Journal of Tropical Forest Science 25(2): 154–165 (2013)

ECOSYSTEM CARBON POOLS IN MIXED STANDS OF HARDWOOD SPECIES AND MASSON PINE

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Received September 2011

FAN HB, LIU WF, WU JP, LI YY, YUAN YH, LIAO YC, HUANG RZ & SU XQ. 2013. Ecosystem carbon pools in mixed stands of hardwood species and Masson pine. Transformation of conifer monoculture into mixed conifer–hardwood plantations has been considered as an efficient management practice to sustain forest productivity. However, effects of this management practice on ecosystem carbon sequestration are still unclear. In this study, seedlings of five hardwood species (*Michelia macclurei, Castanopsis fissa, Castanopsis sclerophylla, Castanopsis kawakamii* and *Cyclobalanopsis myrsinaefolia*) were planted separately under a *Pinus massoniana* (Pm) stand, and designated as Pm–Mm, Pm–Cf, Pm–Cs, Pm–Ck and Pm–Cm respectively. After 16 years of establishment, total ecosystem carbon increased by 18.0, 53.8, 25.2, 21.7 and 38.7 t ha^{-1} in the Pm–Mm, Pm–Cf, Pm–Cs, Pm–Ck and Pm–Cm stands respectively compared with Pm stand. Aboveground carbon storage increased from 97.72 t ha^{-1} in the Pm stand to 109.52, 131.31, 107.77, 115.76 and 123.37 t ha^{-1} in the five mixed stands respectively, greatly due to an increase in hardwood tree biomass. Mineral soil carbon stock (0–60 cm) was 55.0 t ha^{-1} in the Pm stand and 61.0, 72.4, 69.6, 58.6 and 66.8 t ha^{-1} in the five mixtures respectively. Our results suggested that stand improvement by underplanting could be proposed as forest management option for increasing ecosystem carbon sequestration.

Keywords: Mixed conifer–hardwood plantations, carbon sequestration, *Pinus massoniana,* forest management

FAN HB, LIU WF, WU JP, LI YY, YUAN YH, LIAO YC, HUANG RZ & SU XQ. 2013. Takungan karbon ekosistem dirian campur spesies kayu keras dan pain Masson. Langkah mengubah ladang monokultur konifer kepada ladang campur konifer dan kayu keras merupakan amalan pengurusan yang cekap untuk mengekalkan produktiviti hutan. Bagaimanapun, kesan amalan ini terhadap pensekuesteran karbon ekosistem masih belum jelas. Dalam kajian ini, anak benih lima spesies kayu keras (*Michelia macclurei, Castanopsis fissa, Castanopsis sclerophylla, Castanopsis kawakamii* dan *Cyclobalanopsis myrsinaefolia*) ditanam secara berasingan di bawah dirian *Pinus massoniana* (Pm). Dirian ini masing-masing diberi kod Pm–Mm, Pm–Cf, Pm–Cs, Pm–Ck, and Pm–Cm. Selepas 16 tahun, jumlah karbon ekosistem meningkat sebanyak 18.0 t ha^{-1}, 53.8 t ha^{-1}, 25.2 t ha^{-1}, 21.7 t ha^{-1} dan 38.7 t ha^{-1} masing-masing di dirian Pm–Mm, Pm–Cf, Pm–Cs, Pm–Ck dan Pm–Cm. Simpanan karbon atas tanah meningkat daripada 97.72 t ha^{-1} di dirian Pm ke 109.52 t ha^{-1}, 131.31 t ha^{-1}, 107.77 t ha^{-1}, 115.76 t ha^{-1} dan 123.37 t ha^{-1} masing-masing di dirian Pm–Mm, Pm–Cf, Pm–Cs, Pm–Ck dan Pm–Cm, terutamanya akibat pertambahan biojisim pokok. Stok karbon tanah ((0–60 cm) adalah sebanyak 55.0 t ha^{-1} di dirian Pm dan 61.0 t ha^{-1}, 72.4 t ha^{-1}, 69.6 t ha^{-1}, 58.6 t ha^{-1} dan 66.8 t ha^{-1} di lima dirian campur itu. Keputusan kami mencadangkan bahawa penambahbaikan dirian secara tanam bawah dapat disyorkan sebagai pilihan pengurusan hutan bagi meningkatkan pensekuesteran karbon dalam ekosistem.

INTRODUCTION

Forest vegetation and soils store 1146 Pg carbon (C), accounting for about 46% of all carbon in the terrestrial biosphere which plays a critical role in global carbon balance (Houghton et al. 2001). The potential role of forests and forestry in sequestering carbon to reduce the build-up of greenhouse gases in the atmosphere has been well recognised since the signing of the Kyoto Protocol (Schulze et al. 2000). The protocol provides an incentive for developing countries to make their contributions under the Clean Development Mechanism (CDM), through which carbon credits would be gained from activities related

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to reforestation and afforestation during the first commitment period (Boyd et al. 2007). Therefore, expansion of forested land area was suggested as an effective way to mitigate elevated atmospheric carbon dioxide (CO_2) and hence contribute towards the prevention of global warming. Between the mid-1970s and 1998, planted forests in China were estimated to sequester 0.45 Pg C, suggesting Chinese plantation forests had the potential to make a significant contribution to carbon storage (Fang et al. 2001). A report, derived from the seventh national forest resources inventory (2004–2008), showed that the area of planted forests had increased to 61.69 mil ha from the previous reserve of 53.26 mil ha (1999–2003), 31.92% of the nation's total forest area. This makes China a country with the largest area of planted forests in the world (State Forestry Administration of China 2010), indicating that the capacity for carbon sequestration is expected to continue to grow in China.

