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The Impact of Near Natural Forest Management on the Carbon Stock and Sequestration Potential of *Pinus massoniana* (Lamb.) and *Cunninghamia lanceolata* (Lamb.) Hook. Plantations

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Abstract: Quantifying the impact of forest management on carbon (C) stock is important for evaluating and enhancing the ability of plantations to mitigate climate change. Near natural forest management (NNFM) through species enrichment planting in single species plantations, structural adjustment, and understory protection is widely used in plantation management. However, its long-term effect on forest ecosystem C stock remains unclear. We therefore selected two typical coniferous plantations in southwest China, *Pinus massoniana* (Lamb.) and *Cunninghamia lanceolate* (Lamb.) Hook., to explore the effects of long-term NNFM on ecosystem C storage. The C content and stock of different components in the pure plantations of *P. massoniana* (PCK) and *C. lanceolata* (CCK), and their corresponding near natural managed forests (PCN and CCN, respectively), were investigated during eight years of NNFM beginning in 2008. In 2016, there was no change in the vegetation C content, while soil C content in the 0–20 cm and 20–40 cm layers significantly increased, compared to the pure forests. In the *P. massoniana* and *C. lanceolata* plantations, NNFM increased the ecosystem C stock by 31.8% and 24.3%, respectively. Overall, the total C stock of soil and arborous layer accounted for 98.2%–99.4% of the whole ecosystem C stock. The increase in the biomass of the retained and underplanted trees led to a greater increase in the arborous C stock in the near natural forests than in the controls. The NNFM exhibited an increasingly positive correlation with the ecosystem C stock over time. Long-term NNFM enhances ecosystem C sequestration by increasing tree growth rate at individual and stand scales, as well as by likely changing the litter decomposition rate resulting from shifts in species composition and stand density. These results indicated that NNFM plays a positive role in achieving multi-objective silviculture and climate change mitigation.

Keywords: near natural forest management; *Pinus massoniana*; *Cunninghamia lanceolata*; plantation; carbon allocation; climate change

1. Introduction

Recently, climate change has become a major issue that has created global concern [1]. It has been widely recognized that rational plantation management can mitigate climate change by enhancing its carbon (C) sequestration capacity [2]. Understanding the impact of forest management on the C stock in different components of the forest ecosystem is critical for evaluating and enhancing the C sequestration potential of plantations.

China boasts the largest plantation area in the world, 63% of which is located in southern subtropical regions [3]. However, over 70% of the subtropical plantations consist of pure stands of coniferous species, dominated by *Pinus massoniana* (Lamb.), *Cunninghamia lanceolata* (Lamb.) Hook, as well as short-rotation exotic species like *Eucalyptus* spp. The biodiversity, forest biomass and productivity associated with pure stands of *P. massoniana* and *C. lanceolata* are lower than with mixed forests. Thus, C-sequestration capacity and microbial community diversity are both limited in pure stands [4–6]. Some pure coniferous plantations even potentially cause soil acidification [7]. Furthermore, problems such as auto-toxicity, nutrient deficiency, and understory competition have been observed in areas reforested with several rotations of the same species [8,9].

These problems arise from the traditional plantation management. For example, the traditional management of *P. massoniana* plantations in China is clear cutting with a rotation of 29 years, followed by prescribed burning. In contrast, species enrichment planting in single species plantations to form coniferous broad-leaved mixed forest is now becoming a promising silvicultural approach [10]. Near natural forest management (NNFM), focused on multi-functional management and multi-quality products, is widely practiced [11]. The stand density of the original forest is firstly reduced by thinning, and fast-growing tree species are then underplanted, and the pure even-aged coniferous forest is gradually transformed to uneven-aged coniferous broad-leaved mixed forest [12]. The NNFM abandons clear cutting and prescribed burning, and it increases forest productivity, soil fertility, and biodiversity [12]. Previous studies, however, have failed to address NNFM impacts on C sequestration in the whole ecosystem.

Since vegetation and soil pools are the two largest components of C stock in forest ecosystems, they essentially determine the total ecosystem C stock. Species structure, composition, and forest age are the main influencing factors on forest C stock [13]. Our previous study showed that intensive, intermediate and mild thinning increased the C stock of the arborous layer by 11.47%, 11.78%, and 14.49% in a *P. massoniana* plantation, respectively [14]. However, the effects of thinning on forest soil C stocks are controversial [15,16]. In a Norway spruce stand, thinning from 3190 to densities of 2070, 1100 and 820 trees per ha did not affect the organic layer and mineral soil C stock [17]. However, the C stocks in the surface soil of red pine stands in Minnesota decreased in thinning regimes with 10%, 25%, and 35% basal area removal but not in stands where 50% of the basal area was removed [18].

