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Carbon accumulation by *Pinus sylvestris* forest plantations after different periods of afforestation in a semiarid sandy ecosystem

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Abstract

The carbon pool is changing in afforestation ecosystems, which vary in their duration since establishment, in many semiarid sand regions. Understanding this is important for the management of the planted forest. The present study explored the dynamics of afforested forest carbon pool in a semiarid sandy ecosystem, northwest China. We studied afforested forests of pine (*Pinus sylvestris*) of five afforestation ages (20, 30, 40, 50, and 60 years since planting, and bare sand as control), the carbon storage and carbon sequestration rate of the forest aboveground biomass layer, surface litter layer, and soil layer (0–50 cm) were calculated, and the soil water content and soil organic carbon of 0–400 cm soil depth were measured. The results showed that the carbon sequestration rate was highest after 20–30 years, with 0.58 Mg C ha^{-1} yr^{-1} in the soil layer (0–50 cm). We found a rate of 0.13 Mg C ha^{-1} yr^{-1} in the surface litter layer, and a rate of 20.79 Mg C ha^{-1} yr^{-1} in the forest aboveground biomass layer. The carbon storage of the forest aboveground biomass layer was highest after 30–40 years, and the carbon storage of the surface litter increased with time. In the soil layer, the carbon storage at 0–10 cm depth was highest after 60 years, the carbon storage at 20–50 cm depth increased soon after afforestation and then decreased afterward with increasing afforestation ages with the maximum for 20-50 cm occurring after 30–40 years. The total carbon storage [the forest aboveground biomass layer, surface litter layer and soil layer (0-50 cm)] was higher when afforestation ages reached around 30 years, after that it decreased with increasing afforestation age. Our research improves the understanding of the *P. sylvestris* forest ecosystem carbon sequestration in a semiarid sandy area.

KEYWORDS
afforestation, *Pinus sylvestris* forest, plant carbon, sandy soils, soil carbon

1 | INTRODUCTION

Forest ecosystems have a strong capacity for carbon fixation (Dixon et al., 1994). The carbon storage, in the world's forest ecosystems, is approximately 861 ± 66 Pg C, with 44% in soil, 42% in aboveground and belowground live biomass, 8% in deadwood, and 5% in surface litter (Pan et al., 2011). The carbon storage of the worlds forests is more than twice as much as that of the atmosphere (FAO, 2005), and it plays a crucial role in global carbon cycle as a source and sink of carbon (Aryal, Bhattarai, & Devkota, 2013; Chen, Wang, & Wang, 2016). The sandy land ecosystem in semiarid areas of China is generally fragile, and it generally tends to suffer desertification because of intensive exploitation of forest resources, human actions, and poor land management (D'Odorico, Bhattachan, Davis, Ravi, & Runyan, 2013; Mganga, Nyariki, Musimba, & Amwata, 2018).

Desertification commonly leads to the loss of land resources and changes in vegetation composition (D'Odorico et al., 2013; Mganga et al., 2018; Sperry & Hacke, 2002), which has a great impact on the carbon reserves in such environments (Allington & Valone, 2010; Lu, Dong, Li, & Hu, 2014). Revegetation has been widely perceived as an effective measure for countering desertification, improving soil quality, and increasing carbon storage (Geeson, Quaranta, Salvia, & Brandt, 2015; Grandy & Robertson, 2007; Lal, 2009; Li, Niu, & Luo, 2012) in arid and semiarid areas. Afforestation can reduce the transport of wind-generated dust and sand, improve vegetation cover, control soil erosion, and increase state-level carbon sinks (Li, Yi, Son, Jin, & Han, 2010; Liu et al., 2013; Liu, Li, Ouyang, Tam, & Chen, 2008; Piao et al., 2009; Wolf, Eugster, Potvin, Turner, & Buchmann, 2011).

The changes of carbon pool in planted forest ecosystem are affected by factors, such as: forest type, time since afforestation started (Binkley, Stape, Ryan, Barnard, & Fownes, 2002), climate (Yi et al., 2010), human disturbance, land-use history, and so on (Laganiere, Angers, & Pare, 2010; Li et al., 2011; Wang et al., 2013). Yang, Li, Wang, Li, and Wang (2003) have indicated that the net primary productivity of laurel forest was higher than that of coniferous forest in the succession process. Research on carbon density, carbon distribution, carbon sequestration rate, and storage, suggest that the time since afforestation starts is an important factor (Guan, Zhou, Deng, Zhang, & Di, 2015; Lee et al., 2016). In Boreal forest ecosystems, the total ecosystem carbon increased and the net carbon accumulation in five pools (living biomass, coarse woody debris, litter, soil, and total ecosystem) were related to time since afforestation (Pregitzer & Euskirchen, 2004). In the Pearl River Delta, the carbon storage and distribution of the forest ecosystems were analyzed (for artificial forest with young, middle-aged, and mature trees), and the results attested that the soil layer contributed 56.55% carbon storage to young forests, and the forest aboveground biomass layer contributed the most carbon storage for middle-aged and mature forests (Sun & Guan, 2014).

China has the largest afforested area in the world (ca. 62 million ha in 2008) and the planted forest area in China has increased by ca. 1.7 million hectares per year (about 41% of the global afforestation rate) during the last two decades (FAO, 2010; Peng et al., 2014), vegetative production has increased and a significant carbon sink has been created in the Country (Fang, Yu, Liu, Hu, & Chapin, 2018). It has been shown there is a significant effect in vegetation restoration in semiarid areas since the afforestation projects were implemented (Hou, Li, Wang, & Zhang, 2016), afforestation benefits carbon sequestration through the accumulation of aboveground and belowground biomass (Li et al., 2012). The *Pinus sylvestris* planted forest, as an evergreen, cold-resistant, and drought-tolerant tree species, plays a key role in desertification control (Li, Cai, Man, Sheng, & Ju, 2015; Song, Zhu, Li, Zhang, & Lv, 2016) in arid and semiarid desert regions of northern China. Planting *P. sylvestris* is beneficial for increasing soil carbon storage (Gao & Huang, 2020). But some research has found that negative effects have occurred with artificial forests of *P. sylvestris* depending on time since afforestation (Liu, Siddique, Hua, & Rao, 2017; Song, Zhu, Li, Zhang, & Lv, 2016; Zheng, Zhu, Yan, & Song, 2012).

