The effect of afforestation on inorganic carbon in soils of arid and semi-arid lands of northwest China

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Abstract

Alxa is a region with severe land desertification and extreme ecological fragility in China. The plantation in the area has effectively curbed the desertification of the local land. However, Studies on soil inorganic carbon(SIC)dynamics after sandy land afforestation are still relatively few. Understanding SIC profiles' distribution and stock changes after afforestation is essential for assessing regional, continental, and global soil carbon sink potential. Using 5, 11, 22, and 46 years of Haloxylon ammodendron (H. ammodendron) plantations and control sands (MS) in the Alxa region, we studied the variation characteristics of SIC with increasing stand age from 0 to 300 cm. Within the 0-300 cm soil layer, SIC storage increased significantly after afforestation, with 46yrs increasing by 6.52 kg m-2 compared to MS. SIC sequestration rate (CSR) decreased with increasing stand age, in the order of 5yrs(0.054 kg m-2 yr-1)¿11yrs(0.025 kg m-2 yr-1)¿22yrs(0.016 kg m-2 yr-1)¿46yrs(0.009 kg m-2 yr-1). The 100˜300 cm SIC storage accounts for over 60% of the SIC pool. Soil carbon pool estimation will be largely underestimated if only the shallow SIC is considered.

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Abstract: Alxa is a region with severe land desertification and extreme ecological fragility in China. The plantation in the area has effectively curbed the desertification of the local land. However, Studies on soil inorganic carbon(SIC)dynamics after sandy land afforestation are still relatively few. Understanding SIC profiles' distribution and stock changes after afforestation is essential for assessing regional, continental, and global soil carbon sink potential. Using 5, 11, 22, and 46 years of Haloxylon ammodendron (H. ammodendron) plantations and control sands (MS) in the Alxa region, we studied the variation characteristics of SIC with increasing stand age from 0 to 300 cm. Within the 0-300 cm soil layer, SIC storage increased significantly after afforestation, with 46yrs increasing by 6.52 kg m^{-2} compared to MS. SIC sequestration rate (CSR) decreased with increasing stand age, in the order of 5yrs(0.054 kg m^{-2} yr^{-1})¿11yrs(0.025 kg m^{-2} yr^{-1})¿22yrs(0.016 kg m^{-2} yr^{-1})¿46yrs(0.009 kg m^{-2} yr^{-1}). The 100˜300 cm SIC storage accounts for over 60% of the SIC pool. Soil carbon pool estimation will be largely underestimated if only the shallow SIC is considered.

Keywords: Soil inorganic carbon; Haloxylon ammodendron plantations; Stand age; Afforestation

1 Introduction

Land sanding and desertification are the most threatening environmental problems in arid desert areas. More than 70% of arid desert lands suffer from long-term sanding or desertification, and land degradation has resulted in a loss of 19-29 Pg of soil carbon (Lal, 2004; Li et al., 2015). Vegetation construction is one of the main ways to improve land degradation in these areas. Related studies have shown that revegetation of sandy areas leads to changes in soil physicochemical properties, and makes it possible for the soil to capture and sequester atmospheric CO_2, increasing the soil carbon sink potential (Huang et al., 2012). Soil carbon pools, including SOC and SIC, are terrestrial ecosystems' largest carbon pools. Due to the potential rapid response of soil carbon pools to vegetation type changes, SOC has been widely and intensively studied by scholars in China and abroad (Deng et al., 2014; Jackson et al., 2002). Compared to studies on SOC, there are few studies on the dynamics of SIC after revegetation. Since the storage of SIC in arid desert areas far exceeds that of SOC, small revegetation-induced changes in SIC may exert a stronger effect than major changes in SOC in changing the terrestrial carbon balance (Gao et al., 2017; Wang et al., 2016). Therefore, the study of SIC changes after revegetation in arid desert areas is crucial for finding "lost carbon sinks" in terrestrial ecosystems.

In arid desert areas, changes in SIC after revegetation are highly uncertain. The Colorado Plateaus Desert, USA, showed a 53.8% reduction in SIC content on the soil surface after 10 years of poplar planting (Sartori et al., 2007). In the Badangirin Desert, China, the SIC content at the soil surface increased by 45.7% after 7 years of planting poplar trees (Su et al., 2010). In the Loess Plateau of China, studies have shown that the SIC content of cultivated land at 0-100 cm soil depth is significantly lower than that of restored plantation forests (Wang et al., 2016). In addition, other studies in the region showed that reforestation only affected the distribution characteristics of SIC in different soil layers and did not change the amount of SIC storage (Chang et al., 2012). Inorganic carbon after revegetation showed different or even contradictory findings in the context of similar stand types, climatic conditions, and plant species. These results suggest that the response of SIC content to afforestation in arid desert areas needs further study. In addition, studies on SIC in arid desert areas have mainly focused on soil profiles of 100 cm or even shallower (Shi et al., 2012), while the changing pattern of SIC below 100 cm is still a big question. Recent studies have found that deeper SIC levels in arid desert areas are more than twice as high as those in shallow, In contrast, within 1 to 3 m of the shrub deserts and desert soil profiles, the soil carbon pool is composed mainly of SIC (Naorem et al., 2022). Therefore, the change pattern of SIC after revegetation in arid desert areas needs to be urgently studied.

