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Estimation of changes in carbon sequestration and its economic value with various stand density and rotation age of *Pinus massoniana* plantations in China

Yunxing Bai & Guijie Ding✉

Plantations actively participate in the global carbon cycle and play a significant role in mitigating global climate change. However, the influence of forest management strategies, especially planting density management, on the biomass carbon storage and production value of plantations for ensuring carbon sink benefits is still unclear. In this study, we estimated the carbon sequestration and economic value of *Pinus massoniana* plantations with various stand densities and rotation ages using a growth model method. The results revealed that with increasing stand age, low-density plantations at 2000 trees·ha^{-1} (358.80 m^3·ha^{-1}), as well as high-density plantations at 4500 trees·ha^{-1} (359.10 m^3·ha^{-1}), exhibited nearly identical standing volumes, which indicated that reduced inter-tree competition intensity favors the growth of larger trees during later stages of development. Furthermore, an increase in planting density led to a decrease in the average carbon sequestration rate, carbon sink, and number of trees during the rapid growth period, indicating that broader spacing between trees is favorable for biomass carbon accumulation. Further, extending the rotation period from 15 to 20 years or 25 years and reducing the optimal planting density from 3000 to 2000 trees·ha^{-1} increased the overall benefits of combined timber and carbon sink income by 2.14 and 3.13 times, respectively. The results highlighted that optimizing the planting density positively impacts the timber productivity and carbon sink storage of *Pinus massoniana* plantations and boosts the expected profits of forest managers. Thus, future afforestation initiatives must consider stand age and planting density management to shift from a scale-speed pattern to a quality-benefit design.

Keywords Biomass accumulation, Carbon sequestration, Rotation age, Stand density, *Pinus massoniana* plantation

Global climate change and the intensification of the greenhouse effect are currently the most severe challenges faced by nations around the world[1,2]. Nations are committed to limiting global warming below 1.5 ℃ to minimize the risks associated with climate change. This necessitates their dedicated efforts to remove CO_2 from the atmosphere[3]. Forests absorb CO_2 from the atmosphere via photosynthesis and primarily store it in the form of plant biomass, making it a nature-based solution for mitigating global warming[4]. As a result, the global area of plantations has increased from 170 million ha in 1990 to 294 million ha in 2020. In addition to meeting the global demand for timber and forest products, this afforestation across vast areas is considered an effective method for enhancing terrestrial carbon storage[5,6]. While forest management measures have the potential to enhance forest carbon storage from a natural science perspective[7], their economic feasibility is still unclear. The policy of pricing forest carbon can provide effective incentives for expanding forest carbon storage[7]; this often results in longer rotation times for forest management. Therefore, a thorough evaluation of the relationship between planting density, tree biomass, and carbon sequestration potential is crucial for natural resource management decision-makers to make informed choices regarding sustainable forest utilization.

Planting density affects the spatial structure of the stands and also the efficiency of light and water utilization by trees[8,9]. Therefore, there is an optimal density for trees at different stages of their growth. Planting density

Key Laboratory of Forest Cultivation in Plateau Mountain of Guizhou Province, Institute for Forest Resources & Environment of Guizhou, College of Forestry, Guizhou University, Guiyang, China. ✉email: gjding@gzu.edu.cn

above or below this optimal level can reduce productivity and carbon storage[10,11]. Specifically, low stand density promotes biomass accumulation and carbon assimilation in the canopy layer because of reduced competition among neighboring trees. On the other hand, high stand density restricts the growth of biomass and carbon assimilation due to limited natural resources. However, while reducing the stand density increased productivity, it decreased the carbon absorption capacity of trees, leading to a decrease in carbon sequestration[12]. Therefore, further research must investigate the effects of stand density on biomass production and carbon storage in plantations consisting of specific tree species to ensure the sustainable plantation management. In addition, several studies have adopted a carbon fraction value of 0.47 or 0.50 for estimating carbon storage based on biomass[13–15]. However, the value of carbon fraction may slightly vary among different tree species and different parts of the same species[16]. Hence, using the carbon fraction of different components of the tree can improve the accuracy of carbon storage estimation.

Optimizing the harvesting schedule of short-rotation plantations can increase both wood and carbon stocks[17], thereby enhancing the economic benefits for forest managers and harnessing the maximum ecological benefits of plantations. For instance, maximizing the net present value within a single harvesting cycle has emerged as a gold standard for determining optimal rotation and harvesting periods[18]. Plantation density can lead to variations in the optimal rotation period or age at harvest, which in turn affects the biomass carbon stock (BMC). The optimal density provides suitable environmental conditions for the optimal growth of trees, while excessive density escalates the competition between trees and hinders their growth[19]. However, this aspect is often overlooked during large-scale intensive management of plantations because forest managers typically follow traditional management practices that prioritize maximizing timber revenues during harvest periods, with little consideration for forest carbon sequestration[20–22]. The expected value of forest land under a management model that complements timber revenue with carbon sequestration is subject to significant uncertainty due to the effects of variations in plantation density[23]. Therefore, it is imperative to compare the expected land value of different plantation densities under carbon sequestration and traditional management models with respect to the variations in the rotation period. This comparison is valuable in determining the optimal forest management approach in the context of carbon sequestration.