Masson pine (*Pinus massoniana*) is widely distributed in 17 provinces across South China, extending from the Leizhou peninsula in the south (21° 41' N) to Mount Qinling in the north (33° 56' N), westward throughout middle Sichuan Basin (Zhou 2000). Due to its ability to thrive on dry, sandy and infertile soil, its fast growth and favourable pulping characteristics, Masson pine has been considered an excellent and suitable species for afforestation and reforestation on abandoned, heavily eroded and marginal lands in subtropical regions (Kuang et al. 2008). The majority of plantation forests in the world have been established almost exclusively as even-aged monoculture crops with the primary purpose of wood production. There is no exception with Masson pine, the second most commonly planted species in South China (Kelty 2006). However, continuous monoculture with conifer species at the same site has led to soil degradation and rendered the stands more susceptible to pests and diseases such as Masson pine caterpillar (*Dendrolimus punctatus*), the most destructive pest of pine forests in China (Liu et al. 2003, Wang et al. 2005). In the last two decades, interest in the silviculture of mixed Masson pine–hardwood stands has grown in China with an improved understanding of their potential to support a greater biodiversity, reduce impacts from insect and disease problems, improve nutrient availability and consequently increase ecosystem productivity (Fan et al. 2006).

Numerous studies have been conducted to examine biomass and carbon accumulation in Masson pine forests and the role of factors such as stand age, stem density, forest succession and human disturbance on the forest productivity. However, little knowledge exists about how stand conversion and improved forest structure affect carbon sequestration of planted Masson pine stands in China. Stand thinning followed by an underplanting of hardwood species trials in the mid-1980s at Xinkou Experimental Forests in Fujian provided a unique opportunity to examine how stand conversion altered carbon accumulation in Masson pine stand.

The objective of this study was to quantify the ecosystem biomass and carbon storage in five mixed Masson pine–hardwood stands established by planting hardwood seedlings beneath the pine canopy. We also determined differences in size and contribution of these carbon pools between the mixtures and pure pine stands without underplanting. Through these analyses, we will show that stand transformation enhances primary productivity and carbon sink potentials of plantation forests.

MATERIALS AND METHODS

Site description

The study was conducted at Xinkou Experimental Forest Farm (26° 11' N, 117° 26' E), approximately 30 km from the city of Sanming, midwestern Fujian, China. The forest has been managed by Fujian Agriculture and Forestry University since 1958 and serves as a base for research and education in forest ecology and silviculture. The region has subtropical monsoon climate with mean annual temperature of 19.4 °C and annual precipitation of 1741 mm of which about 57% falls from March till June. The mean annual frost-free period is 300 days. Soil is predominantly red earth developed from siltstone deposits with textures ranging from light to medium loam.

The pure Masson pine stand was established in 1959 by planting 1-year-old seedlings on the south-facing slope at altitudes spreading from 190 to 210 m. The site was formerly dominated by evergreen broadleaved forest which was harvested in 1958 and then followed by slash burning to remove logging materials and brush in preparation for planting. In 1984, the 25-year-old pine stand was thinned to 570 stems per ha and had 1200 hardwood tree seedlings per ha planted in the understorey. The hardwood species selected were *Michelia macclurei, Castanopsis fissa, Castanopsis sclerophylla, Castanopsis kawakamii* and *Cyclobalanopsis myrsinaefolia*, each separately interplanted evenly under the overstorey. After 16 years of growth, the mixed Masson pine–hardwood stands developed into closed uneven-aged forest plantations and designated in this study as Pm–Mm, Pm–Cf, Pm–Cs, Pm–Ck and Pm–Cm respectively, with the pure pine stand abbreviated as Pm. Major stand characteristics of pure pine and mixed pine–hardwood stands are presented in Table 1.

Tree measurement and sampling

Three sample plots were established in December 1999 in pure Masson pine stand and in each of the five mixed pine–hardwood stands. Each plot covered an area of 20 m × 20 m. In late December 2000, diameter at breast height (dbh) and tree height were measured for every standing tree. Six individual hardwood trees and one pine tree in each mixed stand, and six pine trees in the pure pine stand, representing the stand-specific dbh range, were selected for destructive sampling.

Live crown was divided into three parts (top, middle, bottom) and all live and dead branches from each part were cut and weighed separately after the foliage were removed. The stem was cut into 1-m sections and weighed and stem discs (2-cm thick) were taken from each section. Fresh weights of stems, dead and live branches and foliage were measured using an electronic balance in the field. Subsamples from each component were taken to the laboratory for determination of fresh-to-oven dry biomass ratio, which was then used to calculate total dry biomass.