Most previous studies on afforestation of semiarid sandy ecosystems in China were focused on three things: changes in vegetation and land use; climate change; and soil ecosystems (Gao & Huang, 2020). But the distribution of the artificial forest carbon pool in relation to afforestation age, especially the relationship between soil water and the soil carbon pool through a chronosequence, is still poorly understood for semiarid sandy regions. This limits our assessment of the long-term characteristics of artificial forest systems; therefore, we chose *P. sylvestris* plantations with different afforestation ages (time since planting), in an semiarid sandy ecosystem, to explore the dynamics of artificial forest carbon through a chronosequence. We assumed that the afforestation age had a significant effect on the C pools of the artificial forest ecosystem. The specific objectives of our study were to: (a) Explore the carbon storage of *P. sylvestris* forests in the aboveground biomass layer, surface litter layer, and soil layer in plantation chronosequences. (b) Determine the response of soil organic carbon to soil water content for various afforestation ages. Understanding the variation of carbon storage in different plant/soil layers and the relationship between soil organic carbon and water content is important for the sustainable management of sandy vegetation and the restoration of sandy ecosystems.

2 | MATERIALS AND METHODS

2.1 | Study site

The study was conducted in the Hongshixia Forest Park (38°19′ N, 109°42′ E) of Yulin City in Shaanxi Province, China, which is at the edge of the Mu Us Desert (Figure 1). The average altitude of Yulin is 1,050–1,500 m. The study area is characterized by a warm temperate zone semiarid continental monsoon climate, the annual average temperature is 8.1°C, and the minimum and maximum temperatures are −32.7 and 37.6°C, respectively. The frost-free period ranges from 134 to 169 days. The annual precipitation of the whole region is 368.9 mm, making it the region with the least precipitation in Shaanxi Province. And the annual evaporation is approximately 1,195.5 mm. This annual evaporation is approximately three-times the annual precipitation in this region (Su, Kang, Xu, & Wang, 2017).

The soil in our study area is classified as aeolian sandy soil (Li et al., 2018) and it is alkaline with a pH of 8.10–8.71, and the mean of total N is 0.38 g kg^{-1} (Cheng, Wu, & Zhao, 2011). The average content of sand is 92.6%, silt and clay is 7.4% (Li et al., 2018). The vegetative transition was from forest steppe zone to typical semiarid steppe zone and desert steppe zone. The native vegetation in the study area was shrubs, which were associated with sandy substrates. The native vegetation is sparse and any understorey of moss is mainly distributed in secondary forest and artificial forest. The area is naturally covered mostly by *Hedysarum scoparium*, *Hippophae rhamnoides*, *Hedysarum mongolicum*, *Salix psammophila*, and affforestation has been with an exotic - *P. sylvestris* var. Mongolica.

