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Carbon storage and sequestration of five planting patterns of *Picea crassifolia* plantations in Qilian mountains

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Forest plantations play a critical role in mitigating climate change, with their carbon storage and sequestration capacity significantly influenced by planting patterns. This study focuses on *Picea crassifolia* plantations in the shallow mountainous region of the Qilian Mountains, aiming to investigate the effects of five planting patterns (pure forests, mixed forests, and uneven-aged forests) on vegetation and soil organic carbon (SOC) dynamics. The research provides a scientific basis for optimizing forest management strategies in arid and semi-arid regions. Fifteen sample plots were established in the Qilian Mountains, Gansu Province, covering five planting patterns: pure forests with 1.5 × 1.5 m (P1.5) and 2 × 2 m (P2) spacing, uneven-aged pure forests (PX), mixed forests of *P. crassifolia* and *Pinus sylvestris* var. mongholica (PC), and mixed forests of *P. crassifolia*, *P. sylvestris*, and *Caragana korshinskii* (PPC). Vegetation biomass (tree height, DBH, crown width) and soil samples (0 – 80 cm depth) were collected. Carbon content was determined using the potassium dichromate oxidation method, and carbon stocks were estimated using national biomass models. Statistical analyses (one-way ANOVA) and membership function evaluation were applied to assess carbon sink potential. Results showed that: 1. Planting spacing: The 2 × 2 m pure forest (P2) exhibited higher vegetation-layer carbon storage (10 $t{\cdot}ha^{-1}$) compared to the 1.5 × 1.5 m pure forest (P1.5, 5 $t{\cdot}ha^{-1}$). 2. Age heterogeneity: The uneven-aged pure forest (PX) showed the highest vegetation-layer carbon storage (6.61 $t{\cdot}ha^{-1}$), but its total carbon stock (106.98 $t{\cdot}ha^{-1}$) was slightly lower than P2 (111.08 $t{\cdot}ha^{-1}$) due to P2's superior SOC content in deeper soil layers (13.64 $g{\cdot}kg^{-1}$ at 60–80 cm). 3. Pure vs. mixed forests: Pure forests (P2) outperformed mixed forests (PC, PPC) in total carbon storage, driven by soil-layer contributions (>95% of total stocks). The 2 × 2 m pure forest (P2) demonstrated optimal carbon sequestration potential in the Qilian Mountains, with soil carbon dominance highlighting the importance of deep-layer SOC accumulation. While uneven-aged forests (PX) showed strong vegetation carbon storage, long-term carbon sinks require integrated soil management. These findings provide critical insights for arid-region plantation configurations. Future studies should combine remote sensing for dynamic carbon monitoring and explore diversified mixed-species systems to enhance ecosystem stability.

KEYWORDS

Qilian mountains, *Picea crassifolia*, carbon storage, mixed planting patterns, ecosystem stratification

1 Introduction

Forest plantations play a critical role in mitigating climate change by sequestering carbon dioxide (CO_2) and adjusting the balance of surface water and heat (Brovkin et al., 2009; Zhang J. et al., 2021). In recent years, as global warming intensifies, countries worldwide have taken measures to reduce carbon dioxide (CO_2) emissions and offset emissions by increasing carbon sinks. The Chinese government has also announced a plan to achieve carbon (C) peaking by 2030 and C neutrality by 2060 (Cheng et al., 2024). Forest carbon sinks not only absorb CO_2 from the atmosphere through photosynthesis but also store carbon over the long term through the accumulation of soil organic carbon (SOC) (Pan et al., 2011). Furthermore, planted forests are recognized as one of the most ecologically efficient, cost-effective, feasible, and impactful measures to enhance carbon sinks (Liu et al., 2023). Consequently, optimizing forest management strategies, especially by improving carbon sequestration capacity through appropriate planting patterns, has become a hot topic in current research.

Globally, the relationship between plantations and soil carbon has been extensively studied. Research shows that the carbon storage and sequestration capacity of plantations are significantly influenced by tree species composition, stand structure, and planting patterns (Waring et al., 2020; Liu et al., 2023). However, many unresolved questions remain regarding the effects of different planting patterns on carbon sequestration, especially under the ecological conditions of arid and semi-arid regions. For example, there is no consensus on the differences in carbon sequestration capacity between pure forest and mixed forests. Pure forest, defined as plantations consisting of a single tree species, and mixed plantations, which include multiple species, are the two main types of afforestation or reforestation (Yu et al., 2023). Most planted forests consist of a single species. Keenan et al. (2015) reported that, compared to pure forest, mixed forests are more stable (Liu et al., 2018). The C sequestration capacity of pure and mixed forests is controversial. Alvaro Redondo-Brenes showed that mixed stands of *Vochysia guatemalensis*, *Jacaranda copaia*, *Tabebuia amazonia*, *Homalium alchorneoides*, and *Dipteryx panamensis* are superior to pure stands in terms of C sequestration (Redondo-Brenes and Montagnini, 2006). In contrast, Berger et al. concluded that the total C stocks in pure Norway spruce (*Picea abies*) forests are significantly higher than those in mixed forests (Berger et al., 2002). The difference in carbon sequestration capacity between pure forest and mixed forests stems from the biological characteristics of tree species themselves, the heterogeneity of ecosystem structure and function, as well as the differences in growth cycle characteristics and stability. SOC is an important component of carbon storage in terrestrial ecosystems (Zeng et al., 2024). SOC storage is affected by detrital inputs to soil (Fornara andTilma, 2008). One perspective suggests that mixed stands have an advantage over pure stands. This is because mixed forests provide a wider range of organic inputs, root secretions, and litter, creating a more diverse resource environment for soil microorganisms, which in turn favors SOC storage (Wang et al., 2013; Hao et al., 2022; Singh et al., 2024). In contrast, another perspective argues that increased competition among tree species may reduce soil organic matter (SOM) inputs to mixed plantations, which is detrimental to SOC sequestration (Manson et al., 2013).

Additionally, planting spacing is a factor influencing the carbon sequestration capacity of plantations. Truax et al. (2018) demonstrated that carbon stocks in the total biomass of 10-year-old hybrid poplars significantly increased as planting density rose from 500 trees per hectare to 1,111 trees per hectare. This highlights the potential of higher planting densities to enhance short-term carbon storage in certain species. However, the relationship between planting density and carbon sequestration is not universally consistent. For instance, Bai and Ding (2024) found that the carbon sink capacity of fast-growing *Pinus massoniana* plantations declined with increased planting density, suggesting that optimal density may vary depending on species and site conditions. Age is also a factor influencing carbon sequestration in planted forests. Pregitzer and Euskirchen (2004) found that the carbon storage capacity of forests increases with age, particularly in mature forests, where carbon storage is significantly higher than in younger stands. However, research on the carbon sequestration potential of young *Picea crassifolia* forests remains limited. These contrasting findings underscore the importance of tailoring planting spacing strategies to specific tree species and ecological contexts to maximize carbon sequestration potential.

The Qilian Mountains are located in the arid regions of Northwest China (Wu et al., 2024), and as one of the most important ecological security barriers in China, it plays a crucial role in biodiversity conservation, water supply, C sequestration and desert edge stabilization (Yang et al., 2018). The shallow mountain zones, characterized by their transitional ecosystems between arid plains and high-altitude forests, are especially vulnerable to climate change and human activities. *Picea crassifolia* is a dominant tree species in the Qilian Mountains accounting for 79.6% of the total forest area (Gao et al., 2018). It plays an important role in sheltering wind, trapping sand, conserving water, and regulating local climate (Du et al., 2022). China's existing planted forest area and potential future afforestation area are mainly located in the arid regions of Northwest China (Zhang Z. et al., 2021). Rodríguez-Loinaz et al. (2013) concluded that replacing existing plantations of exotic species with native species afforestation has the greatest potential to boost C sequestration.

Picea crassifolia exhibits significant spatial variations in stoichiometry across the eastern, central, and western regions of the Qilian Mountains (Liu et al., 2016), which is closely related to environmental factors such as climate, soil and topography in different regions. Previous studies on Qinghai spruce have primarily focused on its ecosystem structure and function (Wang et al., 2016; Liu et al., 2021; Wan et al., 2022) as well as population dynamics (Wang et al.,. 2016; Wang et al.,. 2020). However, within the ecological environment of the Qilian Mountains, the optimal planting configuration for maximizing carbon sequestration remains to be explored. To address this question, we investigated the total organic C content of different planting patterns of *P. crassifolia* plantations. The following questions were proposed to be addressed: (1) Does a larger plant spacing (2 × 2 m) correspond to a stronger C sink capacity in a pure forest plantation pattern? (2) Under the condition of the same plant spacing, does the planting pattern of different age of spruce plantations show a stronger C sink capacity than the same age of forest? (3) By the same plant spacing, is the C sink capacity of pure forest more pronounced than that of mixed forests? This study is not only dedicated to providing a scientific basis for optimizing forest management strategies in the Qilian Mountains and theoretical support for achieving carbon neutrality goals, but also contributes to the global efforts in climate change mitigation.