Located in the interior of northwestern China, Alxa League is a typical arid desert region with the distribution of Ulaanbaatar, Tengger, and Badangirin Deserts. The region's chronic drought and lack of water, combined with sparse vegetation, make it one of the most active areas of wind-sand in China. The region began vegetating sandy areas in the middle of the last century. As a result, it has extensive artificial sand-fixing forests. To a certain extent, land sanding and sand, and afforestation have typical characteristics of arid desert areas. H. ammodendron belongs to the small tree Quinoa family, which is characterized by its resistance to drought and barrenness. It is the largest sand-fixing tree in the desert area of northwest China, and is called a "desert plantation". In this study, we hypothesized that sandy vegetation restoration could increase SIC storage. To test this hypothesis, we selected four stands (5, 11, 22, and 46 years old, respectively) of the H. ammodendron plantation at the edge of the Badangirin Desert in the Alxa League, and used nearby moving sand (MS) as a control. By collecting soils from 0 to 300 cm profiles in the above sample sites, we focused on (1) the characteristics of soil profile changes in SIC along the age sequence of H. ammodendron plantation; (2) the effects of soil moisture(SM) and pH on SIC; and (3) the importance of deep soil SIC in soil carbon storage estimation.

2 Materials and Methods

2.1 Site Description

The study was conducted in Alxa League, the westernmost part of the Inner Mongolia Autonomous Region.

It is located at 37°24' ~ 42deg47'N, 97deg10' ~ 106deg53'E. The area is dominated by high plains, with large desert and Gobi areas, followed by grassland areas, and smaller mountain, forest, and arable areas. It has an altitude range of 820 ~ 1 400 m. The region has an arid climate and strong winds, and is a typical arid desert area. The average annual temperature is about 8.3 , the average annual precipitation is 40-180 mm, mainly in July and August, and the average annual evaporation is 2,400-4,200 mm. Soil types have obvious zonal characteristics, from northwest to southeast, gray-brown desert soil, gray-desert soil and gray-calcium soil are distributed in order, and in the lake basin area there are saline soils. The vegetation types are mainly desert vegetation, oasis vegetation and mountain vegetation. Natural poplar forests grow in the Ejin Oasis area, while the presence of the Helan Mountains enriches the biodiversity and complexity of the Alxa Plateau system. Alxa region is an ecologically fragile area, which is one of the birthplaces of sandstorms in China. In recent years, around the three major deserts, a large area of artificial afforestation has been carried out, and artificial H. ammodendron plantations have become an important artificial barrier to curb land desertification and promote ecological restoration in the region. Fig. 1 shows the geographical location and experimental survey area of Alxa.

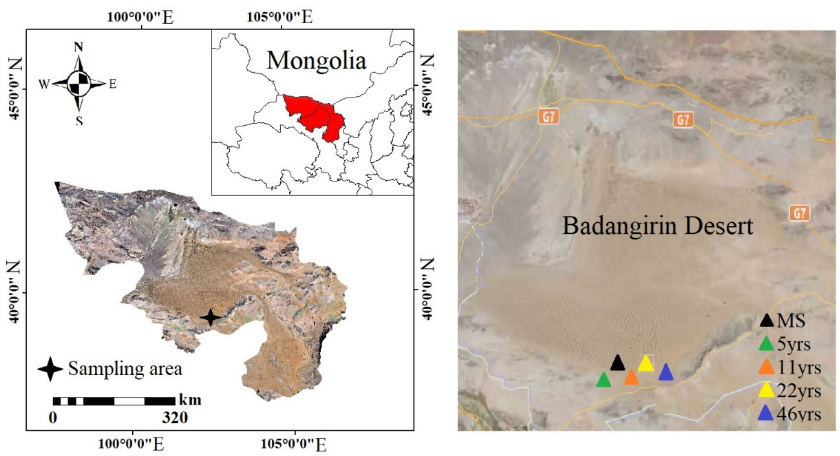

Fig. 1 The geographical location and experimental survey area of Alxa League

2.2 Experimental design

In September 2021, the H. ammodendron plantation at the southeastern edge of the Badangirin Desert in the Alxa League was used as the study object. Using the method of spatial substitution of time, we sequentially selected the H. ammodendron plantation in 2016, 2010, 1999, and 1975 (5, 11, 22, and 46yrs, respectively) for the study, and these four vegetation construction sites were referred to as 5yrs, 11yrs, 22yrs, and 46yrs, respectively, with nearby moving sands (MS) as controls. Because all eras of the H. ammodendron plantation were in moving sands when planted and in the same location, soil texture, standing conditions, and meteorological conditions, satisfying the comparative study of pike soil samples from different eras. The information of each stand age sample site is shown in Table 1.