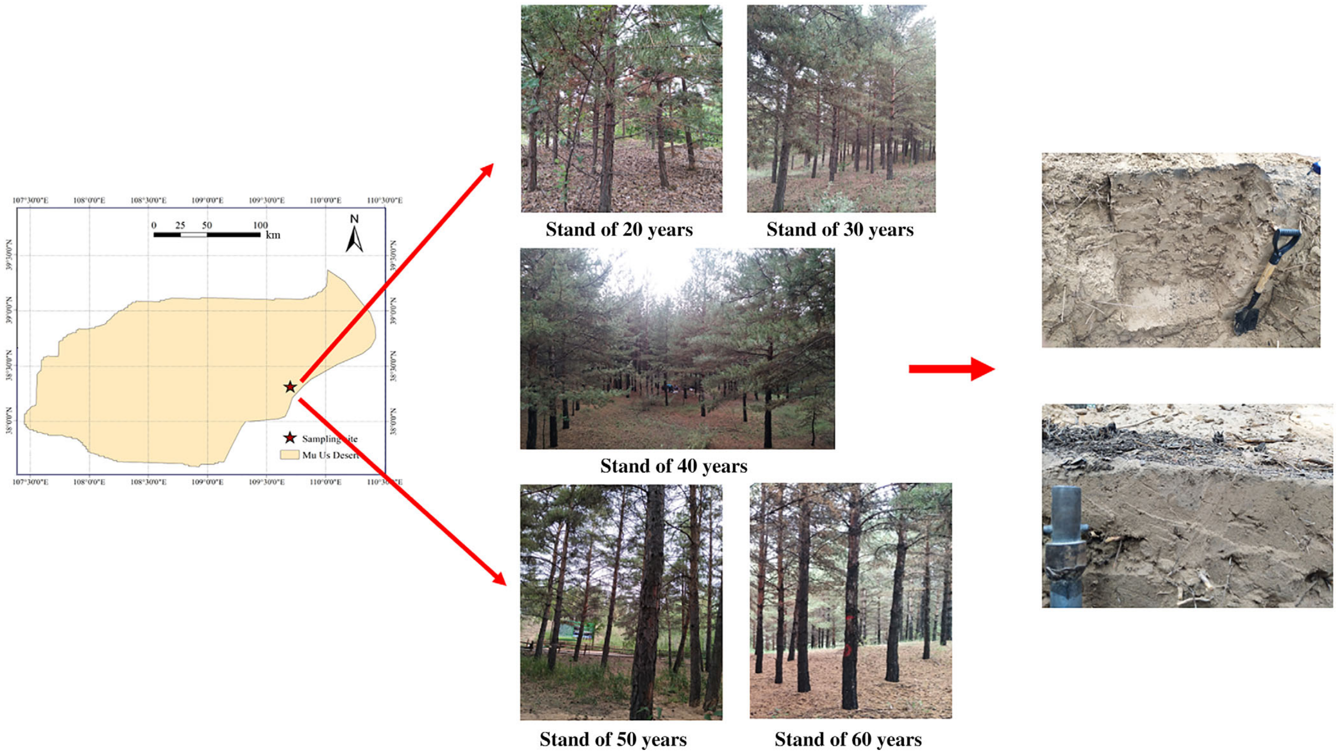

FIGURE 1 Location of the studied semiarid sandy ecosystem (left) (the Hongshixia Forest Park on the southern rim of the Mu Us Desert), the artificial forests can be divided into five age classes (shown in middle figures), and the soil profile (two right-hand figures) [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Density of *P. sylvestris* for different afforestation ages (20, 30, 40, 50, and 60 years)

Afforestation ages (year)	20	30	40	50	60
Density of trees (N ha^{-1})	1,440 ± 403	1,420 ± 460	1,960 ± 594	1,460 ± 329	700 ± 100

2.2 | Experimental design and sampling

To mitigate desertification, *P. sylvestris* was introduced to the region was introduced in 1964 by the Forestry Bureau of Honghuaerji in Hulun Buir, Inner Mongolia. We selected 20-, 30-, 40-, 50-, and 60-year-old *P. sylvestris* plantations as study stands, and the bare land was referred as plantation age of 0.

Five sampling plots (10 m × 10 m) were constructed on areas of each age class (20-, 30-, 40-, 50-, and 60-year-old plantations). For each plot, the density of trees (Table 1) and the diameter at breast height (DBH) were recorded. The tree fresh biomass was calculated as follows (Gerwing & Farias, 2000):

$$\text{For trees} < 20\text{cm DBH} : \ln(\text{mass}) = -1.754 + 2.665 \ln(\text{DBH}), \quad (1)$$

$$\text{For trees} > 20\text{cm DBH} : \ln(\text{mass}) = -0.151 + 2.170 \ln(\text{DBH}). \quad (2)$$

Dry biomass was calculated by multiplying the amount to the fresh biomass × 0.603 according to Gerwing & Farias (2000).

The surface litter was collected and weighed from three sampling plots (each 10 m × 10 m) for each age class (afforestation age). All these 15 samples of surface litter were reweighed after drying at 75°C until constant weight. The net biomass of litter was calculated as dry mass.

Soil samplings were conducted in the three replicative plots for each ages class (20-, 30-, 40-, 50-, and 60-year-old plantation) site and for bare land. For each plot, the nutrient content of surface soil layer is influenced by litter and more fluctuates, to investigate the effects of litter of at afforestation ages on soil carbon storage, soil samples from 0–2 cm, 2–5 cm, and 5–10 cm were collected using a small shovel and ruler. Soil samples to a depth of 10–400 cm were obtained with a soil auger (40 mm diameter), collecting at 10 cm intervals. Then, all soil samples were ground, and these 756 ground soil samples were determined for soil organic carbon using the established method of potassium dichromate oxidation-external heating (Bao, 2000). The soil bulk density was measured from samples collected at 10 cm intervals by cutting ring (with 100 cm^3 capacity) from plantation areas of five different afforestation age classes. There were three replicate samples averaged for each soil layer.

The carbon content of forest plants was assumed to be 50% of total dry biomass (Berenguer et al., 2014), so the carbon storage in the aboveground, litter, and soil pools was calculated as follows:

$$\mathrm{VS/LS} = \sum B_i C_i, \tag{3}$$

Where: VS (Mg ha^{-1}) is the carbon storage of vegetation, LS (Mg ha^{-1}) is the carbon storage of litter, B (Mg ha^{-1}) is dry biomass, C is 50%, and i is forest aboveground biomass layer or litter layer.

$$\mathrm{SS} = \sum C_i D_i E_i / 10, \tag{4}$$

Where: SS (Mg ha^{-1}) is the soil carbon storage, C (g kg^{-1}) is the soil organic carbon, D (g cm^{-3}) is soil bulk density, E (cm) is the thickness of soil, and i is soil layer.

$$\mathrm{TS} = \mathrm{VS} + \mathrm{LS} + \mathrm{SS}, \tag{5}$$

Where: TS (Mg ha^{-1}) is total carbon, VS (Mg ha^{-1}) is the carbon storage of vegetation, LS (Mg ha$^{-1)}$ is the carbon storage of litter, and SS (Mg ha^{-1}) is the soil carbon storage.

The carbon sequestration rate (CSR, Mg C ha^{-1} yr^{-1}) was calculated as follows (Berhane et al., 2020):

$$\mathrm{CRS} = (\mathrm{SCS_f} - \mathrm{SCS_i})/t, \tag{6}$$

Where: $\mathrm{SCS_f}$ is the mean soil carbon storage during the final year, $\mathrm{SCS_i}$ is the soil carbon storage in the initial year, and t (yr) is the duration.

Three parallel points were randomly selected in each ages class (20-, 30-, 40-, 50-, and 60-year-old plantation) site and bare land for measuring soil water. The soil samples were taken at 0–400 cm depth using an auger (4 cm diameter) at 10 cm intervals for one point. The soil samples were placed in an aluminum box and weighed on an electronic balance, and then all 720 soil samples were oven-dried at 105°C to constant weight.

