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Assessing the effects of vegetation types on carbon storage fifteen years after reforestation on a Chinese fir site

Qinkui Wang [a], Silong Wang [a,b,*], Jianwei Zhang [c]

[a] Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, PR China
[b] Huitong Experimental Station of Forest Ecology, Chinese Academy of Sciences, Huitong 418307, PR China
[c] USDA Forest Service, Pacific Southwest Research Station, 3644 Avtech Parkway, Redding, CA 96002, USA

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ABSTRACT

Forest ecosystems play a significant role in sequestering carbon (C) in biomass and soils. Plantations established in subtropical China since the 1980s, mainly of Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) in monocultures, have proved to be major C sinks. However, information is lacking about whether mixing Chinese fir with broadleaved tree species will increase stand growth and C sequestration. We address this question by comparing a pure Chinese fir plantation and two mixed plantations established in 1990 at Huitong Experimental Station of Forest Ecology, Hunan Province, China. The mixed plantations include Chinese fir and either *Kalopanax septemlobus* (Thunb.) Koidz or *Alnus cremastogyne* Burk., planted at 4:1 ratios. We found that total C storage was 123, 131 and 142 Mg ha^{-1} in the pure plantation, mixed plantation with *K. septemlobus*, and mixed plantation with *A. cremastogyne*, respectively. The mixed plantation with *A. cremastogyne* increased C storage in biomass relative to the pure Chinese fir plantation ($P < 0.05$). No significant difference was detected between mixed plantations. Soil C storage did not differ among these plantations, ranging from 67.9 ± 7.1 to 73.3 ± 9.1 Mg ha^{-1}, which accounted for about 55% of the total C pools. Our results indicated that as the mixture of Chinese fir and broadleaved species will increase both biomass C and soil C storage over pure Chinese fir, and will do it, within 15 years of planting.

1. Introduction

Terrestrial ecosystems remove about 30% of all CO_2 emissions from fossil fuel burning and deforestation (Canadell and Raupach, 2008). Forests play a significant role in this carbon (C) sink. It has been reported that forests store about 45% of terrestrial C, more than double the amount of C in the atmosphere (FAO, 2006). In China, terrestrial ecosystems absorbed 0.19–0.26 Pg C per year, 28–37% of its cumulative fossil C emissions, during the 1980s and 1990s (Piao et al., 2009). Forests in southern China, mainly as part of a large-scale plantation program initiated in the 1980s, contributed about 65% of the C sink in southern China terrestrial ecosystems. Therefore, forest ecosystems influence significantly the global C cycle; even a small shift in the balance between photosynthesis and ecosystem respiration can lead to a large change in uptake or emission of CO_2 from forests to the atmosphere. Thus, enhancing C storage in forest ecosystems will be a key factor in the maintenance of the atmosphere's C balance.

Globally, many attempts have been made to estimate C storage in forest ecosystems because sequestering C in biomass and soil is widely believed to be an effective method to mitigate an increase of atmospheric CO_2 concentration (Davis et al., 2003; Hazlett et al., 2005; Zhang et al., 2007; Zhou et al., 2008). For example, Davis et al. (2003) reported that C storage in 125-year-old pole stands was 219 Mg ha^{-1} and declined to 192 Mg ha^{-1} as the stands matured (>150 years old). Zhou et al. (2008) also reported that the 10-year reforestation program increased C storage by 41.7 Tg from 1994 to 2003 in Guangdong Province, China. However, most of these publications were focused on boreal, temperate and tropical forests, and few studies were carried out on C storage in the forests of southern China, some of the most important subtropical forests in the world.

Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook), an important coniferous timber species with fast growth and good timber quality, has been widely planted for more than 1000 years. Its planting area has reached over 12 million ha, accounting for about 6.5% of all plantation forests in the world (FAO, 2006; West, 2006). Therefore, Chinese fir forests should play a significant role in global C sequestration. Since the 1980s, it has

* Corresponding author at: Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, PR China. Tel.: +86 24 8397 0344;
fax: +86 24 8397 0300.
E-mail address: slwang@iae.ac.cn (S. Wang).