The entire root system of the sampled trees was excavated and divided into coarse roots

Table 1 Stand characteristics of pure Masson pine and mixed Masson pine–hardwood plantation forests

Stand type	Stem density (stems ha^{-1})		Dbh (cm)		Tree height (m)		Stand volume (m^3 ha^{-1})	
	Pine	Hardwood	Pine	Hardwood	Pine	Hardwood	Pine	Hardwood
Pm	456 ± 19.2		28.1 ± 0.3		20.1 ± 0.1		244.5 ± 10.4	
Pm–Mm	475 ± 22.4	1100 ± 98.6	25.6 ± 0.1	9.4 ± 0.3	21.1 ± 0.2	9.1 ± 0.3	224.4 ± 12.9	36.6 ± 2.1
Pm–Cf	450 ± 21.6	1094 ± 88.4	28.5 ± 0.2	12.3 ± 0.5	23.0 ± 0.4	15.6 ± 0.1	281.8 ± 15.3	104.0 ± 9.5
Pm–Cs	483 ± 37.3	767 ± 54.1	26.6 ± 0.2	10.8 ± 0.4	21.5 ± 0.1	9.8 ± 0.5	249.5 ± 10.1	35.7 ± 1.8
Pm–Ck	417 ± 18.9	815 ± 62.9	27.0 ± 0.3	12.4 ± 0.7	19.4 ± 0.3	10.1 ± 0.4	200.7 ± 15.5	50.7 ± 2.9
Pm–Cm	504 ± 27.9	756 ± 45.9	27.2 ± 0.4	10.7 ± 0.1	20.6 ± 0.1	11.0 ± 0.1	260.4 ± 19.1	38.9 ± 2.1
Average	464 ± 30.7	906 ± 175	27.2 ± 1.0	11.1 ± 1.3	21.0 ± 1.3	11.1 ± 2.6	244 ± 28.4	53.1 ± 29.1

Pm = *Pinus massoniana*, Mm = *Michelia macclurei*, Cf = *Castanopsis fissa*, Cs = *Castanopsis sclerophylla*, Ck = *Castanopsis kawakamii* and Cm = *Cyclobalanopsis myrsinaefolia* (including stump, dbh < 20 mm), small roots (2 mm < dbh < 20 mm) and fine roots (dbh < 2 mm). Subsamples from these were taken to determine dry root biomass.

Based on data derived from the six sampled hardwood trees and five pine trees (each from different mixed stand), allometric equations for the mixed stands were developed in the form of $W = a(D^2H)^b$, where W = species biomass (kg for each component), a and b = constants, D = dbh (cm) and H = tree height (m). For the pure pine stand, six sampled pine trees were used to develop the equations. The resulting equations were used to estimate biomass for each component as well as for total tree biomass. By adding the biomass of all individual trees in the plot, we obtained the stand-level biomass on area basis.

Understorey biomass determination

Five subplots of 1 m × 1 m were set up randomly in each plot to determine the understorey vegetation biomass in October 2000. In each subplot, aboveground parts of all shrubs and herbs (including ferns and grasses) were cut at the soil surface and weighed in the field separately. Roots were excavated and weighed after being washed clean. Subsamples were taken from each understorey vegetation component and oven dried in the laboratory for the determination of dry biomass on an area basis.

Forest floor and soil sampling

In the five subplots, forest floor (LFH layer) materials were sampled, air dried and weighed. Sampling was carried out separately for an upper layer of relatively undecomposed material (L layer) and a lower layer of fragmented or decomposed material (F and H layers). Subsamples were oven dried to constant weight to determine air-to-oven dry biomass ratios.

After removing all organic matter from the forest floor in each subplot, mineral soil samples were collected using a hand auger (diameter 53 mm). All mineral soil samples extended to a depth of 60 cm were separated into three strata (0–20, 20–40 and 40–60 cm). The samples were used to determine bulk density before being air dried at 70 °C and sieved over a 2-mm mesh for carbon concentration analysis.

Carbon concentrations of the samples were determined using an elemental analyser. Carbon concentrations in mineral soils were determined by the modified Walkley and Black method (Kalra & Maynard 1991). Samples were oxidised by a mixture of $K_2Cr_2O_7$ and H_2SO_4, followed by titration with $FeSO_4$. In order to obtain the carbon content for each stand and depth class, soil carbon concentration was multiplied by soil bulk density and volume of each depth class.

