Forests **2015**, *6*, 3665-3682; doi:10.3390/f6103665

OPEN ACCESS

forests

ISSN 1999-4907

www.mdpi.com/journal/forests

Article

Biomass Stock and Carbon Sequestration in a Chronosequence of *Pinus massoniana* Plantations in the Upper Reaches of the Yangtze River

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Academic Editor: Mark E. Harmon

Received: 12 July 2015 / Accepted: 30 September 2015 / Published: 15 October 2015

Abstract: Planted forest plays a significant role in carbon sequestration and climate change mitigation; however, little information has been available on the distribution patterns of carbon pools with stand ages in *Pinus massoniana* Plantations. We investigated the biomass stock and carbon sequestration across a chronosequence (3-, 5-, 7-, 9-, 12-, 15-, 19-, 29-, 35- and 42-year) of stands with the main objectives: (1) to determine the biomass and carbon stock of the forest ecosystem; and (2) to identify factors influencing their distribution across the age series. Simple random sampling was used for collecting field data in the ten (10) stand ages. Three 20 × 20 m standard plots were laid out in February 2015 across the chronosequence. The diameter at breast height (DBH) and tree height (H) of each tree within each plot were measured using calipers and height indicator. Sub-plots of 2 × 2 m were established in each main plot for collecting soil samples at a 0–30- and 30–60-cm depth. Plantation biomass increased with increasing stand ages, ranging from 0.84 tonnes per hectare ($t \cdot ha^{-1}$) in the three-year stand to 252.35 $t \cdot ha^{-1}$ in the 42-year stand. The aboveground biomass (AGB) contributed 86.51%; the maximum value is 300-times the minimum value. Carbon concentrations and storage in mineral soil decreased with increasing soil depth, but were controlled by the management history of the ecosystem. The total ecosystem carbon storage varies with stand ages, ranging from 169.90 t·ha^{-1} in the five-year plantation to 326.46 t·ha^{-1} in the 42-year plantation, of which 80.29% comes from the mineral soil carbon and 19.71% from the vegetation. The ratio of the total carbon sequestration by the 42-year to the three-year stand was 1.70, implying substantial amounts of carbon accumulation during the transition period from young to mature-aged trees. The forest ecosystem had the capacity of storing up to 263.16 t·ha^{-1} carbon, assisting in mitigating climate change by sequestrating 965.83 t·ha^{-1} of CO_2 equivalents, indicating that the forest is an important carbon sink.

Keywords: *Pinus massoniana*; stand age; aboveground biomass; carbon sequestration; subtropical sub-humid forest

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1. Introduction

Daily carbon dioxide (CO_2) average concentrations went above 400 ppm for the first time at Mauna Loa station in May 2013 [1]. It climbed from 310 parts per million (ppm) CO_2 from 1850 up to 394 ppm in 2012 [2]. Increasing global carbon (C) sequestration through enlargement of the proportion of plantation forest lands on the planet has been suggested as an effective measure for mitigating elevated concentrations of atmospheric carbon dioxide [3,4]. Trees in the forests, as well as woody and herbaceous forest products are primary carbon sequestration mechanisms, and approximately 50.8% of coniferous wood consists of carbon [5]. Forests are thought to offer a mitigation strategy to reduce global warming [6]. As a C pool, the forest ecosystem stores more C than any other terrestrial ecosystem and accumulates organic compounds with long C residence time [7,8]. As a result, the C pool of the forest ecosystem has been the focus of the climate change community in recent years [9].

When forests grow, carbon is removed from the atmosphere and stored in wood, leaves and soil. This carbon remains stored in the forest ecosystem, but can be released into the atmosphere when forests are burned [10]. Forests nearly covers one-third of the Earth's land area, containing up to 80% of the total above-ground terrestrial C and 40% of the below-ground C, hence having a critical role in the global C cycle [11]. Estimates made by the Global Forest Resources Assessment show that the world's forests store more than 650 gigatonnes (Gt) of C, 289 Gt in the biomass (44 percent), 72 Gt in dead wood and litter (11 percent) and 292 Gt in soil (45 percent) [12]. The area of planted forest has now reached 264 million hectares and accounts for 7% of the global total forest area [13]. Although planted forests have only contributed a small portion to the total terrestrial C balance, their potential to absorb and store C has been recognized to play a more important role in the future mitigation of climate change [14].

In China, the C sequestration function of forest ecosystems has significantly increased during the last two decades [15]. Plantation forests contributed about 80% of the total forest C sink increment of China [16]. The total land area under tree plantations has reached 69.33 million hectares, accounting for 36% of China's total forest area [17]. Most of these plantations are still immature [18] and show a substantial potential for C sequestration [19]. C sinks in southern China accounted for more than 65%

of the national C sinks [20]. The largest proportion (63%) of the total plantations area in China is located in subtropical regions, which provide hot and humid conditions appropriate for tree growth [21]. Most of these subtropical plantations consists of stands containing either a single coniferous species or an exotic tree, such as *Pinus massoniana*, *Cunninghamia lanceolata* and *Eucalyptus* [22].

Forest establishment for C sequestration has ecological, environmental, social and economic values, and its conservation not only act as a source of global C pool, but also provides a wider range of services and goods to humans. Forests have a higher C density than other types of ecosystems [23,24]; their management, therefore, could play an important role in reducing atmospheric CO_2 [25]. While sustainable management, planting and rehabilitation of forests can conserve or increase forest C stocks, deforestation, forest degradation, forest fire and burning of fossil fuels produces enormous amounts of greenhouse gases [26].