Over recent decades, China has experienced the most extensive and rapid growth in plantations worldwide. The development of plantations has emerged as China's strategic response to global climate change, contributing approximately 40% of the overall carbon sinks in China's terrestrial ecosystems[13,24]. *Pinus massoniana* Lamb. (Masson pine) is a high-quality and fast-growing timber tree species widely cultivated in subtropical regions of China, with a plantation area of around 14.2 million ha[25]. Initially, these plantations were established primarily to enhance forest coverage and produce timber. However, due to inadequate research, planning, afforestation, and management techniques, several plantations have faced challenges such as suboptimal stand structure, low productivity, and diminished carbon sink function. Stand density regulation could potentially improve plantation performance, but its effects on productivity, ecosystem carbon storage, and rotation period remain uncertain. Specifically, our objectives were to: (1) evaluate the influence of varying planting densities on biomass and carbon storage of the plantation during stand development; and (2) determine the optimal stand density based on carbon sink and timber income. We hypothesized that selecting an optimal planting density can enhance the stand volume, thereby augmenting forest carbon sinks; furthermore, the rotation period may influence the expected benefits derived from carbon sinks and timber.

Materials and methods

Study site description

The study site is located on the Longli Forest Farm of Longli County, Guizhou Province, China (106° 59′ 18″ E and 26° 27′ 33″ N). The region experiences a subtropical monsoon humid climate of Central Asia, with elevations ranging from 1090 to 1170 m. The average annual temperature is 14.8 ℃, and the average precipitation is 1089.3 mm, with a relative humidity of 79%. The cumulative annual temperature above 10 ℃ reaches 4467.1 ℃. According to the soil classification of the United States Department of Agriculture, the major soil type is Inceptisols, predominantly developed from sandy shale, with a pH ranging from 4.5 to 5.5, indicating a slightly acidic nature. The primary vegetation type is Masson pine plantation, with understory vegetation primarily composed of *Castanea seguinii* Dode, *Quercus fabri* Hance, *Vaccinium bracteatum* Thunb., *Lespedeza bicolor* Turcz., *Camellia oleifera* Abel, *Dicranopteris dichotoma* (Thunb.) Bernh, ferns, etc.

Plot-level estimates of tree biomass

Twelve experimental forests with different densities were selected under the same environmental conditions at the study site (Table 1). The stand age (8–30 years) and site index (12.35–19.35 m) of these forests were determined based on the afforestation records. Each experimental forest was divided into three standard plots of 600 m^2 (20 × 30 m) with a minimum interval of 20 m. All forests underwent the same forest tending within the first three years of afforestation. Individual tree measurements, including tree height, diameter breast height (DBH), and stand density, were conducted in each plot. Tree DBH was classified within a fixed range of 4 cm, and 1 to 2 trees were selected from each diameter stage as representative samples for logging, with the aim of collecting biomass data to ensure the comprehensiveness and accuracy of the survey data. A total of 265 sample trees were harvested, with the height of trees ranging from 4.90 to 19.04 m and DBH ranging from 5.28 to 19.95 cm. To determine the biomass of each sample tree, a stratified harvesting method was employed, which included stem, bark, branch wood, foliage, and roots (cone analysis was excluded from this study due to the high variability in biomass among different research sites and growing seasons). Specifically, the stem was cut at 1.3, 3.6, and 5.6 m heights, and the diameters of debarked stems were measured using a disc sampler to evaluate the proportion of these components in the biomass. The underground root biomass was measured using the whole excavation

Plot ID	Stand age (yr)	Current planting density (tree·ha^{-1})	Tree height (m)	Diameter breast height (cm)	Stand volume (m^3·ha^{-1})	Site index (m)	Slope (°)	Aspect
1	8	6700	4.90 ± 0.50	5.28 ± 0.72	41.86 ± 8.20	15.70	5	Southeast slope
2	8	6576	4.91 ± 0.51	5.30 ± 0.70	41.46 ± 8.06	15.73	5	Southeast slope
3	12	800	8.85 ± 0.92	10.17 ± 1.21	29.69 ± 5.11	16.20	5	Southeast slope
4	12	1750	7.45 ± 0.81	10.51 ± 1.33	58.55 ± 9.05	14.90	6	Southeast slope
5	12	2725	8.95 ± 0.91	9.23 ± 1.10	85.40 ± 12.15	16.32	5	Southeast slope
6	12	6425	9.00 ± 0.91	7.95 ± 1.00	66.88 ± 10.26	16.62	5	Southeast slope
7	18	4600	11.58 ± 1.23	10.69 ± 1.53	242.23 ± 18.31	15.01	6	Southeast slope
8	22	1830	15.85 ± 1.57	16.50 ± 2.01	291.11 ± 22.27	16.50	5	Southeast slope
9	22	1035	19.04 ± 1.80	19.95 ± 2.52	279.08 ± 25.03	19.35	5	Southeast slope
10	22	2730	11.96 ± 1.42	11.75 ± 1.64	176.69 ± 15.08	12.35	7	Southeast slope
11	30	1365	14.80 ± 1.60	16.70 ± 2.23	208.66 ± 20.36	12.70	7	Southeast slope
12	30	1140	18.00 ± 1.80	19.40 ± 2.41	276.58 ± 28.28	15.50	5	Southeast slope

Table 1. Basic information about the sample plot and the number of trees sampled. n = 265.

method and divided into four categories: fine roots (root diameter < 1 cm), medium roots (root diameter 1–2 cm), coarse roots (root diameter > 2 cm), and root piles. Once the fresh weight of each component was measured in the field, the samples were carefully transported to the laboratory for further analysis. Next, the samples were dried at 75 ℃ to a constant weight in a drying oven to determine the moisture content. The total biomass of the forest stand was extrapolated based on the detailed biomass measurements of the standard wood, employing recognized forestry methodologies and allometric equations.