Many studies have demonstrated the effects of species enrichment planting on C stock. This planting can not only directly affect above-ground productivity, it can also influence soil C stock by affecting the quality and decomposition of litter. Compared with pure coniferous plantations, native broad-leaved mixtures increase plant diversity, vegetation and soil C stocks [19,20]. The soil C concentrations and stocks were affected in pure stands of Norway spruce and mixed species stands [21]. In our study site, the soil C stock in the 0–20 cm layer in a mixed *P. massoniana* and *Castanopsis hystrix* plantation was 14.3% higher than that in the *P. massoniana* pure plantation [20]. Examples of underplanting with nitrogen-fixing species in planted forests to enhance the productivity of soil and vegetation are also widely documented [22]. However, no significant difference was found among the soil C stocks of the pure and mixed forests of *Erythrophleum fordii* and *P. massoniana* [23].

Because NNFM involves mixed forest establishment and thinning, it inevitably shifts the vegetation community composition and structure, thus altering the production and composition of litter as the main source of soil C. Therefore, NNFM is very likely to affect C processes and stocks in forest ecosystems. A three-year NNFM through *C. hystrix* and *Michelia hedyosperma* significantly reduced the soil C contents in the 0–20, 20–40 and 40–60 cm layers in a *P. massoniana* plantation, and it slightly increased those in a *C. lanceolata* plantation [24]. Conversely, the effects of NNFM on soil C stock in pure *Fagus sylvatica* and *Picea abies* plantations varied with soil nutrient content [25]. Our previous research showed that soil CO_2 emissions in *P. massoniana* and *C. lanceolata* plantations were increased by NNFM [26]. Therefore, there are uncertainties on how soil C stock responds to NNFM. Though

NNFM is one promising option to improve extensive pure coniferous plantation, its long-term effect on the ecosystem C stock and its allocation, as well as the underlying mechanisms, remain unclear.

We therefore selected two typical coniferous plantations in subtropical China, *P. massoniana* and *C. lanceolata*, to explore the effects of long-term NNFM (i.e., thinning and species enrichment planting) on ecosystem C stock in subtropical *P. massoniana* and *C. lanceolata* plantations, as well as the underlying mechanisms. The C content and stock in different above- and below-ground ecosystem components were investigated. We hypothesized that: (1) The changes in tree species composition and stand density that are induced by NNFM increase the C stocks of the vegetation and soil, and (2) the ecosystem C stock is enhanced due to the increased C stock in both vegetation and soil layers. This study could provide an empirical and theoretical basis for multi-objective silviculture and ecosystem C management in subtropical China.

2. Materials and Methods

2.1. Study Site

This study was conducted at the Guangxi Youyiguan Forest Ecosystem Research Station, the Experimental Center of Tropical Forestry, Chinese Academy of Forestry (22°10′ N, 106°50′ E, Pingxiang, Guangxi, China). It is one of the forest ecology research stations under the jurisdiction of the State Forestry and Grassland Administration. The site has a subtropical monsoon climate, with a semi-humid climate and obvious dry and wet seasons. The annual sunshine duration is 1200–1600 h. Precipitation is abundant, with an annual average of 1200–1500 mm, mainly from April to September. The annual evaporation is 1200–1400 mm, the relative humidity is 80%–84%, and the average annual temperature is 20.5–21.7 °C. The main types of landforms are low hills and hills. The soil is mainly composed of laterite and red soil based on the Chinese soil classification; this is classified as a ferralsol in the World Reference Base for Soil Resources. Soil depth is generally greater than 80 cm. Subtropical evergreen broad-leaved forests comprise the local vegetation.

There are nearly 20,000 ha of various plantation types in the Experimental Center of Tropical Forestry. *P. massoniana* and *C. lanceolata* are the main coniferous tree species. Native broad-leaved tree species include *Quercus griffithii* (Hook.f. and Thomson ex Miq.), *Erythrophleum fordii* Oliver, *Castanopsis hystrix* Miq., *Mytilaria laosensis* Lecomte., *Betula alnoides* Buch.-Ham. ex D. Don, and *Dalbergia lanceolata* Zipp. ex Span. Among these species, *E. fordii* and *D. lanceolata* are nitrogen-fixing trees, and *Q. griffithii* is a fast-growing broad-leaved tree species with strong natural regeneration abilities. The near natural management of pure plantations of *P. massoniana* and *C. lanceolata* with *E. fordii* and *Q. griffithii* has been widely applied, as it not only meets the need for short-period timbers and valuable large-diameter logs but also realizes the natural regeneration of native broad-leaved species and achieves the goal of near natural management.

2.2. Experimental Design

A single-factor and two-level stochastic block design was used. There were four blocks representing four replicates. Four forest types were set up in each block: The near natural *P. massoniana* plantation (PCN), the unimproved *P. massoniana* pure plantation (PCK), the near natural *C. lanceolata* plantation (CCN), and the unimproved *C. lanceolata* pure plantation (CCK). There were thus a total of sixteen 0.5 ha experimental plots.