Tab. 1 The basic description of the studied sites

Stand Age (a)	Stand Age (a)	MS	5yrs	11yrs	22yrs	46yrs
Year of planting	Year of planting	/	2016	2010	1999	1975
Altitude (m)	Altitude (m)	1203.97	1204.86	1204.95	1203.69	1204.37

Stand Age (a)	Stand Age (a)	MS	5yrs	11yrs	22yrs	46yrs
Diameter at breast height (cm)	Diameter at breast height (cm)	/	3.5 ± 1.2	8.9 ± 3.8	12.4± 5.5	22.1 ± 7.5
Mean tree height (cm)	Mean tree height (cm)	/	55± 12	140 ± 28	220 ± 46	420 ± 81
Bulk Density (g cm^{-3})	0 ~ 100cm	1.49	1.49	1.51	1.52	1.52
	100 ~ 200cm	1.49	1.52	1.52	1.52	1.53
	200 ~ 300cm	1.5	1.51	1.52	1.53	1.53

2.3 Soil collection and indoor analysis

In this study, we first selected three sample sites with approximately the same plant community composition within each of the five sample plots of MS, 5yrs, 11yrs, 22yrs, and 46yrs, and sampled the same soil stratum in three replicates at each sample site in 20 cm strata. The soil collected in each stratum was mixed thoroughly and divided into two groups of samples within the three sample points of the five forest age sample plots. One group measured the SIC content and the other group tested soil moisture. To determine the soil volume, we collected complete soil samples using a stainless steel soil sampler with a volume of 100 cm^3. After collecting the soil, we air dried it and passed it through a 2 mm sieve to remove any rocks or root systems larger than 2 mm. To analyze these samples, we ground them with a ball mill and passed them through a 100 mesh soil sieve. Soil inorganic carbon was determined by the air volumetric method, soil pH (water to soil ratio of 2.5:1) was determined by the electrode method, and soil bulk weight was the dry mass per unit volume of soil at 105°C. Soil moisture was determined by weighing the fresh weight of the soil, then drying it at 105°C and weighing the dry weight.

2.4 Data analysis

SIC density and storage(kg m^{-2}) were calculated from soil bulk weight and inorganic carbon content according to the following equation:

(1)

(2)

where SIC_i (g[?]kg^{-1}) is the SIC contents of the i -cm soil profile, BD_i(g[?]cm^{-3}) is the soil bulk density of the i -cm soil profile, and Di (cm) is the soil layer thickness.

SIC sequestration rate (CRS, kg $m^{-2}yr^{-1}$) is calculated as follows:

(3)

where CS_f is the SIC storage in the final year, CS_i is SIC storage in the initial year, and$t$ (years) is the interval between year i and year$f$. A positive value indicates an increase in the SIC pool, while a negative value indicates a decrease.

All statistical analyses were performed using Origin 2022 and SPSS 23.0.One-way ANOVA followed by the Tukey's HSD test (P¡0.05) was used to compare the effects of vegetation restoration on SIC in the study sites.

3 Results

3.1 Profile changes in soil pH, soil moisture, and SIC

The profile changes of soil pH and soil moisture d during the growth of H. ammodendron plantation from MS to 46yrs are shown in Figs. 2a and 2b. The mean soil pH increased and then decreased along the depth of the profile as the age of the H. ammodendron plantation increased. In the 0 ~ 240 cm soil layer, the pH showed an overall increasing trend, and within the 240 ~ 300 cm soil layer, the pH showed a decreasing trend. The soil pH varied from 7.07 to 9.0 throughout the stand age stage, with an overall alkaline soil. Soil moisture, on the other hand, showed a trend of decreasing and then increasing. In the 0 ~ 200 cm soil layer, the soil moisture showed a decreasing trend with a varied range of 3.99 ~ 9.24 cm^3 cm^{-3}, and in the 200 ~ 300 cm soil layer, it showed an increasing trend with a varied range of 4.78 ~ 8.09 cm^3 cm^{-3}.

The profile variation of the SIC content is shown in Fig. 2c. With increasing soil depth, the SIC content showed an overall trend of first increasing and then decreasing. The SIC content first decreased in the surface layer from 0 to 40 cm and then increased again in the soil layer from 40 to 100 cm. Within the 100-260 cm soil layer, the SIC content first decreased and then increased, followed by a continuous decrease in the 260-300 cm soil layer. In the 0 ~ 300 cm soil profile, the SIC content varied from 0.751 to 4.413 g kg^{-1}.

