ± 0.8	12.9 ± 0.3	12.2 ± 0.2	11.9 ± 0.3	11.4 ± 0.3
Exchangeable bases (cmol kg^{-1})	4.4 ± 0.5	3.8 ± 0.6	3.3 ± 0.3	3.2 ± 0.4	2.5 ± 0.4
Base saturation (%)	32 ± 3	29 ± 4	27 ± 3	27 ± 4	22 ± 3
Soil pH in water	5.8 ± 0.3	5.3 ± 0.3	5.1 ± 0.2	5.1 ± 0.3	4.8 ± 0.3
Leaf-litter decomposition constant (k) (a^{-1})	4.52	4.46	4.62	3.92	1.16

[1] CF, Chinese fir (*Cunninghamia lanceolata*) plantation forest; FH, *Fokienia hodginsii* plantation forest; OX, *Ormosia xylocarpa* plantation forest; CK, *Castanopsis kawakamii* plantation forest; NF, natural forest of *C. kawakamii*. The abbreviations are the same as elsewhere.
[2] *Castanopsis kawakamii* is only involved.
[3] Six soils were randomly taken from each plot, totaled 30 soil samples per forest (5 plots per stand).

stellaris. In 1966, part of this NF was clear-cut, slashed and burned. In 1967, the soil was prepared by digging holes and then 1-year-old seedlings of *C. lanceolata* (Chinese fir), *F. hodginsii*, *O. xylocarpa*, and *C. kawakamii* were planted with density of 3000 trees per ha. The area of each plantation is larger than 20 ha. The plantation forests were managed with similar practices, such as weed-controlling and fertilizing during the first 3 years, and thinning twice between 10 ~ 15 year old. The normal rotation length is 30 years for the CF and the FH and 40 years for the CK and the OX, respectively.

2.2. Methods

2.2.1. Estimation of carbon storage

In January 1999, five 20 m × 20 m plots were located at each forest. Diameters at breast height (DBH) of all trees on each plot were measured. In the NF, all stems 4 cm DBH and above were identified by species; diameter was determined using standard diameter measuring tapes. For trees with epiphytic cover on the trunk, the epiphytes were pulled a short distance away from the trunk, sufficient to allow determination of the trunk diameter. Dead stems were inventoried and identified where possible.

Biomass components (wood, bark, branch, twig, leaf, root) were estimated by harvest. Fifty-six trees from 8 dominant tree species (including 10 individuals of *C. kawakamii*, 8 of *Pinus massoniana*, 8 of *Schima superba*, six each of *Lithocarpus glaber*, *Symplocos caudate*, *Machilus velatina*, *Randia cochinchinensis* and *Symplocos stellaris*) in the NF, 12 of *C. kawakamii* in the CK, 11 of *O. xylocarpa* in the OX, 12 of *F. hodginsii* in the FH, and 12 of Chinese fir in the CF were felled. The selected harvest trees of each species covered the range of size present in the plots. The selected harvest species in the NF account for over 95% of the total stand basal area.

Samples for carbon analysis were obtained from each of the harvested species. These samples were derived from material collected during harvests to determine allometric relationships. Four to six branches from different levels of the canopy were removed from each tree. Samples of branch wood and foliage were obtained from each branch. Samples of trunk wood and bark were obtained from each tree using an 11 mm tree corer or wedges of wood cut using a chainsaw. Root samples were obtained by excavation. All samples obtained were field weighed, placed into plastic bags and kept cool until they could be transported to the laboratory.

Allometric regression equations (power functions) relating tree DBH and biomass were developed for each species at these sites. The allometric regression equations were well fitted for each components ($R^2 > 0.8$, $P < 0.05$). The standing dead wood of each species was calculated by using the species-specific allometric regression for stem component.

Understorey biomass was determined using destructive harvests of five randomly located replicate 1 m^2 quadrates sampled at each plot. Forest floor samples consisting of the O_i (leaves, twigs) and O_e (fragmented leaves and twigs) layers combined were collected from fifteen 0.25 m^2 areas placed randomly within each plot. Samples were separated into two categories: fine litter and coarse woody litter, by identifying the coarse woody litter as all dead wood above 2 cm diameter and 40 cm length on the ground.

At each plot of each site, 6 soils were excavated to a depth of 1 m or bedrock, whichever was reached first. Using an 8 cm bulk density corer, soil samples were taken at depth intervals of 0–10, 10–20, 20–40, 40–60, 60–80, > 80 cm. Rocks and gravel (> 2 mm diameter) were removed from each sample and the remaining soil ground and oven-dried for bulk density and C concentration determination.

2.2.2. Carbon input

2.2.2.1. Aboveground litterfall

Fifteen 0.5 m × 1.0 m litter traps made of nylon mesh (1 mm mesh size), were arranged in each forest and were raised 25 cm above the ground, and the litterfall was collected at 10-day intervals from January 1999 to December 2001 [51]. The collected litter at each time was oven-dried at 80 °C to constant weight. At the end of each month, the oven-dried litter was combined by month and trap, and sorted into leaves, twigs (< 2 cm in diameter), flowers, fruits, and miscellaneous material (insect fecal, unidentified plant parts, etc.). Furthermore, collected leaf and twig litter in the NF were separated into two classes, viz. *C. kawakamii* and other tree species in tree layer. Thereafter monthly mass of each fraction was determined and sub-samples of litters of each forest were taken by month, trap, and fraction for carbon analysis.

2.2.2.2. Belowground litterfall

Fine root (< 2 mm) biomass was measured by the sequential core method [49]. On each sampling date, 30 soil cores (1 m in depth) were randomly collected from each forest bimonthly during January 1999–January 2002 using a steel corer (6.8 cm diameter, 1.2 m length). Soil cores were stored at 4 °C in refrigerators until processed. Cores were washed with tap water to remove adhering soil and accompanying organic debris. Fine roots were classified by diameter, trees or undergrowth (shrubs and herbages), and physiological status (live or dead) based on color, texture and shape of the root [49]. Only fine roots of trees were collected and included in this study. All fine root samples were oven-dried (80 °C) to constant weight and weighed.