2 Materials and methods

2.1 Overview of the study zone

The study area, located in Minle County, Zhangye City, Gansu Province (100°43′3.09″E, 38°26′10.86″N) (Figure 1), is characterized by a semi-arid climate with an average annual temperature of 3.2°C and precipitation of 350 mm. The average annual temperature was 3.2°C, ranging from 0°C to 7.6°C. The annual frost-free period lasted for 118 days, while the total annual sunshine hours amounted to 2,966.3 h. The annual precipitation in the region is approximately 350 mm, while the total evaporation throughout the year reaches 1,638 mm. (Climatic data were sourced from the Minle County Meteorological Station.) The study area, located in the shallow mountainous region of the Qilian Mountains, was previously characterized by sparse vegetation and limited tree cover due to historical grazing and minor agricultural activities. The afforestation plots involved in this study originally lacked tree cover, supporting only herbaceous plant communities. Given the absence of pre-existing forest, afforestation was chosen to establish new forest plantations in this region. The study area is characterized by low vegetation cover and a limited variety of plant species. The primary afforestation species include *P. crassifolia* and *Pinus sylvestris* var. *mongholica* Litv., with shrubs consisting of *Caragana korshinskii* Kom. and herbaceous plants represented by *Agropyron cristatum* (L.) Gaertn. Utilizing high-quality seedlings sourced from the Longqu Seed Garden in Zhangye, Gansu. Sample plots were surveyed in May to evaluate growth status and carbon sequestration capacity, avoiding the influence of seasonal precipitation on soil carbon dynamics. The study plots were established in the eastern section of the Qilian Mountains' low-altitude region, characterized by a typical temperate continental semi-arid alpine climate (mean annual temperature 0°C–4°C, annual precipitation 250–350 mm) and Haplic Cambisols soil type, ensuring ecological representativeness. *Picea crassifolia* was selected as the primary study species due to its dominant role in the regional forest ecosystem and its significant contribution to carbon sequestration. Comparative analysis revealed that the ecological conditions of the selected plots are highly comparable to those in the central and western sections of the Qilian Mountains, particularly in terms of the accumulated temperature above 10°C (1,200°C–1,500°C·d), which meets the thermal threshold requirements of the region (Yang et al.,. 2018).

2.2 Sample plot survey and vegetation biomass measurement

2.2.1 Specific methods for vegetation biomass measurement

The five planting patterns investigated include: (1) P1.5: pure forest with a planting spacing of 1.5 × 1.5 m; (2) P2: pure forest with a planting spacing of 2 × 2 m; (3) PX: pure forest with a planting spacing of 2 × 2 m but with trees of mixed ages (15 and 20 years); (4) PC: mixed forest with *P. crassifolia* and Pinus sylvestris var. mongholica; (5) PPC: mixed forest with *P. crassifolia*, *P. sylvestris* var. *mongholica*, and *C. korshinskii*. (Table 1). For each planting pattern, three repeated quadrats were set, each with a volume of 10 m × 10 m, and the spacing between adjacent quadrats was at least 20 m, for a total of 15 quadrats. Tree and shrub measurements were conducted using standard methods: tree height was measured with a 3 m standard measuring pole to the nearest 0.1 m; diameter at breast height (DBH) was measured at 1.3 m above ground level using a diameter tape to the nearest 0.1 cm; basal diameter (BD) was measured at 0.3 m above ground level using a vernier caliper to the nearest 0.01 mm; and crown width (CW) was determined by measuring the north-south and east-west diameters using a 5 m tape measure and calculating the arithmetic mean to the nearest 0.1 m. Additionally, three 1 m × 1 m herbaceous sample plots were randomly selected within each sample plot, and all herbaceous plants in these plots were collected.

In each plot, three representative trees and shrubs were randomly selected for sampling. Branches were divided into three size groups (large, medium, and small), with 3-5 branches collected from each group. Leaves and bark were separated from these branches. A 10 cm section of stem was cut from below the new parts and the corresponding bark was collected. A 15 cm section of root was cut near the main trunk. Samples (branches, leaves, stem wood, bark, and roots) from each plant were mixed together. These mixed samples were put into plastic bags, labeled, and recorded for tracking. In the lab, all plant samples were heated at 105°C for 30 min to stop enzyme activity and prevent decay. Then, they were dried in an oven at 85°C until they reached a constant weight. The dried samples were ground into a fine powder. A 5 g portion of each powder was sifted through a 2 mm sieve to prepare for carbon content testing. Soil sampling was conducted using a diagonal method to select three sampling points, where a pit of 1 × 1 × 1 m^3 was excavated to create a soil profile. A 100 cm^3 soil ring sampler was employed for stratified sampling within this soil profile, specifically at depths of 0–20 cm, 20–40 cm, 40–60 cm, and 60–80 cm. Three soil sample plots were collected from each stratum, and all collected sample plots were placed in sealed bags. The soil sample plots were then brought back to the laboratory, dried at 105°C until a constant weight was achieved, and passed through a 2 mm sieve to remove gravel, roots, and other debris, in order to determine soil moisture content and average organic carbon

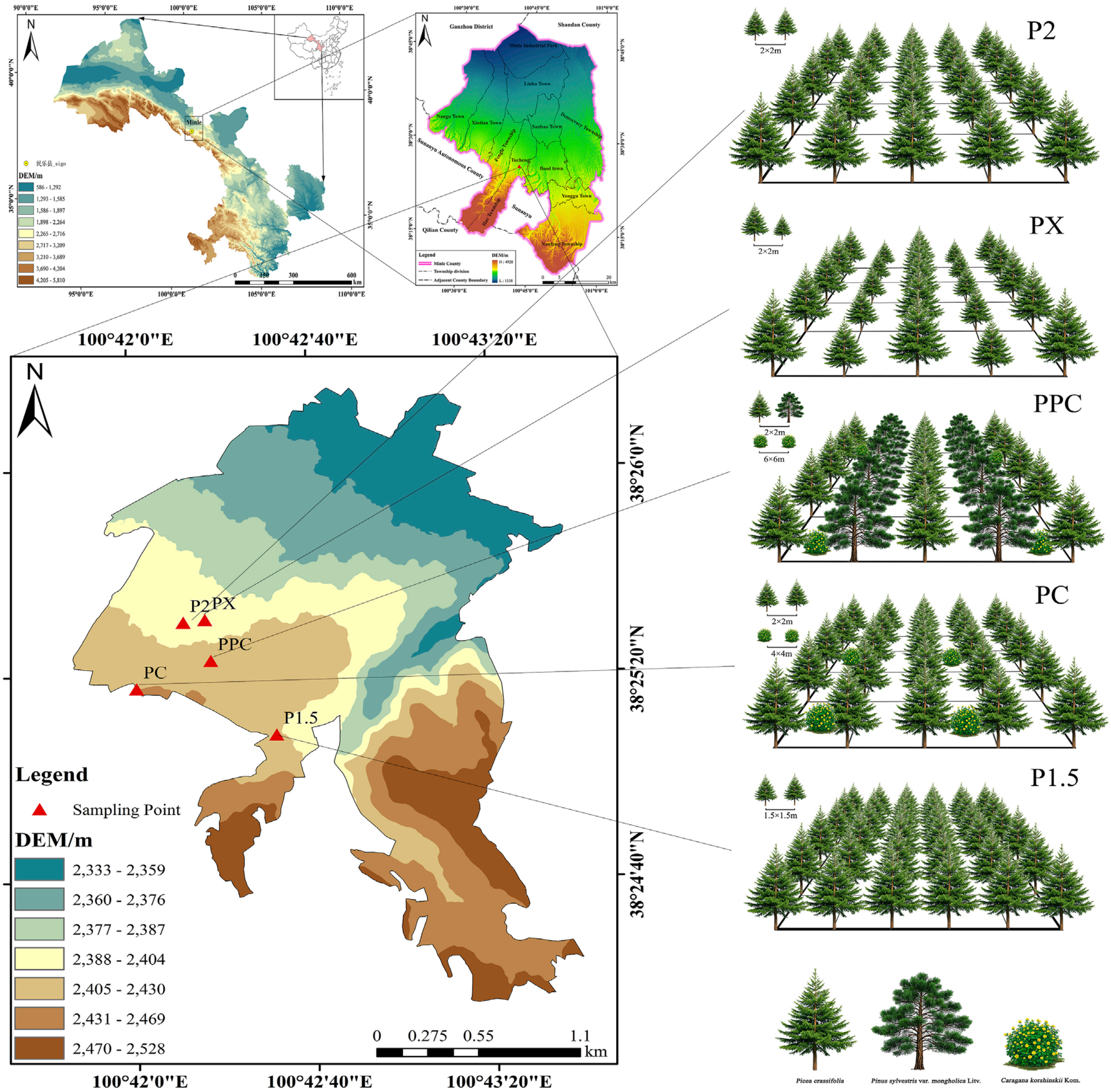

FIGURE 1
Overview of the experimental zone and schematic diagram of five planting patter.

density. The organic carbon content of the plant layer (trees, shrubs, and herbs) and soil was measured using the potassium dichromate oxidation method (Zhai et al., 2024). In addition, all samples were measured in parallel three times to improve the accuracy and reliability of the data. The average of three parallel measurements was taken as the final carbon content of the sample.

