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Effects of close-to-nature forest management on carbon stocks in *Pinus tabulaeformis* plantations in northern China

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Scientifically understanding how to increase the carbon stocks of plantations under the great demand for forest carbon sinks to meet the 2.0 or 1.5°C target of the Paris Agreement is attracting mounting attention. As one of the most promising plantation management regimes, it is pertinent to ask whether close-to-nature management could improve the carbon stocks of *Pinus tabuliformis* plantations in trees, shrubs, grasses, litter, and soil. This study investigated and analyzed the effects of close-to-nature management, in comparison with no human intervention, on the carbon stocks of *P. tabuliformis* plantations in three age-classes (10-, 47-, and 56-year-old stands) over 6 years in the Wangyedian Experimental Forest Farm of Chifeng, China. The results showed under close-to-nature management and no human intervention, the amounts of carbon stocks of *P. tabulaeformis* plantations were similarly ranked (soil > trees > litter > grasses > shrubs), and the trees, vegetation, and ecosystem carbon stocks of *P. tabuliformis* plantations increased significantly with stand age ($p < 0.05$). Close-to-nature management increased the annual increment of the tree carbon stock in 47- and 56-year-old stands, as well as that of the soil carbon stock and ecosystem carbon stock in 56-year-old stands, and also that of litter carbon stock in all stands, whereas it decreased both soil and ecosystem carbon stocks' annual increment in 10- and 47-year-old stands. The annual increment of the ecosystem carbon stock was greater in 56-year-old (7.49 $\text{Mg}\bullet\text{hm}^{-2}\bullet\text{a}^{-1}$) than 47-year-old stands (5.82 $\text{Mg}\bullet\text{hm}^{-2}\bullet\text{a}^{-1}$) under close-to-nature management, but vice versa under no human intervention (56-year-old: 3.98 $\text{Mg}\bullet\text{hm}^{-2}\bullet\text{a}^{-1}$ vs. 47-year-old: 6.78 $\text{Mg}\bullet\text{hm}^{-2}\bullet\text{a}^{-1}$). This inverted response indicates that reasonable management measures could increase the ecosystem carbon stock of mature forest as defined by current Chinese age classification standards. Additionally, since the tree carbon stock of *ca.* 60-year-old *P. tabuliformis* stands is still growing, this suggests the plantation maturity of this pine specie can and should be extended to produce timber with larger diameters that sequester more carbon.

KEYWORDS

***Pinus tabulaeformis* plantations, close-to-nature management, carbon stock, carbon dynamics, Wangyedian Experimental Forest Farm**

1 Introduction

Forest ecosystems, being among the largest carbon pools on land, harbor approximately 652–927 gigatonnes (Gt) of carbon, representing 33–46% of the global carbon stock in terrestrial ecosystems (Pan et al., 2011; Liu W. W. et al., 2015), and arguably play an irreplaceable role in maintaining the global carbon balance and mitigating climate change (Bonan, 2008; Wani et al., 2015; Bastin et al., 2019). Despite the alarming rates of deforestation and forest degradation leading to a continued global decline in total forest area, the extent of planted forests has been steadily increasing (FAO, 2020). Planted forests, which accounting for 7% of the world's forested area (FAO, 2020), play a significant role in enhancing terrestrial carbon sinks through their high land productivity and the timber products produced, thereby slowing the accumulation of CO_2 in the atmosphere. With intensive management practices, planted forests grow faster than natural forests. Research shows that the average productivity of planted forests in South America surpassed 24 m^3 ha^{-1} $yr.^{-1}$ from 1990 to 2015 (Payn et al., 2015), significantly outperforming the estimated global average productivity of natural forests, which is reported to be 3 m^3 ha^{-1} $yr.^{-1}$ or lower (Paquette and Messier, 2010).

Planted forests in China encompass 36.5% of the country's total forest area, representing 27% of the global total planted forests in 2020, making them an extremely important biological reservoir of carbon in the Northern Hemisphere (Piao et al., 2009; Chen et al., 2016) and a primary contributor of bolstering the vegetation carbon stock in China (Xu et al., 2007; Zhang et al., 2022). From 1981 to 2018, China's forest carbon stock increased by 3.79Gt, with planted forests contributing 1.54Gt to this growth (Zeng et al., 2023). Despite their significance, China's planted forests encounter a range of challenges, including the low stand productivity, high risk of diseases and insect pests, poor stand structure in terms of spacing, density, species composition, age distribution and degraded soil fertility due to the lack of appropriate and adequate management practices (Li Z. et al., 2020). These plantations yield a stock volume of only 52.76 m^3•ha^{-1}, which falls below the global average by more than 50%, impeding their capacity for effective carbon sequestration. However, planted forests play a more important role in China's future timber production and are a powerful supplement to the supply of timber in the context of the comprehensive ban on commercial logging of natural forests in China. Moreover, enhancing carbon sequestration stands out as a pivotal objective for China in its pursuit of dual carbon goals centered on peak carbon emission by 2030 and reach carbon neutrality by 2060.

Optimized management practices have the potential to not only accelerate the growth of planted forests but also enhance their capacity to sequester carbon effectively (Liu et al., 2018), as well as increase harvested biomass which is also a big carbon pool (Kauppi et al., 2022). Improved management of existing forests may offer nearly three-fourths of the total unrealized potential carbon storage (Walker et al., 2022). Specifically, the carbon stocks of various pools within forest ecosystems are closely associated with the intensity of forest management and thinning operations (He et al., 2022), particularly within 3 years following the thinning (Wang et al., 2022). In order to achieve objectives of increasing forest carbon stock and decreasing natural disturbance risks, the management practices of planted forests mainly include multi-function management, structure-based management, close-to-nature forest management, and ecosystem management in China. Close-to-nature forest management, acknowledged as a highly promising management approach for planted forests (O'Hara, 2016), has been found to alter the accumulation of carbon stocks in the trees, vegetation, and soil in *Cunninghamia lanceolata* plantations by changing tree species composition and community structure (Huang et al., 2020), as well as increases biodiversity (Fang et al., 2021).