Decomposition rate of fine roots was quantified by the litterbag technique [48]. The fine roots of tree species were collected from each stand by sieving from the top 0–20 cm soil. In the NF, only roots of *C. kawakamii* were collected for decomposition. In May 1999, the nylon litter bags (18×18 cm^2 size and 0.25 mm mesh) containing 5 g air-dried root samples (a total of 240 bags were placed at each forest site, 80 for each size) were placed on the sites at a soil depth of 10 cm at random locations for an 24 months period. Six bags were retrieved from each forest site occasionally after sample placement. The residual materials were oven-dried to constant mass at 80 °C, and weighed.

Belowground litterfall (or root mortality) was calculated with the compartment-flow method, according [22, 49].

2.2.3. Laboratory analyses

The biomass samples were oven-dried, ground and passed through a 1 mm sieve. Mineral soil samples were sieved through a 0.149 mm sieve before chemical analysis of organic C. Carbon concentrations of plant samples were determined using an ELEMEMTAR Vario EL III CNHOS Analyzer. For the determination of soil organic C, the soil samples were digested in $K_2Cr_2O_7$-H_2SO_4 solution using an oil-bath heating and then C concentration was determined from titration [28]. Mass of carbon stored in tree compartments, understorey vegetation, forest floor, and standing dead wood was estimated by multiplying their measured biomass by their carbon concentration. Content of mineral soil organic C per unit area for each horizon was estimated by multiplying mean organic C concentrations by bulk density and soil sampling depth. Storage of organic C in the 0–100 cm profile was the sum of their contents for each horizon.

2.2.4. Statistical analysis

One-way analysis of variance was used to test the differences between forests in mass, carbon concentrations and carbon contents of various tissues of tree, undergrowth, forest floor and standing dead wood. Two-way analysis of variance was used to test differences in soil bulk density, SOC concentration and SOC content among forests and depths and to test differences in annual above- and belowground carbon inputs among forests and years. All statistical analyses were conducted using SPSS 13.0 for Windows.

3. RESULTS

3.1. Vegetation carbon storage

On average, woody tissues (trunk, branches, twigs and coarse roots) made up 96 ~ 97% of a tree's carbon mass. These woody tissues generally have relatively higher carbon concentrations than the soft tissues: leaves and fine roots (Tab. II). By weighting the carbon concentrations of the different tissue types by the proportion of the total tree biomass they represent, we obtain a significantly lower average of tree carbon concentration (46.5 ~ 47.0%) for the CF and FH than for the NF, CK and OX (49.8% ~ 50.4%) ($P < 0.01$). Contribution to the total tree carbon pool by the above-ground stem components (wood plus bark) in the CF and FH (both 74%) was higher than that in the NF, CK, and OX (55% ~ 58%). A similar proportion of tree carbon was allocated belowground among these forest (11% ~ 20%), and less than 2% was allocated to fine roots (live + dead). The combined tree carbon pool was at a maximum in the NF where it contributed 64% of the total ecosystem pool, while the OX had the lowest contribution by trees at only 49%.

Undergrowth contributions were highest in the OX where they accounted for 2.0% of the total pool and lowest in the CK where they made up only 0.2% of the carbon pool (Tab. II).

3.2. Detritus carbon stock

Carbon stocks in the forest floor ranged from 4.8 Mg ha^{-1} in the NF to 1.4 Mg ha^{-1} in the FH, and there was a significant effect for stand type ($P < 0.05$) (Tab. III). Fine litter contributions were highest in the OX at 1.4% and lowest in the CF and FH at 0.6%. The coarse woody litter made small contributions (~ 0.3%) to the total carbon pool, and occupied 27% of the forest floor C in the NF and 6% in the CK (Tab. III). The standing dead wood accounted for 2.6% of total ecosystem C pool in the NF, while they were not found in the plantations (Tab. III).

Both carbon concentration and bulk density changed with depth (Fig. 2). Though there was no significant difference in soil bulk density ($P > 0.01$), there was significant difference in terms of surface soil (0–10 cm and 10–20 cm) SOC concentrations and storage between native forest and the plantations ($P < 0.01$). No significant difference was found between the plantations at any soil depth ($P > 0.01$) (Fig. 2). The total C stock for 0–100 cm soil ranged from 123.9 Mg ha^{-1} in the NF to 102.3 Mg ha^{-1} in the FH (Tab. III).

3.3. Ecosystem carbon stock

Overall estimates of total ecosystem carbon pools ranged from a high of 399.1 Mg ha^{-1} in the NF to a low of 210.6 Mg ha^{-1} in the FH (Fig. 3). The total ecosystem carbon stock was dominated

Table II. Biomass (Mg ha^{-1}), carbon concentration (%) and storage (Mg ha^{-1}) in vegetation pools of the NF, CK, FH, CF, and OX stands (date are mean ± SD).