The pure plantations of *P. massoniana* and *C. lanceolata* were established in 1993 with an initial planting density of 2500 trees ha^{-1} after the clear-cutting of *C. lanceolata*. The coniferous plantations were improved by planting *Q. griffithii* and *E. fordii* in 2008. The detailed management processes for the plantations are described in Table 1 and in our previous work [26]. Presently, the improved plantations are uneven-aged mixed stands with multilayer structures.

In 2016, eight years after the NNFM, we did a field survey and took plant and soil samples to determine the C stock of the four forest ecosystems. The average diameter at breast height (DBH) and average tree height of *Q. griffithii* were 14.7 cm and 15.4 m, respectively, and the average DBH and average tree height of *E. fordii* were 5.2 cm and 6.3 m, respectively.

Table 1. Basic information and management history of the four plantations.

Year	Management	Plantation Type			
		PCK †	PCN †	CCK †	CCN †
1993	Afforestation	2500 trees ha^{-1}	2500 trees ha^{-1}	2500 trees ha^{-1}	2500 trees ha^{-1}
1993–1995	Tending for new plantations	6 times	6 times	6 times	6 times
2000	Released thinning	1600 trees ha^{-1}	1600 trees ha^{-1}	1600 trees ha^{-1}	1600 trees ha^{-1}
2004	Increment felling	1200 trees ha^{-1}	1200 trees ha^{-1}	1200 trees ha^{-1}	1200 trees ha^{-1}
2007	Intensity thinning	No 1200 trees ha^{-1}	Yes 600 trees ha^{-1}	No 1200 trees ha^{-1}	Yes 600 trees ha^{-1}
2008	Complementary planting	No	Planting *Q. griffithii* and *E. fordii* with 300 trees ha^{-1}, respectively	No	Planting *Q. griffithii* and *E. fordii* with 300 trees ha^{-1}, respectively
2009	Tending	No	2 times	No	2 times
2016	Average DBH ‡	22.2 ± 1.3 cm for *P. massoniana*	32.2 ± 1.6 cm for *P. massoniana*	17.1 ± 2.1 cm for *C. lanceolata*	22.3 ± 0.8 cm for *C. lanceolata*
2016	Average height	16.7 ± 0.5 m for *P. massoniana*	17.3 ± 0.7 m for *P. massoniana*	17.1 ± 0.4 m for *C. lanceolata*	17.2 ± 0.4 m for *C. lanceolata*

† PCK, PCN, CCK, and CCN represent the pure and near natural managed *P. massoniana* plantation and the pure and near natural managed *C. lanceolata* plantation, respectively. ‡ DBH represents diameter at breast height.

2.3. Sampling, Measurement and Statistical Analysis

2.3.1. Determination of Tree Biomass

In each year from 2007 to 2016, the C content and stock of each component in the forest ecosystem were measured. One 30 m × 30 m subplot was established in each of the 16 plots. All trees in the subplots were inventoried. The biomass of *P. massoniana*, *C. lanceolata* and *E. fordii* were calculated using existing biomass equations in the research area [14,27,28]. The biomass of *Q. griffithii* was calculated using a newly developed equation (Table 2). The DBH distribution diagram was drawn after all trees were tallied, and the fresh weight of each organ (i.e., stem, bark, branch, leaf and root) was measured by selecting 9 sample trees in each 2 cm interval in the DBH range.

After weighing all the fresh samples, approximately 200 g of subsamples were taken from each organ and dried to constant weight at 65 °C to calculate dry mass as follows:

$$w_2 = \frac{w_1}{200} \times w_0 \tag{1}$$

where W_0, W_1, and W_2 are the fresh weight of the sample, the dry mass of the subsample, and the dry mass of the sample, respectively.

Table 2. Biomass allometric equations of *Quercus griffithii*.

Organ	Regression Equation	Number of Sampled Trees	R^2	*F* Value	*p* Value
Stem	W = 0.027(D^{2}H) − 0.125 †	9	0.981	379.405	<0.001
Branch	W = 0.013(D^{2}H) − 0.354 †	9	0.911	72.487	<0.001
Leaf	W = 0.004(D^{2}H) + 0.169 †	9	0.979	332.336	<0.001
Root	W = 0.009(D^{2}H) − 0.35 7 †	9	0.863	44.145	<0.001
Whole tree	W = 0.054(D^{2}H) − 0.666 †	9	0.969	225.052	<0.001

† W, D and H represent dry mass, DBH and plant height, respectively.

2.3.2. Measurement of Understory Vegetation Biomass and Litter Quantity

Above- and below-ground fresh weight of shrubs and herbs was determined using destructive sampling techniques (i.e., total harvesting, including roots). The sampling was conducted in five randomly selected 2 m × 2 m subplots within each plot. To measure the un-decomposed and semi-decomposed biomass of the litter, the branches, leaves, flowers, and fruits of all plants were sampled from five 1 m × 1 m subplots in each plot. Approximately 200 g of each sample were dried to constant weight at 65 °C to calculate dry mass using Equation (1).