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been recognized that yield and soil fertility of pure Chinese fir stands tends to decline due to successive cropping, short rotation times of about 20 years, and whole-tree harvesting (Chen et al., 1990). Fortunately, some studies have showed that planting mixed forest of Chinese fir and broadleaved tree species could increase productivity and improve soil fertility (Feng et al., 1988; Chen et al., 1990). To date, however, little information is available about the impacts of mixed plantations on C storage in Chinese fir mixed forest ecosystems.

In this study, we measured and compared total ecosystem C among one pure Chinese fir plantation (PC) and two mixed plantations with Chinese fir and either *Kalopanax septemlobus* (MCK) or *Alnus cremastogyne* (MCA). The aim is to determine whether mixed plantations will increase biomass accumulation and C sequestration and storage in the 15-year-old plantations.

2. Materials and methods

2.1. Site description

This study was conducted at Huitong Experimental Station of Forest Ecology (latitude 26°40′–27°09′N and longitude 109°26′–110°08′E), Chinese Academy of Sciences, Hunan Province, China. This experimental Station lies at the transition zone from the Yunnan-Guizhou plateau to the lower mountains and hills on the southern side of the Yangtze River at an altitude of 300–1100 m above mean sea level. The climate of this region is humid mid-subtropical monsoon with mean annual temperature of 15.8 °C from 1990 to 2005. The mean annual precipitation was 1200 mm of which about 67% occurred between April and August.

After the first-generation Chinese fir forest was clearcut in autumn of 1989, a pure Chinese fir plantation and two mixtures of Chinese fir and either *A. cremastogyne* or *K. septemlobus* were planted in early spring of 1990. Each plantation is about 2.5 ha. The ratio of Chinese fir to *A. cremastogyne* or *K. septemlobus* in the mixed forests was 4:1. Planting density was 2000 tree ha^{-1}. The plantations were established at an altitude of 521–554 m above sea level.

The soil bulk density and texture did not significantly differ among plantations in 2005 (Table 1). The soil texture is classified as a clay loam. The soil is predominantly derived from slate and shale, and classified as an Oxisol under the USDA taxonomy.

Table 1
Soil bulk density and texture at different depths collected from a 15-year-old pure Chinese fir plantation (PC) and mixed plantations with *K. septemlobus* (MCK) and *A. cremastogyne* (MCA) grown in subtropical China.

	Depth (cm)	Bulk density ($g\ cm^{-3}$)	Sand (%)	Silt (%)	Clay (%)
PC	0–10	1.26 (0.06)	9.0 (1.2)	41.2 (3.5)	49.8 (2.6)
	10–20	1.31 (0.09)	8.3 (0.7)	42.9 (5.2)	48.8 (4.3)
	20–40	1.37 (0.13)	7.4 (1.0)	41.8 (2.8)	50.8 (3.1)
	40–60	1.44 (0.04)	5.1 (0.3)	41.9 (3.7)	53.0 (2.9)
	60–80	1.46 (0.15)	4.6 (0.8)	41.1 (5.1)	54.3 (6.0)
	80–100	1.47 (0.09)	4.8 (0.5)	42.3 (2.9)	52.9 (2.4)
MCK	0–10	1.22 (0.08)	10.9 (1.1)	44.7 (2.9)	44.5 (3.2)
	10–20	1.26 (0.06)	13.6 (0.9)	41.1 (3.3)	45.3 (3.7)
	20–40	1.33 (0.13)	12.2 (1.5)	43.5 (5.8)	44.2 (4.6)
	40–60	1.39 (0.09)	14.0 (0.8)	41.5 (2.7)	44.5 (2.4)
	60–80	1.42 (0.05)	9.9 (1.0)	46.3 (4.2)	43.7 (5.3)
	80–100	1.44 (0.07)	9.3 (1.1)	45.6 (3.5)	45.1 (4.0)
MCA	0–10	1.21 (0.09)	8.8 (0.9)	45.2 (2.5)	46.0 (3.1)
	10–20	1.29 (0.03)	6.3 (0.5)	44.7 (3.2)	49.0 (3.6)
	20–40	1.34 (0.16)	7.9 (1.2)	44.0 (4.1)	48.1 (2.8)
	40–60	1.33 (0.09)	6.7 (0.8)	44.7 (2.7)	48.6 (2.9)
	60–80	1.38 (0.11)	7.8 (0.4)	44.0 (2.2)	48.2 (2.4)
	80–100	1.43 (0.10)	7.6 (1.1)	45.7 (3.9)	46.7 (2.0)