The soil water content (SWC) calculation formula is as follows:

$$\mathrm{SWC}\,(\%) = (\text{Wet weight} - \text{dry weight})/\text{dry weight} \times 100\%. \tag{7}$$

Mean soil water content (MSWC) is calculated as follows (Qiu, Fu, Wang, & Chen, 2001):

$$\mathrm{MSWC}\,(\%) = \frac{1}{N_L}\sum_{i=1}^{L}\mathrm{SWC}, \tag{8}$$

Where: MSWC represents mean soil water content, N is the number of sampling soil layers, SWC is the soil water content at soil layer of i, $i = 1, 2, 3, \ldots L$.

2.3 | Statistical analyses

Statistical analyses were performed using the SPSS 22.0 software (IBM, Montauk, NY). One-way ANOVA followed by the Tukey's HSD test was used to analyze the differences of the carbon storage (forest aboveground biomass layer, litter layer, and soil layer from 0–50 cm), and the carbon sequestration rate in different soil layers (between 0–50 cm) for different afforestation ages. The analysis of correlation relationships between SWC and soil organic carbon in the soil profiles and afforestation ages were carried out using ORIGIN 9.0. Significant differences were evaluated at the 0.05 probability level. All data are presented as means ± standard errors of means. All figures were created with ORIGIN 9.0.

3 | RESULTS

3.1 | Effect of afforestation age on carbon storage in *P. sylvestris* plantations

The carbon storage exhibited a tendency to vary in various layers according to afforestation age (Figure 2). In the forest aboveground biomass layer, carbon storage after 30 years was significantly higher than recoded for plantations with other ages (Figure 2a). The carbon storage in the surface litter layer increased from 0.80 Mg ha^{-1} to 3.35 Mg ha^{-1} along the afforestation age gradient (Figure 2b). In the soil layer (0–50 cm), carbon storage after 30 years was 22.57 ± 0.39 Mg ha^{-1} and after 40 years 20.46 ± 1.15 Mg ha^{-1}; this was significantly higher relative to other afforestation ages ($p < 0.05$) (Figure 2c). The carbon storage in the forest aboveground biomass layer comprised the largest proportion of the total carbon pool compared to other pools, with 29.42% for the 20 years plantations, 77.31% for 30 year plantations, 71.81% for 40 year plantations, 80.35% for 50 year plantations, and 67.37% for 60 year plantations (Figure 2). Further analysis found that the carbon storage of each soil layer changed irregularly under different afforestation-age classes (Figure 3). For example, maximum carbon storage occurred in the 60 year afforestation age class at shallow depth (0–2 cm, 2–5 cm, and 5–10 cm) (Figure 3), and the maximum carbon storage occurred for the 30–40 years class in the10–50 cm soil profile.

3.2 | Effect of afforestation age on carbon sequestration rate for *P. sylvestris* forests

The highest carbon sequestration rates for soil layer, litter layer, and forest aboveground biomass layer occurred 20–30 years after planting, with 2.46 Mg C ha^{-1} yr^{-1}, 0.13 Mg C ha^{-1} yr^{-1} and 18.90 Mg C ha^{-1} yr^{-1}, respectively. The rates then decreased significantly with increasing afforestation age, falling to less than 0 in the aboveground biomass layer (Figure 4). But in the soil layer (0–50 cm), the carbon sequestration rate after 60 years was significantly higher in the shallow sections (0–2, 2–5, and 5–10 cm) ($p < 0.05$). While the carbon sequestration rate was higher in the 10–50 cm soil layer which planted for 20-30 years (Figure 5).