Since the forest area was protected and full harvesting for biomass determination was not permissible, the flux biomass method was employed for estimation. The biomass of *P. crassifolia* and *P. sylvestris* var. *mongholica* Litv. was calculated according to the national standard of the People's Republic of China, GB/T 43648-2024, which outlined the standing tree biomass modeling of major tree species using C measurement parameters. For *C. korshinskii* Kom., the biomass was estimated using the model developed by Zhao et al. (2023).

$$M_A = 0.30798 D_Y^{1.55710} H_Y^{0.25663}$$

$$M1 = \frac{1}{1 + g_1 + g_2 + g_3} \times M_A$$

$$M2 = \frac{g_1}{1 + g_1 + g_2 + g_3} \times M_A$$

$$M3 = \frac{g_2}{1 + g_1 + g_2 + g_3} \times M_A$$

TABLE 1 Environmental factors and stand status of sample plots.

Sample plot	Elevation/m	Forest type	Species	Age/a	Planting spacing/m	Diameter at breast height/cm	Average tree height/m	Quantity
P1.5	2456.3	Pure forest	*Picea crassifolia*	15	1.5 × 1.5	1.97 ± 0.10	1.14 ± 0.03	41
P2	2444.5	Pure forest (even aged forest)	*Picea crassifolia*	15	2 × 2	3.30 ± 0.13	1.16 ± 0.05	24
PX	2444.5	Pure forest (uneven aged forest)	*Picea crassifolia* (older)	20	2 × 2	5.13 ± 0.14	2.08 ± 0.09	15
			Picea crassifolia (younger)	15		3.30 ± 0.14	1.27 ± 0.07	12
PC	2476.6	Mixed of trees and shrubs	*Picea crassifolia*	15	2 × 2	3.53 ± 0.09	1.19 ± 0.05	28
			Caragana korshinskii Kom.	5		—	1.46 ± 0.07	6
PPC	2464.2	Mixed of trees and shrubs	*Picea crassifolia*	20	2 × 2	4.48 ± 0.19	1.74 ± 0.07	12
			Pinus sylvestris var. *mongholica* Litv.	15		3.17 ± 0.22	3.11 ± 0.17	12
			Caragana korshinskii Kom.	5		—	1.02 ± 0.01	3

Note: This study uses an experimental design with Qinghai spruce trees of different ages, such as 15 and 20 years, to analyze carbon sequestration capacity at various growth stages, evaluates the impact of age diversity, and provides data for optimizing forest management strategies in arid and semi-arid regions.

$$M4 = \frac{g_3}{1 + g_1 + g_2 + g_3} \times M_A$$

$$g_1 = 0.37394{D_Y}^{-0.05756}{H_Y}^{-0.25077}$$

$$g_2 = 2.02924{D_Y}^{1.09296}{H_Y}^{-1.75814}$$

$$g_3 = 3.18649{D_Y}^{0.95997}{H_Y}^{-2.01311}$$

$$M_B = 0.094151{D_Y}^{2.22593}{H_Y}^{-0.34753}$$

$$M_Y = W_1 + W_2 + W_3 + W_4 + M_B \tag{1}$$

In the Formula 1, M_A, M_1, M_2, M_3, M_4, M_B, and M_Y represent the aboveground, stem, bark, branch, leaf, underground, and total plant biomass of *P. crassifolia* (kg). DY refers to the diameter at breast height (cm) and H_Y represents the height of the tree (m). The variables g_1, g_2, and g_3 indicate the ratios of bark, branch, and leaf biomass of *P. crassifolia* to its stem biomass, as well as the ratio of the total bark, branch, and leaf biomass of the plant to its stem biomass.

$$M_C = 0.17577{D_Z}^{1.50770}{H_Z}^{0.34775}$$

$$M_5 = \frac{1}{1 + g_4 + g_5 + g_6} \times M_C$$

$$M_6 = \frac{g_4}{1 + g_4 + g_5 + g_6} \times M_C$$

$$M_7 = \frac{g_5}{1 + g_4 + g_5 + g_6} \times M_C$$

$$M_8 = \frac{g_6}{1 + g_4 + g_5 + g_6} \times M_C$$

$$g_4 = 0.72483D^{0.35205}H^{-1.01956}$$

$$g_5 = 0.60969D^{1.41189}H^{-1.85506}$$

$$g_6 = 1.68820D^{0.95959}H^{-2.09131}$$

$$M_D = 0.033432D^{1.89875}H^{-0.03984}$$

TABLE 2 C content of each component in plant layer of different plantation types (g·kg^{-1}).

Sample plot	Stand type	Species	Stem	Bark	Branch	Leaf	Root	Flower	Grass
P1.5	Pure forest	*Picea crassifolia*	468.02 ± 2.33 a	426.06 ± 27.56 ab	447.05 ± 3.66 a	448.47 ± 14.3 a	386.47 ± 14.16 b	—	494.98 ± 8.29 A
P2	Pure forest (even aged forest)	*Picea crassifolia*	439.44 ± 15.53 a	381.85 ± 4.79 a	409.94 ± 47.02 a	434.13 ± 7.46 a	388.04 ± 2.69 a	—	349.41 ± 3.2 D
PX	Pure forest (Uneven aged forest)	*Picea crassifolia*(older)	451.02 ± 8.65 a	411.34 ± 15 ab	450.16 ± 6 a	429.7 ± 8.43 a	367.69 ± 32.47 b	—	382.9 ± 8.95 C
		Picea crassifolia (younger)	444.74 ± 18.29 a	405.31 ± 6.05 a	414.66 ± 27.33 a	455.69 ± 10.46 a	403.23 ± 9.22 a	—	
PC	Mixed of trees and shrubs	*Picea crassifolia*	437.31 ± 22.87 ab	405.85 ± 24.28 ab	454.5 ± 8.25 a	454.54 ± 7.97 a	392.59 ± 19.64 b	—	331.6 ± 2.64 D
		Caragana korshinskii Kom.	—	—	362.18 ± 2.95 a	394.5 ± 1.81 a	383.35 ± 7.18 a	380.69 ± 16.84 a	
PPC	Mixed of trees and shrubs	*Picea crassifolia*	412.05 ± 27.37 b	434.6 ± 9.84 ab	460.42 ± 25.12 a	451.09 ± 14.02 a	373.03 ± 9.82 ab	—	444.39 ± 8.27 B
		Pinus sylvestris var. *mongholica* Litv.	409.31 ± 30.95 a	434.83 ± 43.55 a	454.52 ± 26.62 a	473.09 ± 20.06 a	414.94 ± 22.14 a	—	
		Caragana korshinskii Kom.	—	—	395.6 ± 3 b	379.91 ± 3.96 c	415.09 ± 1.99 a	380.77 ± 4.7 c	

Note: The table illustrates the C content of various organs (mean ± SE, n = 9). Lowercase letters indicate significant differences in C content among different organs within the same samples plots ($p < 0.05$). Uppercase letters denote significant differences in the grass layer across different sample plots ($p < 0.05$).

$$M_Z = W_5 + W_6 + W_7 + W_8 + M_D \tag{2}$$

In the Formula 2, M_C, M_5, M_6, M_7, M_8, M_D, and M_Z represent the aboveground, stem, bark, branch, leaf, underground, and total biomass (kg) of the *P. sylvestris* var. *mongholica* Litv.; D_Y denotes the diameter at breast height (cm), and H_Y indicates the tree height (m); g_4, g_5, and g_6 refer to the biomass ratios of the bark, branches, and leaves of the *P. sylvestris* var. *mongholica* Litv. relative to the stem biomass.

$$W_N = 1.281V^{0.645}$$

$$V = HC$$

$$C = \pi\frac{D^2}{2}$$

$$D = \frac{D_1 + D_2}{2} \tag{3}$$

In the Formula 3, W_N represents the biomass of the *C. korshinskii* Kom., V denotes the plant volume (m^3), H indicates the height of the plant (m), D refers to the crown diameter (m), while D1 and D2 represent the north-south and east-west crown diameters (m), respectively. CA signifies the crown area (m^2).