Data are means followed by standard deviations in the parentheses.

2.2. Overstory and understory biomass

Five 400-m^2 plots (20 m × 20 m) were established at each plantation in November 2005. We measured the DBH (diameter at breast height at 1.3 m height), tree height, and crown length of all trees on the five plots of each stand. We harvested 32 Chinese fir trees, 19 *A. cremastogyne*, and 21 *K. septemlobus* trees in the three stands. After a tree was felled, we measured total height with a steel tape (accuracy, 0.1 m). Each bole was then cut into 2-m sections, and each section was separated into stem, bark, leaf and branch. All components were dried at 80 °C to constant weight. The dry weight of standing individuals in the sampling stands was estimated by means of allometric regression equations for individual trees. We then used this equation to calculate the aboveground biomass of each tree and the total aboveground biomass for each stand.

Roots were also excavated to a depth of 100 cm in these plots. Excavations were centered on the stumps of the harvested trees. Roots from the harvested tree were collected, washed, and dried at 70 °C until a constant weight was reached. The understory and herbaceous biomass were determined by destructively harvesting six randomly located 1 m^2 plots in each stand. Forest floor litter was sampled using fifteen 0.25 m^2 subplots randomly located within each 20 m × 20 m plot. After sampling, forest floor litter was transported to the laboratory and then dried to constant weight at 70 °C.

2.3. Mineral soil sampling

Volumetric samples of mineral soil were taken for calculating the soil C storage. Soils were sampled to a depth of 100 cm. In each of the three stands, five points were systematically located. At these points, three samples were taken from the following depth ranges: 0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm, and pooled by sampling point and layer. All samples were transported to the laboratory and then air-dried for determining C. Soils were also assessed for bulk density with a bulk density corer (diameter 5 cm) at the same depth range. Rocks and gravel (>2 mm diameter) were sieved from each soil sample.

2.4. Laboratory C analyzing

The biomass samples were oven-dried and ground to 500 μm. Mineral soil samples were ground to 250 μm before chemical analysis for organic C. C concentration of plant and soil samples were measured with a C/N analyzer (Elementar, Germany). Mass of C stored in tree compartments, understory vegetation, and forest floor was estimated by multiplying their measured biomass by their corresponding concentrations. The total stock (C_t, $g\ cm^{-2}$) of soil organic C to a depth of 100 cm was calculated based on the organic C content, sampled depth, and bulk density (Guo and Gifford, 2002) as: $C_t = BD \times C_c/100 \times D$, where BD is the soil bulk density ($g\ cm^{-3}$), C_c (%) the soil C concentration, and D is the soil sampling depth (cm).

2.5. Statistical analysis

Data analyses were performed using SPSS Version 11.5 for Windows (SPSS Inc., Chicago, IL, USA). All comparisons were performed using analysis of variance (ANOVA) followed by least-significant-difference tests. Significance levels were set at $P < 0.05$ in all statistical analyses.

Table 2
Biomass (Mg ha^{-1}) of various compartments in a 15-year-old pure Chinese fir plantation (PC) and mixed plantation with *K. septemlobus* (MCK) and *A. cremastogyne* (MCA) grown in subtropical China.

