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Effects of afforestation on soil carbon and its fractions: a case study from the Loess Plateau, China

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Abstract Afforestation has been implemented to reduce soil erosion and improve the environment of the Loess Plateau, China. Although it increased soil organic carbon (SOC), the stability of the increase is unknown. Additionally, the variations of soil inorganic carbon (SIC) following afforestation needs to be reconfirmed. After planting *Robinia pseudoacacia*, *Pinus tabuliformis*, and *Hippophae rhamnoides* on bare land on the Loess Plateau, total soil carbon (TSC) was measured and its two components, SIC and SOC, as well as the light and heavy fractions within SOC under bare lands and woodlands at the soil surface (0–20 cm). The results show that TSC on bare land was 24.5 Mg ha^{-1} and significantly increased to 51.6 Mg ha^{-1} for *R. pseudoacacia*, 47.0 Mg ha^{-1} for *P. tabuliformis* and 39.9 Mg ha^{-1} for *H. rhamnoides*. The accumulated total soil carbon under *R. pseudoacacia, P. tabuliformis, and H. rhamnoides,* the heavy fraction (HF-SOC) accounted for 65.2, 31.7 and 76.2%, respectively; the light fraction (LF-SOC) accounted for 18.0, 52.0 and 4.0%, respectively; SIC occupied 15.6, 15.3 and 19.7%, respectively. The accumulation rates of TSC under *R.*

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pseudoacacia, P. tabuliformis, and *H. rhamnoides* reached 159.5, 112.4 and 102.5 g m^{-2} a^{-1}, respectively. The results demonstrate that afforestation on bare land has high potential for soil carbon accumulation on the Loess Plateau. Among the newly sequestrated total soil carbon, the heavy fraction (HF-SOC) with a slow turnover rate accounted for a considerably high percentage, suggesting that significant sequestrated carbon can be stored in soils following afforestation. Furthermore, afforestation induces SIC sequestration. Although its contribution to TSC accumulation was less than SOC, overlooking it may substantially underestimate the capacity of carbon sequestration after afforestation on the Loess Plateau.

Keywords Soil carbon sequestration · Soil organic carbon · Organic carbon fractions · Soil inorganic carbon · Afforestation

Introduction

Soil carbon, the largest carbon pool in terrestrial ecosystems, has received considerable attention because of its influence on global warming (Schulze and Freibauer 2005; Mi et al. 2008; Trumbore and Czimczik 2008; Wei et al. 2012a). It is composed of soil organic carbon (SOC) and soil inorganic carbon (SIC) pools. SOC, as one of the most important indicators of soil quality, provides basic data for studying soil productivity, hydrology and greenhouse gas balances. Similarly, the variation of SIC also plays an important role in the dynamic changes in soil carbon pools and atmospheric CO_2 concentrations (Emmerich 2003; Singh et al. 2007). Both the SOC and SIC may be greatly influenced by land use and land cover changes (LUCC) (Gamboa and Galicia 2011; Mujuru et al. 2013; Yu et al.

2014; Teferi et al. 2016). During numerous patterns of LUCC, afforestation and its effect on SOC and SIC have attracted considerable attention (Wei et al. 2012b; Korkanç 2014; Cheng et al. 2015; Hu et al. 2016).

Generally, afforestation can elevate SOC stock by introducing plant litter from leaves and roots into the soil. The SOC pool can be subdivided into the light fraction of SOC (LF-SOC) and heavy fraction of SOC (HF-SOC), according to densities and turnover rates (Christensen 2001). The LF-SOC can represent small changes in the soil caused by human activities or natural changes before the variation in total soil carbon (TSC), which is a unstable, changing compose with strong biological activities in soil (Murage et al. 2007). The HF-SOC is considerably more stable because of its lower decomposition rates due to varying degrees of physical and chemical protection (Golchin et al. 1995). The HF-SOC plays an important role in the process of synthesis and decomposition of soil organic carbon. Based on the different turnover rates, changes in LF-SOC and HF-SOC reflect the stability of SOC following afforestation, which is crucial to assess whether afforestation can permanently fix atmospheric CO_2 in soils. However, the dynamics of LF-SOC and HF-SOC after afforestation have been rarely reported for arid and semiarid regions. Moreover, compared to the attention often given to SOC, the dynamics of SIC following afforestation have received much less consideration. Nevertheless, SIC is the dominate form of soil carbon in arid and semiarid areas and its subtle fluctuation has the potential to alter the balance of soil carbon pool in these regions (Mi et al. 2008; Wang et al. 2010). Although it was proposed that SIC could be induced by vegetation rehabilitation (Lal 2001, 2009), relevant field data has been lacking. Some studies, which showed afforestation reduced or redistributed SIC, aggravated the complexity of SIC variation following afforestation (Sartori et al. 2007; Chang et al. 2012).