2.2.2 Determination of organic C in vegetation layer and soil layer

Calculation formula for C stocks in the arbor layer:

$$C_D = B_S \times CF_S + B_B \times CF_B + B_L \times CF_L + B_R \times CF_R \tag{4}$$

In the Equation 4, C_D represents the C stock in the tree layer (t·hm^{-2}); B_S, B_B, B_L, and BR denote the biomass per unit area of the stem, branches, leaves, and roots, respectively (t·hm^{-2}); CF_S, CF_B, CF_L, and CF_R indicate the C content percentages of the stem, branches, leaves, and roots (%).

Formulas for calculating C content in shrub and herb layers:

$$C = B \times CF \tag{5}$$

In the Equation 5, Where C signifies the organic C stock (t·hm^{-2}); B represents the total biomass (t·hm^{-2}); and CF denotes the C content percentage (%).

Formulas for calculating SOC stock in soillayers:

$$T_{SOC} = \sum_{i=1}^{n} 0.1 \times H_i + B_i + O_i \tag{6}$$

In the Equation 6, T_{SOC} stands for the total soil organic carbon storage in the soil layer (t·hm^{-2}). H_i is the thickness of the i-th soil layer (cm); B_i is the average bulk density of the i-th soil layer (g·cm^{-3}); O_i is the average organic C density of the i-th soil layer (g·kg^{-1}); and n represents the number of soil layers.

2.3 Data statistics and analysis

The basic data collected during the study were systematically organized and pre-processed using Microsoft Excel (version 2019), which facilitated initial data cleaning, sorting, and preliminary calculations. Statistical analyses were performed using SPSS 25.0, with one-way ANOVA (Analysis of Variance) applied to assess significant differences among treatment groups. Data visualization was carried out using Origin 2021, which enabled the creation of high-quality graphs, including bar charts and percentage chart, with customized formatting to enhance clarity and presentation. All statistical results were reported as mean ± standard deviation (SD).

The membership function method was used to comprehensively evaluate the carbon sink potential of the five planting modes. The calculation formula of the membership function method is as follows:

$$\mu\left(X_{ij}\right)=\frac{X_{ij}-X_{i_{\min}}}{X_{i_{\max}}-X_{i_{\min}}} \tag{7}$$

In the Equation 7 $\mu(X_{ij})$ is the membership function value of growth index j of treatment group i; X_{ij} is the measured value of ij index, and $X_{max}X_{min}$ are the maximum and minimum values of the index. In this study, i is the index coefficient of principal component composite index of age, spacing, DBH, height, BDH, Vegetation and Total Carbon Storage for five different planting modes (P1.5, P2, PX, PC and PPC). J is the index coefficient of principal component composite index of age, spacing, DBH, height, BDH, Vegetation and Total Carbon Storage.

3 Results

3.1 Vegetation and SOC in different planting patterns

According to Table 2, the average C content in the tree layer of *P. crassifolia* and *P. sylvestris* var. *mongholica* Litv. from 367.69 to 468.02 g·kg^{-1} and from 409.31 to 473.09 g·kg^{-1}, respectively. For *P. crassifolia*, the average C content in each organ is ranked as follows: leaf > stem > branch > bark > root, with values of 445.60, 442.09, 439.45, 410.83, and 385.18 g·kg^{-1}. For *P. sylvestris* var. *mongholica* Litv., the average C content in each organ is 409.31, 473.09, 454.52, 434.83, and 414.94 g·kg^{-1}. The shrub layer shows similar values, indicating that the average C contents are 409.31, 473.09, 454.52, 434.83, and 414.94 g·kg^{-1}. Notably, the average C content of the grass layer showed no significant difference across the five sample plots, with a mean value of 402.51 g·kg^{-1}.

In sites P2 and PPC, the soil organic carbon (SOC) content in the 20–40 cm layer is significantly lower than in other layers, measured 7.60 g·kg^{-1} and 8.22 g·kg^{-1} (Figure 2), indicating potential differences in carbon sequestration potential. This 20–40 cm layer consistently has the lowest organic C content across all sample plots, with values of 7.596 g·kg^{-1} in P1.5, 7.45 g·kg^{-1} in P2, and 9.50 g·kg^{-1} in PX and PC. In PPC, there is a noticeable decreasing trend in SOC content with increasing depth. In the 0–20 cm and 20–40 cm soil layers, P2 and PC exhibit relatively high organic C contents. Conversely, the 40–60 cm soil layer shows the highest concentration in PC at 11.58 g·kg^{-1}, while PPC has a significantly lower value of only 8.54 g·kg^{-1}. For the 60–80 cm soil layer, P2 and PC again show significantly higher organic C contents, measured 13.64 and 12.57 g·kg^{-1}, respectively.

3.2 Vegetation layer biomass in different planting patterns

The total biomass of the tree layer varied significantly among planting patterns, with P2 (2 × 2 m pure forest) exhibiting the highest biomass (11.38 t hm^{-2}), followed by PX (age-heterogeneous mixed forest) and P1.5 (1.5 × 1.5 m pure forest) (Table 3). This was much higher than the combined biomass of the shrub and herb layers. The leaf and root biomass accumulation of *P. crassifolia* was significantly greater than that of *P. sylvestris* var. *mongholica* Litv.; however, the stem biomass accumulation of *P. sylvestris* var. *mongholica* Litv. was notably higher than that of *P. crassifolia*. The biomass of the shrub layer was the second highest (Table 4), following the tree layer. In contrast, the herb layer showed Limited growth, with biomass ranging only from 0.01 to 0.02 t·hm^{-2}. Overall, the ranking of biomass among the plots was as follows: PX > PC > PPC > P2 > P1.5.

Soil bulk density greatly among the plots, with PPC showing the highest values in the 0–20 cm layer (1.50 g cm^{-3}) and PC the lowest (1.10 g cm^{-3}) (Figure 3). In the vertical space, the soil bulk density of the samples tended to decrease with the deepening of the soil layer, and the bulk density of the PPC was significantly greater in the 0–20 cm than in the 20-40 and 60–80 cm. In the horizontal space, the average values of the soil bulk density of the 0-20, 40-60, and 60–80 cm samples were the highest in the layer, with the values of 1.50, 1.46, and 1.42 g·cm^{-3}, respectively; PC, on the other hand, was the smallest, with 1.30, 1.11, and 1.10 g·cm^{-3}.

3.3 C stocks in different planting patterns

3.3.1 C stocks in pure forest plantation patterns

According to Figure 4, P1.5 adopts 1.5 × 1.5 row spacing, in the vegetation layer, due to the dense row spacing, the growing space of plants is limited, and it is difficult to develop the biomass of a single plant, resulting in a lower level of C storage, which is about 5 t·hm^{-2}. On the other hand, P2 adopts 2 × 2 row spacing, the growing space of plants is relatively wide, the single plants can grow better, the biomass of single plant is increased, and the C storage of the vegetation layer is about 10 t·hm^{-2}, which is higher than P1.5. P2 is a same-age forest of 15a, and PX is a heterogeneous forest age of 15a and 20a. The C storage was about 10 t·hm^{-2}, higher than that of P1.5. Overall, its P2 C stock is larger than that of PX, with 111.079 t·hm^{-2}. PX C stock in the vegetation layer is significantly higher than that of P2, and there is no significant difference in the soil layer.