	PC	MCK			MCA		
		Cunninghamia lanceolata	*Kalopanax septemlobus*	Total	*Cunninghamia lanceolata*	*Alnus cremastogyne*	Total
Stem wood	55.2 (12.4) a	46.7 (10.1)	13.4 (2.1)	60.1 (11.1) ab	52.3 (9.9)	19.1 (2.8)	71.4 (10.0) b
Bark	14.9 (3.8) a	12.4 (3.4)	2.8 (0.9)	15.2 (3.6) a	13.8 (3.1)	2.4 (1.1)	16.2 (3.2) a
Branch	10.9 (3.1) a	9.2 (2.8)	3.7 (1.5)	12.9 (4.0) a	10.0 (2.8)	3.9 (1.3)	13.9 (2.9) a
Leaf	12.8 (3.3) a	10.8 (3.3)	2.0 (0.9)	12.8 (3.4) a	11.3 (3.4)	2.1 (0.8)	13.3 (3.4) a
Root	9.3 (3.6) a	8.1 (2.7)	4.2 (1.1)	12.2 (2.9) ab	9.0 (3.1)	4.8 (1.4)	13.8 (3.2) b
Understory	1.9 (0.5) a			2.0 (0.8) a			2.5 (0.7) a
Litter	0.8 (0.3) a			1.1 (0.4) ab			1.4 (0.3) b
Total	105.6 (13.8) a			116.4 (15.6) ab			132.5 (14.4) b

Data are means followed by standard deviations in the parentheses. For each compartment, values with the different letters denote significant difference among plantations at α = 0.05 based on the least-significant-difference tests.

3. Results

3.1. Biomass C pools

Total biomass storage increased significantly in the mixed *Cunninghamia*/*Alnus* (MCA) plantation, but not in the mixed *Cunninghamia*/*Kalopanax* (MCK) plantation, as compared to the pure *Cunninghamia* (PC) plantation (Table 2). There was no significant difference in biomass for bark, branch, leaf, and understorey among the plantations. The broadleaved tree species accounted for about 22% total overstory aboveground biomass (stem wood, bark, branch and leaf) in the mixed plantations, while root biomass from the broadleaved tree species was approximate 34% of the total root biomass. Stem wood was the main component of biomass and accounted for over 50% of the total biomass in the three plantations.

The C concentration in the same biomass compartments did not differ significantly among the three tree species (Table 3). Neither did that of the understory species. Stem wood had the highest C concentration and understory had the lowest C concentration among all biomass compartments for these plantations.

After biomass was converted to C pools, we found that C storage in biomass was significantly higher in the MCA plantation than in the PC plantation (Table 4). The pools of C in stem wood, branch, root and litter compartments in MCA plantation were significantly greater than those of the PC plantation. In the plantations investigated, stem wood accounted for about 53% of the total biomass C storage, while the litter C storage accounted for only about 1% of total biomass C storage. Broadleaved tree species contributed over 22% of the total biomass C storage in the mixed plantations.

Table 3
Carbon concentration (g kg^{-1}) in various biomass compartments of Chinese fir, *K. septemlobus* and *A. cremastogyne* grown in plantations in subtropical China.

	Cunninghamia lanceolata	*Kalopanax septemlobus*	*Alnus cremastogyne*
Stem wood	536.4 (47.1)	520.3 (40.4)	523.6 (35.9)
Bark	502.7 (42.3)	478.0 (31.4)	484.2 (41.8)
Branch	505.0 (31.4)	483.6 (33.6)	482.8 (37.1)
Leaf	519.6 (20.4)	505.0 (30.1)	501.5 (24.5)
Root	511.6 (52.1)	496.4 (59.9)	494.6 (49.5)
Understory	476.9 (30.3)	467.3 (41.2)	460.7 (33.7)
Litter	515.9 (29.6)	481.2 (23.4)	484.0 (24.4)

Data are means followed by standard deviations in the parentheses. No significant difference was detected in carbon concentration in the same biomass compartments among tree species at α = 0.05 based on the least-significant-difference tests.