	Organs	NF			CK			OX			FH			CF		
		Biomass	C concentration	C storage	Biomass	C concentration	C storage	Biomass	C concentration	C storage	Biomass	C concentration	C storage	Biomass	C concentration	C storage
Tree	Leaf	14.1 ± 1.6	45.7 ± 1.7	6.4 ± 1.1	12.6 ± 1.0	44.9 ± 1.6	5.7 ± 0.9	5.9 ± 0.6	46 ± 2.0	2.7 ± 0.4	4.4 ± 0.4	43 ± 1.5	1.9 ± 0.3	3.8 ± 0.4	44.3 ± 1.9	1.7 ± 0.3
	Branch	118.3 ± 14.2	50.4 ± 1.7	59.6 ± 6.6	80.4 ± 12.9	51.2 ± 1.7	41.1 ± 4.1	70.6 ± 9.0	50.3 ± 2.0	35.5 ± 3.9	19.9 ± 3.2	44 ± 0.9	8.7 ± 1.2	8.8 ± 1.1	47.2 ± 1.3	4.2 ± 0.6
	Stem wood	261.1 ± 23.5	50.1 ± 1.7	130.8 ± 18.4	201.8 ± 20.2	50.7 ± 1.4	102.3 ± 18.0	109 ± 15.3	51.2 ± 2.0	55.8 ± 7.9	142.9 ± 21.4	48.3 ± 2.1	69 ± 7.6	148.1 ± 11.8	46.8 ± 1.6	69.1 ± 9.9
	Stem bark	19.4 ± 2.7	48.2 ± 1.9	9.4 ± 0.8	17.2 ± 2.2	48.6 ± 1.7	8.3 ± 0.9	11.4 ± 1.5	49.2 ± 1.3	5.6 ± 0.5	19.6 ± 2.4	45.5 ± 1.8	8.9 ± 1.3	27.5 ± 4.4	46.6 ± 1.0	12.8 ± 2.1
	Aboveground subtotal	412.9 ± 53.7	49.9 ± 1.3	206.2 ± 36.3	312 ± 25.0	50.4 ± 1.1	157.4 ± 22.2	197 ± 25.6	50.6 ± 1.7	99.7 ± 17.5	186.8 ± 26.2	47.4 ± 1.9	88.6 ± 7.8	188.3 ± 28.2	46.4 ± 2.0	87.8 ± 9.7
	Stump	35.4 ± 4.6	49.4 ± 1.7	17.5 ± 2.9	27.8 ± 4.4	49.5 ± 2.1	13.8 ± 1.2	11.7 ± 1.8	49.1 ± 1.0	5.8 ± 0.6	18 ± 2.3	44.9 ± 1.2	8.1 ± 1.4	18.1 ± 2.2	45.2 ± 1.8	8.2 ± 1.2
	Root > 4 cm	27.3 ± 4.1	49.1 ± 1.0	13.4 ± 1.8	20.5 ± 3.1	50.2 ± 2.0	10.3 ± 1.8	6.2 ± 0.6	49.8 ± 2.1	3.1 ± 0.4	9.1 ± 1.2	44.8 ± 1.5	4.1 ± 0.7	18.4 ± 2.6	46.7 ± 1.5	8.6 ± 0.8
	Root 2–4 cm	10 ± 1.0	50.1 ± 2.1	5 ± 0.8	3.7 ± 0.6	48.9 ± 1.6	1.8 ± 0.3	1.7 ± 0.2	49.9 ± 1.3	0.9 ± 0.1	3.2 ± 0.5	47.1 ± 1.0	1.5 ± 0.2	6.1 ± 0.8	47.1 ± 1.8	2.9 ± 0.5
	Root 1–2 cm	8.2 ± 1.0	48.8 ± 1.3	4 ± 0.6	4.7 ± 0.5	49.3 ± 1.8	2.3 ± 0.3	1.9 ± 0.2	48.8 ± 1.7	0.9 ± 0.2	1.1 ± 0.1	47 ± 2.0	0.5 ± 0.1	1.6 ± 0.2	46.3 ± 1.1	0.8 ± 0.1
	Root 0.4–1 cm	7.3 ± 0.6	49.3 ± 1.7	3.6 ± 0.5	3.9 ± 0.5	48.6 ± 1.7	1.9 ± 0.3	1.1 ± 0.2	48.4 ± 1.0	0.5 ± 0.1	1.1 ± 0.1	47.4 ± 1.3	0.5 ± 0.1	1.4 ± 0.1	45.8 ± 1.7	0.6 ± 0.1
	Root 0.2–0.4 cm	3 ± 0.5	48.4 ± 1.0	1.5 ± 0.2	1.3 ± 0.1	48.6 ± 1.6	0.6 ± 0.1	0.7 ± 0.1	47 ± 2.0	0.3 ± 0.0	0.7 ± 0.1	45.4 ± 1.5	0.3 ± 0.0	0.7 ± 0.1	45.9 ± 1.6	0.3 ± 0.0
	Fine roots living	4.9 ± 0.7	46.7 ± 2.0	2.3 ± 0.3	3.2 ± 0.5	46.6 ± 1.1	1.5 ± 0.2	1.7 ± 0.2	46.1 ± 1.8	0.8 ± 0.1	2.2 ± 0.4	44.5 ± 0.9	1 ± 0.1	1.5 ± 0.2	45.1 ± 1.9	0.7 ± 0.1
	Fine roots dead	3.6 ± 0.4	45.9 ± 1.8	1.6 ± 0.2	2.7 ± 0.3	45.8 ± 1.0	1.3 ± 0.2	1.3 ± 0.2	45.2 ± 1.4	0.6 ± 0.1	1.7 ± 0.3	44.2 ± 1.9	0.8 ± 0.1	1.3 ± 0.2	44.3 ± 1.2	0.6 ± 0.1
	Belowground subtotal	99.6 ± 13.9	49 ± 1.6	48.9 ± 4.3	67.8 ± 8.7	49.3 ± 1.3	33.4 ± 5.9	26.3 ± 3.7	48.8 ± 2.0	12.9 ± 1.7	37.1 ± 5.6	45.2 ± 1.5	16.8 ± 1.8	49.1 ± 3.9	46 ± 1.6	22.6 ± 3.2
	Tree subtotal	512.5 ± 67.1	49.8 ± 1.9	255.1 ± 44.9	379.9 ± 30.4	50.2 ± 1.7	190.8 ± 21.0	223.3 ± 29.0	50.4 ± 1.3	112.5 ± 17.3	223.9 ± 26.9	47 ± 1.0	105.3 ± 14.8	237.4 ± 38.0	46.5 ± 1.0	110.3 ± 18.2
Undergrowth	Shrubs	10.1 ± 1.3	47.4 ± 1.1	4.8 ± 0.8	0.8 ± 0.1	45.7 ± 1.0	0.4 ± 0.1	8.7 ± 1.1	47.5 ± 1.6	4.2 ± 0.6	1.7 ± 0.2	46.4 ± 2.0	0.8 ± 0.1	2 ± 0.3	45 ± 1.8	0.9 ± 0.1
	Herbs	0.9 ± 0.1	46.1 ± 1.7	0.4 ± 0.1	0.3 ± 0.0	44.8 ± 1.9	0.1 ± 0.0	1.1 ± 0.2	45.1 ± 1.0	0.5 ± 0.1	1.8 ± 0.2	45.3 ± 1.8	0.8 ± 0.1	2.5 ± 0.2	44 ± 1.8	1.1 ± 0.2
	Subtotal	11 ± 0.9	47.3 ± 1.6	5.2 ± 0.8	1.1 ± 0.1	45.5 ± 1.7	0.5 ± 0.1	9.8 ± 0.8	47.2 ± 1.6	4.6 ± 0.6	3.5 ± 0.4	45.8 ± 1.1	1.6 ± 0.3	4.5 ± 0.4	44.4 ± 1.5	2 ± 0.3

Table III. Dry mass (Mg ha^{-1}), carbon concentration (%) and storage (Mg ha^{-1}) in detritus pools of the NF, CK, FH, CF, and OX stands (date are mean ± SD).