3.3.2 Pure and mixed forests

According to Table 5, the distribution of carbon (C) stocks across different ecological layers—soil layer, tree layer, shrub layer, and herb layer—follows a clear hierarchical pattern, with the soil layer storing the highest proportion of C, followed by the tree layer, shrub layer, and herb layer. Predominantly, the soil layer exhibited the largest C stock, contributing over 94.02% across all sample plots, particularly the 0–20 cm depth, is the most significant component of total carbon storage (Figure 5B). The total C stocks associated with different planting patterns followed the order of P2 > PX > PPC > PC > P1.5. Notably, the C stocks in both the soil and tree layers of P1.5 were significantly lower compared to other sample plots,

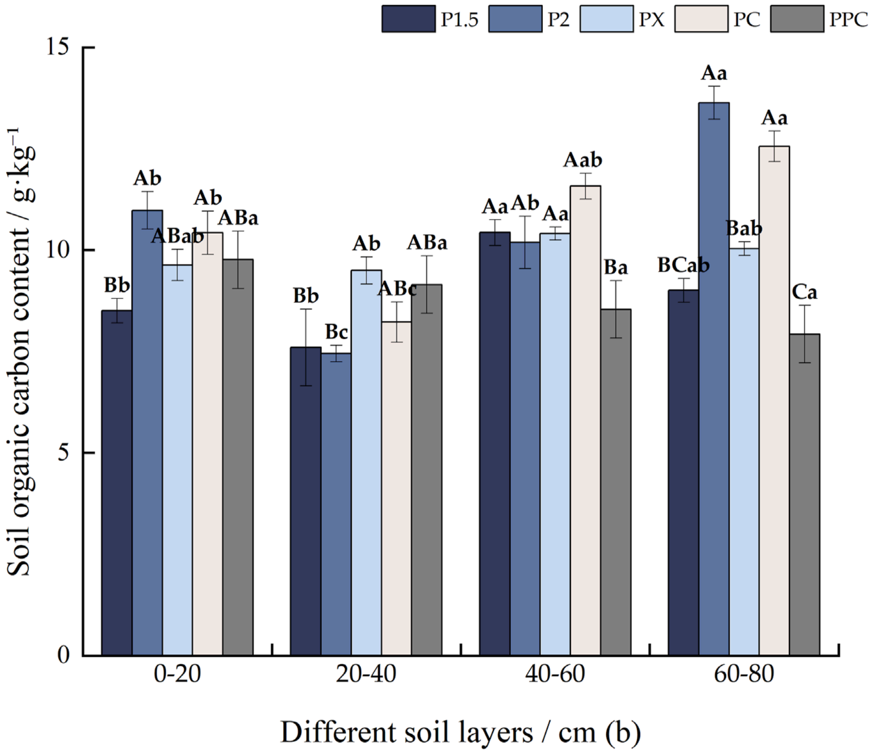

FIGURE 2
Soil organic C content of different cultivation types (g·kg^{-1}). Note: Lowercase letters denote intra-layer differences within the same soil layer, while uppercase letters indicate inter-layer differences between different soil layers ($p < 0$ 0.05). (±SE) (n = 9).

TABLE 3 **Tree layer biomass of different plantation types (t·hm^{-2}).**

Biomass	Species	Stem	Bark	Branch	Leaf	Root	Total
P1.5	*Picea crassifolia*	0.40 ± 0.00 d	0.31 ± 0.01 e	1.37 ± 0.05 c	1.86 ± 0.02 d	1.87 ± 0.01 d	5.81 ± 0.07 d
P2	*Picea crassifolia*	0.33 ± 0.01 e	0.40 ± 0.00 d	1.89 ± 0.06 b	2.43 ± 0.00 c	3.27 ± 0.02 b	8.31 ± 0.09 b
PX	*Picea crassifolia* (older)	0.74 ± 0.01 b	1.43 ± 0.05 a	2.44 ± 0.04 a	2.55 ± 0.07 b	4.22 ± 0.00 a	11.38 ± 0.15 a
	Picea crassifolia (younger)	0.20 ± 0 .00 f	0.25 ± 0.01 e	0.94 ± 0.01 d	1.18 ± 0.01 e	1.51 ± 0.11 e	4.07 ± 0.13 e
PC	*Picea crassifolia*	0.44 ± 0.01 c	0.58 ± 0.01 c	2.52 ± 0.09 a	3.18 ± 0.08 a	4.39 ± 0.16 a	11.11 ± 0.00 a
PPC	*Picea crassifolia*	0.44 ± 0.00 c	0.75 ± 0.03 b	1.74 ± 0.09 b	1.93 ± 0.01 d	2.94 ± 0.01 c	7.80 ± 0.08 c
	Pinus sylvestris var. *mongholica* Litv.	0.94 ± 0.01 a	0.31 ± 0.01 e	0.36 ± 0.00 e	0.43 ± 0.02 f	0.4 ± 0.02 f	2.43 ± 0.01 f

Note: Lowercase letters indicate differences between biomass among organs of different trees ($p < 0.05$).(± SE) (n = 3).

leading to an overall diminished C stock relative to the different planting configurations. The PX pattern demonstrated the highest vegetation layer C stock, which constituted 6.15% of the total stock within that sample plot. Despite PX's favorable vegetation layer C stock, the total C stock of P2 surpassed that of PX, primarily due to P2's top-ranking soil layer C stock of 107.69 t·hm^{-2}. This superiority is associated with the elevated SOC content observed in P2 at both the 0–20 cm and 40–60 cm depths, the highest among all examined planting patterns (Figure 5A). The total C stock is closely linked to the attributes of the tree layer, which retains a dominant proportion in both the PC and PPC planting patterns, even with the addition of contributions from the shrub layer. Conversely, the C stocks within the herbaceous layer were consistently below 0.01 t·hm^{-2}.

TABLE 4 Biomass of shrub layer and herbaceous layer in different types of artificial forests (t·hm^{-2}).

Biomass	Sample plot	Species	Total biomass
Shrub layer	PC	*Caragana korshinskii* Kom.	2.06 ± 0.12 a
	PPC	*Caragana korshinskii* Kom.	0.56 ± 0.01 b
Herbaceous layer	P1.5	*Agropyron cristatum* (L.) Gaertn.	0.01 ± 0.00 b
	P2	*Agropyron cristatum* (L.) Gaertn.	0.01 ± 0.00 b
	PX	*Agropyron cristatum* (L.) Gaertn.	0.01 ± 0.00 b
	PC	*Agropyron cristatum* (L.) Gaertn.	0.02 ± 0.00 a
	PPC	*Agropyron cristatum* (L.) Gaertn.	0.01 ± 0.00 b

Note: Differences in biomass between the shrub and herbaceous layers for different planting patterns are shown in lower case letters ($p<0.05$).(± SE) (n = 3).

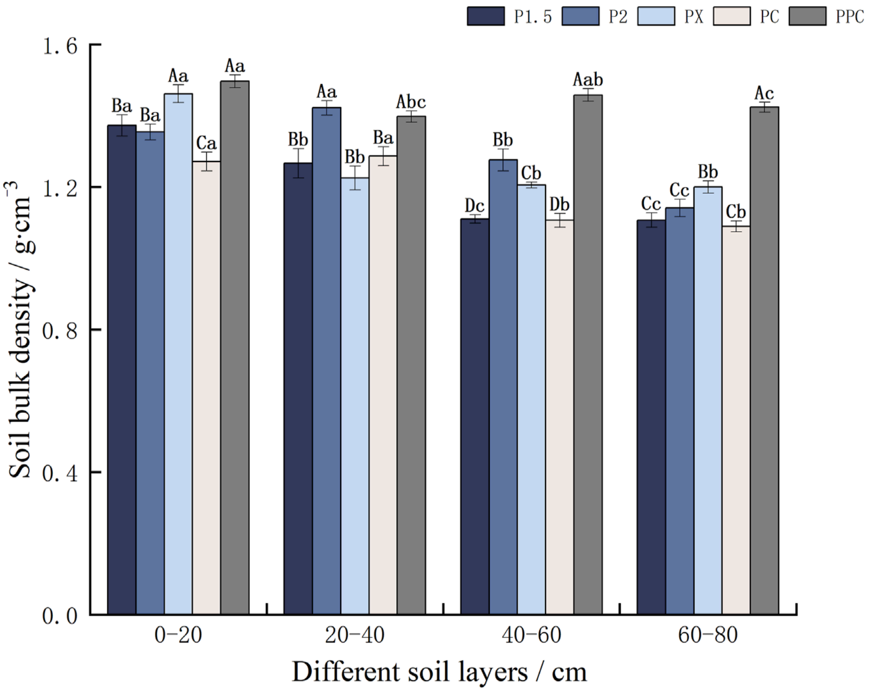

FIGURE 3
Soil bulk density of different plantation types (g·cm^{-3}). Note: Lowercase letters denote intra-layer differences within the same soil layer, while uppercase letters indicate inter-layer differences between different soil layers($p < 0.05$).(± SE) (n = 9)

3.4 Analysis of tree growth, C storage, and planting pattern C sink potential

3.4.1 Correlation analysis of growth indicators and CStorage

In Figure 6, correlations between plot type, species composition, elevation, stand age, planting distance, DBH, tree height, plant number, biomass, soil bulk weight, and carbon storage (vegetation carbon storage, soil layer carbon storage, and total carbon storage) were analyzed. The results show that soil layer carbon storage is positively correlated with total carbon storage and is the main contributor to total carbon storage, while the contribution of vegetation carbon storage is relatively small. Planting distance and DBH were positively correlated with carbon storage, indicating that a greater increase in planting distance and DBH would help increase carbon storage. There was a significant negative correlation between plant number and carbon storage, suggesting that over-dense planting may inhibit carbon fixation. The direct effects of stand age and tree height on carbon storage are weak, but stand age and tree height are strongly positively correlated. There was also a strong positive correlation between soil bulk density and planting distance.