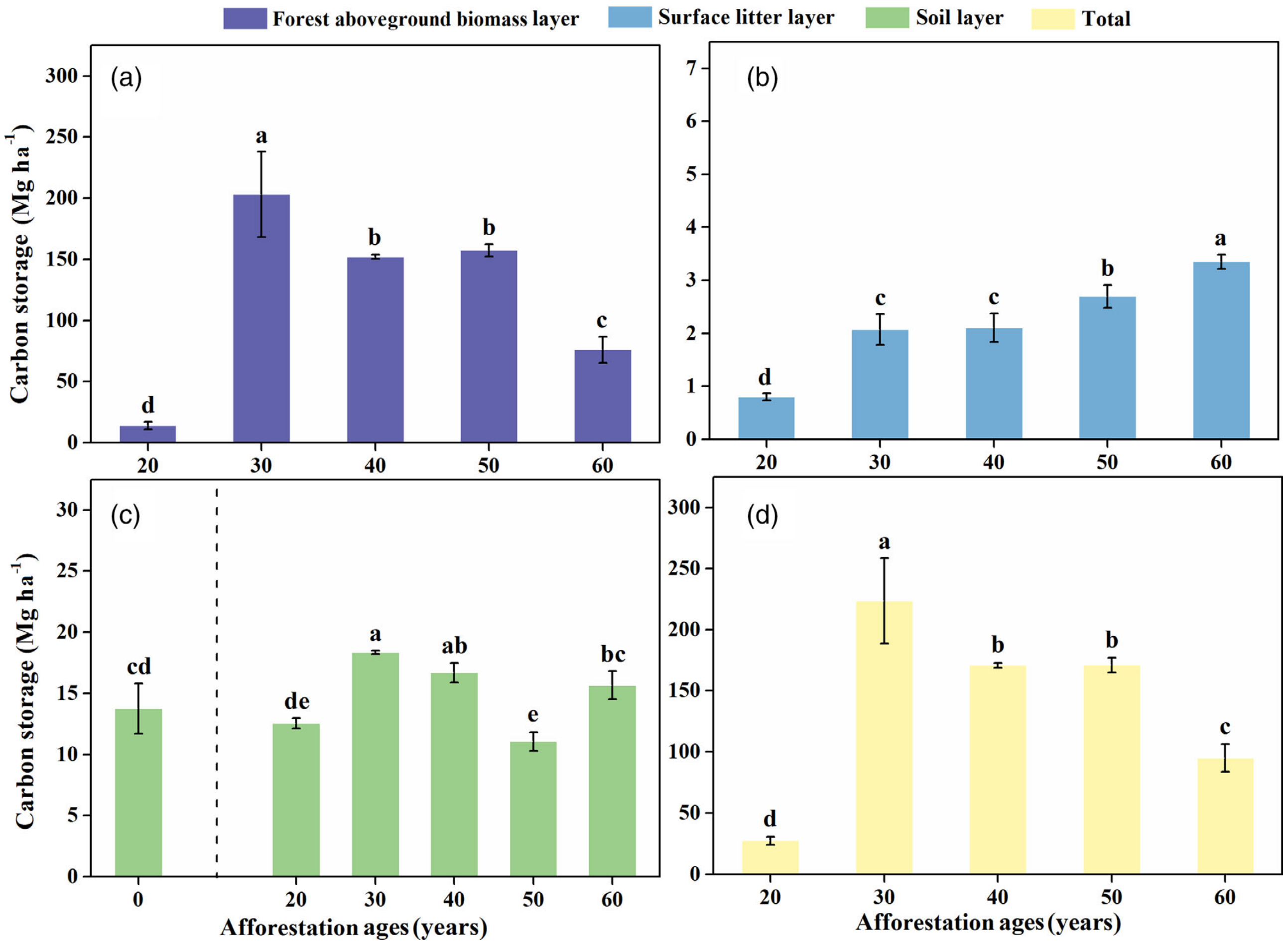

FIGURE 2 Carbon storage in different afforestation age classes (20, 30, 40, 50, and 60 years) under *P. sylvestris* artificial forest. (a) is the carbon storage of vegetation, (b) is the carbon storage of surface litter, (c) is the soil carbon storage (0–50 cm), and (d) was the total carbon storage. All data are presented as means ± standard errors of means. The letters indicate significant difference of mean values for carbon storage ($p < 0.05$) among afforestation ages [Colour figure can be viewed at wileyonlinelibrary.com]

3.3 | The soil water content and soil carbon content associated with *P. sylvestris* plantation forests according to the afforestation age

The MSWC differed for different afforestation age classes (Figure 6). The higher MSWC is associated with 20- and 60-year-old plantation, reaching 5.797% after 20 years and 4.841% after 60 years, and was lower in 30-, 40-, and 50-year-old plantations. But the highest mean soil carbon content occurred after 30 and 40 years (Figure 6), and soil organic carbon was negatively correlated with the SWC (Figure 7, $R^2 = 0.02$, $p < 0.05$) through the whole soil layer (0–400 cm).

4 | DISCUSSION

Improving carbon storage of sandy areas by revegetation is a complex process and one that is impacted by a number of factors (Binkley et al., 2002; Laganiere et al., 2010; Peichl, Arain, Ullah, & Moore, 2010). Numerous studies have reported that afforestation age affects the forest carbon pool to a large extent (Lee et al., 2016; Pregitzer & Euskirchen, 2004). Our study showed that the forest plantations carbon sink was strongly affected by the afforestation age in the semiarid sandy ecosystem. Compared with previous studies, the total carbon storage of *P. sylvestris* forest that afforestation for 0-20 years was less, this may due to the lower environmental background content of soil corbon in sandy ecosystem, and the growth rate of vegetation was lower (Table 2). On the contrary, the carbon sequestration rate for plantations established for 20–30 years was four-times higher than other studies have shown, possibly because our *P. sylvestris* forest was then in the best growth period so the increasing rate of biomass was higher (see: Peichl, Arain, & Brodeur, 2010).

The carbon storage of the forest aboveground biomass layer and soil layer initially increased and then decreased with time since afforestation (20–60 years), and it reached a maximum at 30 years, while carbon storage of surface litter continuously accumulated during vegetation restoration. This may due to the dry branches and fallen leaves accumulating in the plantation forest ecosystem, where the decomposition rate was always less than the accumulation rate. The changes in carbon pools after artificial forest planting were also found to be mainly due to the increase of tree biomass and surface