	Organs	NF			CK			OX			FH			CF		
		Dry mass	C concentration	C storage	Dry mass	C concentration	C storage	Dry mass	C concentration	C storage	Dry mass	C concentration	C storage	Dry mass	C concentration	C storage
Forest floor	Fine Litter	7.7 ± 0.8	45.9 ± 1.7	3.5 ± 0.6	7.4 ± 0.6	44.6 ± 1.6	3.3 ± 0.5	7.2 ± 0.7	44.9 ± 1.9	3.2 ± 0.5	2.7 ± 0.2	43.1 ± 1.5	1.2 ± 0.2	3.2 ± 0.3	44 ± 1.9	1.4 ± 0.2
	Coarse litter	2.6 ± 0.3	49.3 ± 1.7	1.3 ± 0.2	0.4 ± 0.1	49.1 ± 1.6	0.2 ± 0.1	0.6 ± 0.1	48.1 ± 1.9	0.3 ± 0.1	0.5 ± 0.1	44.5 ± 0.9	0.2 ± 0.1	0.6 ± 0.1	47 ± 1.3	0.3 ± 0.1
	Subtotal	10.3 ± 0.9	46.8 ± 1.6	4.8 ± 0.7	7.8 ± 0.8	44.8 ± 1.2	3.5 ± 0.6	7.8 ± 1.1	45.1 ± 1.8	3.5 ± 0.5	3.2 ± 0.5	43.3 ± 1.8	1.4 ± 0.2	3.8 ± 0.3	44.5 ± 1.5	1.7 ± 0.2
Standing dead wood		20.8 ± 2.9	49.1 ± 2.0	10.2 ± 1.8												
Mineral soil				123.9 ± 25.8			105.9 ± 19.5			107.3 ± 18.9			102.3 ± 19.0			103.1 ± 17.3

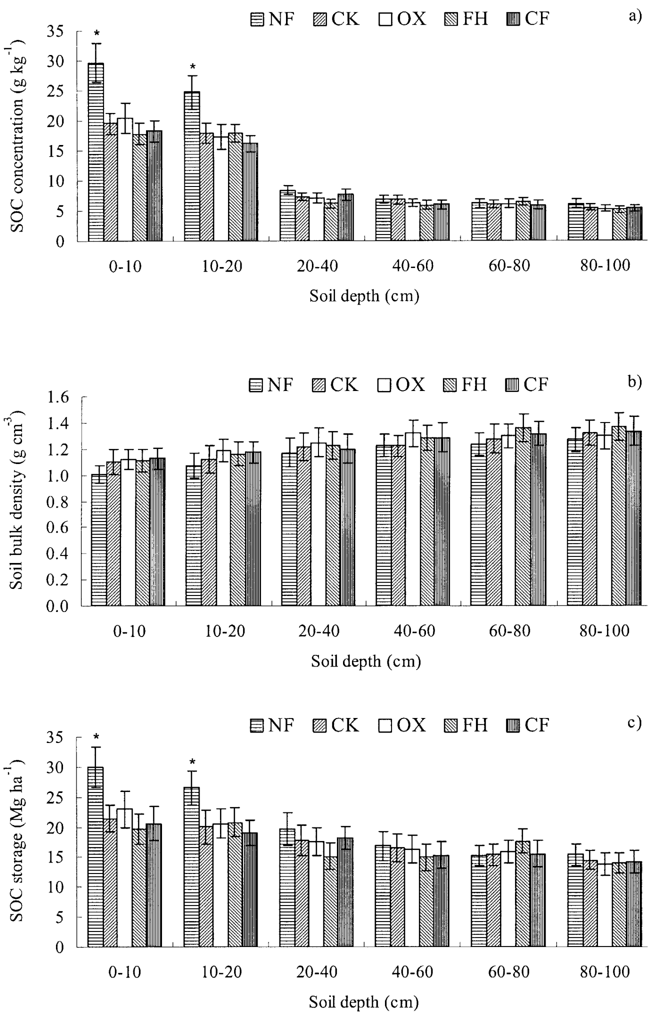

Figure 2. Changes of SOC concentration (**a**), soil bulk density (**b**) and SOC storage (**c**) with soil depth in the NF, CK, OX, FH and CF stands (Bars are standard errors. * indicates significant difference at $P < 0.01$ level).

by the vegetation pool (tree plus undergrowth) in the NF (65%) and CK (64%), while it was evenly distributed between the vegetation and detritus pools in the OX, FH and CF (Fig. 3).

3.4. Carbon input

There was a significant effect of forest type on annual above- and belowground litterfall C ($P < 0.01$) (Tab. IV). Annual aboveground litterfall C was significantly lower in the OX and CF ($P < 0.01$), while no significant difference was detected between the NF and the CK ($P > 0.01$). Annual belowground litterfall C was significantly higher in the NF than in the plantations ($P < 0.01$) (Tab. IV). No significantly yearly fluctuation of above- and belowground litterfall was found for any forest ($P > 0.01$).

4. DISCUSSION

4.1. Vegetation carbon pools

The total carbon storage in trees of the NF (255.1 Mg ha^{-1}) was much higher than those of three Amazonian forests (152 Mg ha^{-1} in Terra Firme forest, 178 Mg ha^{-1} in Tall Caatinga forest and 155 Mg ha^{-1} in Tall Bana forest) [10] and six Central American lowland tropical forests (average of 146 Mg ha^{-1}) [35], and lower than that of a native rain forest (340.467 Mg ha^{-1}) in Mountain Jianfenglin of tropical China [47], while very similar to a 400-year-old southern China subtropical broadleaved forest (244.998 Mg ha^{-1}) [29]. Also, our data are comparable with the estimated average carbon stock in live vegetation in Asian tropical moist and seasonal forests of 200 Mg ha^{-1} [17]. The tree carbon storage of the CK was lower than that of a successional forest (258.996 Mg ha^{-1}, 25-year-old) in Jianfenglin in tropical China [47] and higher than that of a temperate mixed deciduous forest (165.05 Mg ha^{-1}) [36], Panamanian teak mature plantations (120 Mg ha^{-1}, 20-year-old) [21] and gallery forest (64.4 Mg ha^{-1}) [45]. The carbon stored in the trees of the FH and CF plantations is similar to the final stocks of Brazilian slash pine (112 Mg ha^{-1}) on medium site classes [30], while lower than that of Australian radiata pine (171 Mg ha^{-1} over 45-year rotation) [40].