2.3.3. Soil Sampling

Five soil core samples were collected from each plot at depths of 0–20, 20–40, 40–60, 60–80, and 80–100 cm. They were then combined according to soil depth. After carefully removing the fine roots, stones and organic materials, each sample was then air dried to determine the C content. Soil bulk density was measured using the cutting ring method [29].

2.3.4. Determination of C Content and Stock

The C content and stock were measured for all the plant and soil samples. The C contents were analyzed using the potassium dichromate oxidation method, with a 0.8 mol L^{-1} $K_2Cr_2O_7$–H_2SO_4 solution [29]. The vegetation and soil C stock was calculated as follows:

$$Sp = Wp \times Cp \tag{2}$$

$$Ss = \sum_{i=1}^{n} Ti \times Bi \times Ci \tag{3}$$

$$Se = Sp + Ss \tag{4}$$

where *Sp*, *Ss*, and *Se* are the vegetation, soil and ecosystem C stock, respectively. *Wp* is the plant dry mass per hectare. *Cp* is the plant C content. *Ti*, *Bi*, and *Ci* are the thickness, bulk density, and C content of the *i*-th soil layer, respectively. *n* is the number of soil layer.

The vegetation C stock includes the arborous and ground layers. The arborous layer includes the main story (i.e., *P. massoniana* and *C. lanceolata* trees that were retained after thinning) and underwood layer (i.e., the underplanted *Q. griffithii* and *E. fordii* and natural regenerated seedlings), while the ground layer includes shrubs, herbs, and litter (including branches, leaves, flowers, and fruit of all the plants in the plot).

2.3.5. Statistical Analysis

A one-way ANOVA followed by a Duncan test (95% confidence level) were performed to analyze the effects of NNFM on the C content and stock in the forest ecosystem. The heterogeneity of variance was tested, and the original data were normalized by log-transformation or standardization prior to analysis when necessary. The ANOVA model was expressed as:

$$V_{\mathrm{ijkl}} = \mu + B_{\mathrm{i}} + S_{\mathrm{j}} \times T_{\mathrm{k}} + \varepsilon_{\mathrm{ijkl}} \tag{5}$$

where V_{ijk} represents the *l*th variation (i.e., the C content and stock of different ecosystem components) under the *i*th block (B), *j*th plant species (S, *P. massoniana* and *C. lanceolata*) and *k*th treatment (T, control and NNFM); μ is the mean of each corresponding variation; and $\varepsilon_{\mathrm{ijkl}}$ is the unobserved error component.

A multiple stepwise linear regression analysis was used to determine the contributions of the C stock of each ecosystem component (i.e., main story, underwood, shrub, herb, litter layer, and soil layers of 0–20, 20–40, 40–60, 60–80, and 80–100 cm) to the variations in ecosystem C stock. All the analyses were performed using R (version 3.5.3).

3. Results

3.1. C Stock of Each Component in the Forest Ecosystem

After eight years of NNFM, no significant difference was detected in the C content of the organs of *P. massoniana* and *C. lanceolata* between the near natural and unimproved forests ($p > 0.05$, Table 3).

Table 3. Carbon (C) content of different organs of *Pinus massoniana* and *Cunninghamia lanceolata* (mean ± standard error, $n = 4$, g·kg^{-1}).

Organ	PCK †	PCN †	CCK †	CCN †
Stem	476.6 ± 16.0 a	481.2 ± 30.2 a	486.4 ± 19.4 a	488.2 ± 14.3 a
Bark	475.3 ± 13.8 a	488.1 ± 6.9 a	459.3 ± 12.7 b	464.1 ± 12.4 b
Branch	465.4 ± 18.2 a	470.2 ± 11.9 a	460.5 ± 18.5 a	456.0 ± 11.6 a
Leaf	491.7 ± 13.1 b	479.6 ± 10.7 b	513.3 ± 15.7 a	513.0 ± 17.9 a
Root	425.6 ± 14.3 b	426.3 ± 12.8 b	442.8 ± 10.2 a	448.2 ± 14.2 a

† PCK, PCN, CCK, and CCN represent the pure and near natural managed *P. massoniana* plantation and the pure and near natural managed *C. lanceolata* plantation, respectively. Values with different letters indicate significant plantation effects at $p < 0.05$. Data collected in 2016 are shown.

Compared with the control, NNFM significantly increased the C content of the aboveground of the shrub layer in the *C. lanceolata* plantations by 17.5% (Table 4). However, NNFM significantly reduced the C content of the un-decomposed components of the litter layer in the two plantations and the semi-decomposed litter in the *P. massoniana* plantation.

Table 4. C content of the different components in the underground layer of the four plantation ecosystems (mean ± standard error, $n = 4$, g·kg^{-1}).