Pinus tabuliformis, an evergreen coniferous pine tree native to China, serves as the primary afforestation and commercial timber species in semi-arid areas due to its considerable economic and ecological value (Guo et al., 2008). The latest national forest resource inventory in China revealed a notable increase in the total stock volume of *P. tabulaeformis* plantations, rising from 0.66 × 10^8 m^3 in the eighth inventory (2009–2013) to 1.60 × 10^8 m^3 in the ninth inventory (2014–2019); the total carbon stock of *P. tabuliformis* plantations was 22.6 × 10^{12} Tg during the 2009–2013 period (Li et al., 2016). Optimized management practices could maximize the potential ecological value and economic value of *P. tabuliformis* plantation. Studies have explored the carbon stock and carbon density at the tree (Deng and Shangguang, 2011), litter (Li et al., 2013), and ecosystem (Yang et al., 2014; Liu B. Y. et al., 2015) levels, indicating the significant carbon sequestration potential of *P. tabulaeformis* plantations. However, there remains a dearth of research assessing the impacts of various management regimes, including close-to-nature forest management, on the carbon stocks of these plantations.

This study aims to address this gap by examining the effects of close-to-nature forest management (CTN) compared to no human intervention (NHI, with unmanaged sampling plots as the control) on the carbon stocks of *P. tabulaeformis* plantations across different age classes (10-, 47-, and 56-year-old stands) in the Wangyedian Experimental Forest Farm in Chifeng, China during 2013–2019. The area of *P. tabulaeformis* is about 6,000 hm^2 in the Farm, accounting for 26.37% of the forest area. *P. tabulaeformis* is the dominant tree species and in neighboring regions of Hebei province and Inner Mongolia Autonomous Region. The findings are expected to provide a robust knowledge base for policymakers and managers to optimize the management of *P. tabulaeformis* plantations to enhance their carbon sequestration capacity, as well as inform the development of policies and strategies for sustainable forestry investment and land use in China and elsewhere.

2 Materials and methods

2.1 Study area

The experimental site is situated in the Wangyedian Experimental Forest Farm (WYDFF), located in Chifeng City, Inner Mongolia Autonomous Region, China (118°15′–118°30′E, 41°21′–41°39′N) (Figure 1). This region experiences a temperate, semi-arid continental monsoon climate (Li X. et al., 2020). The elevation is between 500 and 1890 meters above sea level, with over 85% of its land classified as hilly and mountainous (Li X. et al., 2020), and its soil types mainly include brown soil, cinnamon soil, meadow soil, and black soil in the mountainous area, among which brown soil covers most of the area (Yan et al., 2015). The rainfall ranging from 300 to 500 millimeters annually, predominantly occurring during July and August, which accounts for 70 to 80% of the total yearly precipitation (Li X. et al., 2020). The area maintains an average yearly temperature of 4.2°C (Li

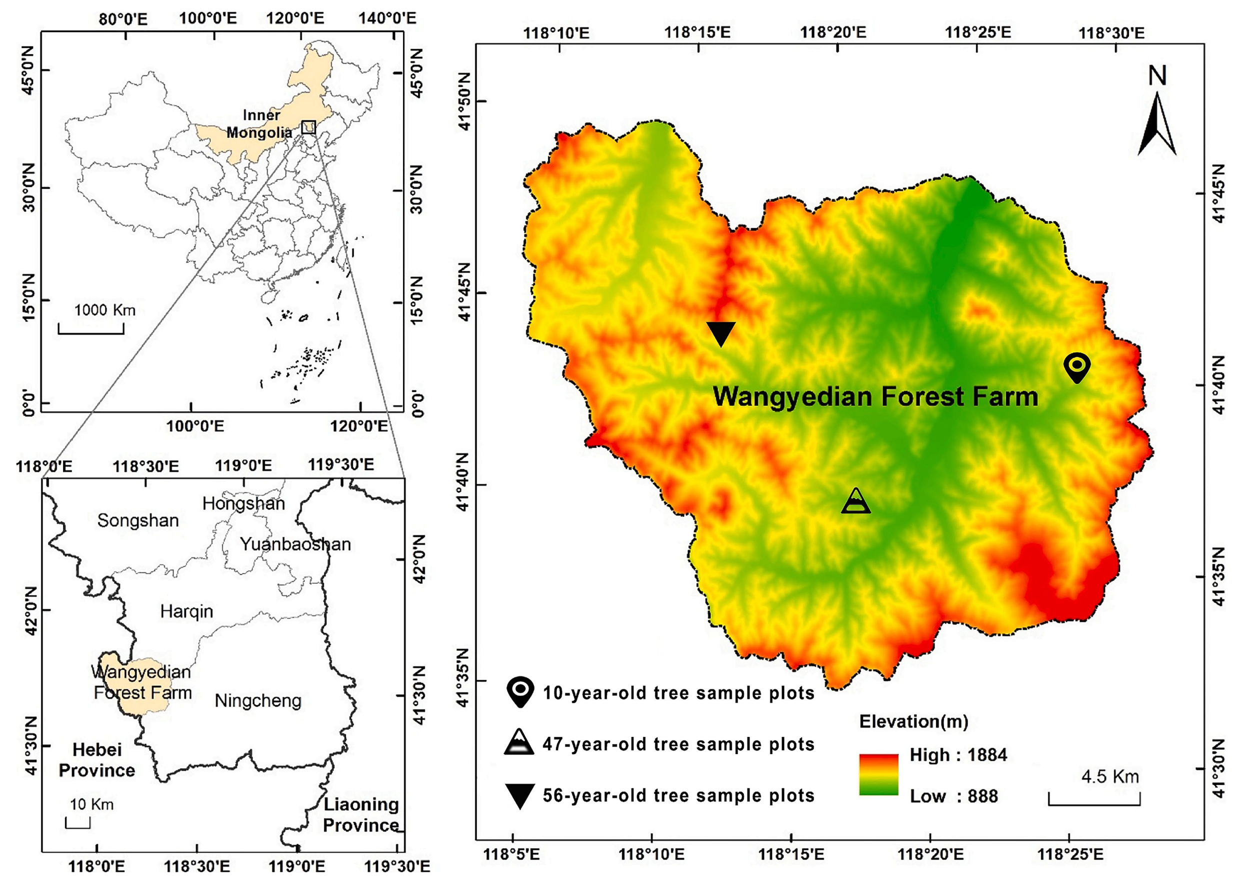

FIGURE 1
Location of the Wangyedian Experimental Forest Farm in China.