3.2. Mineral-soil C pools

In general, mixed plantations showed higher C concentration than the pure Chinese fir plantation at all depths (Table 5) although significant differences were only found at depths 0–10 cm and 60–80 cm. Concentrations of soil C decreased with depth, with relatively low concentrations below 40 cm. The C:N ratio did not differ among the three plantations.

The three plantations showed no significant difference in soil C storage at the individual depth intervals, although soil C storage in the mixed plantations was slightly higher than that in pure plantation (Table 5). Additionally, these plantations had similar total soil C storage summed over the 0–100 cm depth; about 60% of the total soil C was stored in the top 40 cm soil.

Table 4
Carbon storage (Mg ha^{-1}) in various biomass compartments in a 15-year-old pure Chinese fir plantation (PC) and mixed plantation with *K. septemlobus* (MCK) and *A. cremastogyne* (MCA) grown in subtropical China.

	PC	MCK			MCA		
		Cunninghami lanceolata	*Kalopanax septemlobus*	Total	*Cunninghami lanceolata*	*Alnus cremastogyne*	Total
Stem wood	29.6 (3.8) a	25.0 (3.4)	7.0 (1.7)	32.0 (5.1) ab	28.1 (3.2)	10.0 (1.3)	38.1 (6.8) b
Bark	7.5 (1.8) a	6.3 (1.2)	1.3 (0.3)	7.6 (2.3) ab	6.9 (1.3)	1.2 (0.2)	8.1 (1.9) a
Branch	5.5 (1.0) a	4.76 (0.9)	1.8 (0.4)	6.44 (1.4) ab	5.1 (1.2)	1.9 (0.5)	6.9 (1.5) b
Leaf	6.6 (1.5) a	5.6 (1.0)	1.0 (0.3)	6.61 (1.5) ab	5.9 (1.0)	1.0 (0.2)	6.9 (2.0) a
Root	4.7 (0.7) a	4.1 (0.9)	2.1 (0.4)	6.20 (0.7) b	4.6 (0.9)	2.4 (0.5)	7.0 (1.1) b
Understory	0.9 (0.2) a			0.95 (0.2) a			1.2 (0.3) a
Litter	0.4 (0.1) a			0.54 (0.2) ab			0.7 (0.2) b
Total	55.2 (5. 7) a			60.3 (8.3) ab			68.8 (7.3) b

Data are means followed by standard deviations in the parentheses. For each compartment, values with the different letters denote significant difference among plantations at α = 0.05 based on the least-significant-difference tests.

Table 5
Soil organic carbon (SOC) concentration (g kg^{-1}) and storage (Mg ha^{-1}) in a 15-year-old pure Chinese fir plantation (PC) and mixed plantation with *K. septemlobus* (MCK) and *A. cremastogyne* (MCA) grown in subtropical China.

Soil depth (cm)	PC	MCK	MCA
SOC concentration			
0–10	13.2 (1.2) a	14.7 (1.8) ab	16.2 (1.7) b
10–20	8.5 (1.1) a	8.9 (1.2) a	9.7 (0.8) a
20–40	5.1 (0.7) a	5.3 (0.8) a	5.7 (0.5) a
40–60	3.8 (0.5) a	4.0 (0.6) a	4.4 (0.4) a
60–80	3.1 (0.2) a	3.5 (0.6) ab	3.9 (0.3) b
80–100	2.1 (0.1) a	2.4 (0.2) a	2.6 (0.3) a
SOC storage			
0–10	16.6 (3.0) a	17.9 (2.8) a	18.5 (3.4) a
10–20	11.1 (1.5) a	11.2 (1.6) a	11.5 (2.2) a
20–40	14.0 (2.1) a	14.1 (1.6) a	14.1 (2.1) a
40–60	10.9 (1.3) a	11.1 (1.1) a	11.7 (1.5) a
60–80	9.1 (1.1) a	9.9 (1.4) a	10.5 (0.8) a
80–100	6.2 (1.0) a	6.9 (1.3) a	7.0 (0.6) a
Total	67.9 (7.1) a	71.1 (8.3) a	73.3 (9.1) a