RESULTS AND DISCUSSION

Tree carbon storage

Total aboveground tree carbon (foliage, live and dead branches, and stem) was 89.40 t C ha^{-1} in Pm and 98.37, 118.03, 101.58, 99.37 and 113.08 t C ha^{-1} in the mixed Pm–Mm, Pm–Cf, Pm–Cs, Pm–Ck and Pm–Cm stands respectively. In all stands, 76.7 to 88.7% of total aboveground tree carbon was attributed to stem biomass, 10.1 to 18.7% to branch and 1.2 to 4.6% to foliage (Table 2). Significant increase in carbon storage was observed after planting hardwood species, especially *C. fissa* and *C. myrsinaefolia*, under the canopy of pine plantation. Previous studies had shown that mixtures of tree species increased aboveground biomass compared with monocultures (Luis & Monteiro 1998, Wang et al. 2000). In this study, the contribution of hardwood trees to total aboveground tree carbon storage was more than 14% in the five mixed stands after 16 years of development (Table 2). Belowground carbon storage in tree root biomass exhibited less variation between stands. Belowground-to-aboveground tree biomass ratio decreased from 0.22 in the pure pine stand to around 0.19 in the mixed stands. Roots and their turnover are crucial in quantifying ecosystem carbon cycling (Strand et al. 2008, Chen et al. 2009). In this subtropical plantation forest, on average, root

Table 2 Carbon storage in above- and underground tree biomass in pure pine and mixed pine–hardwood stands

Stand type	Species	C in aboveground tree biomass (t C ha^{-1})				C in belowground tree biomass (t C ha^{-1})				Total
		Foliage	Branch	Stem	Subtotal	Coarse root[a]	Small root[b]	Fine root[c]	Subtotal	
Pm	*P. massoniana*	1.08	9.00	79.32	89.40	18.34	0.83	0.14	19.30	108.70
Pm–Mm	*P. massoniana*	0.86	10.06	71.07	81.99	16.18	0.38	0.09	16.64	98.63
	M. macclurei	2.94	3.68	9.76	16.38	2.59	0.40	0.08	3.06	19.44
	Whole stand	3.80	13.74	80.83	98.37	18.77	0.78	0.17	19.70	118.07
Pm–Cf	*P. massoniana*	0.88	10.32	74.48	85.68	17.37	0.40	0.09	17.86	103.54
	C. fissa	2.71	7.24	22.40	32.35	3.46	0.96	0.17	4.59	36.94
	Whole stand	3.59	17.56	96.88	118.03	20.83	1.36	0.26	22.45	140.48
Pm–Cs	*P. massoniana*	0.95	10.58	75.23	86.76	17.54	0.41	0.09	18.04	104.80
	C. sclerophylla	2.23	4.77	7.82	14.82	1.63	0.26	0.05	1.94	16.76
	Whole stand	3.18	15.35	83.05	101.58	19.17	0.67	0.14	19.98	121.56
Pm–Ck	*P. massoniana*	0.82	8.68	64.93	74.43	15.44	0.55	0.07	16.06	90.49
	C. kawakamii	3.77	9.89	11.27	24.93	2.73	0.68	0.08	3.49	28.42
	Whole stand	4.59	18.58	76.20	99.37	18.17	1.23	0.15	19.55	118.92
Pm–Cm	*P. massoniana*	0.99	11.25	81.46	93.70	17.30	0.41	0.10	17.81	111.51
	C. myrsinaefolia	2.73	5.59	11.06	19.38	2.61	0.53	0.02	3.15	22.53
	Whole stand	3.72	16.84	92.52	113.08	19.91	0.94	0.12	20.96	134.04

Pm = *Pinus massoniana*, Mm = *Michelia macclurei*, Cf = *Castanopsis fissa*, Cs = *Castanopsis sclerophylla*, Ck = *Castanopsis kawakamii* and Cm = *Cyclobalanopsis myrsinaefolia*; [a]coarse root > 20 mm, [b]small root 2–20 mm, [c]fine root < 2 mm

biomass accounted for approximately 17% of total tree biomass (Table 2). Therefore, it is imperative to include root biomass in carbon storage estimation.

Carbon storage in standing dead tree biomass was estimated at 4.80 t C ha^{-1} in Pm and 6.21, 7.54, 2.36, 10.05 and 2.78 t C ha^{-1} in the mixed Pm–Mm, Pm–Cf, Pm–Cs, Pm–Ck and Pm–Cs plantations respectively (Table 3), which contributed a small part of total aboveground tree biomass (< 10%). Compared with the amount of carbon stored in pines, carbon storage in dead hardwood trees was very little, representing less than 8% of total standing dead tree biomass in the five mixed stands. However, carbon storage in standing dead hardwoods can be expected to further increase with age and may therefore contribute a considerable portion to the total ecosystem carbon in older mixed stands (Pretzsch 2003). It was interesting to note that dead to live branch carbon ratio in the mixed stands (averaged 0.31) was much greater than the pure pine stand (0.20) (Table 3). Our data suggested that increased stock density formed by the underplanted hardwood trees promoted natural pruning and the increased litterfall would accelerate carbon cycling in the mixtures.