X. et al., 2020). January is the coldest month, averaging −10.4°C, and July is the hottest, averaging 21.7°C. The area enjoys lengthy sunshine, with an annual sunshine duration of 2,800–2,900 h, and an average frost free-period lasting 117 days (Jiang et al., 2020).

The WYDFF manages a total land area of 25,262 hectares, of which 24,921 hectares are designated as forest land. Within this forest land, arboreal forest covers 23,219.8 hectares, accounting for 93.18% of the total forest area. Sparse forest land occupies 315.8 hectares, or 1.27%, while shrubbery forest land encompasses 720.4 hectares, equivalent to 2.89%. In WYDFF, the forested areas are categorized based on their origin into natural secondary forests (since primary forests are absent in WYDFF) and planted forests. The natural forests, excluding naturally originated shrubbery forests, extend over 12,942.6 hectares. Key species in these secondary forests include Mongolian oak (*Quercus mongolica*), poplar (*Populus davidiana*), Dahurian birch (*Betula dahurica*), and Asian white birch (*Betula platyphylla*). The planted forests in WYDFF cover 10,277.3 hectares, with predominant species of larch varieties (*Larix principis-ruprechtii* and *Larix olgensis*), Scots pine (*Pinus sylvestris*), and Chinese pine (*Pinus tabuliformis*).

2.2 Study site and data collection

In 2013, eighteen circular tree sampling plots (each 600 m^2) were established in *P. tabulaeformis* plantations aged 10, 47, and 56 years under both CTN and NHI management regimes (with similar site index and initial plantation status) (Table 1). Each age-class has three plots positioned at the lower, upper and middle slopes respectively, all with the same mountain orientation. The CTN concept was introduced and associated silviculture practices are applied in the CTN plots. These practices included target tree selection and cultivation, cutting competitor trees (those impacting the growth of target trees), assisted natural regeneration, and enrichment planting with local species. Additional tree species were planted as appropriate, with thinning intensities kept below 20%, determined based on the tree species and structure of the pine stands. The goal was to reduce the stand density and gradually convert the monoculture plantations into a multi-aged, diverse forest with a structural and species composition that mimic of a natural forest in later successional stages. Conversely, no forestry operations were conducted in the control (NHI) sampling plots after their establishment. In these plots, target trees, competitor trees, and normal trees were identified but left unmanaged.

In the summer of 2013, trees with DBH (diameter at breast height) ≥ 1 cm were surveyed in the 10-year-old tree sampling plots, while trees with a DBH ≥ 5 cm were surveyed in the 47- and 56-year-old tree sampling plots. The target trees, competitor trees and normal trees were identified, accordingly, based on indexes such as tree height, DBH, dominance, and health status (Lu et al., 2009). Competitor trees, diseased and decayed trees, and shrubs and grasses were removed according to CTN guidelines. In each tree sampling plot, three shrub

TABLE 1 General profiles of the sampling plots in 2013 and 2019.

Stand age	Management regime	Mean diameter (cm)		Tree density (plant•hm^{-2})		Soil bulk density (g•cm^{-3})		Thinning intensity	Elevation (m)	Slope (°)
		2013	2019	2013	2019	2013	2019			
10	CTN	2.28 ± 0.06	5.10 ± 0.09	3,261 ± 106	3,211 ± 96	1.25 ± 0.10	1.23 ± 0.04	17% ± 0%	1,142–1,202	≤20
	NHI	2.30 ± 0.04	5.01 ± 0.06	3,700 ± 88	3,578 ± 74	1.23 ± 0.05	1.29 ± 0.09	0% ± 0	1,205–1,259	≤23
47	CTN	17.84 ± 0.30	19.70 ± 0.16	789 ± 48	783 ± 44	1.18 ± 0.03	1.35 ± 0.07	18% ± 1%	1,165–1,201	≤20
	NHI	17.42 ± 1.06	19.01 ± 1.08	1,056 ± 174	1,022 ± 164	1.27 ± 0.05	1.29 ± 0.06	0 ± 0%	1,148–1,171	≤22
56	CTN	24.69 ± 0.85	27.56 ± 0.76	578 ± 20	578 ± 20	1.10 ± 0.03	1.13 ± 0.05	16% ± 2%	1,322–1,359	≤16
	NHI	24.40 ± 0.71	26.84 ± 0.75	645 ± 40	622 ± 34	1.16 ± 0.04	1.14 ± 0.02	0% ± 0	1,342–1,367	≤15

Values are presented as the mean ± standard error. Different lowercase letters indicate significant differences between the two management regimes within the same stand age ($p < 0.05$); $n_{trees} = 3$, $n_{soil} = 9$.