Data are means followed by standard deviations in the parentheses. For each depth, values with the different letters denote significant difference among plantations at $\alpha = 0.05$ based on the least-significant-difference tests.

4. Discussion

4.1. Biomass C storage

Vegetation is a very important C pool in forests, where wood acts as a substantial C reservoir (Dixon et al., 1994). After 15 years growth and development of newly established plantations on the clearcut areas, the vegetation C ranged from 55.2 Mg ha^{-1} in the pure plantation, 60.3 Mg ha^{-1} in the *Cunninghamia*/*Kalopanax* plantation, to 68.8 Mg ha^{-1} in the *Cunninghamia*/*Alnus* plantation. The differences in biomass C storage between pure and mixed plantations were due to several reasons. First, growth of Chinese fir and the broadleaved trees was different. In the mixture of Chinese fir and *A. cremastogyne*, for example, biomass for Chinese fir was 96.4 Mg ha^{-1}, accounting for 67% of total ecosystem biomass. However, biomass for *A. cremastogyne*, with 25% of the stems in the plantation, was 32.3 Mg ha^{-1}, or about 33% of total biomass. The results indicate that the broadleaved species, *A. cremastogyne*, proportionally accumulated more biomass than did Chinese fir (Table 2). Similarly trend was hold for the *Cunninghamia*/*Kalopanax* plantation. Second, mixed plantations improved soil quality by increasing more litter production and litter decomposition (Wang et al., 2007), on which Chinese fir increased productivity. Third, a N_2-fixing tree such as alder has been reported to significantly increase soil fertility and therefore conifer growth in a 70-year-old Douglas fir (*Pseudotsuga menziessii* (Mirb.) Franco) stand (Binkley, 2003), which may explain the difference in biomass accumulation between the mixed plantations in this study. Last, the higher stand-level production in mixed plantations can be explained by a mechanism called the competitive production principle (Kelty, 2006). Chinese fir and the broadleaved trees, occupying different ecological niches, may use site resources more efficiently in C fixation and subsequent growth.

Chinese fir, because of its adaptation and growth rate, has been extensively planted in eastern and southern China. Its productivity and C stocks have been studied with mixed results. For example, Xiao et al. (2007) reported that a 15-year-old Chinese fir forests carried 57.0 Mg C ha^{-1} and Zhou et al. (2000) found that an average C storage was 57.1 Mg ha^{-1} for the major Chinese forest types. The C storage in this study is very comparable to these numbers. However, only 28.5 Mg C ha^{-1} was reported for this species at ages from 6 to 41 years by Zhang et al. (2007) in Zhejiang Province, eastern China. Yang et al. (2005) found a 41-year-old forest contained 149 Mg C ha^{-1} in the Yizhou State Forestry Center in Fujian Province, southeastern China. The difference in biomass C storage among these studies could be explained by differences in forest age, although other sources of variation such as management intensity and site quality might also contribute (Giese et al., 2003).

4.2. Soil C storage

Globally, over two-thirds of C pools in forest ecosystems are contained in soil organic matter (Dixon et al., 1994). In the present study, about 55% of the C in a 15-year-old Chinese fir forest ecosystem was contained in soils. Because soil C storage in forest ecosystems is controlled by the total C stocks in biomass and soil, it is no surprise that the topsoil at 0–40 cm accounted for a large proportion of the mineral soil C storage in these forests. This finding is consistent with the results of Yang et al. (2005) who found that 60% of soil C storage was in the 0–40 cm soil layer for a Chinese fir forest in eastern China. Xiao et al. (2007) found that soil C in the 0–40 cm depth represented about 78% of total C storage in 0–60 cm depth. This was due to the majority of C being returned to the soil through litter decomposition and turnover of the fine roots (Wang et al., 2008).