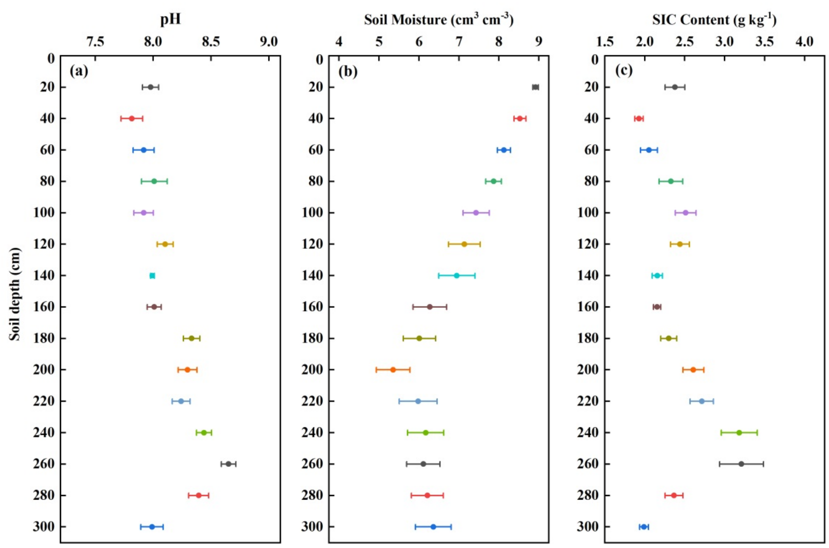

Fig. 2 Variation of pH、SM and SIC along the soil profile

3.2 Variation of SIC density with stand age

The statistical results of SIC density in different stand ages are shown in Table 2. The variation of SIC density for MS, 5yrs, 11yrs, 22yrs, and 46yrs ranged from 0.37 ~ 0.57 kg m^{-2}、0.51 ~ 1.05 kg m^{-2}、0.59 ~ 1.08 kg m^{-2}、0.60 ~ 1.28 kg m^{-2}, and 0.68 ~ 1.35 kg m^{-2}。It can be seen from the mean values that SIC density showed an overall increasing trend with stand age.

Tab. 2 Descriptive statistics of SIC density at 0 ~ 300 cm depth

Planting Age	Min (kg m^{-2})	Max (kg m^{-2})	Mean (kg m^{-2})	SD (kg m^{-2})	CV (%)
MS	0.37	0.57	0.46	0.50	28.70
5yrs	0.51	1.05	0.74	0.16	21.62
11yrs	0.59	1.08	0.74	0.12	16.22
22yrs	0.60	1.28	0.81	0.17	20.99
46yrs	0.68	1.35	0.90	0.19	21.11

The distribution characteristics of SIC density at different stand ages from 0 to 100 cm, 100 to 200 cm, and

200 to 300 cm are shown in Fig. 3. In the comparison of SIC density of MS, 5yrs, 11yrs, 22yrs, and 46yrs, it was found that SIC density gradually increased with the increase of stand age in 0-100cm soil layer, and the difference of SIC density between MS and other stand age stages was significant, and SIC density of 46yrs was significantly higher than that of 5yrs and 11yrs. In the 100-200 cm soil layer, the SIC density with increasing stand age was similar to that of 0-100 cm. In the 200-300 cm soil layer, the change in SIC density with increasing stand age was not significant, and only the difference in inorganic carbon density between MS and other stand age stages was significant, while the difference in inorganic carbon density between other stand ages was not significant ($P < 0.05$). From 0 to 300 cm soil layer, the SIC density values of MS and other stand ages were 46yrs (13.57 kg m^{-2}) > 22yrs (12.16 kg m^{-2}) > 11yrs (11.16 kg m^{-2}) > 5yrs (11.07 kg m^{-2}) > MS (7.04 kg m^{-2}) in order.

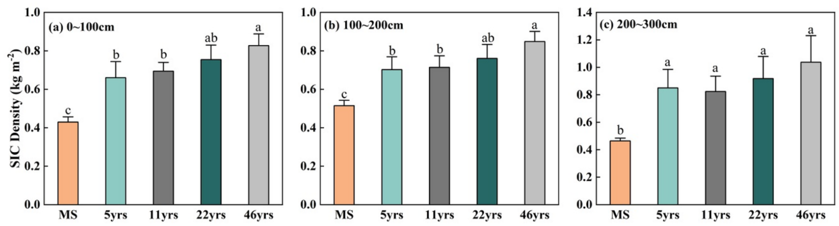

Fig. 3 Variation of SIC density with stand age in different soil layers

Figure 4 reflects the linear fit trend of SIC density with increasing stand age. Within the 0-100 cm soil layer, soil inorganic carbon density in the top 0-40 cm layer increased significantly ($P < 0.05$) with increasing stand age, and within the 100-200 cm soil layer, the 120-140 cm and 160-180 cm layers increased significantly ($P < 0.05$) with increasing stand age, while the rest of the soil layers did not change significantly with stand age. As can be seen from Figure 4, soil inorganic carbon density increased overall with increasing stand age (not significant).