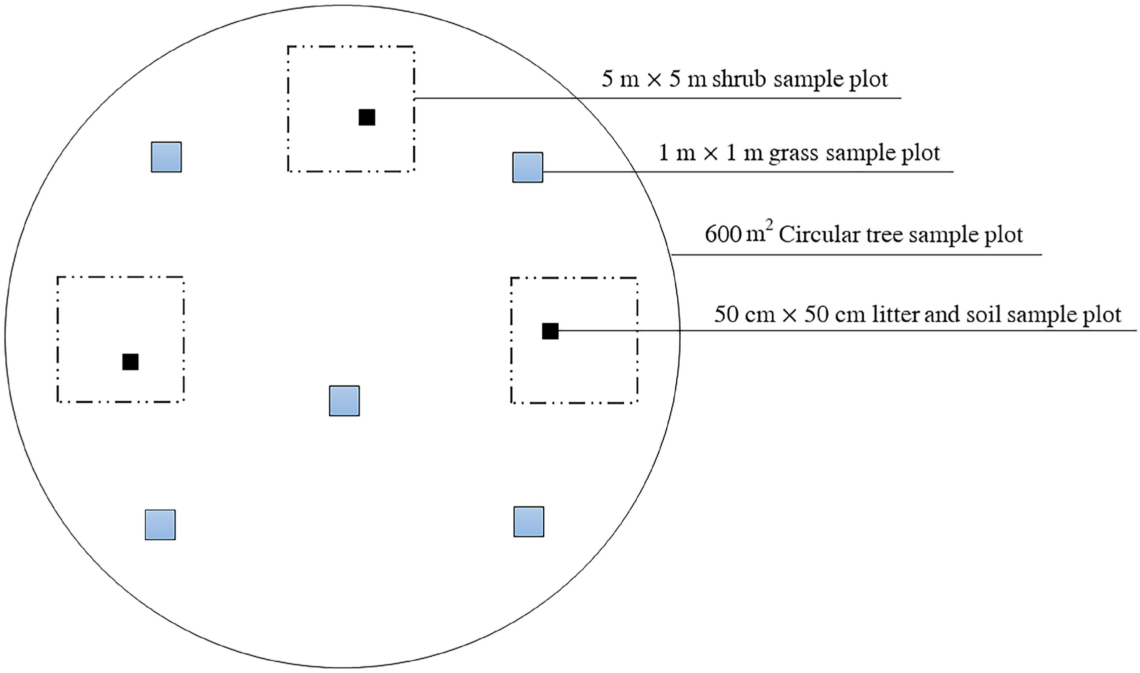

FIGURE 2
Layout of sampling plots.

sampling plots, five grass sampling plots, and three litter and soil sampling plots were established after the initial thinning (Figure 2). Samples of shrubs, grasses, litter, and soil were collected simultaneously. All the aboveground parts of shrubs and grasses, and all litter in their respective plots, were collected and weighed in the field to obtain their fresh weight values. These samples were then dried in the laboratory at a constant temperature of 65°C to determine their constant dry weight. Soil samples were collected from three depth layers: 0–10, 10–20, and 20–40 (the average soil depth in sampling plots was about 40 cm). Soil bulk density was measured using the soil ring knife method, and the volume and weight of gravel with a diameter ≥ 2 mm were measured using the drainage method and deducted from the total volume and weight of soil. Soil organic carbon (SOC) was quantified by potassium dichromate oxidation using an external heating method. Six years later, in the summer of 2019, the same field and laboratory methods described above were used to re-survey and re-measure of trees, shrubs, grasses, litter, and soil in the same tree sampling plots.

2.3 Data analysis

The carbon stock of a forest ecosystem primarily comprises the carbon stored within vegetation, litter, and soil components. The vegetation carbon stock represents the aggregate carbon stored in various plant species, including trees, shrubs, and grasses. The wood density (D), biomass expansion factor (B_{ef}), and the root-shoot ratio (R), and carbon factor (C_f) outlined in Table 2 were extracted from the *Guidelines for Carbon Sequestration Measurement and Monitoring of Afforestation Projects*, as published by the State Forestry Administration of China in 2011. The carbon factor associated with litter was referenced from Li et al. (2013), whereas the remaining parameters were sourced from the *Methodology of Carbon Sequestration Afforestation Projects*, issued by the National Development and Reform Commission of China in 2013.

The carbon stocks associated with trees, shrubs, grasses, and litter were calculated using formulae (1), (2), (3), and (4), respectively. The soil organic carbon content (Mg•hm^{-2}) representing the carbon stock attributed to soil in this study, was calculated using Equation 5. The CS_{trees}, CS_{shrubs}, $CS_{grasses}$, and CS_{litter} terms, respectively, refer to the carbon stock (Mg•hm^{-2}) of trees, shrubs, grasses, and litter; V is the stand volume (m^3•hm^{-2}), determined using the functions detailed in Table 3. Wood density (D) in Mg•m − 3 was calculated based on the fresh weight (m1) and dry weight (m2) of a sample, with M1 representing the total fresh weight of all samples in a plot, and M2 denoting the dry weight of litter within a plot. G_i is the percentage of gravel with a diameter ≥ 2 mm in the *i-th* layer; C_i is the mass fraction of soil organic carbon in the *i*-th layer (g•kg^{-1}); D_i is the bulk density of the *i-th* layer (g•cm^{-3}); and E_i indicates the soil thickness of the *i-th* layer (cm). The biomass of shrubs, and likewise of grasses, was measured using the harvest method, as outlined in the study conducted by Jing-yun et al. (2009).

$$CS_{trees} = V \times D \times B_{ef} \times (1 + R) \times C_f \tag{1}$$

$$\mathrm{CS_{shrubs}} = \mathrm{M_1 \times m_2 / m_1 \times 10000 / 25 \times (1 + R) \times C_f} \tag{2}$$

$$CS_{grasses} = M_1 \times m_2 / m_1 \times 10000 \times (1 + R) \times C_f \tag{3}$$

$$CS_{litter} = M_2 \times 10000 / 0.25 \times C_f \tag{4}$$

$$SOC = \sum_{i=1}^{n} (1 - G_i) \times C_i \times D_i \times E_i / 10 \tag{5}$$

Based on the sampling design, a one-way analysis of variance (ANOVA) was used to compare the variations in mean carbon stock across different stand ages under the same management regime. Date processing and statistical were conducted using SPSS 25 software, while graphical representations were generated using OriginPro 2018 software.

3 Results

3.1 Carbon stocks of *P. tabuliformis* plantations under two management regimes

The carbon stocks of trees, vegetation, and the overall ecosystem within *P. tabulaeformis* plantations managed under close-to-nature forest management (CTN) and no human intervention (NHI) regimes exhibited significant increases with stand age ($p < 0.05$), with estimated maximum values reached 90.35–95.38, 90.67–95.51, and 199.22–205.70 Mg hm^{-2} in the 56-year-old stands, respectively.

The carbon stocks of shrubs and grasses remained relatively low across both management regimes. Under CTN management, the shrub carbon stock initially increased and then declined with stand age, surpassing the values observed in 10-year-old stands for 56-year-old stands. In contrast, both shrub and grass carbon stock under NHI were lower in 2019 compared to 2013, with the 56-year-old stands generally showing lower values than 10-year-old stands (Table 4).

TABLE 2 Calculation parameters used for carbon stock.

Species	Carbon factor	Root-shoot ratio	Wood density	Biomass expansion factor
Pinus tabuliformis	0.521	0.251	0.360	1.59
Larix principis-rupprechtii	0.521	0.212	0.490	1.40
Betula platyphylla	0.491	0.248	0.541	1.37
Populus davidiana	0.496	0.227	0.378	1.59
Shrubs	0.47	0.40		
Grasses	0.47	2.80		
Litter	0.421			

TABLE 3 Functions used to calculate stand volume.