Layer	Component	PCK †	PCN †	CCK †	CCN †
Shrub layer	Above-ground	435.3 ± 43.5 a	414.2 ± 19.2 a	365.3 ± 34.2 b	429.4 ± 24.6 a
	Below-ground	442.0 ± 29.7 a	426.8 ± 34.1 a	407.0 ± 26.7 a	438.3 ± 36.1 a
Herb layer	Above-ground	420.7 ± 21.9 a	400.7 ± 11.5 a	419.3 ± 19.4 a	400.3 ± 13.7 a
	Below-ground	343.1 ± 31.8 a	345.0 ± 31.1 a	342.5 ± 23.7 a	341.0 ± 12.3 a
Litter layer	Un-decomposed	496.4 ± 16.6 a	435.4 ± 37.8 b	491.6 ± 14.1 a	428.6 ± 33.2 b
	Semi-decomposed	434.6 ± 26.1 a	413.9 ± 38.2 b	416.4 ± 21.8 b	394.9 ± 18.7 b

† PCK, PCN, CCK, and CCN represent the pure and near natural managed *P. massoniana* plantation and the pure and near natural managed *C. lanceolata* plantation, respectively. Values with different letters indicate significant plantation effects at $p < 0.05$. Data collected in 2016 are shown.

The soil C content declined significantly with soil depth. Though not significantly affecting the C stock of deep soil, NNFM significantly increased soil C content at 0–20 and 20–40 cm in the *P. massoniana* and *C. lanceolata* plantations (Figure 1).

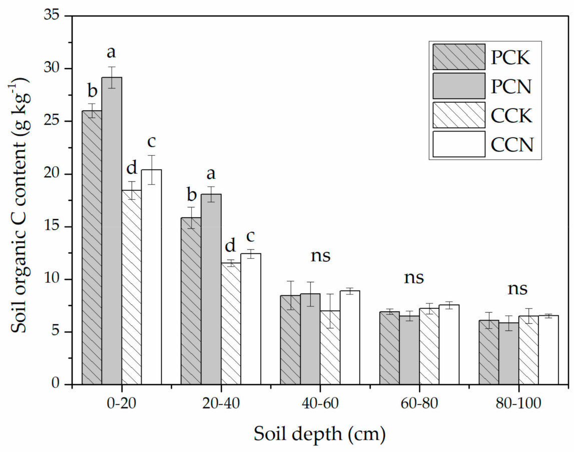

Figure 1. Soil C content at different depth in the four plantations (mean ± standard error, $n = 4$). PCK, PCN, CCK, and CCN represent the pure and near natural managed *P. massoniana* plantation and the pure and near natural managed *C. lanceolata* plantation, respectively. Values with different letters indicate significant plantation effects at $p < 0.05$. Data collected in 2016 are shown. ns, $p > 0.05$.

3.2. Ecosystem C Stock and Its Allocation

By 2016, in the *P. massoniana* plantation, NNFM had significantly increased the C stocks of the arborous layer and its components; the herb layer; the 0–20, 20–40, 40–60, and 0–100 cm soil layers; and the ecosystem C stock (Table 5). In contrast, in the *C. lanceolata* plantation, NNFM significantly increased the C stocks of the underwood and arborous layer; the 0–20, 20–40, and 0–100 cm soil layers; and the ecosystem C stock, but it reduced that of the shrub and herb layers.

Table 5. C stock of the different components in the four plantation ecosystems (mean ± standard error, $n = 4$, $t{\cdot}ha^{-1}$).

Layer	Component	PCK †	PCN †	CCK †	CCN †
Arborous layer	Main story	120.44 ± 9.71 b	151.62 ± 11.4 a	48.15 ± 12.03 c	39.33 ± 4.37 c
	Underwood	0.23 ± 0.01 d	26.06 ± 1.41 b	0.32 ± 0.02 c	29.68 ± 1.60 a
	Sum	120.67 ± 10.91 b	177.68 ± 12.35 a	48.47 ± 13.17 d	69.01 ± 6.12 c
Ground layer	Shrub	0.16 ± 0.03 ab	0.14 ± 0.02 ab	0.22 ± 0.04 a	0.10 ± 0.05 b
	Herb	0.15 ± 0.02 b	0.08 ± 0.02 c	0.24 ± 0.03 a	0.10 ± 0.05 bc
	Litter	2.02 ± 0.14 a	1.81 ± 0.13 ab	1.75 ± 0.09 b	1.78 ± 0.22 b
	Sum	2.33 ± 0.23 a	2.04 ± 0.11 a	2.21 ± 0.21 a	1.98 ± 0.17 a
Soil layer	0–20 cm	55.40 ± 3.36 bc	66.80 ± 4.07 a	51.09 ± 3.05 c	63.18 ± 3.72 ab
	20–40 cm	36.80 ± 2.75 b	45.86 ± 3.33 a	35.94 ± 2.49 b	46.80 ± 3.04 a
	40–60 cm	22.25 ± 1.70 b	26.28 ± 2.06 a	20.98 ± 1.54 ab	24.57 ± 1.88 a
	60–80 cm	19.97 ± 1.56 a	24.03 ± 1.89 a	22.11 ± 1.41 a	20.50 ± 1.72 a
	80–100 cm	15.50 ± 1.29 a	17.06 ± 1.56 a	15.33 ± 1.17 a	17.81 ± 1.42 a
	Sum	149.92 ± 5.52 b	180.03 ± 6.69 a	145.45 ± 5.00 b	172.86 ± 6.10 a
Ecosystem	Total	272.93 ± 13.63 c	359.75 ± 15.74 a	196.14 ± 14.94 d	243.84 ± 0.12 b