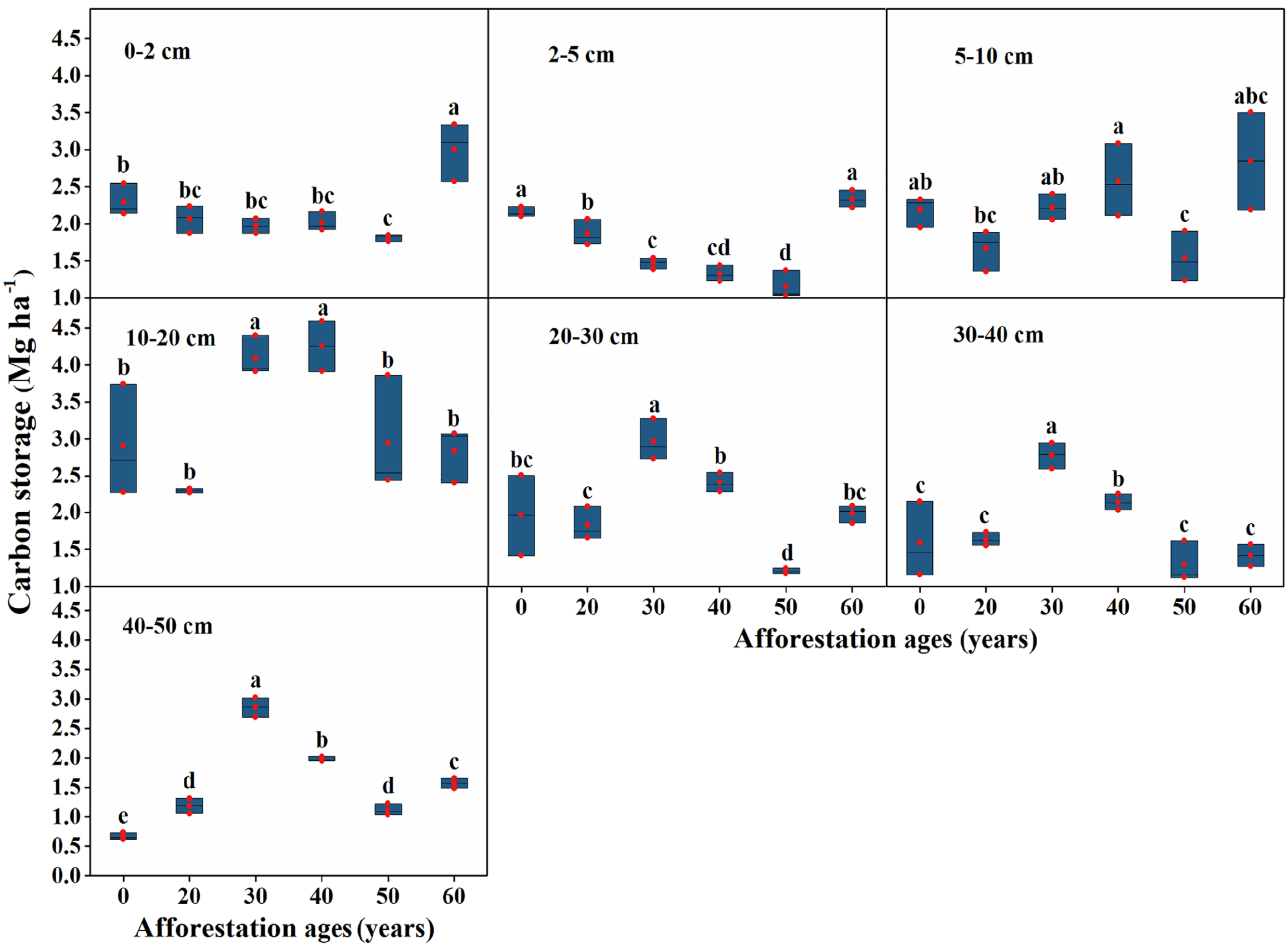

FIGURE 3 Soil carbon storage for *P. sylvestris* forest in different soil layers (0–50 cm). The letters indicate significant differences among the different afforestation ages ($p < 0.05$) [Colour figure can be viewed at wileyonlinelibrary.com]

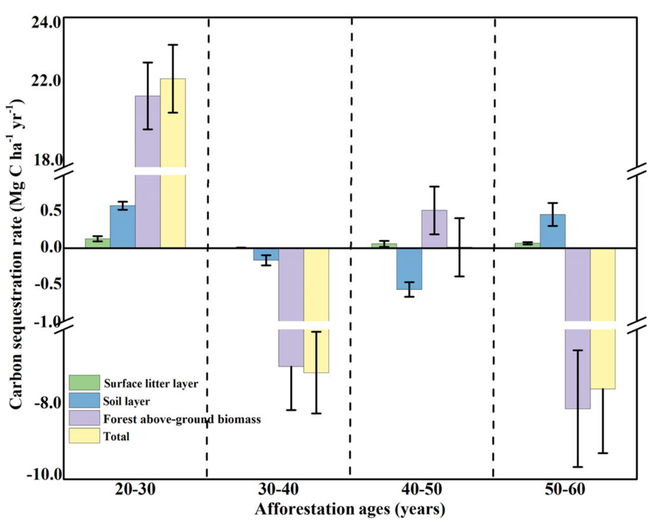

FIGURE 4 Carbon sequestration rate of the soil layer (0–50 cm), litter layer, vegetation layer, and total carbon for the four afforestation ages. The error bars indicate standard deviation of the mean [Colour figure can be viewed at wileyonlinelibrary.com]

litter by various authors (Harmon, Ferrell, & Franklin, 1990; Nosetto, Jobbagy, & Paruelo, 2006). The literature suggests trees grow rapidly at the inception phase of artificial forest plantation and the young forest has higher carbon sequestration potential compared to the old trees (see: Binkley et al., 2002; Coursolle et al., 2012; Liu et al., 2013). We found there was a high initial carbon sequestration rate (from 0–30 years) in forest aboveground biomass layer, litter layer, and soil layer (0–50 cm) (Figure 4). We suspect the photosynthesis of forest was mainly used for its own growth, and later the carbon storage in the aboveground biomass layer and litter layer increased significantly. Peichl, Arain, & Brodeur (2010) evaluated age-related patterns of ecosystem carbon fluxes in a chronosequence of *Pinus strobus*, and found that the net ecosystem productivity of carbon usually peaked in 20–30 years, which is consistent with our results. Our *P. sylvestris* forest probably entered mature stand stage after 35 years, then there was more plantation dieback and less increase because of the natural conditions (see also: Li et al., 2011; Song, Zhu, Li, & Zhang, 2016). When the growth rate of trees was slows, the decomposition rate of the surface litter layer also decreases, and the accumulation degree slows down. Then, carbon storage of the forest aboveground biomass