Estimating soil organic carbon (SOC) is important, because soil contains the world's largest terrestrial active C pool, which plays a major role in the global C cycle [27]. The estimated amount of organic C stored in the world's soils is about 1100–1600 petagrams (Pg), more than twice the C in living vegetation (560 Pg) or in the atmosphere (750 Pg) [28]. Soil C sequestration differs from other atmospheric C mitigation mechanisms in that it both removes CO_2 concentrations from the atmosphere and also decreases soil erosion, improves surface water quality and improves soil physical properties [29]; this makes soils a good source of C pool and, thus, a C sink. However, anthropogenic activities, such as deforestation, cause the release of C from the soil, which may significantly increase the concentration of greenhouse gas (GHG) in the atmosphere [26]. Encouraging sound forestry practices that do not degrade soils and their productivity, using reforestation practices that can heal harvested lands, will quickly restore productive atmospheric C removal vegetation systems [29].

Pinus massoniana (masson pine or Chinese red pine) is a species of pine native to a wide area of central and southern China, including Hong Kong, Taiwan and northern Vietnam, growing at an altitude mostly below 1500 m, but rarely up to 2000 m [30]. It is one of the main afforestation tree species in southern China and the Yangtze River Basin. Many studies were conducted on the roles played by planted forests in climate change mitigation in southern China, but little information has been available on the distribution patterns of carbon pools with stand ages. The objectives of our study were: (1) to determine the vegetation biomass and soil carbon stocks of the forest ecosystem; (2) to identify factors influencing their distribution across the chronosequence; and (3) to estimate the carbon sequestration potentials of the forest ecosystem.

2. Materials and Methods

2.1. Study Area

The study site under investigation is located in Gao County, Sichuan Province, at an elevation of 453 m above sea level between grid reference (28°34′–28°36′ N, 104°32′–104°34′ E). The climate of the area is subtropical, sub-humid monsoon with an annual total mean rainfall of 1021 mm. The mean annual temperature is 18.1 °C with the lowest temperature of 7.8 °C in the month of January and the highest temperature of 36.8 °C in the month of July. The soil type in the study area is classified as yellow earth with low base saturation and a large proportion of secondary minerals, including layered silicate clays and other small crystalline and amorphous minerals [31]. The texture is fine clay sediment to fine silty clay. Soils in this region are deep, well drained, with high water holding capacity. The study site is a planted forest dominated by *Pinus massoniana*, which has been transformed from a traditionally-managed natural forest ecosystem, it has a long reforestation history of about 500 years, and a close to nature practice is currently on trial at the site. The forest comprises the tree layer, the shrub layer and the herb layer. The dominant overstory vegetation in all stand ages was *Pinus massoniana*. The shrub layer includes *Rubus pirifolius*, *Viburnum setigerum*, *Myrsine africana*, and the herb layer includes grasses, such as *Pteridium aquilinum*, *Dicranopteris dichotoma* and *Setaria plicata.* The vegetation of Gao County is the evergreen subtropical type. The detailed characteristics of these forest stands are shown in Table 1.

Table 1. Characteristics of the *Pinus massoniana* plantation forest in Gao County, Sichuan Province.

Stand Age (Years)	Altitude (m)	Aspect	Slope Position	Mean DBH (cm)	Range (cm)	Mean Height (m)	Range (m)	Stand Density (tree·ha^{-1})	Soil Bulk Density (g·cm^{-3})	
									0–30-cm	30–60-cm
3	470	SE	Upper	2.28	1.20–3.40	1.71	1.30–2.15	3500	1.12 ± 0.24	1.23 ± 0.21
5	427	W	Middle	4.40	3.30–6.80	4.53	4.20–4.80	3500	1.03 ± 0.25	1.37 ± 0.21
7	442	NE	Upper	6.60	4.80–9.00	4.85	4.20–5.63	3100	1.03 ± 0.13	1.05 ± 0.37
9	427	W	Upper	10.31	6.10–14.8	8.04	7.40–8.80	3100	0.95 ± 0.09	1.3 ± 0.17
12	445	S	Lower	10.61	7.40–16.1	9.95	9.60–10.4	3100	0.93 ± 0.08	1.12 ± 0.23
15	553	W	Upper	11.72	7.90–16.4	12.08	10.6–13.5	1600	1.18 ± 0.19	1.32 ± 0.09
19	479	SW	Lower	13.55	8.40–19.2	11.04	10.0–12.0	1800	1.15 ± 0.07	1.32 ± 0.05
29	382	W	Upper	20.64	16.7–26.1	14.25	12.8–15.3	1400	0.85 ± 0.26	1.32 ± 0.11
35	544	W	Middle	20.77	16.8–24.9	14.36	13.4–15.8	1400	1.21 ± 0.39	1.32 ± 0.05
42	400	S	Ridge	22.85	17.0–29.7	16.45	15.7–17.5	1100	0.94 ± 0.11	1.32 ± 0.05

N = north, S = south, E = east, W = west, ha = hectare.

2.2. Sampling and Biophysical Measurements

Simple random sampling was used for collecting field data in the ten (10) sites with stand ages of 3, 5, 7, 9, 12, 15, 19, 29, 35 and 42 years. In each stand, three 20 × 20 m standard plots were laid out in February 2015. A non-destructive sampling method was used to estimate the aboveground biomass carbon in the tree component. This method involves measurement of the main aboveground tree variable, such as the diameter at breast height (DBH) and height (H), of the standing trees in the sampling plots. The DBH of each tree within each plot was measured using calipers and diameter tapes, while specialized equipment, such as a height indicator (NIKON 550A S, Tokyo, Japan), was used for measuring the tree height (H).