† PCK, PCN, CCK, and CCN represent the pure and near natural managed *P. massoniana* plantation and the pure and near natural managed *C. lanceolata* plantation, respectively. Values with different letters indicate significant plantation effects at $p < 0.05$. Data collected in 2016 are shown.

From 2008 to 2016, the C stocks of the four forest ecosystems all continuously increased (Figure 2). The annual rate of increase in the near natural *P. massoniana* and *C. lanceolata* plantation (22.64 and 14.17 $t{\cdot}ha^{-1}{\cdot}a^{-1}$, respectively) was significantly higher than that of the controls (8.54 and 4.62 $t{\cdot}ha^{-1}{\cdot}a^{-1}$, respectively). The total C stock of each near natural forest began to overtake that of the unimproved forests from 2011. NNFM exhibited an increasingly positive impact on the ecosystem C stock over time. In 2016, after eight years of NNFM, the C stock of the transformed *P. massoniana* and *C. lanceolata* forests was 359.75 and 243.84 t·ha^{-1}, respectively, which was 31.8% and 24.3% higher than their corresponding controls.

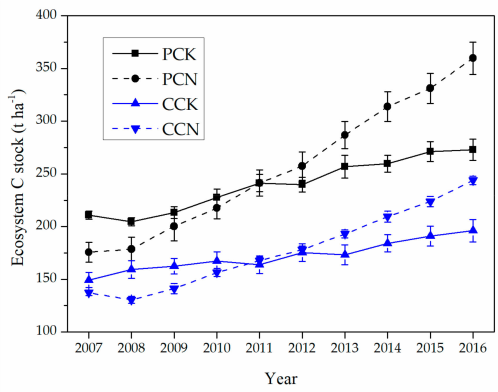

Figure 2. Dynamics of ecosystem C stock in the four plantations (mean ± standard error, n = 4). PCK, PCN, CCK, and CCN represent the pure and near natural managed *P. massoniana* plantation and the pure and near natural managed *C. lanceolata* plantation, respectively.

The arborous and soil layer stored 12.2%–49.4% and 50.0%–86.6% of the whole C stock in the ecosystem, respectively, with a sum of 98.2%–99.4%. Meanwhile, the C stock of the arborous layer accounted for 89.1%–98.9% of the vegetation layer (Figure 3). From 2008 to 2011, the arborous layer in each near natural plantation stored less C than the control. However, 2015 and 2016 saw an increase of C stock in the arborous and vegetation layers in the near natural forests compared to the controls (Figure 3a,c).