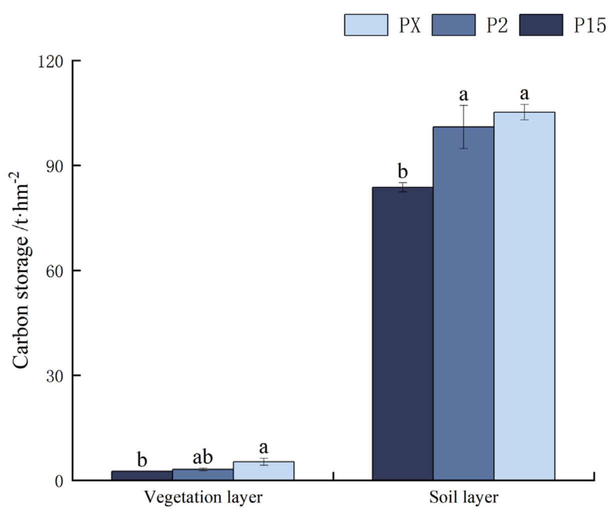

FIGURE 4
C stocks in pure forest plantation patterns. Note: Lowercase letters indicate the difference in C stocks between pure forests with different cropping patterns.

3.4.2 Membership function analysis and C sink potential evaluation

In the membership function analysis, the correlation among variables was initially assessed through a correlation coefficient matrix (Figure 6). The analysis revealed that biomass exhibited a strong positive correlation with DBH, while quantity was negatively correlated with biomass. Additionally, soil layer carbon storage showed a high correlation with total carbon storage. To mitigate redundancy and multicollinearity issues, representative variables such as DBH, Spacing, and Total_C were selected, whereas elevation, which demonstrated weak correlations with other variables, was excluded. Subsequently, the standardized values of Age, Spacing, DBH, Height, BDH, Veg_C, and Total_C were subjected to factor extraction using SPSS 26.0 software. Based on the Kaiser criterion (eigenvalue >1) and the principle of cumulative contribution rate exceeding 85%, two principal components were extracted (Table 6). Principal component 1, accounting for 67.46% of the total variance, primarily represented growth structure factors, while principal component 2, explaining 20.52% of the variance, was predominantly associated with carbon accumulation factors. Together, these two components explained 87.98% of the total variance, demonstrating a robust extraction effect, with the communality of each variable exceeding 0.67 (Table 7). The score values for the two principal components, denoted as X(x), were calculated by multiplying the standardized data by the respective index coefficients of the principal component composite indices. Membership values were derived using the corresponding membership functions, and the weights of the principal components were determined as 0.77 and 0.23 based on their variance contribution rates. The composite score was computed using the formula: Score = 0.77 × μ1 + 0.23 × μ2. The overall ranking of the planting patterns was PX > PPC > PC > P2 > P1.5 (Table 8). The PX planting pattern achieved the highest composite score, indicating superior performance in both growth characteristics and carbon storage. Specifically, PX scored the maximum membership value of 1.00 for principal component 1 and a moderate value of 0.52 for principal component 2. The PPC model excelled in principal component 2 with a membership value of 1.00 but performed moderately in principal component 1 with a value of 0.68, resulting in a composite score of 0.75. In contrast, the P1.5 model performed poorly across both principal components, yielding the lowest composite score of 0.06. These findings underscore that the PX planting pattern exhibits the highest carbon sequestration potential among the evaluated models.

4 Discussion

4.1 Vegetation C and SOC content

Carbon content in Qinghai spruce organs followed the order: leaf > stem > branch > bark > root, consistent with findings by Liu et al. (2016). This pattern reflects higher photosynthetic efficiency and carbon allocation to leaves under stress conditions. The higher C content of leaves implies a lower photosynthetic rate, slower growth rate, and higher adaptability to adverse external environments (Li et al.,. 2022). The size of the organic C content of each organ of *P. sylvestris* var. *mongholica* Litv. in this study was in the order of stem, leaf, branch, bark, and root. This result is similar to that of Dai et al., (2021). There was a difference in the order of C content of the organs of *P. crassifolia* and *P. sylvestris* var. *mongholica* Litv., as shown by the difference in the order of leaves and stem. The organ with the highest Carbon sequestration capacity varied among different tree species, reflecting their unique growth characteristics and ecological roles (Widagdo et al.,. 2021). This may be due to the different antagonistic strategies adopted by the two tree species in response to environmental stress. *Picea crassifolia* may be more inclined to increase foliar C storage to improve photosynthetic efficiency, while *P. sylvestris* var. *mongholica* Litv. may focus more resources on stem growth, resulting in a different pattern of C allocation. In global carbon stock estimations, the average carbon content of tree layers is typically assumed to be 0.45 or 0.50. However, this approach fails to account for the diversity of tree species and ecosystems, potentially leading to significant estimation errors (Pan et al., 2011). In this study, systematic measurements of carbon content in different organs provide foundational data to improve carbon stock estimation models.

The SOC content was highest in the 0–20 cm layer, followed by a significant decrease in the 20–40 cm layer, while a certain rebound and stabilization trend was observed in the deeper layers (40–80 cm). The reason why the organic C content of the surface soil (0–20 cm) is higher than that of the deep soil is that the decomposition of surface litter and plant roots has a direct effect on the surface layer of the soil, and organic matter will first enter the surface layer of the soil, while the deeper layers of the soil show a gradual decrease due to the weakening of plant decomposition and the attenuation of the accumulation and sedimentation of organic matter (Zhang et al.,. 2009). Similarly, SOC accumulates most in the surface layer, which is similar to the results of previous studies (Yu et al.,. 2023).

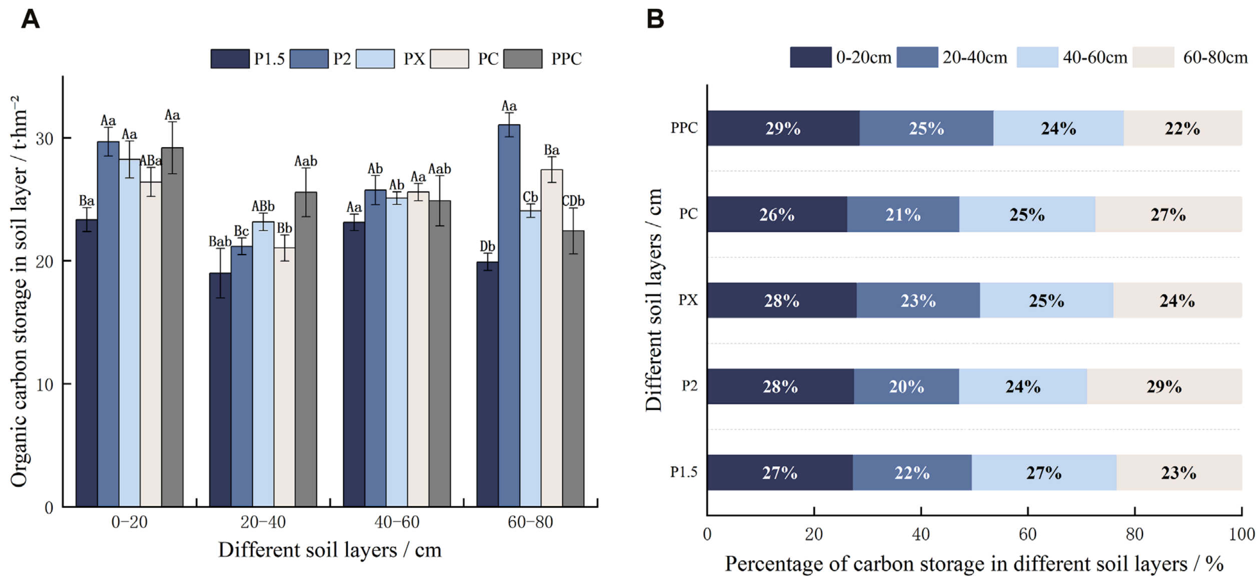

FIGURE 5
Soil C storage in different plantation types **(A)** (t·hm^{-2}) and C storage percentage (%) in different soil layerss **(B)**. Note: Lowercase letters denote intra-layer differences within the same soil layer, while uppercase letters indicate inter-layer differences between differet soil layers ($p < 0.05$).