Understorey vegetation

Carbon concentration in understorey components ranged from 37.2 to 44.9% of dry biomass in the stands, with shrubs consistently having higher carbon concentration than herbs (Table 4). Understorey vegetation biomass and carbon storage were largest in the pure pine stand (3677.6 and 1532.3 kg C ha^{-1} respectively). In contrast, understorey biomass and carbon storage in mixed stands were less than the pure stand. For instance, understorey vegetation carbon storage was much less under the mixed stands, i.e. between 421.4 and 898.2 kg

Table 3 Above- and belowground ecosystem carbon pools (t C ha^{-1}) in the pure and mixed Masson pine stands

Ecosystem component	Pm	Pm–Mm	Pm–Cf	Pm–Cs	Pm–Ck	Pm–Cm
Foliage	1.08	3.80	3.60	3.17	4.58	3.72
Live branches	7.51	10.24	13.03	11.66	14.85	12.94
Dead branches	1.49	3.49	4.52	3.69	3.72	3.90
Stem wood	72.34	75.35	86.98	75.78	69.66	83.97
Stem bark	6.98	5.48	9.90	7.27	6.53	8.55
Aboveground live tree	89.40	98.36	118.03	101.57	99.34	113.08
Standing dead tree	4.80	6.21	7.54	2.36	10.05	2.78
Understrorey vegetation shoots	1.13	0.60	0.33	0.50	0.50	0.36
Forest floor	2.39	4.35	5.41	3.34	5.87	7.15
Aboveground ecosystem	97.72	109.52	131.31	107.77	115.76	123.37
Tree roots	19.30	19.70	22.46	19.98	19.55	20.96
Understorey vegetation roots	0.41	0.30	0.05	0.27	0.19	0.06
Soil (0–60 cm)	55.02	60.95	72.42	69.64	58.62	66.77
Belowground ecosystem	74.73	80.95	94.93	89.89	78.36	87.79
Total ecosystem	172.45	190.47	226.24	197.66	194.12	211.16

Pm = *Pinus massoniana*, Mm = *Michelia macclurei*, Cf = *Castanopsis fissa*, Cs = *Castanopsis sclerophylla*, Ck = *Castanopsis kawakamii* and Cm = *Cyclobalanopsis myrsinaefolia*

C ha^{-1} (Table 4). When comparing with other studies in similar climatic region, carbon storage in understorey vegetation in these pine stands was relatively low. For example, understorey vegetation carbon (shrubs and herbs) was between 3.17 and 12.08 t C ha^{-1} in mixed plantations of *P. massoniana* with the naturally regenerated *Schima superba* (Fang et al. 2003). Forest types and management strategies contribute to variations between plantations (Vilà et al. 2003). In South China, understorey plants distribute widely and grow densely, making up to 17.5% of aboveground biomass of the regenerated vegetation (Chen et al. 1998), which is much larger than boreal forest (Nilsson & Wardle 2005).

When plantation canopies are open, large coverage of shrubs and grasses develop under enough light penetration. Understorey plants play an important role in driving ecosystem processes and function (Nilsson & Wardle 2005) such as nutrient cycling and soil carbon emission (Wu et al. 2011a, b). Consequently, ecosystem carbon cycling would also be affected by understorey performance (Wu et al. 2011a). In this experiment, development of underplanted hardwood species reduced light transmission through forest canopy, inhibiting understorey growth and leading to less carbon accumulation in mixed stands.

Litterfall production

Annual litterfall production for mixed stands was higher than pure pine stand. The total annual values of litterfall were 7137.3, 6741.1, 8041.7, 7151.3 and 7533.2 kg ha^{-1} year^{-1} in Pm–Mm, Pm–Cf, Pm–Cs, Pm–Ck and Pm–Cm stands respectively, which were more than twice the amount of pure pine stand (3442.8

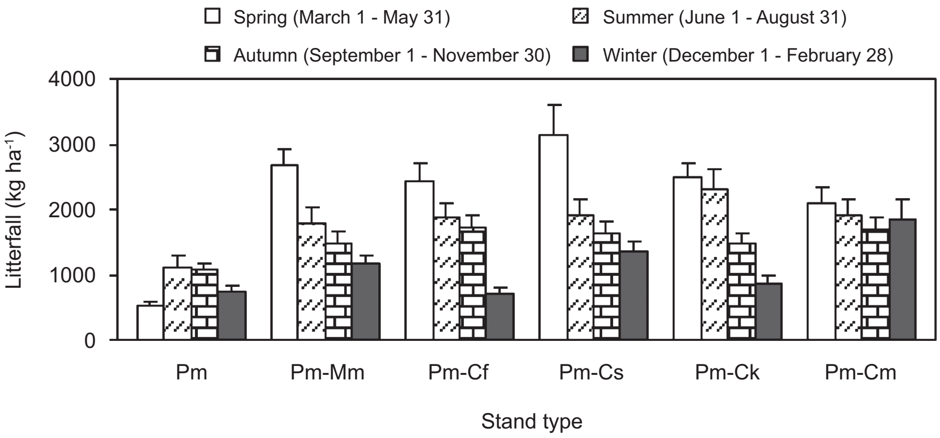

Figure 1 Seasonal dynamics of litterfall production in pure pine stand compared with mixed pine–hardwood stands; values are means ± SD

kg ha^{-1} year^{-1}) (Figure 1). Leaves and needles accounted for 55–71% of the total litterfall production, branches and twigs 6–26%, barks 8–19%, reproductive organs approximately 1% and miscellaneous materials 5–17%. In the five mixed stands, hardwood litterfall contributed 42–50% to the total litterfall (excluding other dropping components). Our results indicated that the underplanted broadleaved trees provided large amount of easily decomposed litterfall. Broadleaved litter usually has high quality and this will accelerate nutrient cycling for the forest ecosystem even in the early stage of plantation development (Gholz et al. 2000).