Mixed-species plantations have a potential to improve C sequestration in soil (Kaye et al., 2000; Resh et al., 2002). In this study, we did not find the mixed stand between Chinese fir and the broad-leaved tree species significantly increased soil organic C concentration and storage. The similarity in soil C storage among these plantations was possibly due to the young stand ages of these plantings. If current trends continue, mixed plantations may show a significant higher soil C storage than the pure Chinese fir plantation. In fact, Wang and Wang (2007) found higher soil organic C concentration in a broadleaved forest than Chinese fir plantation in the subtropical region. Tree species did affect the soil organic C content and its vertical distribution in the mineral soil (Rothe et al., 2002; Oostra et al., 2006; Schulp et al., 2008).

Litter constitutes an important flux of soil organic C. The leaf litter production in mixed plantations was higher than that in pure Chinese fir plantation, which increased their surface soil organic C concentrations (Wang et al., 2007, 2008). Mo et al. (2002) suggested that the changes in the C stocks of the top soil in the different forest types might reflect the differences in the quantity and quality of litter input, litter C decomposition, and litter biomass C. Compared with broadleaved litter, conifer litter contains more components that are difficult to decompose, resulting in litter accumulation in the forest floor and less C incorporation into the mineral soil (Berg, 2000).

Fine root turnover is another important flux of soil organic C with an amount of C that equals to leaf litter (Rasse et al., 2005). Broadleaved trees may allocate more biomass to their roots, which can transfer more root detritus to the soil (Jandl et al., 2007). In the present study, *A. cremastogyne* and *K. septemlobus* had significantly higher root to shoot (including stem wood, bark, branch and leaf) ratios than Chinese fir (Table 2). Liao et al. (2000) also reported that C from live and dead fine roots in a mixed plantation of Chinese fir with *A. cremastogyne* was about 50% higher than that of the mixed plantation of Chinese fir with *K. septemlobus*. This may be a reason that a mixed plantation of Chinese fir and *A. cremastogyne* significantly increased soil organic concentrations at the 0–10 cm depth, but a mixed plantation of Chinese fir and *K. septemlobus* did not.

Soil fauna are known to incorporate organic material from the forest floor into mineral soil, and may strongly affect soil C dynamics (Bohlen et al., 2004; Fox et al., 2006). In turn, tree species affect these fauna densities and abundance (Zou, 1993; Yan et al., 2004). Yan et al. (2004) found that the richness and abundance of soil macrofauna were higher in the mixed stand of Chinese fir and *A. cremastogyne* than the pure Chinese fir stand. Zou (1993) found greater earthworm densities in mixed stands of *Eucalyptus saligna* and *Albizia falcataria* than in pure *Eucalyptus* stands. In the pure stand, the soil pH was lower and soil fauna were less active, which decreased the amount of organic material incorporated into mineral soils (Thuille and Schulze, 2006). Therefore, these results may explain the higher C concentration in 0–10 cm soil depth in the mixed plantation of Chinese fir and *A. cremastogyne* than pure coniferous plantation.

5. Conclusions

Mixed *Cunninghamia*/*Alnus* plantations increase C sequestration and storage by 11% in both biomass and soils compared to pure Chinese fir plantations at age 15 years. The biomass C accounted for about 45% of the total C pool in the Chinese fir forest ecosystems, of which 53% was stored in the stem wood. With a 4:1 Chinese fir and broadleaved species composition in the mixed plantations, over 22% of the biomass C was from the broadleaved trees. The results suggest that mixed forests of Chinese fir and broadleaved tree species may help to offset CO_2 emissions by sequestering more CO_2 from atmosphere.

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