Establishment of the relative growth relationship

The biomass of different components of the trees can be revealed by the changes in the DBH and tree height. Therefore, allometric functions were developed for all the biomass components. For each allometric function (Table 2), ten regression models were computed and the best model was selected based on the coefficient of determination (R^2) and relative error[26]. A higher R^2 and a lower relative error indicate greater accuracy. A reliable growth-harvest model system for predicting forest biomass dynamics was provided in the supplementary material, with a case analysis using an average site index of 16 m.

Estimation of the biomass carbon stocks

The carbon storage in forests was determined using the biomass and carbon content coefficients. In this study, for accurate carbon storage estimation, the carbon content coefficients of different components were determined from the Chinese Forestry Industry Standard "Tree biomass models and related parameters to carbon accounting for *Pinus massoniana*" (Table S1). Furthermore, the rates of BMC at different growth stages are given by Eqs. (1)–(3).

$$\Delta BMC = BMC_a - BMC_b \tag{1}$$

$$BMC_{SR} = \frac{\Delta BMC}{n} \tag{2}$$

$$n = a - b \tag{3}$$

where $\triangle$BMC represents the increment of BMC (t·ha^{-1}), BMC_a indicates the biomass carbon stock in year a (t·ha^{-1}), BMC_b indicates the biomass carbon stock in year b (t·ha^{-1}), BMC_{SR} indicates the rate of biomass carbon sequestration (t·ha^{-1}·yr^{-1}), and n denotes the accumulation period of biomass carbon (yr).

Component	Equation	Parameters			R^2	Relative error (%)
		a	b	c		
Stem without bark	$W = aD^bH^c$	0.037148953	1.79208523	0.904601135	0.83	2.6
Bark	$W = aD^bH^c$	0.011078165	1.3962633	0.94372188	0.90	−1.2
Branch wood	$W = a(D^2H)^b$	0.018647142	0.78288805	NA	0.78	3.1
Foliage	$W = a(D^2H)^b$	0.015272559	0.67806495	NA	0.74	−2.8
Root	$W = aD^bH^c$	0.009164734	1.9114539	0.67549623	0.95	−2.1

Table 2. Parameters of the forecast equations for different biomass. W represents biomass, D represents diameter breast height (range from 5.28 cm to 19.95 cm), H represents tree height (range from 4.90 m to19.04 m). *NA* not applicable.

Estimation of the economic value of carbon storage and wood production

The total biomass carbon of trees is directly related to CO_2. According to IPCC guidelines[27], the carbon stock value ($t\cdot ha^{-1}$) should be multiplied by 3.67, which represents the difference in atomic weights of C and CO_2, for quantifying the CO_2 sequestration of each forest stand. Therefore, the CO_2 equivalent (CO_2eq) storage of each forest stand is given by Eq. 4.

$$CO_2eq = BMC \times 3.67 \tag{4}$$

Carbon market value estimation

The average price of CO_2eq was derived from the Chinese carbon emissions rights trading market in 2023 (i.e., 8.22 $USD\cdot t^{-1}$). Its noteworthy advantage is its ability to comprehensively capture the economic benefits that forest owners can potentially reap from the market through carbon mitigation, without disregarding transaction costs. Hence, the expected economic value of forest carbon storage ($USD\cdot t^{-1}\cdot ha^{-1}$) is given by Eq. 5.

$$EV_{carbon} = CO_2eq \times 8.22 \tag{5}$$

Based on the field investigations and Chinese timber market price data (www.wood-china.com), the average net prices of Masson pine for medium-sized logs (top diameter: 18–24 cm, length: > 2 m), small-sized logs (top diameter: 6–16 cm, length: > 2 m), and firewood (top diameter: < 4 cm, length: < 1.8 m) were 133.81, 104.07, and 52.04 $USD\cdot m^{-3}$, respectively. The analysis of the long-term afforestation data indicated that the silviculture costs (including labor, seedlings, land preparation, fertilization, etc.) for planting densities of 2000, 2500, 3000, 3300, 3900, and 4500 $tree\cdot ha^{-1}$ for Masson pine plantation in this study corresponded to 1343.23, 1682.40, 2014.85, 2216.34, 2619.30, and 3022.28 $USD\cdot ha^{-1}$, respectively. The silvicultural measures such as forest nurturing are typically indispensable within the first three years of cultivating young stands of Masson pine, resulting in management costs of approximately 223.01 $USD\cdot ha^{-1}\cdot yr^{-1}$ and harvesting and transportation costs amounting to around 8.92 $USD\cdot m^3$. Moreover, the timber conversion rate was determined based on the long-term production data (Table S2). Therefore, the anticipated timber value ($USD\cdot t^{-1}\cdot ha^{-1}$) is calculated by Eq. 6.

$$EV_{timber} = TV \times (NP - 8.92) - CS - 223.01 \times 3 \tag{6}$$

where TV is the tree volume ($m^3\cdot ha^{-1}$), NP represents the net price of commercial timber ($USD\cdot m^{-3}$), and CS represents the silviculture cost corresponding to different planting densities ($USD\cdot ha^{-1}$).