Tree species	Function	Reference
Pinus tabuliformis	$V = 0.001178 + 0.0000602542D^{2.630118}$	QTSB (2018b)
Larix principis-rupprechtii	$V = 0.017407 - 0.006783 \times D + 0.000889 \times D^2$	QTSB (Quality and Technology Supervision Bureau of Inner Mongolia China) (2018a)
Betula platyphylla	$V = 0.0001322D^{2.4047}$	Zhao (1993)
Populus davidiana	$V = 0.0000827D^{2.6344}$	Zhao (1993)

TABLE 4 Carbon stocks (Mg•hm^{-2}) of *P. tabuliformis* plantations under contrasting management regimes in 2013 and 2019.

Stand age		10-year-old stands		47-year-old stands		56-year-old stands	
Management regime	Year	CTN	NHI	CTN	NHI	CTN	NHI
Trees	2013	1.75 ± 0.09c	1.85 ± 0.21c	42.02 ± 0.99b	46.44 ± 1.48b	69.16 ± 3.44a	75.50 ± 1.26a
	2019	8.47 ± 0.25c	8.61 ± 0.19c	56.11 ± 1.28b	56.56 ± 1.24b	90.35 ± 3.69a	95.38 ± 1.32a
Shrubs	2013	0.03 ± 0.00a	0.24 ± 0.06a	0.20 ± 0.10a	0.01 ± 0.00b	0.09 ± 0.04a	0.11 ± 0.03b
	2019	0.07 ± 0.04a	0.07 ± 0.02a	0.13 ± 0.13a	0.00 ± 0.00b	0.08 ± 0.04a	0.02 ± 0.00b
Grasses	2013	1.70 ± 0.53a	0.68 ± 0.09a	0.94 ± 0.32a	0.90 ± 0.05a	0.26 ± 0.12a	0.25 ± 0.06b
	2019	0.22 ± 0.13a	0.09 ± 0.04a	0.97 ± 0.35a	0.47 ± 0.02a	0.24 ± 0.13b	0.12 ± 0.04b
Litter	2013	2.05 ± 0.69b	1.64 ± 0.10b	2.61 ± 0.20b	1.21 ± 0.40b	4.33 ± 0.30a	3.80 ± 0.39a
	2019	8.03 ± 1.76a	6.93 ± 0.34a	11.88 ± 0.79a	8.51 ± 1.10a	10.20 ± 0.43a	6.73 ± 0.81a
Soil	2013	18.59 ± 7.50b	41.47 ± 3.81b	50.34 ± 12.23b	31.26 ± 4.68b	86.91 ± 9.33a	95.70 ± 13.29a
	2019	33.67 ± 8.82b	72.16 ± 7.60a	61.94 ± 17.68ab	54.98 ± 8.17a	104.83 ± 9.89a	96.97 ± 13.88a
Vegetation	2013	3.48 ± 0.47c	2.77 ± 0.29c	43.16 ± 0.78b	47.35 ± 1.43b	69.52 ± 3.32a	75.85 ± 1.31a
	2019	8.75 ± 0.28c	8.77 ± 0.13c	57.21 ± 0.95b	57.03 ± 1.23b	90.67 ± 3.55a	95.51 ± 1.37a
Ecosystem	2013	24.12 ± 6.42c	45.88 ± 3.47c	96.11 ± 12.37b	79.83 ± 5.16b	160.75 ± 10.55a	175.36 ± 13.39a
	2019	50.45 ± 7.13c	87.86 ± 7.67b	131.03 ± 17.78b	120.52 ± 7.09b	205.70 ± 10.38a	199.22 ± 13.33a

The values are presented as the mean ± standard error. Different lowercase letters indicate those values in different stand ages that differ significantly under the same management regime ($p < 0.05$); $n_{trees} = 3$, $n_{shrubs} = 9$, $n_{grasses} = 15$, $n_{litter} = 9$, $n_{soil} = 9$.

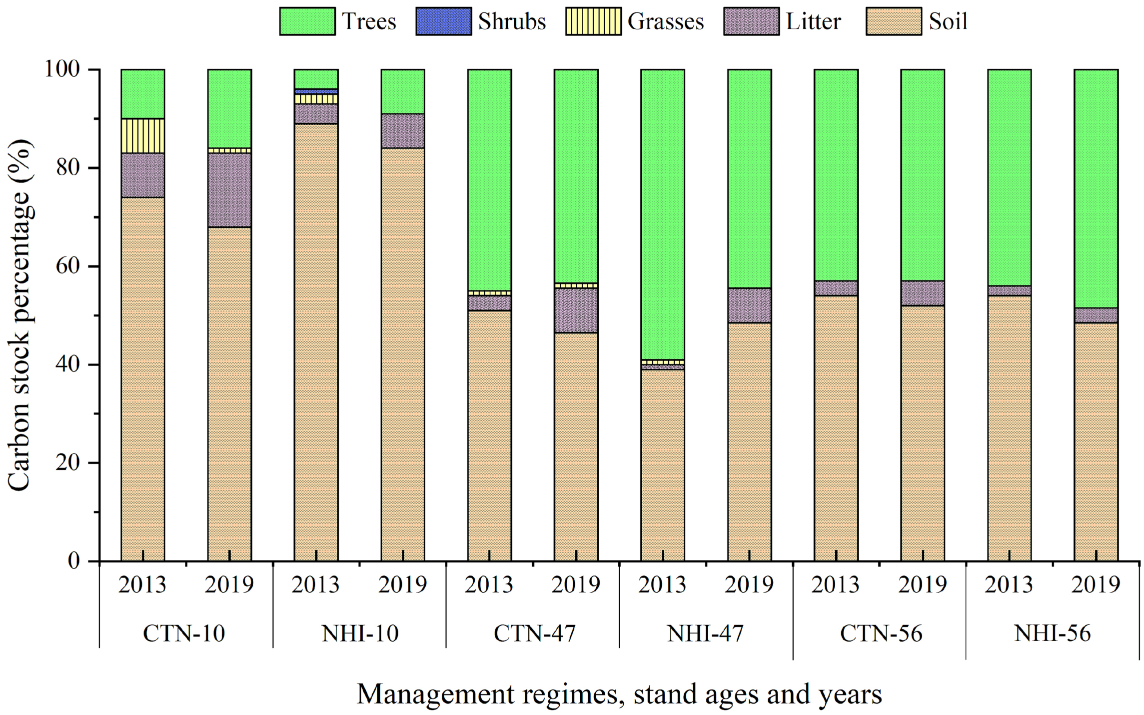

FIGURE 3
Distribution of carbon stocks in *P. tabuliformis* plantations.