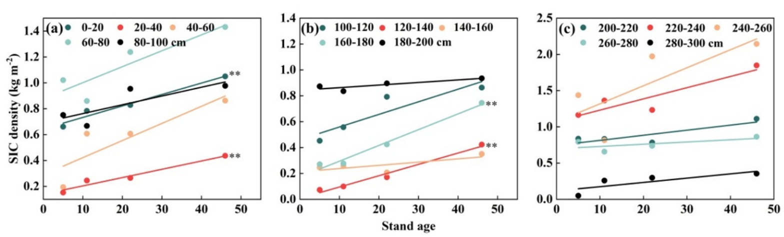

Fig. 4 Correlation between SIC and Stand age

3.3 Effect of soil moisture and pH on SIC content

The relationship between SIC content and pH and soil moisture was evaluated by the linear regression method, as shown in Figure 5. In the 0-300 cm soil layer, SIC content showed a significant negative correlation with soil moisture ($P < 0.001$), while a significant positive correlation with pH ($P < 0.05$) was observed only in the deeper 200-300 cm soil layer. It showed that the degree of influence of soil pH on SIC varied with increasing soil depth, while soil moisture had a significant effect on SIC in all the different soil layers.

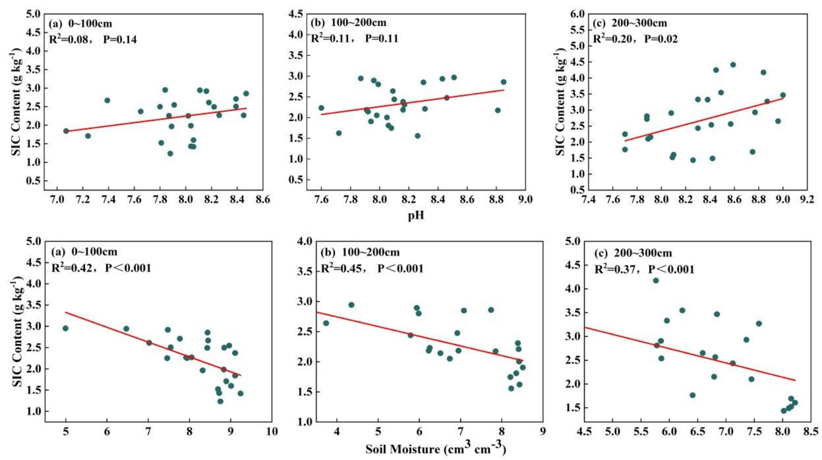

Fig. 5 Correlation of SIC with soil pH and soil moisture

3.4 Variation in SIC storage

The SIC storage in the soil layers of 0 ~ 100 cm and 100 ~ 300 cm at different stand ages are shown in Fig. 6. The SIC storage of MS, 5yrs, 11yrs, 22yrs, and 46yrs in 0 ~ 100 cm soils was 2.15 kg m^{-2} 、 3.30 kg m^{-2} 、 3.47 kg m^{-2} 、 3.77 kg m^{-2}, and 4.14 kg m^{-2}, respectively. The SIC storage in the 100 ~ 300 cm soil layer was 4.89 kg m^{-2} 、 7.76 kg m^{-2} 、 7.68 kg m^{-2} 、 8.39 kg m^{-2}, and 9.43 kg m^{-2}, respectively. Figure 6b indicates that there is still a large amount of SIC storage in the soil layer below 100 cm, and its proportion accounts for more than 60% of the SIC storage in the soil layer from 0 to 300 cm. This result indicates that in arid and semi-arid regions, SIC below 1 m is not negligible in soil carbon stock estimation.

As can be seen from Figure 7, CSR was greatest at 5yrs and least at 46yrs during the MS to 46yrs stand age growth stage. That is, the proportion of the net increase in inorganic carbon stock from MS to 46yrs decreases with increasing stand age. Throughout the study period, CSR in the 0-300 cm soil layer was in the following order: 5yrs (0.054 kg m^{-2} yr^{-1}) > 11yrs (0.025 kg m^{-2} yr^{-1}) > 22yrs (0.016 kg m^{-2} yr^{-1}) > 46yrs (0.009 kg $m^{-2}yr^{-1}$). The results of this study indicate that CSR decreases continuously with increasing stand age.