Results

Characteristics of the variations in biomass

The allometric growth model (Table 2) accurately described the aboveground and belowground biomass of Masson pine, based on the tree height and DBH (Fig. 1). During the 10–15 year period, tree height and DBH exhibited rapid growth in Masson pine forests at different planting densities (Fig. 1a,b); however, the rate of growth declined with an increase in planting density. The standing timber volume increased at higher planting densities (Fig. 1c), but this rate of increase gradually reduced with an increase in stand age.

The biomass of various components of Masson pine increased with the increase in stand age (Fig. 2). However, with the increase in plantation density, the biomass of stem without bark increased during the 10-year and 15-year stages (Fig. 2a) but decreased during the 20-year and 25-year stages. In contrast, the biomass of bark increased with the increase in plantation density (Fig. 2b), while the biomass of branches, leaves, and roots exhibited an opposite trend (Fig. 2c–e).

Variation in the potential carbon storage of each component

The carbon storage of different components of Masson pine increased with stand age (Table 3). In 10- and 15-year-old stands, an increase in the carbon storage of stem without bark was observed with an increase in planting density. However, in 20- and 25-year-old stands, the carbon storage of stem without bark decreased gradually with an increase in planting density. Additionally, the carbon storage of bark increased, whereas that for branch wood, foliage, and roots decreased with increasing planting density. Further, the 10-year-old stands accumulated the maximum carbon storage of 13.70 $t\cdot ha^{-1}$ at the planting density of 3300 $tree\cdot ha^{-1}$; while in the case of the 15-, 20-, and 25-year-old stands, the planting density of 2000 $tree\cdot ha^{-1}$ accumulated the maximum carbon storage of 50.14, 85.86, and 115.17 $t\cdot ha^{-1}$, respectively.

The carbon sequestration rates of different components of Masson pine varied significantly (Fig. 3). Specifically, the carbon sequestration rates of both stem without bark and with bark exhibited an increasing followed by a decreasing trend with the increase in stand age (Fig. 3a,b). Additionally, except at the planting density of 2000 $tree\cdot ha^{-1}$, the carbon sequestration rates of branch wood, foliage, and roots of Masson pine stands increased with an increase in stand age (Fig. 3c–e). Notably, at the planting density of 2000 $tree\cdot ha^{-1}$, the carbon sequestration rates of branch wood, foliage, and roots of Masson pine stands increased rapidly between 10 and 15 years, corresponding to 0.54, 0.20, and 0.53 $t\cdot ha^{-1}\cdot yr^{-1}$, respectively.

Optimal rotation age with biomass carbon sinks at different initial planting densities

For the 10-year-old Masson pine stand, the carbon sink benefit was the highest at the planting density of 3300 $tree\cdot ha^{-1}$ (Table 4). However, in the case of the 15-, 20-, and 25-year-old Masson pine stands, the carbon sink benefits decreased gradually with the increase in planting density. The optimal carbon sink benefit density was found to be 2000 $tree\cdot ha^{-1}$. Furthermore, the timber and total benefits exhibited an increase followed by a decreasing trend with the increase in planting density for 15-year-old stands. Specifically, the timber and total benefits