2.3. Soil Sampling

Three subplots of (2 × 2 m) were selected from each sample plot across the different stand ages of the *Pinus massoniana* plantation. Soil samples of (1.0 kg) were collected at different mineral soil layers in the center of the subplot at depths of 0–30- and 30–60-cm. Two sample points per plot were randomly taken and kept separately. The sampling points were taken at a 1-m distant from tree stems and animal holes, disturbances like wind-thrown trees and trails were avoided [32]. A soil core sampler (100 cm^3) were used for collecting sub-samples for soil bulk density, and the collected samples were packed into ice bags and transported to the Key Laboratory of Ecological Engineering, Institute of Ecology and Forestry, Sichuan Agricultural University. Samples for soil bulk density were oven dried for 24 h at 105 °C, while samples for soil carbon content analysis were air dried and sub-samples oven dried. The bulk density of the two soil layers was calculated according to the method developed by [33]. The soil bulk density in grams per cubic centimeter ($g \cdot cm^{-3}$) was calculated as follows;

$$\rho b = \mathbf{M}_s / \mathbf{V}_t \quad (1)$$

where:

ρb = bulk density of the soil in grams per cubic centimeter ($g \cdot cm^{-3}$),
$\mathbf{M_s}$ = oven dry mass total sample in grams,
$\mathbf{V_t}$ = core volume in cm^3.

2.4. Biomass and Carbon Estimation of the Trees

Biomass was estimated from the DBH and total tree height (H) as explanatory variables [34]. For the estimation of the aboveground biomass, the model developed by the FAO Forest Resources Assessment was used [35]. Total forest biomass in tons per hectare ($t \cdot ha^{-1}$) was calculated as follows;

$$\text{Total forest biomass } t \cdot ha^{-1}\ (\mathbf{BV}) = \mathbf{VOB} \times \mathbf{WD} \times \mathbf{BEF} \quad (2)$$

where:

BV = aboveground biomass of the tree layer components,
VOB = volume over bark ($m^3 \cdot ha^{-1}$),
WD = volume-weighted average wood density ($g \cdot cm^{-3}$), to tonnes of oven dry biomass per cubic meter green volume,
BEF = biomass expansion factor (ratio of aboveground oven-dry biomass of trees to oven-dry biomass of inventoried volume) [12]; the wood density and BEF default values of 0.42 and 1.3 provided for *Pinus massoniana* plantations in China were applied in this study [35].

Belowground biomass density was estimated using the below equation based on default values for belowground biomass densities in subtropical humid forests [35].

$$\text{Belowground biomass density } t \cdot ha^{-1}\ (\mathbf{BGBD}) = \mathbf{AGBD} \times \mathbf{DV} \quad (3)$$

where:

BGBD = Belowground biomass density ($t \cdot ha^{-1}$),
AGBD = Aboveground biomass density ($t \cdot ha^{-1}$),
DV = Default value for calculating belowground biomass density from the aboveground biomass density (%). **DV** = 0.2 for AGB < 125 $t \cdot ha^{-1}$, and 0.24 for AGB > 125 $t \cdot ha^{-1}$.

2.5. Soil Analysis

Air-dried soils were passed through a 0.25-mm sieve for determination of the soil C concentrations as described by Lu [36]. The organic C concentration of the soil samples was determined by the dichromate oxidation-ferrous sulfate titration method after digestion with 8 mL H_2SO_4 ($\rho = 1.84$ g·cm^{-3}) [36].

2.6. Calculation of Carbon Storage

To determine the C stock for the tree layer, C concentration was applied to the biomass estimates in the different stand ages, summed up and scaled on the basis of an area (t·ha^{-1}). We used the below equations to calculate the carbon content:

Carbon storage (CS) in different tree organs of the different stand ages (t·ha^{-1}) = carbon density (t/t) × biomass (t·ha^{-1}) (4)

It has traditionally been assumed that the carbon content of dry biomass of a tree was 50% [37,38].

Soil organic carbon (SOC) storage in the different layers of the different sampled profiles in the different stand ages (t·ha^{-1}) was calculated according the equation developed by Broos and Baldock [39], where:

$$\text{SOC (t·ha}^{-1}\text{)} = \text{organic C content (\%)} \times \text{soil bulk density (g·cm}^{-3}\text{)} \times \text{depth (m)} \times \text{area (m}^2\text{)} \quad (5)$$

The total carbon stock in the forest ecosystem is then converted to tons of CO_2 equivalent by multiplying it by 44/12 or 3.67 of the molecular weight ratio of CO_2 to O_2 in order to understand the climate change mitigation potential of the study area [40].

2.7. Data Analysis

Data for trees biomass C and soil mineral C were processed using an MS Excel spreadsheet and analyzed using the Statistical Package for the Social Sciences for Windows Version 16.0 (SPSS Inc., Chicago, IL, USA) software package.

3. Results

3.1. Forest Biomass

The biomass of the tree layer was estimated in the ten (10) *Pinus massoniana* stands (Table 2). Total aboveground and belowground biomass of the ten (10) stands ranged from 0.84 in the three-year to 252.35 t·ha^{-1} in the 42-year stands in the chronosequence.

Table 2. Biomass (t·ha^{-1}) and its allocation in the tree layer of the different stand ages of *Pinus massoniana* plantations in Gao County, Sichuan Province.

Stand Age	Aboveground Biomass		Belowground Biomass		Total Biomass
(Years)	Biomass	%	Biomass	%	Biomass
3	0.74 ± 0.04	88.1	0.10 ± 0.03	11.9	0.84 ± 0.01
5	6.84 ± 3.43	90.24	0.74 ± 0.37	9.76	7.58 ± 3.80
7	14.39 ± 1.23	90.22	1.56 ± 0.13	9.78	15.95 ± 1.36
9	59.33 ± 8.72	85.32	10.21 ± 4.02	14.68	69.54 ± 12.13
12	78.11 ± 10.48	90.21	8.47 ± 1.14	9.78	86.59 ± 11.62
15	58.76 ± 1.03	85.49	9.97 ± 3.14	14.51	68.73 ± 3.53
19	81.90 ± 1.60	83.33	16.38 ± 0.32	16.67	98.28 ± 1.92
29	184.53 ± 8.58	80.65	44.29 ± 2.06	19.36	228.81 ± 10.65
35	187.21 ± 16.46	80.65	44.93 ± 3.95	19.35	232.14 ± 20.41
42	203.50 ± 15.12	80.64	48.84 ± 3.63	19.34	252.35 ± 18.75
Mean	87.53 ± 6.67	82.51	18.55 ± 1.88	17.49	106.08 ± 8.42

The distribution pattern of *Pinus massoniana* biomass within the tree layer organs was in the order; aboveground > belowground in the 3-year, 5-year, 7-year, 9-year, 12-year, 15-year, 19-year, 29-year, 35-year and 42-year stands. The biomass increased with increasing age, and the maximum value is 300-times the minimum value. The variation of biomass stocks amongst the different stand ages (3–7-year, 9–19-year and 29–42-year classes) was statistically significant. There was a positive, significant relationship between biomass and stand age (Figure 1a–c).