The biomass-weighted mean carbon concentration was close to the 50% value often used for estimation of carbon storage from dry biomass information [5, 45]. Compared with the plantations, the large amount of carbon maintained by trees of the NF might result from its multi-strata community structure and higher tree species diversity, as well as from the absence of anthropogenic disturbance. While differences in tree carbon among the plantations might be caused not only by difference in the standing crop (Tab. I), but also by the wood specific density and the carbon concentration. The higher wood specific gravity for the broadleaveds (CK: 0.53 Mg m^{-3}; OX: 0.58 Mg m^{-3}) than for the coniferous (FH: 0.43 Mg m^{-3}; CF: 0.41 Mg m^{-3}) in the present study agree well with Cannell (1984) [7] who reported that broadleaved species have greater mean wood basic specific gravity than conifers. The wood specific gravity of the broadleaveds in this study is similar to the estimated value (0.57 Mg m^{-3}) for tropical forests [3, 4]. The result that the higher weighted carbon concentration for the broadleaved than for the coniferous in this study was also reported by Wu et al. [47] and Mo et al. [29] in Southern China.

The mean root-to-shoot ratios found in these studied forests (NF: 0.24; CK: 0.22; OX: 0.13; FH: 0.20; CF: 0.26) are comparable with the more general ratio that Cairns et al. [6] produced from a review of tropical forest biomass studies. They found the average R:S for primary and secondary tropical forests was 0.24. The biomass and carbon, which turned over yearly in the trees of the studied native forest and plantations, was small relative to their total biomass, while long-lived, woody tissues made up above 95% of the biomass. The greatest reservoir of carbon was the tree stem, especially for that of the conifers. In the case of clear-cutting, the majority of carbon is moved out from the land, and the longevity of this carbon store depends on the fate of this wood once it has been harvested.

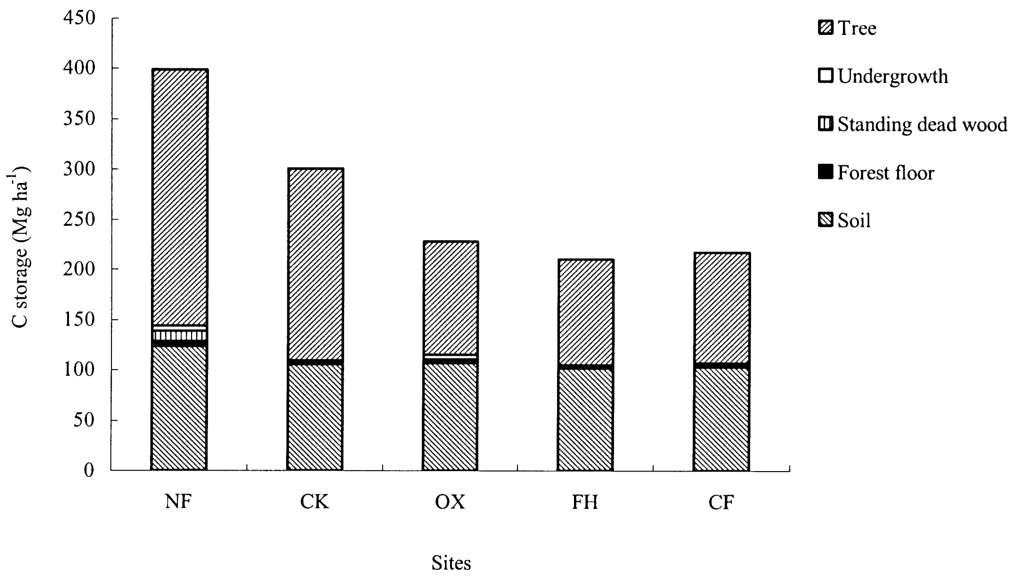

Figure 3. Ecosystem carbon storage in the NF, CK, OX, FH and CF stands.

Table IV. Annual carbon input above- and belowground (Mg ha^{-1} a^{-1}) in the NF, CK, OX, FH and CF stands (date are mean ± SD).

Year	Aboveground litterfall					Belowground litterfall				
	NF	CK	OX	FH	CF	NF	CK	OX	FH	CF
1999	4.46 ± 0.411	4.70 ± 0.536	2.40 ± 0.264	2.95 ± 0.280	2.39 ± 0.222	3.97 ± 0.401	1.99 ± 0.255	1.41 ± 0.124	1.72 ± 0.189	1.30 ± 0.123
2000	4.15 ± 0.436	4.23 ± 0.596	2.81 ± 0.253	3.21 ± 0.312	2.05 ± 0.256	4.27 ± 0.517	2.45 ± 0.324	1.13 ± 0.102	1.27 ± 0.114	1.20 ± 0.171
2001	4.56 ± 0.583	4.61 ± 0.438	2.50 ± 0.300	3.42 ± 0.387	2.01 ± 0.286	4.81 ± 0.602	2.26 ± 0.201	1.28 ± 0.153	1.47 ± 0.166	1.27 ± 0.191
Mean	4.39 ± 0.508	4.51 ± 0.650	2.57 ± 0.334	3.19 ± 0.447	2.15 ± 0.322	4.35 ± 0.571	2.24 ± 0.289	1.27 ± 0.175	1.48 ± 0.292	1.25 ± 0.185

Undergrowth has a very small contribution to total ecosystem carbon storage. The scarcity of undergrowth in the CK relative to the other plantations might result from the high canopy closure (Tab. I).

4.2. Litterfall C inputs

The measured annual aboveground litterfall fell into the range from tropical forests (0.9–6.0 Mg C ha^{-1} a^{-1}) [9]. Mean annual C returns through aboveground litterfall in the NF (4.36 Mg C ha^{-1} a^{-1}) was higher than those in natural forest of *Lithocarpus xylocarpus* in Ailao mountain (3.24 Mg C ha^{-1} a^{-1}) [24] and mixed forest of *Pinus massoniana* and *Schima superba* in Dinghu mountain (4.02 Mg C ha^{-1} a^{-1}) [12]. The aboveground carbon input from the plantations was much lower in comparison with old growth coniferous forest of *Picea abies* (20 Mg C ha^{-1} a^{-1}) [32].