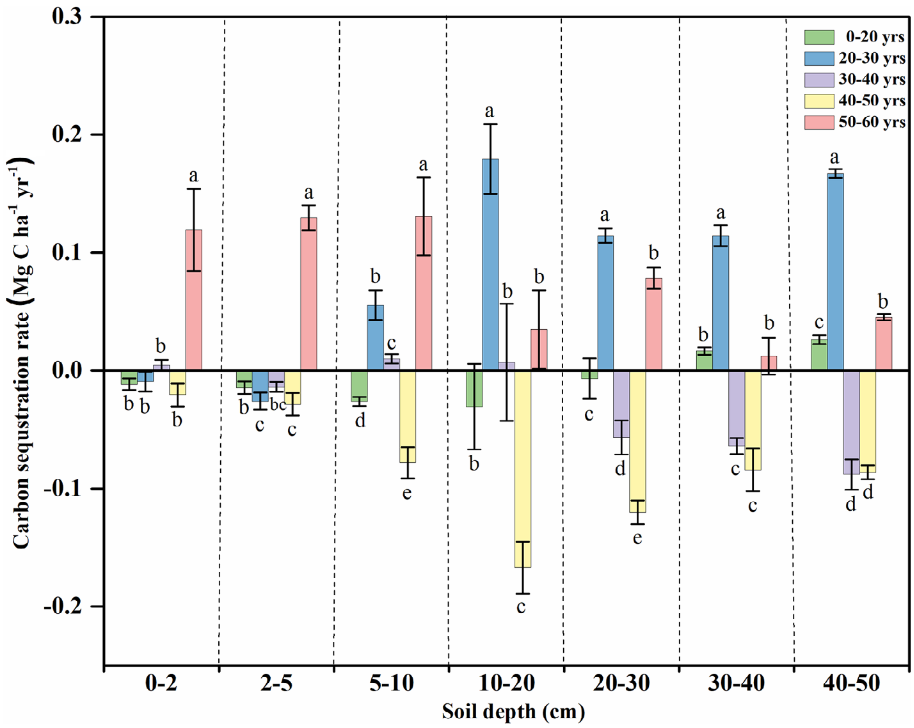

FIGURE 5 Soil carbon sequestration rate of *P. sylvestris* forest in different soil layers (0–2 cm, 2–5 cm, 5–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, and 40–50 cm). The error bars indicate standard errors. Significant differences in soil carbon sequestration rate of different afforestation ages in four soil layers are labeled with different lowercase letters ($p < 0.05$) [Colour figure can be viewed at wileyonlinelibrary.com]

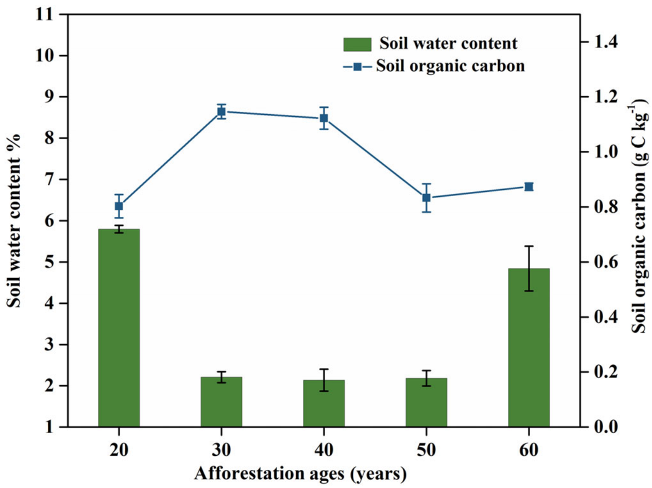

FIGURE 6 Change of soil water content and soil organic carbon under five *P. sylvestris* afforestation chronosequences (each 20, 30, 40, 50, and 60 years) in 0–400 cm depth [Colour figure can be viewed at wileyonlinelibrary.com]

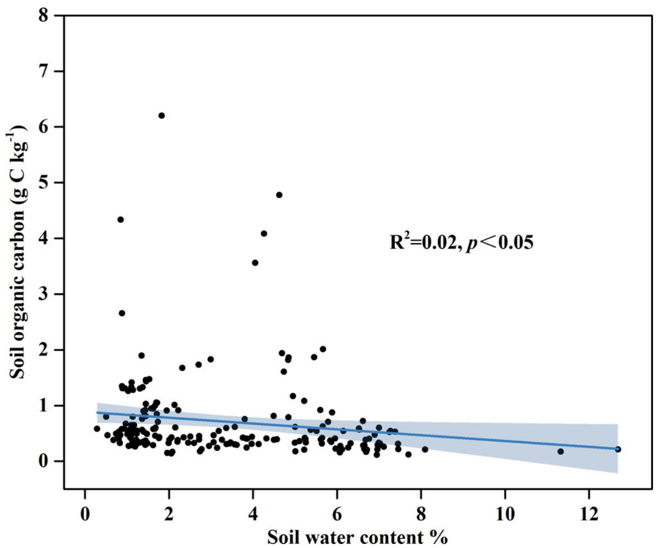

FIGURE 7 Relationship between soil water content and soil organic carbon storage in the 0–400 cm soil layer [Colour figure can be viewed at wileyonlinelibrary.com]

layer and soil layer was also significantly decreased, and the total carbon content was reduced accordingly. The total carbon sequestration rate tended to fall to 0 after 40–50 years. This maybe due to the balance of carbon sequestration rate between soil layer and aboveground biomass layer. In a sandy ecosystem, water and nutrient holding capacity of the soil is lower, thus the nutrients were easy to lose. In addition, the growth of plants would cause the soil carbon storage to transfer to the forest aboveground biomass layer, which leads to the decrease of carbon sequestration rate in the soil profile.