3.2. Carbon in the Mineral Soil

The soil bulk density of the two sampled soil layers (0–30- and 30–60-cm) across the different stand ages in the chronosequence increased with increasing soil depth (Table 1). The soil C concentrations of the mineral layer are shown in (Figure 2).

The highest carbon concentration was found in the 0–30-cm depth, and the carbon concentration storage in the stand ages decreased with increasing soil depth from approximately 4.58% at the 0–30-cm depth to 1.98% at the 30–60-cm depth with an average of 3.28% for the 0–60 cm sampled soil profile.

3.3. Carbon Storage in the Forest Ecosystem Components

The total C pools of the investigated forest ecosystem components in the ten (10) *Pinus massoniana* stand ages are summed up in (Table 3). Tree layer C content of the different stand ages ranged from 0.42 t·ha^{-1} in the three-year stand to 126.17 t·ha^{-1} in the 42-year stand with a total mean value of 53.04 t·ha^{-1}, 82.52% of it coming from the aboveground biomass carbon and 17.48% from belowground biomass carbon. Vegetation C was positively and significantly correlated with stand age (Figure 1d–e). Mean C content of the mineral soil layers from the 0–60-cm depth ranged from 166.10 to 200.29 t·ha^{-1} in the three-year and 42-year stands with a mean value of 216.12 t·ha^{-1}. The greatest mineral soil C content was within the 0–30-cm soil depth in comparison to soil carbon content in the 30–60-cm depth (Table 3). A negative, non-significant relationship was observed between mineral soil

C and stand age (Figure 1f). About 67.97% of the total mineral soil carbon was sequestered at the upper soil layer of the 0–30-cm depth in each of the different stand ages (Figure 3).

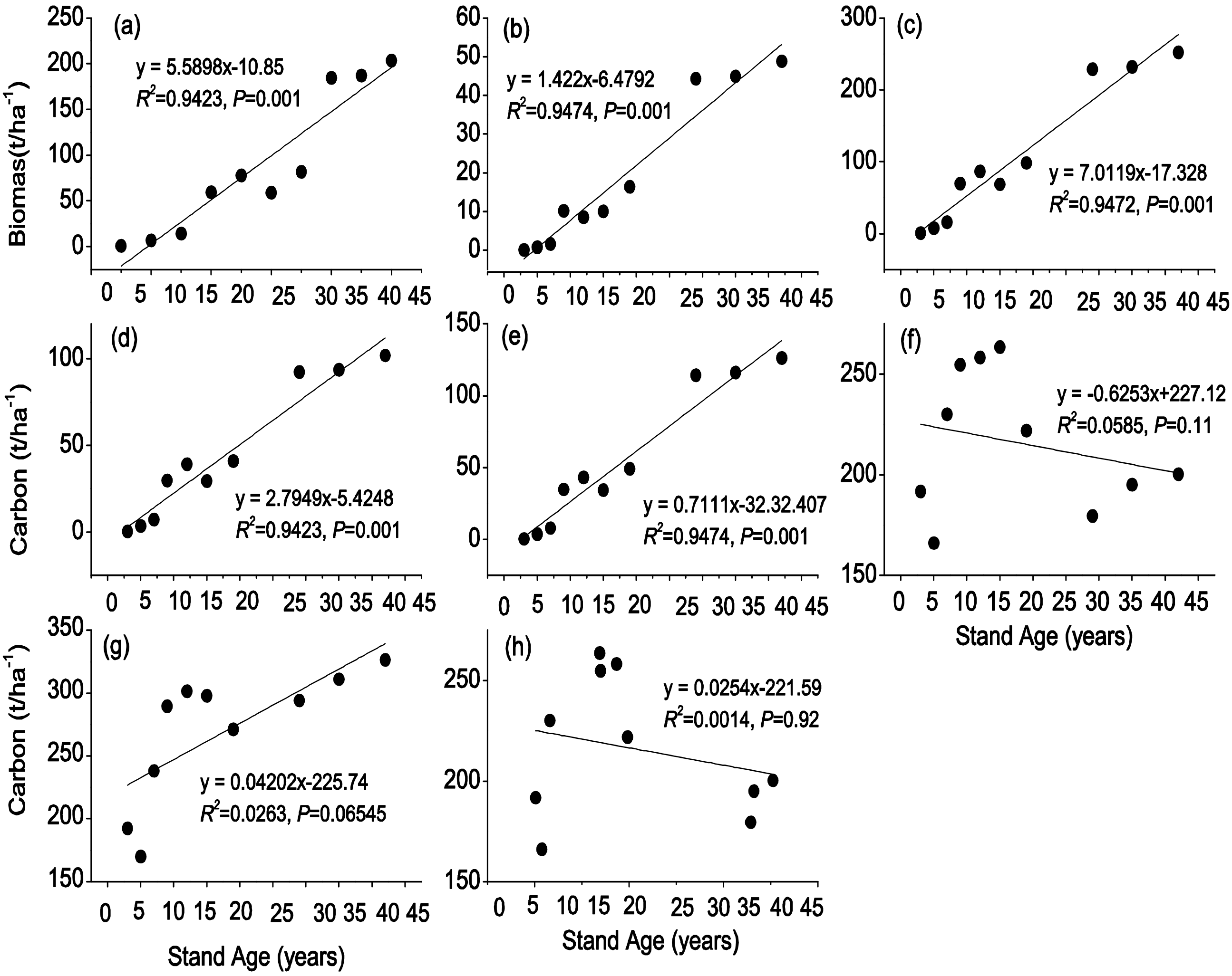

Figure 1. Relationship between biomass C, soil C and stand age. (**a**) Relationship between aboveground biomass and stand age; (**b**) relationship between belowground biomass and stand age; (**c**) relationship between total biomass and stand age; (**d**) relationship between aboveground C and stand age; (**e**) relationship between belowground C and stand age; (**f**) relationship between soil C and stand age; (**g**) relationship between ecosystem C and stand age; (**h**) relationship between plant C and soil C.