Litter carbon stocks under CTN and NHI regimes ranged from 1.21 to 11.88 Mg•hm^{-2}, notably higher in the 56-year-old stands than in the 10-year-old stands, and greater in 2019 than in 2013. In the case of soil carbon stock, the levels under CTN exhibited a significant increase with stand age ($p < 0.05$), peaking at 104.83 Mg•hm^{-2} in the 56-year-old stands; the average soil carbon stock under NHI in 2019 surpassed that of 2013. Overall, the five carbon pools of *P. tabulaeformis* plantations were ranked as follows: soil > trees > litter > grasses > shrubs, as illustrated in Figure 3.

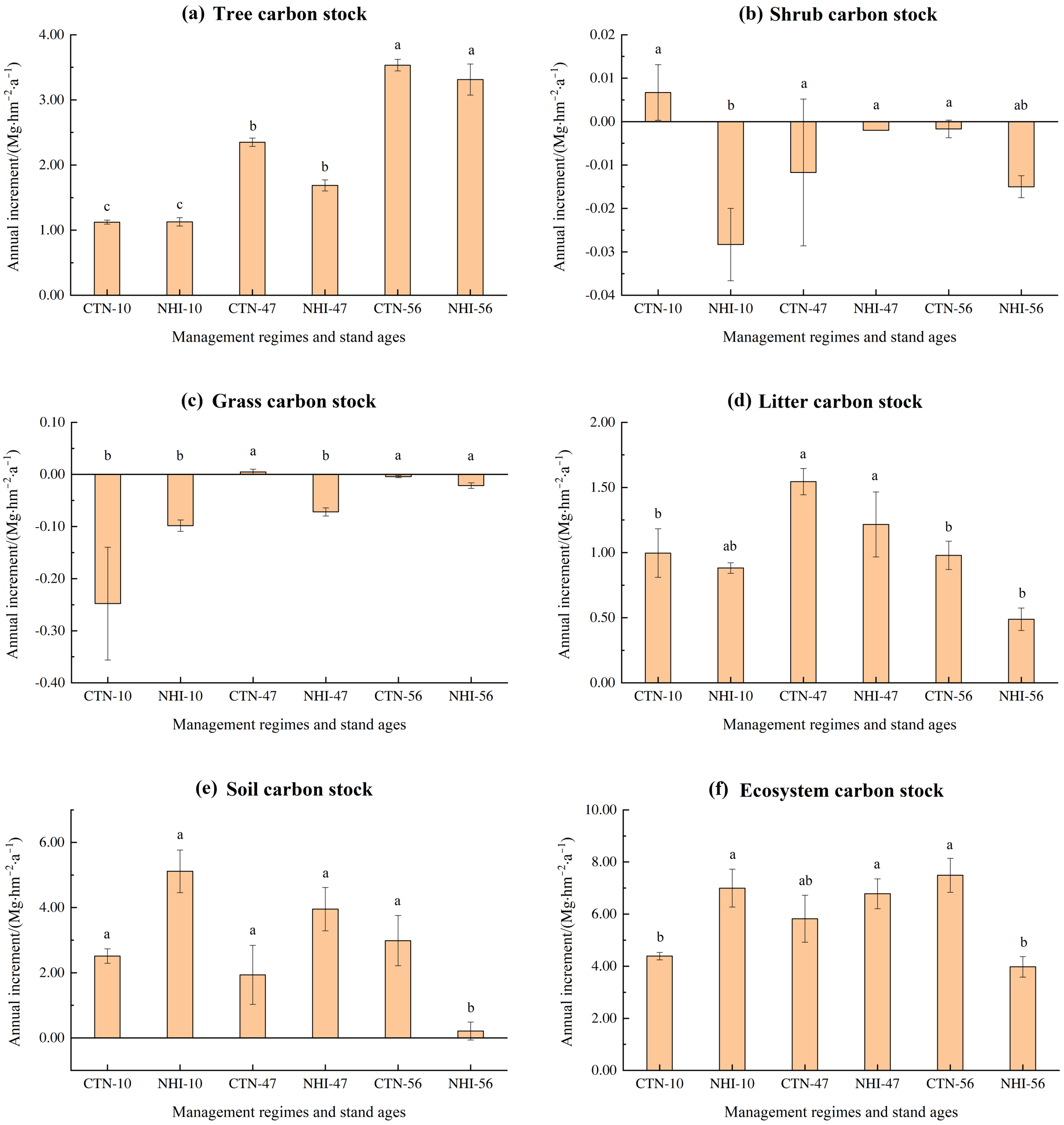

FIGURE 4

Carbon dynamics in *P. tabuliformis* plantations in the 2013–2019 period. Different lowercase letters indicate significant differences among stand ages under the same management regime ($p < 0.05$); $n_{\text{trees}} = 3$, $n_{\text{shrubs}} = 9$, $n_{\text{grasses}} = 15$, $n_{\text{litter}} = 9$, $n_{\text{soil}} = 9$.

3.2 Carbon dynamics in *Pinus tabuliformis* plantations under two management regimes

The average annual increment of the tree carbon stock increased significantly with stand age under both CTN and NHI management regimes ($p < 0.01$), attaining maximum values of 3.53 and 3.31 Mg•hm^{-2}•a^{-1}, respectively, in 56-year-old stands (Figure 4A). Notably, the implementation of CTN led to enhanced tree carbon accumulation rate in in 47- and 56-year-old stands, performing better in the former, while it reduced the tree carbon accumulation in 10-year-old stands.

For the shrub carbon stock, the average annual change under CTN initially decreased and subsequently increased with stand age, exhibiting the opposite trend under NHI ($p < 0.05$). Only the 10-year-old stands managed under CTN displayed a positive average annual change in shrub carbon stock, with CTN increasing the rate of carbon accumulation by shrubs in both 10- and 56-year-old stands (Figure 4B).