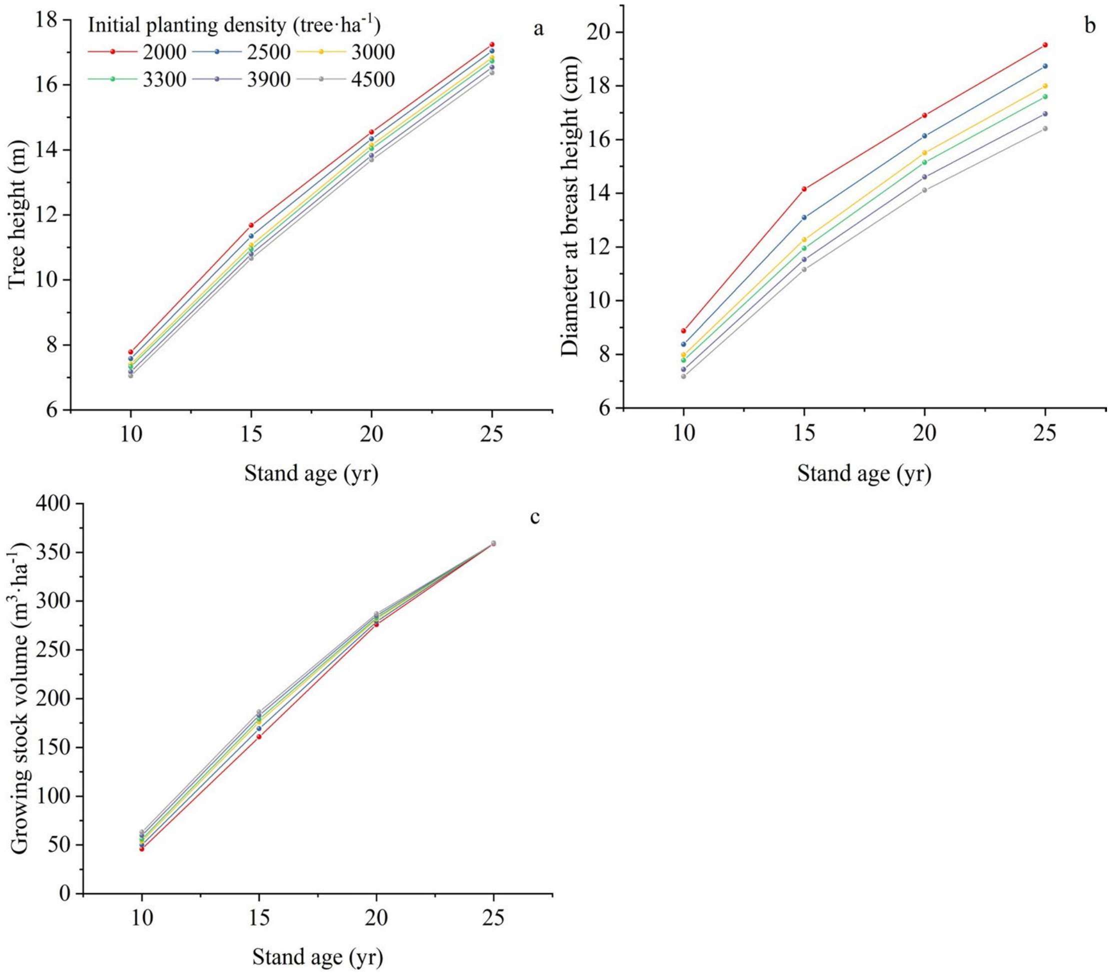

Figure 1. Effects of plantation density on tree height (**a**), diameter at breast height (**b**), and growing stock volume (**c**) during the plantation stand growth at the site index of 16 m.

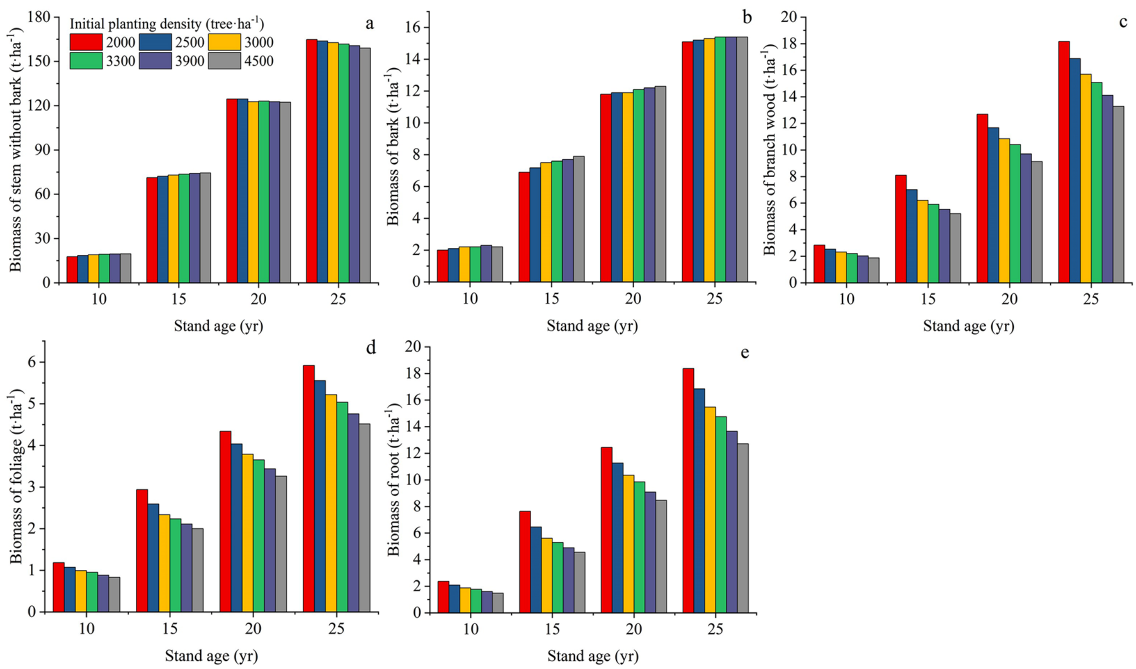

Figure 2. Effects of plantation density on the biomass of different components during the plantation stand growth at a site index of 16 m. (**a**) Stem without bark, (**b**) Bark, (**c**) Branch wood, (**d**) Foliage, and (**e**) Root.