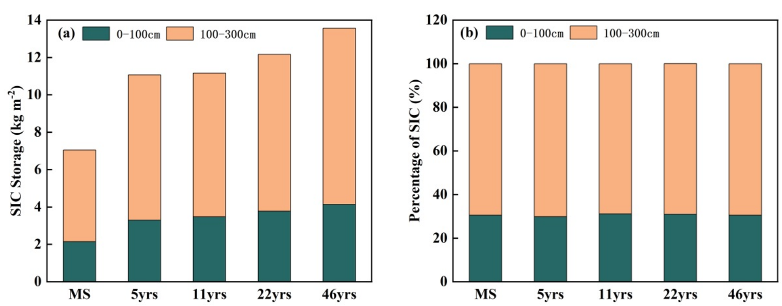

Fig. 6 Distribution characteristics of SIC storage in different soil layers

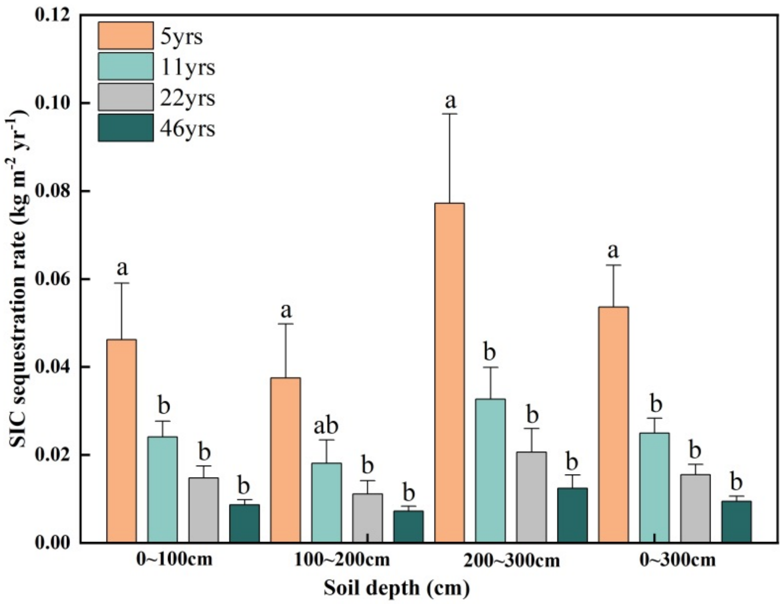

Fig. 7 Variation of SIC sequestration rate with stand age in different soil layers

4 Discussions

4.1 Reasons for profile variation of SIC content

In general, the variation of SOC content with soil depth after afforestation of arid desert areas mainly depends on the distribution of below-ground biomass (Schlesinger and Pilmanis, 1998). In contrast, the variation of SIC content is controlled by a variety of complex factors, such as soil properties, effective precipitation, soil moisture, and partial pressure of CO_2, thus forming a complex profile distribution characteristic (Diaz-Hernandez et al., 2003). (Chang et al., 2012) reported that reforestation of the central Loess Plateau resulted in a redistribution of SIC along different soil layers. This study found that revegetation in sandy areas also caused redistribution of SIC content along the soil profile. The stratification characteristics of the SIC content with increasing stand age further corroborate this view. The accumulation process of carbonate, the main component of inorganic carbon, involves two main chemical reactions (Eqs. 4 and 5). On the one hand, there is an abiotic "inorganic respiration" process in arid sandy soils, which absorbs CO_2 from the atmosphere. Sufficient CO_2can advance reactions (4) and (5) to the right to form loam-forming carbonate rocks. On the other hand, after planting vegetation in sandy areas, the root system releases large amounts of CO_2into the soil by decomposing SOC, producing large amounts of free HCO_3^-和H^+ (Zamanian et al., 2016). The accumulated HCO_3^-can drive reaction (5) to the right, and when Ca^{2+} is sufficient, carbonate can be precipitated to increase the accumulation of SIC (Li et al., 2012; Wang et al., 2015).

(4)

(5)