Regarding grasses, the annual change in carbon stock under CTN initially ascended but then declined with stand age ($p < 0.05$), while under NHI, it exhibited a continual significant increase ($p < 0.01$). Only 47-year-old stands under CTN demonstrated a positive average annual change in grass carbon stock. Notably, CTN enhanced the rate of carbon accumulation by grasses in 47- and 56-year-old stands, but decreased it in 10-year-old stands (Figure 4C).

The annual increment in litter carbon stock under CTN or NHI initially increased and subsequently decreased with stand age ($p < 0.05$), being lower in 56- than 10-year-old stands (Figure 4D). As stand age increased, CTN further augmented the rate of carbon accumulation by litter, with the average annual increment of litter carbon stock ranked as follows: 56-year-old stands >47-year-old stands >10-year-old stands.

For the average annual increment of soil carbon stock, under CTN it first decreased but then increased with stand age, while under NHI it only decreased significantly ($p < 0.01$). Evidently, CTN reduced the rates of soil carbon accumulation in 10- and 47-year-old stands, but increased it in 56-year-old stands (Figure 4E).

Examining the ecosystem carbon stock, its annual average increment under CTN increased significantly with stand age ($p < 0.05$), whereas it decreased significantly under NHI ($p < 0.05$) (Figure 4F). The average annual increment of the ecosystem carbon stock at the three age-classes under CTN and NHI were all positive and significantly varied ($p < 0.01$). Specifically, the corresponding values for 10- and 47-year-old stands in *P. tabuliformis* plantations under CTN (4.39 and 5.82 $\text{Mg•hm}^{-2}\text{•a}^{-1}$) was lower than that under NHI (7.00 and 6.78 $\text{Mg•hm}^{-2}\text{•a}^{-1}$). Nevertheless, the rate of ecosystem carbon accumulation under CTN was higher in 56-year-old stands (7.49 $\text{Mg•hm}^{-2}\text{•a}^{-1}$) than in similar aged stands under NHI (3.98 $\text{Mg•hm}^{-2}\text{•a}^{-1}$).

4 Discussion

4.1 Impact of management on vegetation carbon stocks of *Pinus tabulaeformis* plantations

In this study, the average annual increments of the tree carbon stock in 47- and 56-year-old stands under CTN (close-to-nature management) exceeded those under NHI (no human intervention). However, this effect was not observed in the 10-year-old stands. The lower competition among the 10-year-old pines, attributed to their sparse canopy density, resulted in the faster growth of reserved trees post-thinning not fully offset the loss of growth from removed trees (Lei et al., 2005). This also indicated that management practices significantly influence the annual average change of tree carbon stock in older stands but have limited impact on younger stands. Therefore, in the management of young and middle-aged Chinese *P. tabulaeformis* plantations, attention should be paid to accurately improving the quality of the plantations and reducing their mortality. Zhao et al. (2020) highlighted that thinning had a more pronounced effect on the growth of older *Cunninghamia lanceolate* plantation stands, while Jiang (2015) suggested that the optimal thinning intensity for the growth of older stands in *P. tabulaeformis* plantations would not have the same beneficial effect on their younger stands. Compared to NHI, CTN generally slowed down the decline in shrub and grass carbon stocks. With improved lighting conditions in forest stands, reduced interspecific and intraspecific competition, and creating favorable growth conditions for understory vegetation post-thinning (Flóra and Péter, 2016; Zhou et al., 2016), the biomass of understory plant would grow faster as the thinning intensity increases (Wang et al., 2021).

4.2 Impact of management on the litter carbon stock of *Pinus Tabulaeformis* plantations

Litter plays a key role in linking the aboveground carbon pool of vegetation with the soil carbon pool belowground (Zhang et al., 2013). The quantity of litter produced directly impacts the size of the carbon stock. The accumulation of litter is mainly influenced by vegetation growth (Liu et al., 2021), climatic conditions (Zhang et al., 2008), and management practices (Tang et al., 2018). Following forest management activities, such as thinning and tending, changes in forest structure and competitive dynamics can create a more favorable environment for plant growth (Wang Q. T., 2014), leading to increased litter input to the forest floor. In this study, the average annual increases in the litter carbon stock for the three stand age-classes under CTN were higher than those under NHI. This result aligns with the findings of Dong et al. (2011) on *Larix pricipis-rupprechtii* forest and Huang et al. (2020) on *Cunninghamia lanceolata* plantations, indicating that CTN can lead to short term increases of litter quantity.

4.3 Impact of management on the soil carbon stock of *Pinus Tabulaeformis* plantations

Soil carbon is a crucial component of forest ecosystem carbon reservoir, often surpassing tree carbon stock and significantly exceeding litter, shrub, and grass carbon stocks (Weixia et al., 2013; Wang N., 2014). Our study revealed that the distribution pattern of carbon stocks remained consistent, with CTN not altering this pattern. Similar to the research findings of Badalamenti et al. (2019) and Liao et al. (2020), the soil carbon stocks of *P. tabulaeformis* plantations always increased with stand age, regardless of whether managed under CTN or NHI. Forest management practices have a substantial impact on soil carbon stock; for example, forest thinning can enhance the total soil carbon concentration by 50% (Zhou et al., 2019) or SOC stocks in planted forests by 7.2% (Gong et al., 2021). Sawlog harvesting can increase soil carbon by up to 18% (Johnson and Curtis, 2001). Moreover, SOC stocks in planted forests can see significant gains more than 5 years after thinning (Gong et al., 2021).

In our study, the accumulation rate of the soil carbon stock slowed with stand age under NHI, particularly evident in 56-year-old stands ($p < 0.01$). In contrast, the accumulation rate of the soil carbon stock under CTN was faster, changing only slightly at different stand ages. Factors contributing to this include soil carbon increases from logging residues (Kurth et al., 2014), soil organic matter accumulation from decomposing of removed trees' roots and the accelerated growth of fine roots in remaining trees and understory plants (Vargas et al., 2009; Slodicak et al., 2005), soil carbon reduction in response to greater surface soil respiration after tending (Lei et al., 2018; Zhang et al., 2018), and decreases in soil carbon inputs (such as litter) (Cheng et al., 2014; Venanzi et al., 2016). Forest thinning may reduce the SOC stocks by destabilizing soil structure, altering microclimatic conditions to stimulate microbial activity and litter decomposition (Trentini et al., 2017; Yang et al., 2022). Therefore, the intensity of forest management practices, such as thinning and other interventions, should be carefully controlled to avoid excessive loss of the soil carbon stock (Sun et al., 2016).