Plantation density (tree·ha^{-1})	Stand age (yr)	Stem without bark (t·ha^{-1})	Bark (t·ha^{-1})	Branch wood (t·ha^{-1})	Foliage (t·ha^{-1})	Root (t·ha^{-1})	Total (t·ha^{-1})
2000	10	9.18	1.00	1.47	0.69	1.21	13.54
	15	36.92	3.45	4.19	1.70	3.88	50.14
	20	64.57	5.89	6.57	2.51	6.32	85.86
	25	85.47	7.54	9.4	3.43	9.34	115.17
2500	10	9.59	1.05	1.31	0.62	1.06	13.64
	15	37.44	3.59	3.62	1.50	3.28	49.43
	20	64.57	5.94	6.04	2.33	5.72	84.60
	25	84.95	7.59	8.73	3.21	8.56	113.04
3000	10	9.85	1.10	1.2	0.57	0.95	13.68
	15	37.86	3.75	3.21	1.35	2.85	49.02
	20	63.63	5.94	5.61	2.19	5.26	82.64
	25	84.38	7.64	8.12	3.02	7.86	111.02
3300	10	10.01	1.10	1.14	0.55	0.90	13.70
	15	38.17	3.80	3.06	1.29	2.69	49.00
	20	63.84	6.04	5.38	2.11	5.01	82.38
	25	83.91	7.69	7.8	2.91	7.50	109.81
3900	10	10.11	1.15	1.05	0.51	0.82	13.64
	15	38.43	3.85	2.86	1.22	2.49	48.84
	20	63.63	6.09	5.02	1.99	4.62	81.35
	25	83.29	7.69	7.3	2.75	6.94	107.97
4500	10	10.16	1.10	0.97	0.48	0.75	13.47
	15	38.58	3.95	2.69	1.16	2.32	48.69
	20	63.48	6.14	4.72	1.89	4.30	80.52
	25	82.46	7.69	6.87	2.61	6.46	106.09

Table 3. Effects of plantation density on carbon storage of biomass of different components during the plantation stand growth at a site index of 16 m.

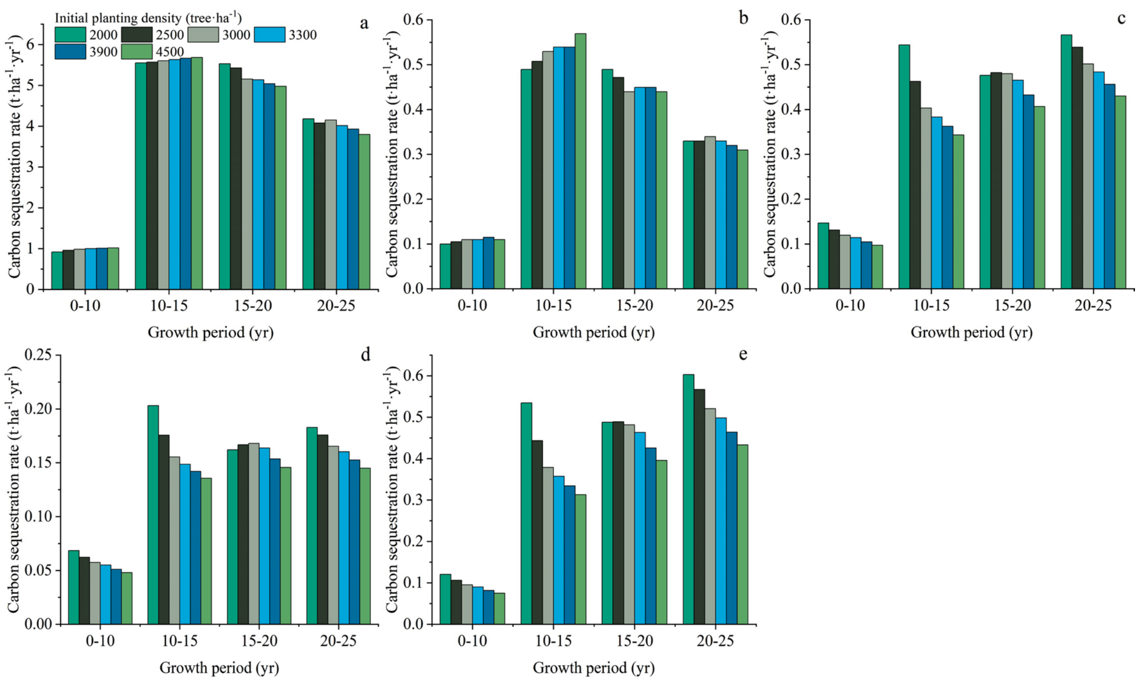

Figure 3. Effects of plantation density on carbon sequestration rates of different components during the plantation stand growth at a site index of 16 m. (**a**) Stem without bark, (**b**) Bark, (**c**) Branch wood, (**d**) Foliage, and (**e**) Root.