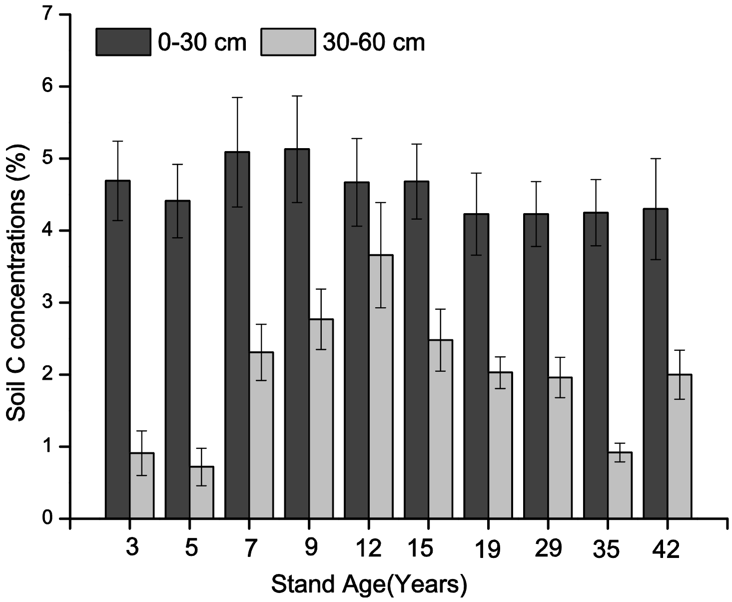

Figure 2. Mineral soil C concentrations in the different sampled soil layers of the different stand ages; values are the means; error bars are the standard deviations, n = 3. Conc = concentration.

Table 3. Carbon pool (t·ha^{-1}) and its allocations in the *Pinus massoniana* plantation with different stand ages in Gao County, Sichuan Province.

Stand Age (Years)	Vegetation Carbon Pool			Soil Carbon Pool			Total Ecosystem Carbon
	ABGC	BGC	ABGC + BGC	0–30-cm Depth	30–60-cm Depth	0–60-cm Depth	
3	0.37 ± 0.02	0.05 ± 0.02	0.42 ± 0.00	156.78 ± 18.30	34.98 ± 11.99	191.77 ± 21.95	192.19 ± 21.95
5	3.42 ± 1.72	0.37 ± 0.19	3.79 ± 1.90	136.59 ± 15.44	29.51 ± 10.68	166.10 ± 23.95	169.90 ± 23.13
7	7.19 ± 0.61	0.78 ± 0.07	7.97 ± 0.68	157.53 ± 23.41	72.60 ± 12.34	230.13 ± 24.63	238.11 ± 25.31
9	29.67 ± 4.36	5.10 ± 2.01	34.77 ± 6.06	146.42 ± 21.04	108.32 ± 16.59	254.74 ± 19.23	289.51 ± 13.78
12	39.06 ± 5.24	4.24 ± 0.57	43.29 ± 5.81	156.32 ± 20.36	101.89 ± 20.19	258.20 ± 32.16	301.49 ± 27.00
15	29.38 ± 0.51	4.98 ± 1.57	34.36 ± 1.77	165.09 ± 18.17	98.44 ± 17.08	263.53 ± 31.60	297.89 ± 31.20
19	40.95 ± 0.80	8.19 ± 0.16	49.14 ± 0.96	146.65 ± 19.63	75.26 ± 8.04	221.91 ± 28.69	271.05 ± 28.23
29	92.26 ± 4.29	22.14 ± 1.03	114.41 ± 5.32	109.30 ± 11.48	70.27 ± 9.91	179.57 ± 11.92	293.98 ± 17.21
35	93.61 ± 8.23	22.47 ± 1.97	116.07 ± 10.20	154.77 ± 16.72	40.18 ± 5.48	194.95 ± 19.52	311.02 ± 26.55
42	101.75 ± 7.56	24.42 ± 1.81	126.17 ± 9.38	120.73 ± 19.64	79.56 ± 13.45	200.29 ± 30.43	326.46 ± 23.44
Mean	43.77 ± 3.33	9.27 ± 0.94	53.04 ± 4.21	145.02 ± 18.42	71.10 ± 12.57	216.12 ± 24.41	269.16 ± 23.78

Values are means ± SD, n = 3; ABGC = aboveground biomass carbon in the tree layer; BGC = belowground biomass carbon in components of the tree layer.