Because investigations on root turnover are labor intensive, belowground litterfall is less quantified as compared to aboveground litterfall, and often neglected in many forest carbon budgets. Studies have indicated that litter input belowground could account for 6.2–88.7% (average 50%) those aboveground and constitute 14–86.6% (most above 40%) of total soil organic input (e.g., [27, 44]). In the present study, C inputs belowground in the NF almost equaled those aboveground, and amounted to about half of aboveground C input respectively in the plantations. Because soil organic matter derived from belowground litter is often fixed with minerals, and exists in a more recalcitrant form as compared to that from aboveground litter [2], we can expect that the higher proportion of carbon input belowground in the NF will be of more benefit to long-term carbon sequestration.

4.3. Detritus carbon pools

The total standing dead wood in the NF equals only about 3.3% of the total living tree carbon, which is comparable with the estimated average of 5% for global forests [1]. Both the standing dead and the coarse woody litter compartments were severely reduced in the plantations. This might be due to the relative short-term growth period for plantation to form these compartments and due to loss during slash burning and decay.

Thus, carbon storage on the silvicultural landscape is further decreased by the lack of these important detrital components. These results have implications of simplification of the habitat of plantation forests. Plantations have few standing dead or coarse woody debris, which are required by numerous species of wildlife as critical habitat features. Large quantities and greater varieties of carbon storage media are important to the integrity and biodiversity of forest ecosystems [14, 26].

The carbon stored in the first metre of the soil of the plantations was much higher than that of a Norway spruce mixed forest in eastern Finland (52.8 Mg C ha^{-1}) [13] and also slightly higher than that of a Douglas-fir plantation in western Oregon (91.9 Mg C ha^{-1}) [38] and an Australian Douglas-fir plantation (98.2 Mg C ha^{-1}) [42]. The C storage in soil of the NF is close to that of a native *Eucalyptus* forest (127.6 Mg C ha^{-1}) studied by Turner and Lambert [42] and that recorded in an *Euxylophora paraensis* forest (116.0 Mg C ha^{-1}) [41]. Overall, the pools of C in whole soil in this study were in the middle of the range recorded for various forests in the world [11], but were at the lower end of the ranges reported for tropical 0–100 cm soils (130–160 Mg ha^{-1}) [20]. When examining the total ecosystem carbon pool, tree biomass proves to be the main contributor to the carbon gains across the study sites. This dominance is in line with other studies of tropical and subtropical China [29, 47]. However, our data contrast with general estimates of soil organic carbon that point to a 2-to-3 times greater carbon accumulation in soils than in vegetation [45]. The low C content in soil might be due to the higher loss potential of organic matter resulted from fast decomposition rate and erosion loss, and due to low carbon accommodates of soils [54].

Land use change or shifts in cultivation can affect soil organic matter. In the top 20 cm of soil, the carbon concentration was higher in the NF and lower in the plantations, suggesting that conversion of native forest and subsequent slashing and burning was accompanied by some carbon loss from the topsoil. Similar results have been reported in a variety of studies [15, 16, 34, 41, 42].

In South China where high rainfall, steep slopes and fragile soil are characteristic, the establishment management practices for plantations in the initial years, including clearing of original vegetation, burning of vegetation residues, soil disturbance through site preparing, and control of competing vegetation, probably represent a maximum decrease of surface soil C, though the nature and detail of such disturbance occurring approximately 34 yr ago are not available for appropriate comparisons. In a similar site, Yang [52] have reported that soil organic content in the surface 0–10 cm soils had a decrease of 6.6% immediately after slash burning; Ma et al. [25] reported that decomposition loss of soil organic had a significantly increase after soil preparation due to higher soil aeration. Accelerated decay of soil organic carbon was also evidence due to increased soil temperature that resulted from less ground cover in the initial 3 ~ 5 years after replanting [52]. Serious carbon loss further happened owing to rapid soil loss in the initial stage of plantation. Soil organic carbon loss as high as 284 kg ha^{-1} was reported in young Chinese fir stand by Ma et al. [25] during the first year after burning.

In addition, the difference in soil organic carbon between the NF and the plantations might be partly attributed to differences in the amount, chemical composition, and transformation rate of organic materials derived from leaf and root litter between these forest types. In the present study, the total above- and belowground litterfall C was much higher in the NF than in the plantations (Tab. IV). Yang et al. [51] also noted that leaf-litters of the NF and the broadleaveds were characterized by lower lignin content and narrower lignin/N ratio than those of the conifers. Further, the higher concentration of fine roots in the topsoil in the NF than in the plantations can transfer much more root detritus from roots to superficial soils [49].

No significant effect of forest conversion was found on the soils below 20 cm, indicating that effect of forest conversion and site management on soil carbon concentrations was largely restricted to the topsoil. This is similar to Schroth et al. [37] who found the carbon concentrations below 10 cm were very similar under secondary forest and monoculture plantations in Amazonia.

Many studies (e.g., [18, 31, 33, 41]) have suggested that tree species have different impacts on soil C pools and dynamics. However, No significant differences in soil total C were observed between the plantations, indicating that tree species did not have significant impacts on soil total C, at least in the 33 years period after conversion. This is similar to Shiels et al. [39] who found that there was no significant difference in soil C under adjacent krummholz tree species (*Picea engelmanni* krummholz and *Pinus aristata* krummholz Engelm.). As compared to the NF, the broadleaves and the conifers had a similar decline in total soil C, this is different to Guo and Gifford [16] who found that, as compared to previous native forest, planting coniferous trees significantly reduced soil carbon stock by 15%, but planting broadleaf trees had little effect on soil carbon. However, as there exists differences in the quantity and quality of above- and belowground litter inputs between the plantations, we might expect that the absence of species effect between the plantations will be changed over a longer period of forest growth.

5. CONCLUSIONS

The conversion from NF to both broadleaved and coniferous plantations led to a reduction in total ecosystem C pools. It is worthwhile to note that this is a case study and future studies are needed to further support these findings. These differences between the NF and the plantations may be attributed to a combination of factors including more diverse species communities, more C store types, higher quantity and better quality of above- and belowground litter materials under the NF than under the plantations and site disturbance during the establishment of plantations. For this reason, the NF forests, and the other remaining natural ecosystems must be protected and restored for their important ecological functions.