Litterfall in all mixed stands was not distributed evenly over the year but consistently fell at a maximum rate in spring, contributing 28–39% to total annual litterfall (Figure 1). Minimum litterfall normally occurred during the winter season except for Pm–Cm stand. In contrast, maximum peak of litterfall in pure pine stand was not evident, with a large amount falling in summer and autumn seasons and much less in spring and winter months. Significant seasonal pattern of litterfall exhibited by the mixed stands was largely attributable to the seasonal variations of leaf shedding from the hardwoods, as leaves were the major constituent of total litterfall. In subtropical regions of China, many evergreen hardwood species shed their leaves with pronounced peaks at the beginning of the wet months, mostly in March or April, whereas other species had weaker dependence, showed several peaks per year or were dry-season shedders (Zou et al. 2006).

Forest floor

Our results indicated that planting hardwood trees under pine canopy increased carbon storage in the forest floor by 40 to 199% (Table 5). The average carbon concentration of forest floor for all stands ranged from 44.4% in the F and H layers to 46.3% in L layer. The amounts of carbon accumulated in the forest floor were 2.39 t C ha^{-1} in Pm, and 4.35, 5.41, 3.34, 5.87 and 7.15 t C ha^{-1} respectively in the mixed Pm–Mm, Pm–Cf, Pm–Cs, Pm–Ck and Pm–Cm stands (Table 5). However, the amount of increment depended on the underplanted species. Litter quality play an important role in forest floor carbon storage. Nutritional status of broadleaved litter was higher than in conifer litter, which would also benefit stand production through input of more nutrients into the ecosystem (Thelin et al. 2002). Significant differences in forest floor carbon between pure and mixed coniferous stands were observed in a 16-year-old Chinese fir plantation and its mixed stand with *M. macclurei*, with values of 3.62 and 12.61 t ha^{-1} respectively (Cai 2007).

Carbon content in L layer represented 87.0% of total forest floor materials in Pm but reduced to an average of 67.6% in mixed

Table 4 Biomass and carbon storage in the understorey vegetation in the stands

Component		Pm		Pm–Mm		Pm–Cf		Pm–Cs		Pm–Ck		Pm–Cm	
		Biomass (kg ha^{-1})	C stock (kg C ha^{-1})	Biomass (kg ha^{-1})	C stock (kg C ha^{-1})	Biomass (kg ha^{-1})	C stock (kg C ha^{-1})	Biomass (kg ha^{-1})	C stock (kg C ha^{-1})	Biomass (kg ha^{-1})	C stock (kg C ha^{-1})	Biomass (kg ha^{-1})	C stock (kg C ha^{-1})
Shrub	Aboveground	1101.6 ± 129.0	473.9 ± 16.4	810.8 ± 45.2	353.8 ± 18.9	468.6±26.2	199.2±18.7	591.8 ± 29.5	264.2 ± 21.0	1086.8 ± 129.4	474.6 ± 17.1	446.2±22.1	197.7±17.6
	Belowground	431.9 ± 16.5	166.2 ± 16.1	452.4 ± 76.5	180.1 ± 16.3	85.9±10.7	33.0±4.5	352.6 ± 27.8	144.1 ± 9.8	267.6 ± 16.6	105.2 ± 12.3	76.0±5.5	29.6±8.1
Herb	Aboveground	1523.5 ± 150.1	652.8 ± 23.0	587.2 ± 40.1	242.3 ± 9.5	325.6±24.9	131.2±8.7	546.2 ± 29.3	233.1 ± 10.8	51.2 ± 15.9	21.2 ± 5.3	395.7±22.7	166.9±13.9
	Belowground	620.7 ± 11.6	239.4 ± 22.1	327.6 ± 20.4	122.0 ± 11.8	57.3±10.4	21.0±4.4	325.4 ± 28.0	127.9 ± 15.5	219.4 ± 39.2	84.5 ± 11.1	69.6±9.5	27.2±4.2
	Total	3677.6 ± 169.1	1532.3 ± 124.0	2178.0 ± 285.2	898.2 ± 62.0	937.4 ± 105.2	384.4±22.7	1816.0 ± 128.1	769.3 ± 39.4	1625.0 ± 129.2	685.5 ± 55.6	987.4 ± 93.0	421.4±29.7