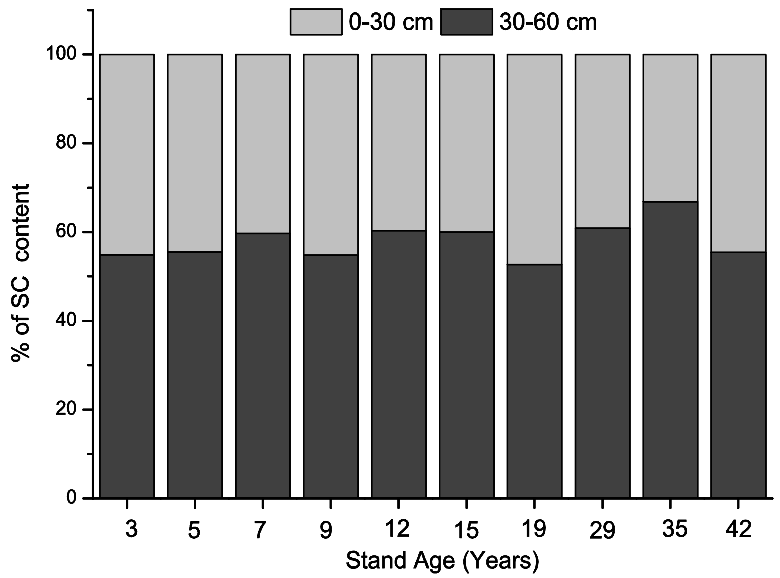

Figure 3. Percentage of mineral soil carbon content in the different soil layers of the different stand ages.

The total C storage in the ten (10) stands of the *Pinus massoniana* plantation forest ecosystem varies with stand age; it ranged from 192.19, 169.91, 238.11, 289.51, 301.49, 297.89, 271.05, 293.98, 311.02 and 326.46 t·ha^{-1} for the 3-year, 5-year, 7-year, 9-year, 12-year, 15-year, 19-year, 29-year, 35-year and 42-year stands (Table 3). The average mean total ecosystem C in this masson pine's chronosequence was 269.16 t·ha^{-1}. C stock variations in the forest ecosystem were moderately high in the 3–7-year stand age classes, but relatively low in the 9–42-year stand age classes. The ten (10) stand ages of the forest demonstrated different patterns of C distribution in the ecosystem components, and variations exist in the ecosystem C storage amongst the stand age classes. Figure 4 showed the percent contribution of each individual C pool to the total ecosystem C content in this chronosequence.

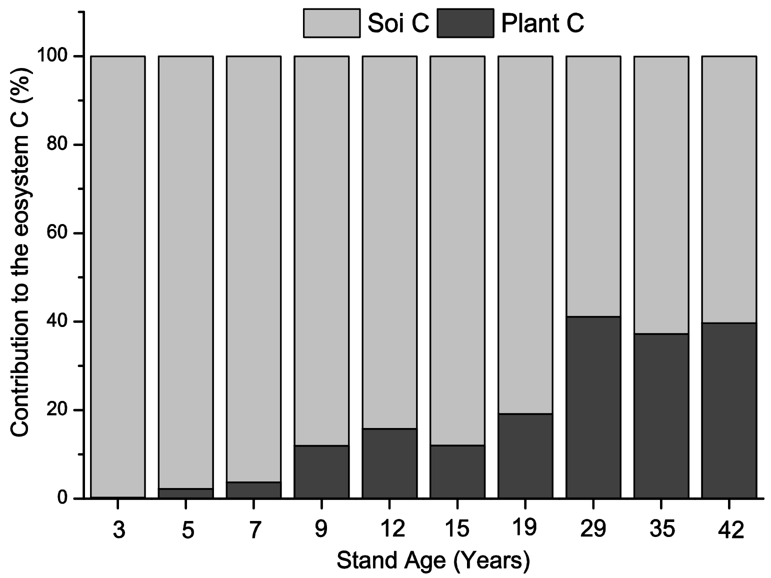

Figure 4. Changes in the percent contribution of C stocks in soil and plant systems to the *Pinus massoniana* plantation ecosystem with stand age in Gao County, Sichuan Province.

The distribution of the total forest ecosystem C to vegetation and mineral soil peaked in the 42-year stand for vegetation (38.65%) and three-year stand for mineral soil (99.78%), respectively. A very weak non-significant relationship was observed between total forest ecosystem carbon and stand age (Figure 1g). The ratio of vegetation carbon to soil carbon was 0.002, 0.022, 0.035, 0.136, 0.168, 0.13, 0.221, 0.637, 0.595 and 0.629 for the 3-year, 5-year, 7-year, 9-year, 12-year, 15-year, 19-year, 29-year, 35-year and 42-year stands. There was no relationship observed between vegetation and mineral soil C in the forest ecosystem (Figure 1h).

4. Discussion

In our study, total tree component biomass C increased with increasing age, the biomass ranged from 0.84 t·ha^{-1} in the three-year aged stand to 252.35 t·ha^{-1} in the 42-year aged stand with a mean value of 106.08 t·ha^{-1}, and 82.51% of this comes from the aboveground biomass. Our results showed fast biomass increase from the 3–12-year aged stands with a sharp decline in the 15-year aged stand, which is attributed to under stocking, as indicated in Table 1. The biomass then increased rapidly from the 19–29-year aged stand with a relatively low increase from the 29–42-year stand, indicating fast accumulation of biomass in the younger stand ages and a slow rate of biomass accumulation in the middle and mature-aged stands. The trend in the older aged stands clearly explains the transitional period between the middle aged and mature forests where the stands are nearer to their rotational ages in which the biomass accumulation will stabilize, which is in accordance with the longstanding theoretical models that predicted attainment of equilibrium (stability) in mature to early old-growth developmental stages [41–43].

Growth and yield tables of even-aged plantation forests generally suggest that stand productivity declines significantly in mature forest stands [42,44], and young forests display rapid growth up to a certain age; however, with time, they gradually decrease their production [4,42,45]. Dixon *et al.* [11] reported that forest biomass accounts for approximately 90% of all living terrestrial biomass on the Earth, and young forests take up CO_2 at higher rates than most other ecosystems, since biomass is the carbon dioxide stored in wood. The proportion of aboveground biomass decreased with increasing age, this allocation pattern might be a result of older trees allocating more resources to roots to meet their demand for nutrients and water resources from the soil and anchorage than the younger plants, which allocate more resources to aboveground components to meet their higher photosynthetic demands for the manufacturing of food (biomass), resulting in greater aboveground biomass in the younger than in the older stands.