The implications from this study are that plantation establishment systems may lead to declines in ecosystem carbon pool compared to native forest. To rapidly maximize total carbon accumulation in the system, there is the requirement to rapidly develop the plantation through modified silvicultural systems, minimize soil disturbance, and change the nutritional status of the stand using fertilizers to increase total production. Where the operational objective is to maximize carbon accumulation, the system of management will need to be modified from that traditionally used for timber production. Fast growing, short rotation plantations, especially where there is no major modification to overall nutritional status and no cause to soil organic carbon loss, will lead to maximized ecosystem carbon store.

Acknowledgements: This work was funded by the National Natural Science Foundation of China (No. 30170770 and No. 30300272), the Teaching and Research Award program for MOE P.R.C. (TRAP-OYT), the Key Basic Research Project of Fujian Province (2000F004), and the Natural Science Foundation of Fujian Province (B0310014). We are thankful to the two anonymous reviewers for helpful comments on the manuscript.

REFERENCES

[1] Ajtay G.L., Ketner P., Duvigneaud P., Terrestrial primary production and phytomass, in: Bolin B., Degnes E.T., Kempe S., Ketner P. (Eds.), The global carbon cycle, Chichester, UK, John Wiley, 1979, pp. 129–181.

[2] Bouwman A.F., Leemans R., The role of forest soils in the global carbon cycle, in: McFee W.W., Kelly J.M. (Eds.), Carbon forms and functions in forest soils, Soil Science Society of America, Madison, WI, USA, 1995, pp. 503–525.

[3] Brown S., Estimating biomass and biomass change of tropical forests: A Primer, FAO Forestry, Rome, 1997, 134 p.

[4] Brown S., Lugo A.E., Biomass of tropical forests: A new estimate based on forest volumes, Science 223 (1984) 1290–1293.

[5] Brown S., Lugo A.E., The storage and production of organic matter in tropical forests and their role in the global carbon cycle, Biotropica 14 (1982) 161–87.

[6] Cairns M.A., Brown S., Helmer E.H., Baumgardner G.A., Root biomass allocation in the world's upland forests, Oecologia 111 (1997) 1–11.

[7] Cannell M.G.R., Woody biomass of forest stands, For. Ecol. Manage. 8 (1984) 299–312.

[8] Chen G.S., Yang Y.S., Xie J.S., Li L., Gao R., Soil biological changes for a natural forest and two plantations in subtropical China, Pedosphere 14 (2004) 297–304.

[9] Clark D.A., Brown S., Kicklighter D.W., Chambers J.Q., Thomlinson J.R., Ni J., Holland E.A., Net primary production in tropical forests: an evaluation and synthesis of existing field data, Ecol. Appl. 11 (2001) 371–384.

[10] Cuevas E., Medina E., Nutrient dynamics within Amazonian forests. I. Nutrient flux in fine litterfall and efficiency of nutrient utilization, Oecologia 68 (1986) 466–472.

[11] Dixon R.K., Houghton R.A., Carbon pools and flux of global forest ecosystems, Science 263 (1994) 185–190.

[12] Fang Y.T., Mo J.M., Huang Z.L., Ouyang X.J., Carbon accumulation and distribution in *Pinus massoniana* and *Schima superba* mixed forest ecosystem in Dinghushan Biosphere Reserve, J. Trop. Subtrop. Bot. 11 (2003) 47–52.

[13] Finér L., Mannerkoski H., Piirainen S., Starr M., Carbon and nitrogen pools in an old-growth, Norway spruce mixed forest in eastern Finland and changes associated with clear-cutting, For. Ecol. Manage. 174 (2003) 51–63.

[14] Freedman B., Zelazny V., Beaudette D., Fleming T., Flemming S., Forbes G., Johnson G., Woodley S., Biodiversity implications of changes in the quantity of dead organic matter in managed forests, Environ. Rev. 4 (1996) 238–265.

[15] Goh K.M., Heng S., The quantity and nature of the forest floor and topsoil under some indigenous forests and nearby areas converted to *Pinus radiata* plantations in South Island, New Zealand, N. Z. J. Bot. 25 (1987) 243–254.

[16] Guo L.B., Gifford R.M., Soil carbon stocks and land use change: a meta analysis, Global Change Biol. 8 (2002) 345–360.

[17] Houghton R.A., Hackler J.L., Continental scale estimates of the biotic carbon flux from land cover change: 1850–1980, ORNL/CDIAC-79, NDP-050, Oak Ridge National Laboratory, Oak Ridge, TN, 1995.

[18] Howard P.J.A., Howard D.M.L., Lowe L.E., Effects of tree species and soil physico-chemical conditions on the nature of soil organic matter, Soil Biol. Biochem. 30 (1998) 285–297.

[19] Huet S., Forgeard F., Nys C., Above- and belowground distribution of dry matter and carbon biomass of Atlantic beech (*Fagus sylvatica* L.) in a time sequence, Ann. For. Sci. 61 (2004) 683–694.

[20] Jobággy E.G., Jackson R.B., The vertical distribution of soil organic carbon and its relation to climate and vegetation, Ecol. Appl. 10 (2000) 423–436.

[21] Kraenzel M., Castillo A., Moore T., Potvin C., Carbon storage of harvest-age teak (*Tectona grandis*) plantations, Panama, For. Ecol. Manage. 173 (2003) 213–225.

[22] Kurz W.A., Kimmins J.P., Analysis of some error in methods used to determine fine root production in forest ecosystems: a simulation approach, Can. J. For. Res. 17 (1987) 909–912.

[23] Le Goff N., Granier A., Ottorini J., Peiffer M., Biomass increment and carbon balance of ash (*Fraxinus excelsior*) trees in an experimental stand in northeastern France, Ann. For. Sci. 61 (2004) 577–588.

[24] Liu W.Y., Fox J.E.D., Xu Z.F., Biomass and nutrient accumulation in montane evergreen broadleaved forest (*Lithocarpus xylocarpus* type) in Ailao Mountains, SW China, For. Ecol. Manage. 158 (2002) 223–235

[25] Ma X.Q., Liu A.Q., He Z.Y., Effects of site preparations on ecosystem of Chinese fir plantations, J. Mount. Sci. 18 (2000) 237–243.

[26] McCarthy B.C., Bailey R.R., Distribution and abundance of coarse woody debris in a managed forest landscape of the central Appalachians, Can. J. For. Res. 24 (1994) 1317–1329.