Initial planting density (tree·ha^{-1})	Carbon sink benefits (USD·ha^{-1})				Timber benefits (USD·ha^{-1})				Total (USD·ha^{-1})			
	10 (yr)	15 (yr)	20 (yr)	25 (yr)	10 (yr)	15 (yr)	20 (yr)	25 (yr)	10 (yr)	15 (yr)	20 (yr)	25 (yr)
2000	408.38	**1512.54**	**2590.10**	**3474.28**	**499.87**	10080.99	**23087.29**	**34083.06**	**908.25**	11593.52	**25677.40**	**37557.34**
2500	411.45	1491.27	2552.27	3410.13	396.04	10366.03	23030.14	31617.62	807.50	11857.30	25582.41	35,02775
3000	412.61	1478.69	2492.92	3349.11	266.10	**10,53694**	22781.57	31500.88	678.70	**12015.63**	25274.49	34849.99
3300	**413.33**	1478.31	2485.32	3312.74	179.54	10051.52	22706.73	31308.90	592.87	11529.83	25192.05	34621.65
3900	411.35	1473.42	2454.17	3257.19	−15.44	9930.59	18691.65	29122.72	395.91	11404.01	21145.81	32379.91
4500	406.31	1468.94	2429.16	3200.57	−232.34	9787.94	18435.15	28701.70	173.98	11256.88	20864.31	31902.26

Table 4. Effects of plantation densities on carbon sink and timber benefits during the plantation stand growth at a site index of 16 m. The boldly marked parts indicate the maximum values of carbon sink benefits, timber benefits, and total benefits for different stand ages.

of the stand were the highest at 3000 tree·ha^{-1}, corresponding to 10536.94 and 12015.63 USD·ha^{-1}, respectively. Conversely, for 20- and 25-year-old stands, the timber and total benefits were the highest at a planting density of 2000 tree·ha^{-1}.

Discussion

Effect of planting density on the biomass of forest during stand development

One prevalent method for the prediction of forest biomass and carbon storage is by using allometric growth models combined with specific carbon content coefficients for given tree species[28]. The modeled predictions in this study suggested that under the same site conditions, tree height and DBH decreased with an increase in planting density from 10 to 25 years (Fig. 1a,b). However, the growth rates of low-density stands (i.e., 2000 and 2500 tree·ha^{-1}) were relatively higher than those of high-density stands from 10 to 15 years (Fig. 1c), indicating that higher planting density would lead to earlier competition among trees for growing space, light, and soil nutrients during stand growth. Moreover, the degree of individual differentiation within the stand increased with an increase in stand age[29]. During the early stage of stand growth, higher planting density could result in higher standing volume (Fig. 1c), but this effect of planting density on standing volume gradually reduced with the increase in stand age. Especially, as the stand age reached 25 years, the standing volume of stands with planting density of 2000 and 4500 tree·ha^{-1} were almost the same (Fig. 1c). The probable reason for this could be that low-density planting reduced the intraspecific competition and individual differentiation among trees during the rapid growth period (10–20 years)[30], which was conducive to the cultivation of large-diameter timber[31].

Prediction of biomass of different components of the stand revealed that, with the increase in planting density at the stand ages of 20 and 25 years, the biomass of stem without bark decreased (Fig. 2a), while the biomass of bark increased (Fig. 2b). Previous studies have reported that bark is mainly composed of phloem and periderm, which accounts for 9–15% of the total stem biomass[32], which is consistent with the results of this study. Higher planting density leads to greater competition among stands with the development of trees[33], and the increase in bark biomass is beneficial for both water and nutrient storage, as well as the transport of photosynthetic products to alleviate competitive pressure[34]. In addition, this study demonstrated a decrease in the biomass of branches, leaves, and roots with an increase in planting density (Fig. 2c–e). The increase in planting density would intensify the spatial competition among individual trees, which may reduce the crown size and root growth by reducing the available aboveground and belowground growing space for trees[35,36]. Previous studies also indicated that higher-density stands had larger foliage biomass, resulting in enhanced light interception efficiency[37], which was inconsistent with the findings of this study (Fig. 2d). The probable reason for this phenomenon could be that after canopy closure, high-density stands promoted the upward growth of branches, leading to changes in the leaf distribution at the canopy foliage to compete for light interception[38].

Effect of planting density on carbon storage of forest with stand development

It is estimated that to achieve the ambitious goal of carbon neutrality, 11% of carbon sinks in China from 2010 to 2060 should be achieved by afforestation[39]. In the past few decades, China has invested considerable resources in enhancing vegetation cover through ecological restoration projects, but most of the plantations have not been optimized for long-term carbon storage[40]. Due to the lack of regional forest carbon strategies[41], only 10% of the afforested areas have reached their carbon-carrying capacity[42]. Choosing an appropriate stand density is widely regarded as a key management strategy to boost forest productivity and carbon sequestration[26,43]. The results from this study demonstrated that stand age was the predominant factor variations in forest biomass carbon storage. The variations in biomass carbon storage at different stand densities increased with stand age (Table 3), which may be attributed to the strong relationship between carbon storage in trees and biomass density, especially the increase in wood biomass[44]. Additionally, a few research studies have shown that wider spacing among trees positively affects tree growth and biomass accumulation[11,45], which in turn promotes carbon sequestration. Although the root carbon sink was relatively low compared to the aboveground biomass carbon sink of trees (Table 3), it plays a crucial role in forest carbon storage. This is because root turnover contributes significantly to soil carbon sequestration, making it a more stable and long-term component in climate mitigation[46].