TABLE 5 Plant layer C storage of different plantation types (t·hm^{-2}).

Sample plot	Tree layer	Shrub layer	Herbaceous layer	Soil layer	Total C storage
P1.5	2.55 ± 0.074 e (2.90%)	—	0.005 ± 0 a (0.01%)	85.419 ± 1.841 b (97.16%)	87.912 ± 1.799 b
P2	3.47 ± 0.09 d (3.12%)	—	0.004 ± 0 a (0.00%)	107.69 ± 1.024 a (95.95%)	111.079 ± 0.981 a
PX	6.61 ± 0.37 a (6.18%)	—	0.004 ± 0 a (0.00%)	100.583 ± 3.096 b (94.02%)	106.975 ± 2.924
PC	4.85 ± 0.197 b (4.58%)	0.784 ± 0.083 a (0.74%)	0.007 ± 0 a (0.01%)	100.458 ± 0.668 b (94.79%)	105.983 ± 0.72 a
PPC	4.35 ± 0.083 c (4.08%)	0.22 ± 0.003 b (0.21%)	0.004 ± 0 a (0.00%)	102.096 ± 1.294 ab (95.80%)	106.573 ± 1.295 a

Note: Different lowercase letters indicate differences in C stocks across C layers in different cropping patterns ($p < 0.05$). (± SE) (n = 3).

4.2 Pure forest C stocks

P1.5 and P2 were both pure stands of *P. crassifolia*, and the C stocks in both vegetative and soil layers were greater in P2 than in P1.5. The reason for the smaller biomass of P1.5 than that of P2 was due to the difference in planting distance, with a spacing of 1.5 × 1.5 m in P1.5 and 2 × 2 m in P2. The two sample plots were afforested at the same time, and the DBH of P1.5 was small (Table 1). The reason for the smaller diameter growth at higher densities compared to low and medium densities may be due to the very intense competition for belowground resources, which affects the overall growth (Farooq et al.,. 2021). It was inferred that the higher stand density made the trees in P1.5 more competitive, which may have limited their growth and biomass increase, resulting in a relatively low C stock. Ma et al. found that SOC decreased with increasing stand density (Ma et al.,. 2023), which was also verified in this study in the comparison between P1.5 and P2.

Both PX and P2 were established using a planting distance of 2 × 2 m, with the C stock of PX measured at 111.079 t hm^{-2}, which surpassed that of P2. This finding is consistent with the research conducted by Nilsen and Strand, which indicated that C stocks in homogeneous forest systems of the same age tend to be greater than those found in heterogeneous forest systems, specifically within *P. abies* (L.) Karst. Habitats (Nilsen et al.,. 2013). The C stock of PX in the vegetation layer was significantly higher than that of P2. *P. crassifolia* is a long-lived perennial plant (Li et al.,. 2014), in the young forest stage, the C sequestration rate increases with the increase of age (Justine et al.,. 2017). The accumulation of vegetation biomass carbon along the age gradient can be attributed to the increase in leaf area index prior to canopy closure (Wang et al.,. 2019). At the same time, the multi-layered canopy structure formed by trees of different ages in Xeric forests and the vertically elongated light wells at the top of the conical canopy allow light to reach the lower canopy and understory, making more efficient use of light resources and

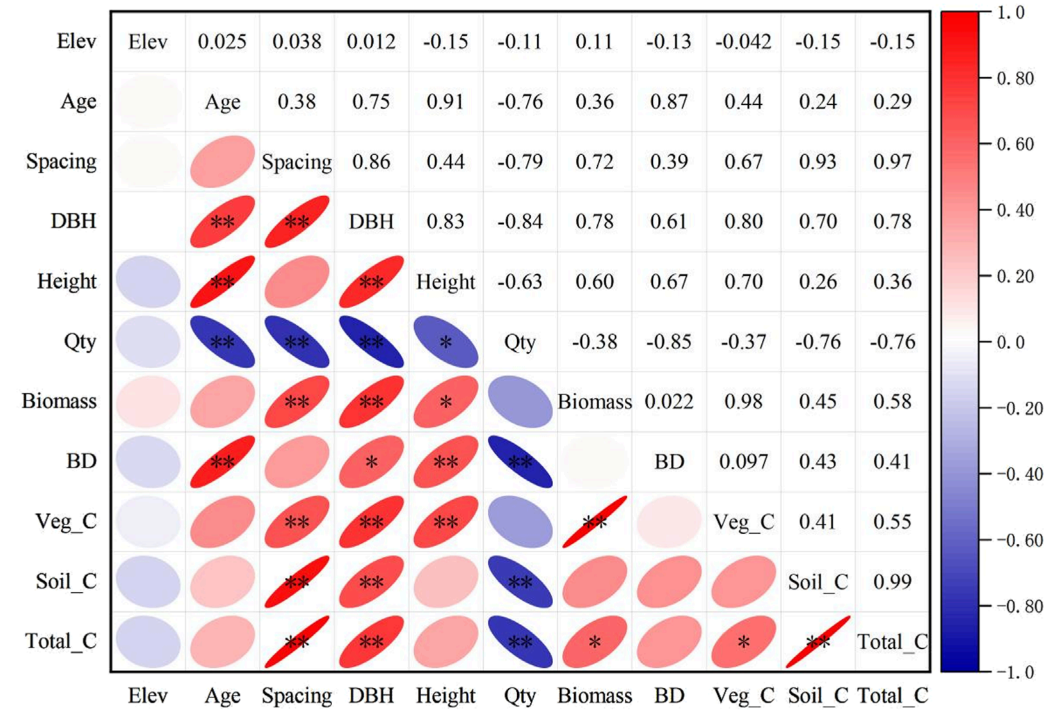

FIGURE 6
Correlation Matrix of Tree Growth Indicators and C Storage. Note: Elevation is abbreviated as Elev, Average tree height as Height, Quantity as Qty, Total Biomass as Biomass, soil bulk density as SBD, vegetation carbon storage as Veg_C, soil layer carbon storage as Soil_C, and total carbon storage as Total_C.**denotes significance at $p < 0.01$, and*denotes significance at $p < 0.05$.

TABLE 6 Total Variance Explained by Principal Components.

Total Variance Explained						
Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	Variance/%	Cumulative/%	Total	Variance/%	Cumulative %
1	4.72	67.46	67.46	4.72	67.46	67.46
2	1.44	20.52	87.98	1.44	20.52	87.98
3	0.80	11.40	99.38			
4	0.04	0.62	100.00			

promoting biomass accumulation and C fixation (Dănescu et al.,. 2016). Although the soil C stocks of PX and P2 did not show significant differences, P2 had a higher soil C stock primarily due to its significantly greater SOC content at a depth of 60–80 cm. This may be attributed to P2's more regular and organized root growth pattern compared to PX, as well as P2's relatively greater root depth and density of distribution in the 60–80 cm soil layer.

4.3 C stocks in pure and mixed forests

The carbon stock in the pure forest PX was larger than that in the mixed forest PC, and it was the vegetation layer carbon stock that was the highest among the five planting modes, which was mainly due to the 15 extra 20-year old *P. crassifolia* trees in the PX. Cheng et al. (2008) demonstrated that C stock increases with the age of the forest. This indicates that in the young forest stage, C stock rises as the trees mature. Since PX has a higher number of individual *P. crassifolia* compared to PC, and as these additional *P. crassifolia* continue to accumulate C with age, this results in the highest level of C storage in the vegetation layer of PX.

The layer C stock of pure forest PX was larger than that of mixed forest PC, and the difference in C stock between PX and PPC was mainly reflected in the vegetation layer, specifically in the tree species. The accumulation of C stock of *P. crassifolia* in PX was larger than that of *P. sylvestris* var. *mongholica* Litv., which might be because

TABLE 7 Communalities and Component Loadings for Extracted Factors.