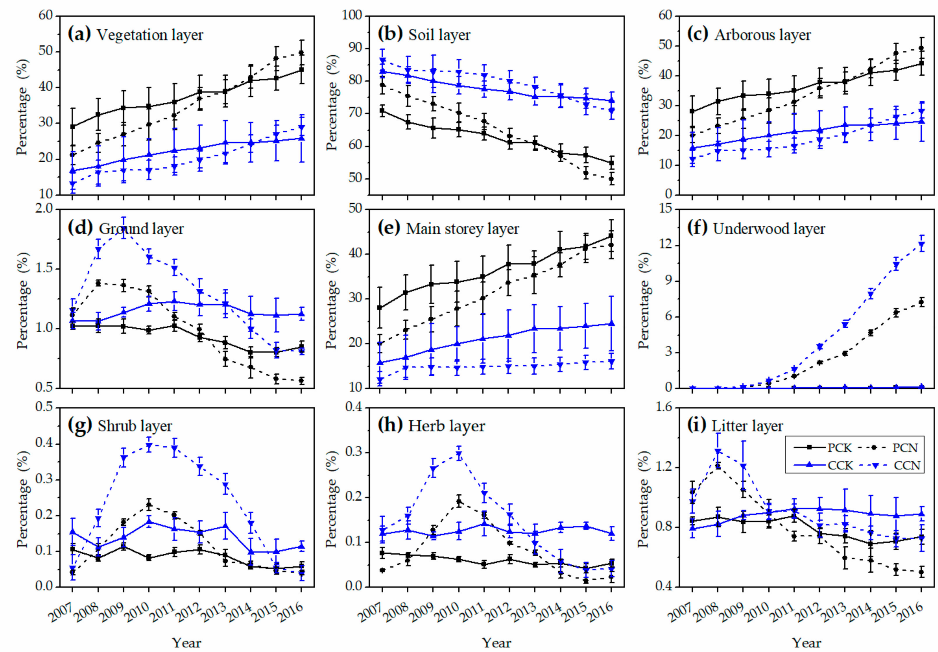

Figure 3. Dynamics of C stock percentage of (**a**) the vegetation layer; (**b**) the soil layer; (**c**) the arborous layer; (**d**) the ground layer; (**e**) the main story layer; (**f**) the underwood layer; (**g**) the shrub layer; (**h**) the herb layer; and (**i**) the litter layer in the four plantations (mean ± standard error, n = 4). PCK, PCN, CCK, and CCN represent the pure and near natural managed *P. massoniana* plantation and the pure and near natural managed *C. lanceolata* plantation, respectively. The main story layer was dominated by *P. massoniana* and *C. lanceolata*, whereas the underwood layer was dominated by the underplanted *E. fordii* and *Q. griffithii* and natural regenerated seedlings.

3.3. Relationship between Ecosystem C Stock and Its Components

Overall, the ecosystem C stock was significantly and positively affected by the C stocks of the main story, the underwood layer, and the 0–20 cm soil layer (R^2 = 0.994, Table 6). Only the C stock in the PCK had a significant positive correlation with that of the underwood layer (R^2 = 0.965), while the C stock in the PCN was positively correlated with that of main story and 0–20 cm soil layer (R^2 = 0.998). The C stock in the CCK and the CCN was positively correlated with the C stock of the main story (R^2 = 0.911) and 0–20 cm soil layer (R^2 = 0.963), respectively.

Table 6. Models of regressions between ecosystem C stock and its components in the four plantations.

Plantation	Equation	R^2	*F* Value	*p* Value
PCK†	Y = 302.754x2 + 205.341‡	0.965	250.677	0.000
PCN†	Y = 1.402x1+1.106x3 + 72.259‡	0.998	2617.328	0.000
CCK†	Y = 1.588x1 + 114.941‡	0.911	92.199	0.000
CCN†	Y = 3.468x3 + 22.321‡	0.963	233.080	0.000
Total	Y = 1.006x1 + 1.354x2 + 1.623x3 + 64.72‡	0.994	2224.522	0.000

† PCK, PCN, CCK, and CCN represent the pure and near natural managed *P. massoniana* plantation and the pure and near natural managed *C. lanceolata* plantation, respectively. ‡x1, x2, x3, and Y represent the C stock of the main story layer, the underwood layer, the 0–20 cm soil layer, and the ecosystem, respectively.

4. Discussion

4.1. Effects of NNFM on Vegetation C Stock

The forest ecosystem C stock included the arborous and ground layer C stocks, with the former accounting for 95.64%–98.87% (Figure 3). Therefore, the C sequestration capacity of vegetation largely depends on the arborous layer, which is similar to previous studies [30]. Any changes in the growth and C content of plants may alter the vegetation C stock in a forest ecosystem. Because NNFM did not affect the C content of the *P. massoniana* and *C. lanceolata* plant components (Table 3), the differences in the vegetation C stock between the near natural and controlled plantations came from the positive effects of NNFM on the biomass of dominant tree species in the arborous layer at a stand-scale. However, the stand-scale increase was highly related to the increase in the growth rate of the retained and underplanted trees under NNFM.

In the near natural managed forest, the intense thinning reduced the original stand density and greatly improved the growth of the retained trees through release of growing space. A previous study also showed improved stem growth by thinning in a spruce forest [31]. In our study, after thinning, the increase in the annual C stock of the retained trees was 13.8 and 2.63 t ha^{-1} a^{-1} in the *P. massoniana* and *C. lanceolata* plantations, respectively. However, it was only 7.0 and 2.52 t ha^{-1} a^{-1} in their corresponding controls (data not shown). This is consistent with a previous study showing that thinning increased the C stock of the arborous layer [14]. In addition, during NNFM, underplanted species usually have a high growth rate and consequently cause an increase in the rate of C stock accumulation [12]. This might also cause the rapid increase in the arborous C stock in the near natural forests. In our study, native fast-growing species *E. fordii* and *Q. griffithii* were planted during NNFM. The increase in the annual C stock which they caused was 3.3 and 3.7 t ha^{-1} a^{-1} in the *P. massoniana* and *C. lanceolata* plantations, respectively (data not shown). Because the increase in the rate of underwood C stock accumulation was only 0.02 and 0.04 t ha^{-1} a^{-1} in the two control forests, the vegetation C stock that was nearly the sum of the original and underplanted tree C stock was increased by NNFM (Table 5). These results suggest that tree species allocation and vegetation structure optimization are important for enhancing vegetation C stock. Increasing biomass through facilitating plant growth and planting trees with high C density is an effective means to achieve this aim.