Pm = *Pinus massoniana*, Mm = *Michelia macclurei*, Cf = *Castanopsis fissa*, Cs = *Castanopsis sclerophylla*, Ck = *Castanopsis kawakamii* and Cm = *Cyclobalanopsis myrsinaefolia*; values are means ± within-stand SD

stands (Table 5). This change in the material proportion of L to F and H layers suggested that addition of litterfall from the hardwood trees promoted litter decomposition. High quality of broadleaved litter compared with that of conifer would result in faster decomposition in mixture plantations (Gholz et al. 2000). In an early study we found that mean turnover time of litter, estimated from annual litterfall production and standing crop of litter on forest floor, was 1.11 years for mixed forests and 1.52 years for pure pine stand (Su et al. 2003). Faster litter decomposition rate in the mixed forests promotes nutrient release and forest productivity. This was demonstrated in an earlier study conducted in the same region whereby introducing broadleaved trees into Chinese fir plantations enhanced within-stand nutrient cycling rate by speeding nutrient release during decomposition (Yang et al. 2002).

Mineral soil carbon

All mixed stands increased soil carbon storage compared with pure pine stand (Table 3). Carbon concentration in mineral soil at various depth classes for each stand decreased from 2.4% at 0–20 cm depth to 0.2% at 40–60 cm depth. On average, 50% of mineral carbon was stored within the upper 20 cm in all the stands (Figure 2). Total carbon storage values in the soils at depth of 0–60 cm were estimated at 55.0 t C ha^{-1} in Pm and 61.0, 72.4, 69.6, 58.6 and 66.8 t C ha^{-1} in the Pm–Mm, Pm–Cf, Pm–Cs, Pm–Ck and Pm–Cm stands respectively (Table 3). Factors such as previous landuse, climate, soil properties and forest type influence soil carbon storage (Pregitzer & Euskirchen 2004). Mixed stands significantly promoted soil carbon storage in the present study. When hardwood trees were added to pure pine stands, litterfall biomass,

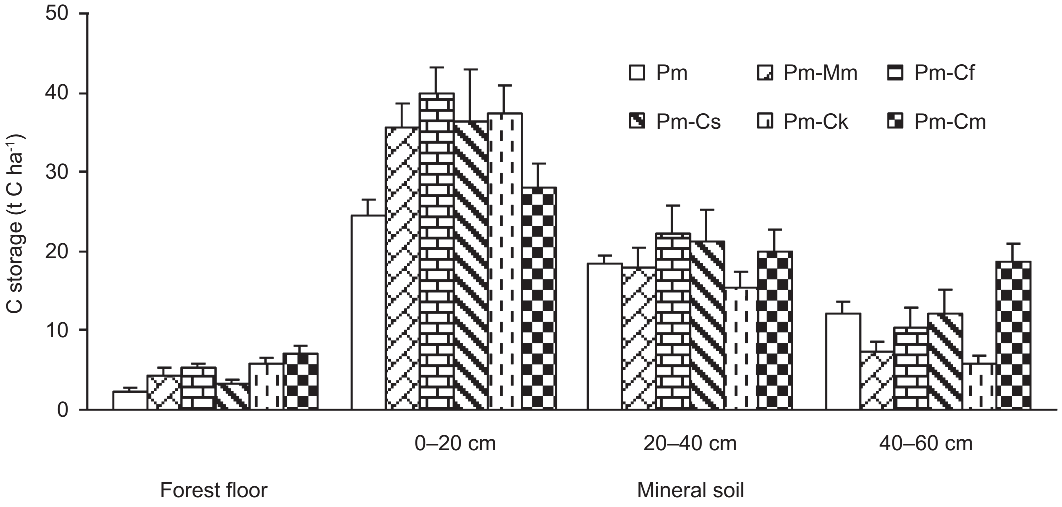

Figure 2 Carbon storage in forest floor and in different depth classes of mineral soil in pure Masson pine and mixed Masson pine–hardwood stands; values are means ± SD

Table 5 Carbon storage accumulated in the undecomposed material (L layer) and the fragmented or decomposed material (F and H layers) of the forest floor in the stands

Stand type	L layer (kg ha^{-1})					F and H layers (kg ha^{-1})	Total (kg ha^{-1})
	Foliage	Twig	Bark	Reproductive parts	Subtotal		
Pm	1117.7 ± 176.3	472.7 ± 52.3	475.7 ± 68.3	17.0 ± 2.7	2083.1±335.6	310.4 ± 36.8	2393.5 ± 179.1
Pm–Mm	1461.3 ± 123.5	1556.2 ± 98.6	168.7 ± 12.6	34.6 ± 6.9	3220.7±418.4	1132.7 ± 67.8	4353.4 ± 284.3
Pm–Cf	1560.0 ± 162.7	899.3 ± 96.4	337.2 ± 56.0	27.9 ± 12.7	2824.4±216.9	2583.4 ± 97.4	5407.8 ± 723.9
Pm–Cs	2038.7 ± 198.5	296.8 ± 45.8	478.4 ± 78.6	62.1 ± 17.4	2876.0±185.6	466.4 ± 32.9	3342.3 ± 321.7
Pm–Ck	1856.6 ± 115.5	1291.9 ± 106.4	508.5 ± 34.8	41.3 ± 2.2	3698.3±294.1	2170.0 ± 45.5	5868.3 ± 482.7
Pm–Cm	2835.2 ± 308.7	1188.5 ± 146.8	413.7 ± 67.2	34.2 ± 7.9	4471.6±656.5	2680.8 ± 344.6	7152.3 ± 923.1
Average	1811.6 ± 175.6	950.9 ± 103.2	397.0 ± 54.6	36.2 ± 9.2	3195.7±422.7	1557.3 ± 132.3	4752.9 ± 467.4