Furthermore, the average carbon sequestration rate of the stand decreased with an increase in stand density (Fig. 3), which may be attributed to the influence of stand density on the structural dimensions of trees[20,47]. This trend could be correlated with the well-known self-thinning phenomenon, which indicates that mature trees would have higher carbon storage, but at the cost of density-dependent mortality or reduced average tree size in high-density populations[47–49]. In the case of low-density stands, the availability of sufficient light resources proves beneficial to facilitate enhanced photosynthesis rate, thereby accelerating carbon accumulation. On the contrary, competition among trees in high-density stands would induce self-pruning or self-thinning, which reduces the accumulation of biomass in branches and leaves (Fig. 2c,d), resulting in reduced carbon accumulation[11]. Hence, our findings demonstrate that critical stand density should be considered a significant factor in the management of subtropical plantations or future reforestation efforts to potentially maximize short-term or long-term carbon sequestration rates and increase carbon storage.

Planting density as a trade-off between timber production and carbon sink

The results also revealed that optimizing planting density is an important trade-off strategy for achieving the goals of maximum carbon and wood benefits. Both carbon sink and wood benefits increased with stand age. However, excessive stand density negatively impacted carbon sink benefits due to reduced biomass accumulation (Fig. 2), and led to a decline in habitat quality of high-density stands[50]. This study highlighted that the optimal stand density for each planting scenario was different. For instance, a planting project aimed at maximizing the comprehensive benefits (combining carbon sink and wood benefits) with a 15-year rotation should control the stand density of plantation at 3000 tree·ha^{-1}, while a planting project aimed at enhancing the biomass carbon storage in 20 years should control the stand density of plantation at 2000 tree·ha^{-1} (Table 4). Therefore, choosing an optimal planting density with specific goals might be a feasible approach to optimize plantation benefits (wood or carbon sink benefits) rather than merely increasing the number of trees[51]. Lower planting densities may reduce the initial afforestation costs and the need for management operations such as long-term thinning of trees, thereby lowering long-term management costs[52]. However, maintaining forest productivity may require a longer time to reach a mature logging state, delaying returns on timber and carbon sinks (Table 4). Further, the optimal forest rotation period is crucial for land managers. The results of this study showed that maintaining the optimal planting density at 2000 tree·ha^{-1} for the rotation periods of 20 and 25 years led to an increase in the comprehensive benefits by 2.14 and 3.13 times, respectively, compared to the 15-year rotation period at planting density of 3000 tree·ha^{-1} (Table 4). Therefore, extending the rotation period appropriately could be a vital forest management strategy for optimizing wood production and carbon sequestration[53]. Moreover, the associated environmental benefits could potentially offset the higher construction costs of high-density plantations, especially in the case of large-scale plantations[54].

It is noteworthy that the optimum forestation density and rotation period are influenced not only by considerations of carbon sequestration and economic value but also by various other factors. These include tree species, stand conditions, thinning intervals, pests and diseases, and the impact of extreme climate events like droughts and heatwaves under global change[55,56]. For instance, different tree species may have varying growth rates and responses to density and competition, which could affect ideal forestation practices[57]. Stand conditions, including soil quality and site index, play a crucial role in determining the productivity and health of the plantation[58]. Thinning intervals influence the competitive relationships within the stand and must be carefully managed to optimize growth and yield. Moreover, the risk of pests and diseases can severely affect tree health, thereby impacting the economic and environmental outcomes of the plantation. The international community, countries, and regions are all striving to develop policies and incentives that protect and enhance forest management to increase forest carbon sinks[59]. However, these policies and measures do not fully consider the impact of ecological and climate-related risks on the stability of forest carbon sinks. Climate change and related risks may weaken the carbon sink function of forests in the twenty-first century[59]. Therefore, while our study focuses on Masson pine plantations, these factors must be considered when developing management strategies for specific species and sites.

Conclusion

The results of this study demonstrated a significant influence of the planting density on biomass and carbon storage of Masson pine plantations. Moreover, these results can also lead to other expected benefits. When compared with high-density Masson pine plantations, lower-density plantations (i.e., 2000 and 2500 tree·ha^{-1}) have higher growth rates in the fast-growing stage, indicating the occurrence of inter-tree competition at the initial stage when there is an increase in planting density. Similarly, with an increase in management time, there was an improvement in wood storage of low-density plantations, which stored more carbon in a shorter time. Further, to achieve combined wood and carbon sequestration benefits, the optimal stand densities for 15- and 20-year rotation periods were 3000 and 2000 tree·ha^{-1}, respectively. Thus, choosing appropriate densities and optimal rotation times can result in higher long-term benefits. Overall, these results improve our understanding of the relationships among planting density, biomass, and carbon storage during stand development. Furthermore, they emphasize that current forest management and future planting efforts must consider the project objectives and optimal stand density to maximize the wood benefits and enhance the stability and persistence of ecosystem carbon sequestration.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Author contributions

Conceptualization: YB and GD; Methodology and Validation: YB and GD; Formal analysis: YB and GD; Investigation: YB and GD; Resources: YB and GD; Data Curation: YB and GD. Writing—Original Draft: YB; Writing—Review & Editing: YB and GD; Visualization: YB; Supervision: YB and GD; Project administration: GD; Funding acquisition: GD. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to G.D.