We compared our study to some published biomass data in subtropical China, the Costa Rican Caribbean region and southern Ontario, Canada (Table 4).

Table 4. Comparison of our study to some published biomass data in subtropical China, the Costa Rican Caribbean region and southern Ontario, Canada.

S/No	Location		Stand Age (Years)	Species	Mean DBH (cm)	Mean H (m)	Density (Tree ha^{-1})	Stand (t·ha^{-1})	Sources
	County/Province								
1	Gao	Sichuan	3	*P. massoniana*	2.28	1.71	3500	0.8	This study
2	Gao	Sichuan	5	*P. massoniana*	4.40	4.53	3500	7.6	This study
3	Costa Rica	Caribbean region	5	*H. alchorneoides*	-	-	-	14.9	Fonseca *et al.*, [46]
4	Gao	Sichuan	7	*P. massoniana*	6.60	4.85	3100	17.0	This study
5	Gao	Sichuan	9	*P. massoniana*	10.31	8.04	3100	70.4	This study
6	Costa Rica	Caribbean region	9	*H. alchorneoides*	-	-	-	111.1	Fonseca *et al.*, [46]
7	Gao	Sichuan	12	*P. massoniana*	10.61	9.95	3100	86.6	This study
8	Longli	Guizhou	12	*P. massoniana*	7.67	8.50	6435	86.9	Ding *et al.*, [47]
9	Costa Rica	Caribbean region	12	*H. alchorneoides*	-	-	-	125.1	Fonseca *et al.*, [46]
10	Daqingshan	Guanxi	13	*P. massoniana*	14.70	10.60	1379	78.8	Kang Bing *et al.*, [48]
11	Jianou	Fujian	14	*P. massoniana*	10.01	10.02	2500	93.4	Wu *et al.*, [49]
12	Costa Rica	Caribbean region	14	*H. alchorneoides*	-	-	-	115.3	Fonseca *et al.*, [46]
13	Southern	Ontario	15	*Pinus strobus*	15.8	9.1	1242	96.7	Peichl and Arain [3]
14	Gao	Sichuan	15	*P. massoniana*	11.72	12.08	1600	68.7	This study
15	Liling	Hunan	16	*P. massoniana*	10.62	10.50	2500	78.5	Chen *et al.*, [50]
16	Costa Rica	Caribbean region	16	*H. alchorneoides*	-	-	-	146.5	Fonseca *et al.*, [46]
17	Dinghushan		15–50	*P. massoniana*	24.5	9.0	213	142.7	Fang Yun *et al.*, [51]
18	Gao	Sichuan	19	*P. massoniana*	13.55	11.04	1800	98.3	This study
19	Huitong	Hunan	20	*P. massoniana*	14.40	12.50	1750	100.0	Chu *et al.*, [52]
20	Gao	Sichuan	29	*P. massoniana*	20.64	14.25	1400	228.8	This study
21	Longli	Guizhou	30	*P. massoniana*	19.40	18.00	1140	234.1	Ding *et al.*, [47]
22	Southern	Ontario		*Pinus strobus*	15.6	11.2	1492	128.0	Peichl and Arain [3]
23	Gao	Sichuan	35	*P. massoniana*	20.77	14.36	1400	232.1	This study
24	Dinghushan		9–70	*P. massoniana*	21.8	11.1	282	200.4	Fang Yun *et al.*, [51]
25	Gao	Sichuan	42	*P. massoniana*	22.85	16.45	1100	252.4	This study
26	Southern	Ontario	65	*Pinus strobus*	34.6	20.20	429	253.8	Peichl and Arain [3]

Our biomass results are within the range of the published biomass data on *Pinus massoniana* in subtropical China, but varied greatly from that of *Hieronyma alchorneoides* mono-stand plantations of the same age in the Costa Rican Caribbean region (Fonseca *et al.* [46]), which is inconsistence with Singh [53], who report that biomass allocation of plants depends on a number of factors, such as the growth habitat of the species, soil quality, the soil on which plants are growing, the age of the plant, management practices and interaction with belowground vegetation. The biomass estimates of our study in the 12-year stand correspond to that of the 12-year stand in Guangxi province, but they differed greatly in terms of stocking densities, which suggests that stocking density has considerable effects on biomass if it exceeds certain limits (carrying capacity) of the area, for example the stocking density of 6435 stems per hectare in Guangxi has the same biomass stock as that of 3100 stems per hectare in Sichuan. While this is true, the reverse is clearly visible in the 15-year stand, whose biomass stock is less than that of the 12-year stand due to under stocking. On the contrary, the biomass in the 42-year stand corresponds to that of the 65-year stand in the chronosequence of white pine (*Pinus strobus* L.) in southern Ontario, Canada [3], implying that stocking density plays a key role in standing biomass stock accumulation and distribution. Stand age is a good predictor of ecosystem structure and function in even-aged stands [19,54] and may affect C storage in forest ecosystems [19].

Carbon storage portioning accords with biomass portioning in the vegetation component, but is age independent in the mineral soil component of the forest ecosystem. The total mean average C storage in this chronosequence was 269.16 t·ha^{-1}. Mineral soil C content accounted for 80.29% of the total forest ecosystem C, contributing the greatest proportion of the total C sequestration in this pine chronosequence, whereas vegetation carbon accounted for 19.71%. This is attributed to the cumulative accumulation of mineral soil C that was transformed from the previous vegetation in to the soils through the decomposition and decay of dead litter, coarse wood debris, fine wood debris, dead roots and microbial activities, whereas the vegetation C itself is lost, since the plantations are managed on a commercial basis in which felled trees are extracted from the forests and converted into various forest products, such as timber, furniture, ply wood, boards, papers, *etc*. Many C sequestration investigations conducted in forest ecosystems reported the highest carbon storage in the mineral soil component, corresponding to our studies, consistent with the report of Dixon *et al.* [11] regarding the soil pool forming the major part of forest C storage, but contradicted the findings of Vesterdal *et al.* [55], who reported that soils contribute about 30% of the total C sequestration in an afforestation ecosystem.