Soil carbon plays an important role in the sandy afforestation ecosystem (Von Lutzow et al., 2006), but there is limited capacity for soil C accumulation (Liao, Luo, Fang, Chen, & Li, 2012). In our study, the soil carbon accumulation varied in different soil layers (0–50 cm) (see: Figure 2). We found obvious carbon sequestration effects in the shallow soil layer (0–10 cm) and for all the afforestation age classes but higher carbon storage was in the 20–50 cm soil layers and occurred between 30–40 years. In sandy land ecosystems, researchers have found that organic carbon transport and conversion in the plantation

TABLE 2 Comparative analysis of the total carbon (0–50 cm soil layer, litter layer, and vegetation layer) storage and sequestration rate of *P. sylvestris* forest and reference forest under different climatic conditions

Land types	Soil depth (cm)	Climatic condition	Age (yr)	Total C storage (Mg ha^{-1})	C sequestration rate (Mg C ha^{-1} yr^{-1})	Reference
Sandy	0–50	Hot and dry	0-20	26.49		Present study
			20-30	223.45	22.34	
			30-40	170.26	−5.49	
			40-50	170.65	0.08	
			50-60	94.68	−6.19	
Mine land	0–30	Dry tropical	0-14	89.62	6.40	Ahirwal & Maiti (2017)
Mine lands	0–30	Dry tropical	0-11	57.16	5.20	Ahirwal, Maiti, & Singh (2017)

vegetation layer–litter layer–soil layer took place as a whole (Vergutz, Manzoni, & Porporato, 2012). The artificial forest in our study area was less disturbed by humans than in such published studies. In one study plant biomass increased in the initial phase of growth, and the litter decomposition and root mass facilitated the development of plants and increased plant biomass with progressive afforestation age (see: Deng & Shangguan, 2017). In our study, compared to 40–50 years, the carbon sequestration rate in the soil layer increased by 50–60 years, and the rates were higher in the 0–10 cm soil layer. This may be due to the surface soil is easily influenced by the environment. And the aboveground biomass layer carbon sequestration rate after 50–60 years was negative, yet positive after 40–50 years. While as a whole (aboveground biomass layer, surface litter layer, and soil layer) our *P. sylvestris* plantation forest ecosystem showed a carbon sequestration rate after 40–50 years that was higher than that after 50–60 years. The indications from other researchers is that organic carbon transformed in the aboveground biomass–litter–soil layer (see: Vergutz et al., 2012). Plant growth will consume soil carbon to accumulate biomass and return it back to the soil in the form of litter, and in different growth stage the conversion rate seems to be different.

Soil water is necessary for revegetation, and vegetation cover is the basis of soil erosion control and carbon sequestration; therefore, soil water should be treated as a supportive service for carbon sequestration (Feng, Zhao, Fu, Ding, & Wang, 2017). The carbon sequestration process needs soil water in a semiarid region, (Lu et al., 2011). In this study, the relationship between SWC and soil organic carbon is inverse across the chronosequence (20–60 years) (see Figure 6). The environment near Yulin City has an average content of sand >90% (Li et al., 2018). In addition, the annual evaporation is much more than the annual precipitation in our study area, approximately three-times (Su et al., 2017). The *P. sylvestris* were in the period of vigorous growth at the beginning of the forest planting, and soil water was continuously consumed for their growth in sand soil (Musa, Zhang, Cao, Wang, & Liu, 2019); however, the groundwater level around Yulin City is approximately 10.4–12.4 m below ground surface (Su et al., 2017), and so the groundwater cannot replenish soil water easily time. As they age, the trees consume soil water for growth, and the higher amounts dry matter were synthesized and accumulated leading to higher litter-fall (Mujuru, Gotora, Velthorst, Nyamangara, & Hoosbeek, 2014). Higher quantities of surface litter improved the quantity of soil microbes and activity of soil microbes, the soil C pool accumulated, and turnover increased (Hu, Wang, & Zeng, 2006). The period of the soil organic carbon accumulation increase corresponds to the lower SWC and a significant negative relationship was found between them. Therefore, one can speculated that carbon accumulation and water consumption are not two independent processes during the growth of vegetation. Soil water and soil carbon are mutually reinforcing.

The afforestation age has great influence on the artificial forest ecosystem of *P. sylvestris* in semiarid regions, which results in imbalance in soil water and carbon storage. Therefore, *P. sylvestris* forest should be managed for lower water consumption and higher carbon sequestration to improve forest sustainability to prepare for face the drier future facing the plantation forest ecosystems. Although the afforestation age has the largest influence in the forest carbon cycle, soil water storage, soil properties, and vegetation composition also have an impact on forest carbon storage. Hence, future study should concentrate on the processes that are affected by many factors.

5 | CONCLUSIONS

This study demonstrated that afforestation age has a significant effect on the C pools of the artificial forest (plantation forests) ecosystem in semiarid sandy regions. The largest carbon storage in the forest aboveground biomass layers occurred in the first 30 years, carbon storage in surface litter increased with time since planting, and carbon storage showed a maximum after 30–40 years taking place especially in the soil layer. The carbon sequestration rate was the highest after 20–30 years, especially in the forest aboveground biomass layer, surface litter layer, and soil layer (0–50 cm). We suggest plantation foresters should take measures that can maintain the carbon sequestration rate so as to increase carbon storage and restore sandy ecosystems. Moreover, significant negative correlation between soil carbon storage and soil water storage through a chronological sequence, suggests time since planting should be considered when seeking to lower water consumption and increase carbon sequestration rate in the management of tree plantations, whith the aim of improving forest sustainability.

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CONFLICT OF INTEREST

The authors declare no competing interests.

AUTHOR CONTRIBUTIONS

Gao-Lin Wu designed the experiments. Ze Huang, Zeng Cui, Yu Liu, and Gao-Lin Wu performed data analyses. Ze Huang, Zeng Cui, Yu Liu, and Gao-Lin Wu wrote the first draft of the manuscript. All authors contributed to editing of the paper and gave final approval for publication.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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