4.2. Effects of NNFM on Soil C Stock

Soil has the largest C pool in the forest ecosystem, accounting for 50.0%–86.6% in our present study (Figure 3). The soil C stock is affected by the soil C content, bulk density, and soil thickness. In our study, NNFM did not affect soil bulk density (data not shown), but it increased the soil C content in the 0–20 and 20–40 cm layers in the *P. massoniana* and *C. lanceolata* plantation, respectively (Figure 1). Consequently, the soil C stocks at 0–20 and 20–40 cm in the near natural forests were significantly greater than that in the unimproved stands (Table 5). This indicated that the NNFM of *P. massoniana* and *C. lanceolata* plantations could enhance the C sequestration potential of the top soil. However, the soil C contents at 0–20, 20–40, and 40–60 cm in a *P. massoniana* plantation were reduced after a three-year NNFM by *C. hystrix* and *M. hedyosperma*, whereas they increased slightly in a *C. lanceolata* plantation [24]. These differing results suggest uncertainties with respect to how NNFM affects soil C content. It is very likely due to the differences in management approach, time period, and vegetation composition.

Numerous studies have confirmed that changing vegetation structure and litter composition can alter soil C content [2,15]. In our study, neither of the C contents of the components in the vegetation layer (i.e., main story, underwood, shrub, herb, and litter) were positively correlated with the soil C content. Therefore, other factors affecting soil C content, including the trait of litter and root [32], the structure and activity of soil microbial community [33], and other soil physical and chemical properties [34], may lead to the increase in soil C content induced by NNFM. One study has indicated that NNFM can accelerate the decomposition rate of plant litter and therefore alter the accumulation of soil C [35]. The modification of tree species structure can change the composition and quality of roots and litter, and it can also alter the soil microbial community, which accelerates litter decomposition and increases the soil C content [36]. Broad-leaved species underplanting also improved the litter quality and its decomposition rate in *P. massoniana* plantations [4]. Further studies are therefore required on exploring the drivers of the higher C content in topsoil under NNFM, as well as the relations between the dynamics of the vegetation community structure and soil C.

4.3. Long-Term Effects of NNFM on Ecosystem C Stock

The arborous and soil layer had the largest C stocks in the forest [4], contributing over 98% to the ecosystem C stock (Figure 3). As a result, they controlled the ecosystem C stock and its dynamics in the four plantations. A multiple regression analysis also indicated that the ecosystem C stock was influenced by the C stocks of the main story, the underwood, and the 0–20 cm soil layer (Table 6). Due to the decline in soil C content with soil depth (Figure 1) and little change in the soil bulk density the soil C stock was concentrated in the topsoil. In 2016, the eight-year NNFM had increased the C stock in the main story, the underwood, and the 0–20 cm soil layer in the *P. massoniana* plantation, as well as the C stock in the main story and the 0–20 cm soil layer in the *C. lanceolata* plantation. Thus, NNFM significantly increased the total C stock of each of the two coniferous plantations (Table 5). However, there was little deadwood in our forests, and we did not measure its C stock. Including the C stock of the deadwood would slightly increase the total ecosystem C stock.

Forest age is another key factor affecting the C stock and its allocation in plantations [30,37]. In China, either the forest biomass or soil C storage is increased exponentially over the stand age [38]. Similarly, NNFM exhibited long-term dynamic impacts on forest ecosystem C stock and its allocation (Figures 2 and 3). During the study period, the proportion of vegetation C stock to that of the ecosystem showed an increasing trend, while the proportion of soil C stock was downward (Figure 3). This is because vegetation C stock is less stable than that of soil and increases with plant growth. At the initial stage of NNFM, the vegetation C stock was lower than the control stands due to the thinning treatment. With the extension of time, the C stock loss from thinning was replaced by the rapid growth of retained and underplanted trees. This led to a significantly greater rate of increase in arborous and vegetation layer C stocks in the near natural forests than in their controls. Finally, it resulted in an increasingly positive correlation between NNFM and C stock in the ecosystem over time (Figure 2).

Meanwhile, combined with our previous findings [26], it can be inferred that increasing the stability of soil C will further boost this positive correlation. These results indicate that NNFM is a promising way to enhance long-term C sequestration in forest ecosystems.

5. Conclusions

The eight-year period of near natural forest management increased the C stock and sequestration potential of the *P. massoniana* and *C. lanceolata* plantations. This can be attributed to the enhanced C stock in the arborous and 0–20 cm soil layers. The improvement in species diversity and stand density increased the individual and stand-scale growth rate, thereby increasing the vegetation C stock. The litter decomposition likely changed to increase the topsoil C stock. Our study indicates that NNFM plays a positive role in enhancing the forest C sink function. Increasing soil C stability and plant biomass through facilitating tree growth is the main way to increase the total C stock in near natural managed plantations.

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