4.4 Impact of management on the overall ecosystem carbon stock of *Pinus Tabulaeformis* plantations

The carbon stock of a forest ecosystem is influenced by various factors, including local climate conditions, management operations, and thinning intensity (Ma et al., 2015; Liu et al., 2014; Yu et al., 2020). Our study observed maximum values for the ecosystem carbon stock values in 62-year-old *P. tabulaeformis* plantations under both CTN and NHI regimes, ranging from 199.22 to 205.70 Mg•hm^{-2}. These values are higher than the 146.06 Mg•hm^{-2} of a 35-year-old *P. tabulaeformis* plantation in the Qinling Mountains (Liu B.Y. et al., 2015) and the 167.71 Mg•hm^{-2} of 33-year-old one in Fuxian County, Shaanxi (Yang et al., 2014), but are lower than the 240.98 Mg•hm^{-2} for a 47-year-old natural stand of *P. tabulaeformis* located in Qinyuan, Shanxi (Chi et al., 2014).

In our study, under NHI, the ecosystem carbon stock's accumulation rate decreased with stand age, particularly notable in 56-year-old stands ($p < 0.01$). Conversely, under CNT, the accumulation rate of ecosystem carbon stock significantly increased with stand age ($p < 0.01$), indicating that CTN could substantially impact the annual growth rate of the ecosystem carbon stock in different age-classes of *P. tabulaeformis* plantations. While the 10- and 47-year-old stands under CTN showed lower annual average increments in ecosystem carbon stock compared to NHI, mainly due to the significant reduction in the soil carbon stock caused by CTN. However, the average annual increase of the ecosystem carbon stock in 56-year-old stands under CTN was higher than that under NHI, mainly because CTN also increased the carbon stock of litter and soil. Although CTN increased the average annual growth rates of the tree carbon stock in 47- and 56-year-old stands, it was insufficient to offset the carbon decrease in other carbon pools of the plantation ecosystem. Additionally, the carbon of plantation ecosystem could be weakened and high risk by aging forests under no human intervention (Pan et al., 2024), while the close-to-nature can improve climate change mitigation and resilience of forests (Blattert et al., 2024) through silvicultural interventions that support natural regeneration, site-adapted tree species, stand structural heterogeneity, and that maintain forest ecosystem integrity (Larsen et al., 2022; Schütz et al., 2016). So, in order to increase the ecosystem carbon stock of *P. tabulaeformis* plantations, human interventions should be minimized as much as possible for their young stands, while other interventions such as CTN can be applied to older stands.

The average annual increments of the tree carbon stock in 56-year-old stands under both CTN and NHI (3.31–3.53 Mg•hm^{-2}•a^{-1}) exceeded those in 47-year-old stands (1.69–2.35 Mg•hm^{-2}•a^{-1}), indicating continued growth of older pine trees in the study area. Those increments were positive in 56-year-old stands under CTN as well as NHI, but the carbon stock in 56-year-old stands under CTN (7.49 Mg•hm^{-2}•a^{-1}) was greater than that in 47-year-old stands (5.82 Mg•hm^{-2}•a^{-1}), highlighting the potential for continued growth in mature forest ecosystems—as defined by existing age classification standards—under appropriate management practices. It also indicates that in order to maintain the high carbon sequestration potential of forests in the long term, it is necessary to adopt scientific forest management practices, update the age structure appropriately, optimize the spatial and temporal layout of forest age, and extend the service time of forest carbon sequestration. These findings align with the conclusions of other studies (e.g., Luyssaert et al., 2008; Gundersen et al., 2021; Feng et al., 2017) that suggest mature forest ecosystems can continue to increase their carbon stock over time with proper management.

The current forestry standard *Classification of Main Tree Species and Age Groups* (LY/T 2908–2017) states that the age of mature *P. tabulaeformis* plantation stands in the northern China is 41–60 years, while that of mature natural stands of *P. tabulaeformis* forest is 61–80 years. Given the situation of wood shortage in China and the need to balance ecological and economic considerations, adjustments to the age classification of mature *P. tabulaeformis* plantations to more than 62 years old may be necessary to ensure optimal ecosystem carbon stock growth and sustainable timber production. Further research should be conducted on the management and development strategies of Chinese *P. tabulaeformis* plantations, taking into account both timber use and ecological protection. The most suitable age for mature forest stands should be determined to avoid premature logging, in order to improve the trend of annual carbon sink decline in Chinese *P. tabulaeformis* plantations.

5 Conclusion

It is possible to gain more ecological value and economic value of plantation under optimized managemant practices. Much higher speed of growth and carbon sequestration of *P. tabulaeformis* plantations can be achieved through Close-to-nature forest management (CTN). CTN has a notable impact on the carbon stocks in *Pinus tabulaeformis* plantations, influencing the annual growth rate across various stand age-classes. No human intervention is particularly effective in sustaining rapid carbon accumulation in young *P. tabulaeformis* plantations, while CTN plays a crucial role in enhancing ecosystem carbon accumulation in older plantations, particularly in promoting carbon storage within trees, litter, and soil. Therefore, CTN is an effective and prudent choice to achieve both the augmentation of the forest ecosystem carbon stock and the cultivation of large-diameter timber trees and helps plantation to meet the demands of future society.

To increase the forest ecosystem carbon stock, field operations should not only focus on increasing the tree carbon stock but also on enhancing soil carbon stock, with management intensity well controlled to avoid a significantly shrinking the soil carbon stock. Notably, the tree and ecosystem carbon stocks in approximately 60-year-old *P. tabulaeformis* plantations at the Wangyedian Experimental Forest Farm continue to exhibit rapid growth, thus, it is necessary to extend the rotation age to optimize the economic and ecological benefits from these plantations. Meanwhile, the age of mature *P. tabulaeformis* plantations should be redefined.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JiX: Investigation, Methodology, Writing – original draft. HT: Writing – review & editing. JuX: Conceptualization, Investigation, Methodology, Writing – review & editing. ZL: Writing – review & editing. WX: Conceptualization, Methodology, Writing – review & editing. RY: Conceptualization, Methodology, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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