In this study, the SIC content of the 0 ~ 20 cm surface layer increased after vegetation restoration. The first reason is the increase in soil organic matter and soil microorganisms originating from dead fallen matter in the topsoil layer. During biological processes, the decomposition of soil organic matter and microbial activity increases the soil CO_2 concentration. Subsequently, under adequate soil moisture conditions, driving equations (4) and (5) to the right, more abundant HCO_3^- is formed to bind with Ca^{2+} in the soil, facilitating the formation and precipitation process of carbonate. The second reason is the possible existence of the process of "inorganic respiration" of the soil as described above, which leads to an increase in the SIC content of the soil surface. In the 20 ~ 100 cm soil layer, the SIC content further increased with the profile and showed a significant negative correlation with soil moisture. This result is consistent with the study on the SIC content of saline soils in the southern Gurbantunggut Desert (Wang et al., 2013). The possible reason for this is that in extremely arid areas, effective precipitation is more likely to affect the shallow soil SIC content. The increased CO_2 in the soil is dissolved at shallow depths and follows the effective precipitation downward. This process continuously reacts chemically with shallow Ca^{2+} and Mg^{2+}, which causes the migration and precipitation of carbonates. In the 120 ~ 240 cm soil profile, the variation of SIC content was mainly influenced by root biomass, CO_2 partial pressure Ca^{2+} and HCO_3^-. With the increase of stand age, the deep soil root biomass is also increasing and growing deeper into the soil. On the one hand, the increased input of root litter stimulates the activity of soil microorganisms and accelerates the decomposition of the litter. During decomposition SOC is mineralized to produce more CO_2, driving equation (4) to the right, further dissolving in the soil solution to form HCO3$^-$, which subsequently combines with Ca^{2+} released from decomposing litter to precipitate as $CaCO_3$ (Zhao et al., 2016). On the other hand, in extremely arid soil environments, secondary carbonates can form in the mucilaginous sheaths around root hairs. The root system is enriched with unused excess Ca^{2+} and a large amount of HCO_3^- accumulates in the mucilaginous sheath due to respiration, allowing the mucilaginous sheath to provide a unique environment for Ca^{2+} and HCO_3^- binding. Under these two effects, the formation of secondary carbonates in deep soils is promoted (Monger et al., 2015). (Liu et al., 2014)studied the profile change characteristics of SIC in agricultural fields, and grasslands restored for 12 years and 22 years of restoration, and finally found that SIC storage decreases with revegetation. This is in contrast to the results of this study where SIC content increased with the vegetation restoration sequence. Some soil carbonates may be temporarily decomposed to CO_2 due to the decrease in soil pH and the increase in soil moisture after the restoration of grassland on agricultural land. In deep soils from 240 to 300 cm, the SIC content was significantly and positively correlated with soil pH. Increasing stand age causes decreasing SIC content, which is due to the large amount of organic acid secreted by the deep root system, which makes the pH decrease. Under the conditions of relatively low $Ca_2{}^+$ and HCO_3^- content, the large enrichment of CO_2 from SOC decomposition and root respiration drives equation (5) to the left, leading to carbonate dissolution and lower inorganic carbon content (Jin et al., 2018). In previous studies, soil samples were collected at depths ranging from 20 cm (Li et al., 2021) to 300 cm (Wang et al., 2010), and SIC profile changes exhibited different responses to different soil layer combinations. These results indicated that after afforestation of sandy areas in arid and semi-arid regions, SIC content was mainly influenced by aboveground litter decomposition, effective precipitation, and CO_2 partial pressure in the shallow layer; and by soil moisture, root litter and pH value in the deep layer.

4.2 Effect of vegetation restoration on inorganic carbon stock

Although there are more studies on the effects of revegetation on SIC (He et al., 2016; Li et al., 2016; Wang et al., 2013), there are no clear conclusions yet. A part of the study found that SIC reserves remained unchanged after revegetation, which was attributed to carbonate leaching in the upper part of the profile and precipitation in the deeper part of the profile (Jin et al., 2014; Monger et al., 2015; Wang et al., 2016). Another part of the study found an increase in SIC attributed to the involvement of exotic Ca^{2+} and Mg^{2+} in the formation of SIC (BOETTINGER and SOUTHARD, 1991; Zhao et al., 2016) , the formation of carbonate from biogenic CO_2 (He et al., 2016), or a decrease in soil erosion (Fu et al., 2009). The study also found a decrease in SIC, which was attributed to the transfer of SIC into groundwater with water infiltration (Kessler and Harvey, 2001), or in low pH soil environments, SIC is released into the atmosphere as CO_2 (Liu et al., 2014). The seemingly contradictory results reflect the uncertainty of the changes in SIC storage after revegetation.

In this study, the SIC storage in the sand showed an increasing trend after afforestation. (Su et al., 2010) reported that planting camphor pine and aspen in the Badangirin sands promoted the accumulation of SIC. (Gao et al., 2017) found that SIC storage also increased with stand age sequence after planting aspen (8 ~ 30 years old aspen) in Mauwusu sands, with significantly higher SIC content after vegetation restoration than in moving sands. The findings of this study are consistent with those of the aforementioned scholars on SIC storage after the afforestation of sandy areas. The increase in SIC after the afforestation of sandy areas is due to the high input of litter and the high rate of decomposition of organic matter, resulting in the release of large amounts of CO_2 into the soil (Zhang et al., 2013). A considerable amount of CO_2 is involved in the chemical reaction of formula (4), forming a large amount of HCO_3^-, which leads to the precipitation of loam-forming carbonates (Zamanian et al., 2016). In addition, the trapping and deposition of fine particles in the wind and sand streams by the plant canopy, after the afforestation of sandy areas also contributes to the accumulation of SIC. Soiling fine particles contain a large amount of carbonate, which leads to rapid accumulation of SIC (Chang et al., 2012). However, our results differ from earlier ones on the Loess Plateau of China and the Colorado Plateau Desert, USA (Chang et al., 2012; Sartori et al., 2007). In their previous findings, vegetation restoration reduced SIC storage. The reduction in SIC storage may be caused by surface runoff, and irrigation in these areas, which could reduce dissolved SIC content from the restored vegetation-soil ecosystem. In arid semi-arid sands are not affected by irrigation or heavy precipitation. Therefore, our results suggest that vegetation construction has the potential to increase SIC storage in arid semi-arid sands.