Mean total vegetation C storage in this *Pinus massoniana* chronosequence is 53.04 t·ha^{-1}, corresponding to that of the *Hieronyma alchorneoides* mono-stand chronosequence of 3–16 years (58.87 t·ha^{-1}) in the Costa Rican Caribbean region (Fonseca *et al.* [46]), much lower than that of the Korean larch plantations' chronosequence of 0–48 years [56], but within the range of 34.4–85.6 t·ha^{-1} and 44.8–118.2 t·ha^{-1} reported for Asian and global forests [13]. In addition to the vegetation biomass C, soil contains the world's largest terrestrial active C pool, which plays a major role in the global carbon cycle [27]. In our study, mineral soil C content increased exponentially from the five-year stand to the 15-year stand and then dropped sharply from the 19-year stand to the 42-year stand, clearly indicating the absence of age effect on mineral soil carbon concentrations and storage (Figure 1g); about 67.97% of the mean total mineral soil C content across the different stand ages in the chronosequence was sequestered in the upper soil horizon (0–30-cm) depth, higher than the 49.22% reported by Kang *et al.* [48] for the 0–20-cm upper mineral soil horizon profile, but lower than the findings of Cao *et al.* [56], who reported an average mean of 70.0% C content sequestered at the 20-cm upper mineral soil horizon. Our average mean total mineral soil C sequestered in the 0–60-cm depth was 216.12 t·ha^{-1}, closer to the findings of Zhou *et al.* [57], who reported a mean soil C content storage of 193.55 t·ha^{-1} in the Chinese forests, which is about 3.4-times that of vegetation, but lower than the findings of Gao *et al.* [58], who reported a mean value of 411 t·ha^{-1} at the profile of 0–100-cm in a *Picea crassifolia* plantation in the semi-arid region of northwest China.

Our findings were twice the average value of 96.00 t·ha^{-1} stored in the whole soil profile of the mid-latitudinal belt of the world [11], but within the ranges of the 121–123 t·ha^{-1}, 96–147 t·ha^{-1} and

247–344 t·ha^{-1} mineral soil C content mean values reported by Lal [59] for tropical, temperate and boreal forest ecosystems. Mineral soil C in this masson pine chronosequence was higher compared to the natural succession chronosequence of white pine described by Hooker and Compton [60]. They reported mineral soil C values ranging from 60 to 100 t·ha^{-1}. The differences might be a result of the different sampling depths in the soil profile and the management history of the ecosystem, climatic, geographical, geological and environmental factors in the study areas. The higher observed mineral soil C content in the three-year aged stand than in the 29-year-old stand does not mean the three-year aged stand has transformed more carbon into the soil, but was a cumulative carbon accumulation from the previous stand, which was clear felled and re-planted, since soil organic carbon is derived mostly from dead plant residues, along with roots in the soil and root exudates. In addition, soil organic carbon is not only found in decomposing plant residues, but also in dead and decaying soil microorganisms and fauna. A relatively total ecosystem C storage increase was observed in the ten (10) stand ages in this chronosequence study. Our results demonstrated that stand age is the dominant factor influencing biomass and carbon storage, and the distribution in the whole ecosystem, stocking density and management history are the main factors influencing carbon storage in this masson pine chronosequence.

5. Conclusions

Stand age is the dominant factor influencing the total forest ecosystem C pool. Vegetation biomass C varies with stand age; it increased rapidly from the three-year stand to the 42-year stand with a slight decline in the 15-year stand due to low stocking density in this stand age. Biomass accumulation was high in the older stands than in the younger stands, making stand age an important variable for ecosystem C sequestration due to the rapid increase in the biomass with age. The highest mineral soil C in the different stand ages in the ecosystem was sequestered in the upper 0–30-cm soil depth profile, representing 67.97% of the total mineral soil C, and approximately 80.29% of the total ecosystem C content was contributed by the mineral soil component, whereas the vegetation only contributed 18.31%. The ratio of vegetation to soil C varies with stand age; it ranged from 0.002 for the three-year stand to 0.629 for the 42-year stand, with a mean value of 0.258. The management history of the forest ecosystem is the major factor influencing mineral soil C storage. The plantation ecosystem was a reservoir of potentially high amounts of C in comparison to similar areas in the sub-tropical region, especially in sub-tropical China. Presently, the plantation had the capacity of storing up to 269.16 t·ha^{-1} C, assisting in mitigating climate change by sequestrating 987.82 t·ha^{-1} of CO_2 equivalents, indicating that the plantation ecosystem is a good mitigation mechanism of climate change. Our research illustrates the benefits of considering stand age in the growth and developmental patterns of forest ecosystems in estimating terrestrial C stocks.

Acknowledgments

We thank Li Jun and Li Hansen for their support during the field data collection, sincere gratitude to Yang the Masson Pine Plantation Manager and his team for their kindness and assistance during the field work. This study was supported by the National Key Technologies R & D Program (2011BAC09B05), the Program of Sichuan Excellent Youth Science and Technology Foundation

(2012JQ0008, 2012JQ0059) and the China Postdoctoral Science Foundation Special Funding (2012T50782).

Author Contributions

Wanqin Yang, Meta Francis Justine, Fuzhong Wu and Bo Tan designed the experiment. Meta Francis Justine, Zhao Yeyi, Li Jun and Li Hansen collected the data. Meta Francis Justine and Wanqin Yang performed the experiments. Meta Francis Justine and Muhammad Naeem Khan analyzed the data. Meta Francis Justine, Wanqin Yang, Fuzhong Wu and Muhammad Naeem Khan contributed to writing the manuscript.

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