Pm = *Pinus massoniana*, Mm = *Michelia macclurei*, Cf = *Castanopsis fissa*, Cs = *Castanopsis sclerophylla*, Ck = *Castanopsis kawakamii* and Cm = *Cyclobalanopsis myrsinaefolia;* values area means ± within-stand SD

belowground tree biomass and forest floor layers showed positive effects. These increased inputs helped soil carbon sequestration in mixed stands (Kaiser & Guggenberger 2003). Similar results were reported in Dinghushan Biosphere Reserve in South China between a pure *P. massoniana* stand and a natural mix stand of *P. massoniana* and *S. superba* (Fang et al. 2003), in which soil carbon storage values were 55.8 and 61.8 t C ha^{-1} respectively. In another study involving managed plantations in southern China, total carbon content of mineral soil from 0–60 cm depth were higher in the mixed plantation of *P. massoniana* and *Cunninghamia lanceolata* than in pure Masson pine stand (Kang et al. 2006).

Nevertheless, mineral soil is a major carbon reservoir and remains an important component of the whole forest ecosystem carbon pool. Kang et al. (2006) suggested that the relative contribution of belowground ecosystem carbon to total ecosystem carbon remained 45–50%, whereas in our six different plant combinations, the relative contribution of belowground ecosystem carbon to total ecosystem carbon was 40–45%.

Ecosystem carbon pools

Ecosystem carbon storage was calculated by combining the components of above- and belowground (Table 3). Results showed that both above- and belowground carbon storage increased in mixed stands in comparison with the pure pine stand (Table 3). The relative contribution of each individual carbon pool to total ecosystem carbon indicated that aboveground live tree biomass was consistently the greatest carbon pool between the six stands (51–54%) followed by mineral soil (30–35%). Average carbon storage in tree root biomass accounted for approximately 10% of total ecosystem carbon and for about 24% of belowground carbon in the six stands. Underplanting with *M. macclurei*, *C. fissa*, *C. sclerophylla*, *C. kawakamii* and *C. myrsinaefolia* increased total ecosystem carbon pools by 10, 31, 15, 13 and 22% respectively compared with pure pine stand. Our finding concurred with results of previous studies involving pine–hardwood species and pure pine stand (Luis & Monteiro 1998, Vilà et al. 2003). Positive effects of mixed stands on ecosystem production were even exhibited in the early stages of development. In this study, underplanted *C. fissa* contributed the greatest portion to ecosystem carbon between the five hardwood tree species. High survival rate (91%) and rapid height and basal area growth of *C. fissa* contributed largely to the ecosystem carbon pool.

Belowground-to-aboveground ecosystem carbon ratio was similar between the six stands, averaging at 0.75 in this study, which was very close to 0.76 observed in a 30-year-old white pine (*Pinus strobus*) stand in southern Ontario, Canada (Peichl & Arain 2006). The contribution of below- and aboveground carbon to total ecosystem carbon pools did not show any sharp difference between the various underplanting combinations although total ecosystem carbon increased in mixed compared with pure pine plantations. Our results indicated that pine and broadleaved trees grew continually during the experimental period. Belowground-to-aboveground ecosystem carbon ratio cannot remain constant and would decrease in old plantations (Peichl & Arain 2006).

CONCLUSIONS

We investigated ecosystem biomass and carbon pools in a pure Masson pine stand and five mixtures of pine–hardwood stands. After 16 years of establishment, the underplanted hardwoods increased the total ecosystem carbon pools from 10 to 31%. More than half of the ecosystem carbon was stored in the aboveground live tree biomass, while belowground carbon pools contributed 40–45% to ecosystem carbon pool. Planting hardwood trees under the pine canopy significantly increased carbon accumulation in the forest floor but reduced its storage in the understorey vegetation biomass due to poor coverage of grasses and shrubs under the dense canopy of mixed stands. The results provided evidence that mixed pine–hardwood stands benefited total ecosystem carbon storage compared with pure pine stand. We recommend that underplanting can be considered as a forest management option for improving ecosystem carbon sequestration.

ACKNOWLEDGEMENTS

This study was financially supported by the National Natural Science Foundation of China (No. 31160153, 31160179, 31200406), Young Scientific Funding from Jiangxi Provincial Department of Education (GJJ12637) and Nanchang Institute of Technology. We are grateful to BQ Su from the Administration Bureau of National Forest Farms of Fujian Province and CH Liu from the Xinkou Experimental Forest Farm for their help in this research. Gratitude is extended to DX Lin and students from Fujian Agriculture and Forestry University for assistance in the field.

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