[27] McClaugherty C.A., Aber J.D., Melillo J.M., The role of fine roots in the organic matter and nitrogen budgets of two forested ecosystems, Ecology 63 (1982) 1481–1490.

[28] Ministry of Forestry, Forest soil analysis methods, Chinese Criteria Press, Beijing, 2000.

[29] Mo J.M., Fang Y.T., Peng S.L., Carbon accumulation and allocation of lower subtropical evergreen broad-leaved forests in a MAB reserve of China, Acta Ecol. Sin. 23 (2003) 1970–1976.

[30] Nabuurs G.J., Mohren J.M.G., Modelling analysis of potential carbon sequestration in selected forest types, Can. J. For. Res. 25 (1995) 1157–1172.

[31] Paul K.I., Polglase P.J., Nyakuengama J.G., Khanna P.K., Changes in Soil Carbon Following Afforestation, For. Ecol. Manage. 168 (2002) 241–257.

[32] Pedersen L.B, Hansen J.B., A comparison of litterfall and element fluxes in even aged Norway spruce, sitka spruce and beech stands in Denmark, For. Ecol. Manage. 114 (1999) 55–70.

[33] Quideau S.A., Anderson M.A., Graham R.C., Chadwick O.A., Trumbore S.E., Soil organic matter processes: Characterization by ^{13}C NMR and ^{14}C measurements, For. Ecol. Manage. 138 (2000) 19–27.

[34] Ryan P.A., Chester R.W., Bevege D.I., Litterfall and decomposition in hoop pine plantations and rain forest, in: Proceedings Australian Forest Nutrition Workshop, Productivity in Perpetuity, Canberra, Australia, CSIRO, Melbourne, 1981, pp. 358–366.

[35] Sanford R.L., Cuevas E., Root growth and rhizosphere interactions in tropical forests, in: Mulkey S., Chazdon R.L., Smith A.P. (Eds.), Tropical Forest Plant Ecophysiology, Chapman & Hall, New York, 1996, pp. 268–300.

[36] Sang W.G., Ma K.P., Chen L.Z., Primary study on carbon cycling in warm temperate deciduous broad-leaved forest, Acta Phytoecol. Sin. 26 (2002) 543–548.

[37] Schroth G., D'Angelo S.A., Teixeira W,G., Haag D., Lieberei R., Conversion of secondary forest into agroforestry and monoculture plantations in Amazonia: consequences for biomass, litter and soil carbon stocks after 7 years, For. Ecol. Manage. 163 (2002) 131–150.

[38] Sharrow S.H., Ismail S., Carbon and nitrogen storage in agroforests, tree plantations, and pastures in western Oregon, USA, Agrofor. Syst. 60 (2004) 123–130.

[39] Shiels A.B., Sanford J., Robert L., Soil nutrient differences between two krummholz-form tree species and adjacent alpine tundra, Geoderma 102 (2001) 205–217.

[40] Smethurst P.J., Nambiar E.K.S., Distribution of carbon and nutrients and fluxes of mineral nitrogen after clear-felling a *P. radiata* plantation, Can. J. For. Res. 20 (1990) 1490–1497.

[41] Smith C.K., Oliveirab F. de A., Gholzc H.L., Baimad A., Soil carbon stocks after forest conversion to tree plantations in lowland Amazonia, Brazil, For. Ecol. Manage. 164 (2002) 257–263.

[42] Turner J., Lambert M., Change in organic carbon in forest plantation soils in eastern Australia, For. Ecol. Manage. 133 (2000) 231–247.

[43] Van Camp N., Walle I.V., Mertens J., De Neve S., Samson R., Lust N., Lemeur R., Boeckx P., Lootens P., Beheydt D., Mestdagh I., Sleutel S., Verbeeck H., Van Cleemput O., Hofman G., Carlier L., Inventory-based carbon stock of Flemish forests: a comparison of European biomass expansion factors, Ann. For. Sci. 61 (2004) 677–682.

[44] Vogt K.A., Grier C.C., Vogt D.J., Production, turnover and nutrient dynamics of above- and belowground detritus of world forests, Adv. Ecol. Res. 15 (1986) 303–377.

[45] Welington B.C.D., Déborah M.B., Carbon and mineral nutrient pools in a gallery forest at Mogi Guaçu River, Southeast Brazil, Ann. For. Sci. 57 (2000) 39–47.

[46] Winjum J.K., Schroeder P.E., Forest plantations of the world: their extent, ecological attributes, and carbon storage, Agric. For. Meteorol. 84 (1997) 153–167.

[47] Wu Z.M., Li Y.D., Zeng Q.B., Zhou G.Y., Chen B.F., Du Z.H., Lin M.X., Carbon pool of tropical mountain rain forests in Jianfengling and effect of clear-cutting on it, Chinese J. Appl. Ecol. 9 (1998) 341–344.

[48] Yang Y.S., Chen G.S., Guo J.F., Lin P., Decomposition dynamic of fine roots in a mixed forest of *Cunninghamia lanceolata* and *Tsoongiodendron odorum* in mid-subtropics, Ann. For. Sci. 61 (2004) 65–72.

[49] Yang Y.S., Chen G.S., Lin P., Xie J.S., Guo J.F., Fine root distribution, seasonal pattern and production in four plantations compared with a natural forest in subtropical China, Ann. For. Sci. 61 (2004) 617–627.

[50] Yang Y.S., Guo J.F., Chen G.S., He Z.M., Xie J.S., Effects of slash burning on nutrient removal and soil fertility in Chinese fir and evergreen broadleaved forests of mid-subtropical China, Pedosphere 13 (2003) 87–96.

[51] Yang Y.S., Guo J.F., Chen G.S., Xie J.S., Cai L.P., Lin P., Litterfall, nutrient return, and leaf-litter decomposition in four plantations compared with a natural forest in subtropical China, Ann. For. Sci. 61 (2004) 465–476.

[52] Yang Y.S., Studies on the sustainable management of Chinese fir, China Forestry Publishing House, Beijing, 1998.

[53] Yu X.T., Silviculture of Chinese fir, Fujian Science and Technology Press, Fuzhou, 1996.

[54] Zhang W.R., Soil conditions for the major plantation tree species in China, China Science and Technology Press, Beijing, 1998.