Factor	Communalities	Component Matrix	
	Extraction	1	2
Age	0.99	0.814	0.573
Spacing	0.946	0.824	−0.517
DBH	0.993	0.992	−0.099
Height	0.895	0.87	0.372
SBD	0.797	0.703	0.55
Veg_C	0.678	0.755	−0.33
Total_C	0.86	0.76	−0.532

TABLE 8 Evaluation and Ranking of Sample Plots Based on Membership Scores and Composite Metrics.

Sample plot	x1	x2	μ1	μ2	Score	Ranking
P1.5	−1.71	−0.33	0.00	0.25	0.06	5
P2	0.36	−0.63	0.83	0.13	0.67	4
PX	0.77	0.35	1.00	0.52	0.89	1
PC	0.60	-0.95	0.93	0.00	0.71	3
PPC	−0.02	1.57	0.68	1.00	0.75	2
Weight				0.77	0.23	—

the current standing conditions were more suitable for the growth of *P. crassifolia*. Zhao et al. (2024) showed that *P. crassifolia* was the dominant species in the Qilian Mountains. The study also found that monoculture plantations typically exhibit higher values in DBH, total height, and tree volume (Redondo-Brenes, 2007). This suggests that under specific ecological conditions, monoculture plantations of well-adapted single tree species may achieve higher carbon sequestration efficiency compared to mixed forests, particularly during the early stages of afforestation. However, their long-term carbon sequestration potential and ecosystem stability require further research and evaluation. In this study, the extent of C storage in the vegetation layer was in the order of tree layer, shrub layer, and herb layer. This is consistent with the results of Ming et al. (2014), where the C stock in the tree layer was dominant in the sample plots. This is because trees can synthesize and accumulate more organic matter than other vegetation types (Cleveland et al.,. 2011). And because the C stock in the shrub layer is smaller than that in the tree layer, even with the addition of the shrub *C. korshinskii* Kom. in the PPC, the C stock in the PX remains the largest. The C stocks in the herbaceous layer are all lower than 0.01 t hm $^{-2}$, indicating Limited growth and low C stock contribution. In the mixed forest PC and PPC, the C stock in the shrub layer was higher than that in the herb layer, which was mainly related to the characteristics of the ecosystem community structure. The shrub layer is above the herb layer, which has an absolute advantage in the competition for sunlight and heat and can effectively absorb sufficient light and fully photosynthesize, thus accumulating more organic matter (Xie et al.,. 2018).

The total carbon storage of P2 *P. crassifolia* plantation (with a planting spacing of 2 × 2 m) is 111.079 t·hm^{-2}. When compared with other plantations globally and within the study area, the carbon storage of *P. crassifolia* plantation is at a moderately high level. For instance, the total carbon storage of a 16 - year - old *Castanea mollissima* plantation is 67.53 t·hm^{-2} (Zhang L. et al., 2021). In contrast, the carbon storage of a 12 - year - old Eucalyptus plantation ecosystem amounts to 151.331 t·hm^{-2} (Lu, 2024). Additionally, the carbon storage of a young mixed - species plantation (*Liriodendron chinense* × *Cinnamomum camphora* × *Liquidambar formosana Hance* × *Schima superba*) in the mid - subtropical region reaches 167.06 t·hm^{-2} (Li et al., 2019), which is significantly higher than that of Picea crassifolia plantation. These comparisons indicate that Picea crassifolia plantation exhibits certain competitiveness in carbon sequestration, especially in arid and semi - arid regions. Its strong adaptability and long growth cycle make it an important carbon - sink tree species. However, compared with Eucalyptus plantations and young mixed - species plantations, there is still room for improvement in the carbon storage of Picea crassifolia plantation. Compared to Picea crassifolia forests in other regions of China, the carbon stock of the spruce forest in this study demonstrates competitiveness. Ji et al. (2014) found that the total organic carbon stock of Picea crassifolia forests in the Helan Mountains of Ningxia reached 247.71 t·hm^{-2}. Peng et al. (2011) reported that the average carbon density of young Picea crassifolia forests in the Qilian Mountains was 83.8 t·hm^{-2}. These studies indicate that the carbon stock of Picea crassifolia forests varies significantly across different regions and age classes, yet it generally exhibits high carbon sequestration potential in arid and semi-arid regions.

Taken together, P2 had the highest C storage of all the planting patterns, although the P2 vegetation layer did not have the highest C storage. Among them, soil C storage was largest (Wang et al.,. 2002; Yang et al.,. 2018). It may be *P. crassifolia* had higher soil C stocks than the exotic species (Eslamdoust and Sohrabi, 2018). Tree C stocks increased significantly with stand age, whereas shrub and herbaceous C stocks did not vary with stand age (Jun et al.,. 2018). However, the process of C stock growth in forest stands is not static, but after reaching a certain age, the magnitude of growth gradually decreases with increasing age (Jiang et al.,. 2015). Therefore, the carbon sequestration of planted forest is mainly stored in vegetation in the short term, while in the long term, soil carbon accounts for a larger proportion in the total carbon sequestration of aged planted forest (Redondo-Brenes and Montagnini, 2007). Therefore, while P2 currently exhibits the highest carbon storage among all planting patterns, the data in Table 8 suggest that the PX planting model may demonstrate greater carbon sequestration potential in the long term. Therefore, regular monitoring and evaluation of the sample plots should be carried out. SOC levels are significantly influenced by mixing patterns, with microorganisms demonstrating selective utilization of C sources based on these patterns (Yang et al.,. 2018). Consequently, it is imperative to investigate and develop diverse silvicultural strategies in future research. These strategies should encompass not only the selection of tree species and planting densities but also integrate various ecological and climatic conditions to optimize the accumulation of soil C stocks. By employing a range of silvicultural approaches, it is possible to enhance the stability and resilience of the ecosystem, ultimately leading to an increase in overall C stocks. This research not only contributes to a deeper understanding of forest carbon dynamics but also provides practical guidance for forestry management. Future research and management efforts should focus on continuous monitoring and the development of innovative silvicultural practices to maximize the carbon sink potential of forest ecosystems, thereby playing a more effective role in mitigating climate change.

5 Conclusion

The C content of each tree layer of *P. crassifolia* was measured in the order of leaf > stem > branch > bark > root. The SOC content was highest in the 0–20 cm layer, followed by a significant decrease in the 20–40 cm layer, while some recovery and stabilization trend was observed in the deeper layers (40–80 cm). The PX cropping pattern had the highest carbon stock in the vegetation layer. The planting distance of 2 × 2 m and the even-aged forest planting pattern corresponded to a stronger C sink capacity in the pure forest planting mode. In both pure and mixed forest planting patterns, pure forest plantation P2 (even-aged forest) outperformed mixed forest in carbon sequestration and exhibited the highest soil carbon sequestration, indicating the potential for pure forest to serve as effective carbon sinks. The 2 × 2 m pure forest (P2) configuration maximizes carbon sequestration in shallow mountain ecosystems, driven by soil carbon dominance (94% of total stocks). Future research should focus on long-term monitoring and adaptive management strategies to sustain carbon sink potential. Moving forward, maximizing the carbon sink potential of forest ecosystems will necessitate innovative research and management strategies, including the development of comprehensive, long-term monitoring systems and the exploration of diverse silvicultural practices. It is essential to establish a comprehensive, long-term monitoring system that integrates satellite remote sensing, ground-based sensors, and UAV mapping to accurately track carbon dynamics and inform adaptive management strategies. Simultaneously, it is crucial to explore diversified silvicultural practices that optimize plantation forest structures by incorporating environmental factors such as rainfall, temperature, and soil texture into management strategies. These efforts will enable forest ecosystems to play a pivotal role in mitigating climate change and ensuring environmental sustainability, thereby contributing to global climate goals.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

YS: Writing – original draft, Investigation. HZ: Writing – review and editing, Conceptualization, Methodology, Project administration. ZZ: Writing – review and editing, Conceptualization, Methodology. EX: Writing – review and editing, Resources, Supervision. DL: Project administration, Supervision, Writing – review and editing. YW: Project administration, Supervision, Writing – review and editing. XZ: Investigation, Project administration, Writing – review and editing. NW: Writing–review and editing. GC: Investigation, Writing – review and editing. JL: Formal Analysis, Investigation, Methodology, Validation, Writing – review and editing. XW: Formal Analysis, Investigation, Methodology, Validation, Writing – review and editing. ZG: Project administration, Writing–review and editing. ML: Project administration, Writing – review and editing.

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Conflict of interest

Author ZG was employed by the Environmental Bridge (Shanghai) Environmental Technology Company Limited. Author ML was employed by the Western C Sink Trading Asset Management (Gansu) Company Limited.

The remaining 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.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2025.1560899/full#supplementary-material

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