The establishment of vegetation on shifting sands at different ages also provided us with a good-time series to study CSR. This study shows that CSR is not a constant value; instead, it tends to decrease with increasing stand age. The CSR of short afforestation time (<5 years) is greater than that of a long time (>5 years). If we classify the H. ammodendron plantation from 5 to 46 years old as young, near-mature, mature, and over-mature forests, respectively. We found that the CSR was greatest in young stands and least in over-mature stands after moving sand afforestation. Therefore, if the change of CSR over time after vegetation restoration is neglected, the magnitude of long-term changes in SIC storage after sand afforestation will be incorrectly estimated, which will greatly increase the uncertainty of soil carbon estimation. Currently, many studies have only estimated the increase or decrease in SIC storage after afforestation (An et al., 2019; Raza et al., 2020), while few studies have quantified how the change of CSR with afforestation time (Chen et al., 2018; Wang et al., 2019)(Chen et al.,2018; Wang et al.,2019)[34-35][34,35][34, 35]. Therefore, the CSR in these studies was assumed to be the same over 30 years, with the result that SIC storage increments with stand age were overestimated. To improve the accuracy of CSR calculations, we strongly recommend long-term monitoring of SIC at different stages in long-term studies or using space-for-time methods.

4.3 The importance of deep SIC

Most previous studies on SIC have focused on the upper layers, especially the top 1.0 m. However, the excavation of deeper soil profiles becomes more important for the study of SIC storage (Mi et al., 2008; NEPSTAD et al., 1994; Veldkamp et al., 2003). (Li et al., 2007) estimated that the SIC storage from 1 m depth to intact soil is about 57% in sandy soils and 61% in gray desert soils. (Wang et al., 2010) reported that more than 50% of the SIC in forests, scrub, grasslands, and sandy areas in temperate regions of northern China were located at a depth of 100 ˜ 300 cm. (Wang et al., 2013) found stratified storage of SIC at 0 ˜ 1 m, 1 ˜ 3 m, 3 ˜ 6 m, and 6 ˜ 9 m depth in saline and alkaline soils in arid northwest China. SIC storage below 1 m is above 80%, and SIC storage below 3 m is above 50%. The values estimated in this study were higher than theirs, and we found more than 60% of SIC storage in the 1m to 3m soil profiles in sandy and post-afforestation areas. The differences between these values may be due to different soil sampling depths and vegetation types. Compared to the estimated total SIC storage in the top 1 m of the soil of 53.3 Pg, soils below 1 m in the arid desert areas of northwest China still contain 6.2 Pg or more of SIC storage (Mi et al., 2008). Recent studies have shown that carbon uptake in saline soils in arid zones can be as high as 62-622 g C m^{-2} y^{-1}. Thus, on a global scale, the deep soil SIC pool and its variability may be more critical than we have recognized. In China, 47% of the land is arid and semi-arid, and the deeper layers of the soil are rich in SIC. The contribution of deep soil SIC storage to total soil carbon storage after vegetation construction has not been well studied for these areas.

Understanding the changes in deep-section SIC storage is essential for assessing the climate change mitigation potential of soil carbon pools(George et al., 2012; Jobbagy and Jackson, 2000). In this study, we analyzed the soil profile variation of SIC storage along the age of artificial H. ammodendron plantation and its influencing factors. On the one hand, the variation characteristics of SIC storage in different forest age stages provide important data for regional carbon estimation. On the other hand, understanding the effect of vegetation restoration on changes in SIC storage under different soil depth conditions helps us to understand the importance of deep SIC for soil carbon pool estimation. Our results suggest that considering only shallow SIC when assessing the impact of regional vegetation restoration on SIC reserves will result in a significant underestimation of the SIC pool. However, all soil samples are difficult to reach down to 300 cm due to a large amount of labor and cost consumption. In this context, the combination of remote sensing techniques and model simulations for in-depth soil sample collection in typical areas is a feasible method for estimating the soil inorganic carbon pool.

5 Conclusion

In this study, we found that SIC stocks increased from 0 to 300 cm after afforestation in arid semi-arid sandy land, indicating that the afforestation of sandy land increased the soil carbon sequestration capacity. 0-300 cm SIC increased continuously (insignificantly) with stand age, while the difference between MS and other stand age stages of soil inorganic carbon was significant. Afforestation in semi-arid sandy areas not only increased SIC storage but also significantly changed the profile distribution characteristics of SIC. Soil moisture had a significant effect on SIC in all layers, while pH had a significant effect on SIC in deep layers. The decreasing rate of inorganic carbon fixation with increasing stand age implies that the rate of soil inorganic carbon fixation is not a constant value, and it is necessary to quantify the temporal pattern of SIC changes to accurately estimate the dynamics of regional SIC stocks. Our study also highlights the importance of deep SIC stocks in semi-arid regions in soil carbon sink estimation.

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