The Loess Plateau is the largest plateau in the world, and is covered by wind-blown silt or loess. It is important to global carbon cycles (Wang et al. 2011). Afforestation with *Robinia pseudoacacia*, *Pinus tabuliformis* and *Hippophae rhamnoides* has been implemented to reduce soil erosion and improve the long-term environment. Recently, studies found that afforestation significantly increased SOC on the Loess Plateau (Qiu et al. 2010; Chang et al. 2011; Feng et al. 2013; Zhan et al. 2013), while the stability of the increased SOC is unknown. Additionally, there has been controversy about the impact of afforestation on the SIC on the Loess Plateau (Chang et al. 2012; Tan et al. 2014), indicating that the variation of SIC following afforestation needs to be reconfirmed in this region. Therefore, we measured TSC, SIC and SOC, as well as LF-SOC and HF-SOC after planting *R. pseudoacacia* (17 years), *P.*

tabuliformis (20 years) and *H. rhamnoides* (15 years) on bare land (BL) on the Loess Plateau. The objectives of this study were to: (1) explore the responses of SOC and its two density fractions to afforestation; and, (2) assess the change in SIC following afforestation.

Materials and methods

Study area description

The study area is located at the Huaiping forest farm ($34°47'–34°51'$N and $108°05'–108°10'$E) in Yongshou County, Shaanxi Province on the Loess Plateau of China. The region has a typical temperate continental climate with an elevation from 1123 to 1417 m.a.s.l. Mean annual temperature is 11.5 °C and the average frost-free period lasts 163 days. Average annual precipitation is 501.7 mm with 48% occurring in summer. Mean annual evaporation is 1378.1 mm, which is greater than the average annual precipitation. The soil type is cinnamon soil (Chinese Soil Taxonomy) with pH 7.9 to 8.3. In the study site, afforestation on bare land with *R. pseudoacacia*, *P. tabuliformis*, and *H. rhamnoides* has been implemented since the 1970s, and has made remarkable achievements.

In our study, four treatments were carried out: BL (control), *R. pseudoacacia*, *P. tabuliformis*, and *H. rhamnoides* plantings on bare land (Table 1).

Soil sampling

Three sample plots were selected within each treatment adjacent and 50 m apart. In October 2014, three 10 m × 10 m subplots were randomly established for soil sampling. In accordance with an S-shaped curve, five soil cores were removed using a soil auger (10 cm in diameter) at the surface soil layers (0–20 cm) after removing litter and were mixed to obtain a homogenized composite sample. The composites air-dried in the laboratory and sieved with a 2-mm mesh sieve for analysis. Soil bulk density was randomly sampled three times using a metal corer (100 cm^3 volume) and calculated from the dry weight of the volume.

Density fractionation

The soil was divided into two portions based on density fractionation. The LF-SOC was isolated by flotation in a sodium iodide (NaI) solution. Ten grams of air-dried soil (< 2 mm) was placed in a 100 ml centrifuge tube with 50 ml NaI (density 1.70 g cm^{-3}). The material was shaken at 200 rpm for 1 h and centrifuged at $1000 \times g$-force for 20 min. Material floating on the surface of the NaI solution was aspirated and filtered with a vacuum filter unit (with

Table 1 General characteristics of the study site

Site	Location	Stand age (year)	Aspect	Slope (°)	Altitude (m)	Density (trees ha^{-1})	Tree height (m)	DBH (cm)	Soil type
R. pseudoacacia	34°50′N–108°05′E	17	NW	15–20	1321	1525 ± 109	8.27 ± 0.38	8.87 ± 0.43	Cinnamon soil
P. tabuliformis	34°50′N–108°06′E	20	NW	15–20	1366	1650 ± 132	11.02 ± 0.50	10.81 ± 0.45	Cinnamon soil
H. rhamnoides	34°49′N–108°08′E	15	NW	10–15	1325	4120 ± 389	4.15 ± 0.24	6.22 ± 0.29	Cinnamon soil
Bare land	34°49′N–108°05′E	–	NW	10–15	1304	–	–	–	Cinnamon soil

0.45 μm nylon filter paper). The shaking-centrifugation-aspiration process was repeated twice. The sample on the nylon filter paper was rinsed thoroughly with 75 ml CaCl$_2$ solution (density 0.01 mol L^{-1}) and 75 ml deionised water, collected in beaker and designated as LF-SOC. The light fractions were dried at 60 °C for 72 h to a constant weight.

The residual material in the centrifuge tube was re-suspended with 100 ml deionised water and shaken for 10 min, then centrifuged for 15 min at 3000×g-force. This process was repeated three times. The sediment was transferred to a beaker and collected as HF-SOC. The heavy fractions were dried to a constant weight.

Carbon contents in the whole soil, and light and heavy fractions

TSC (total soil carbon) was measured with a liqui TOC II total organic carbon analyzer (Elementar, Germany). SOC was determined using the K$_2$Cr$_2$O$_7$-H$_2$SO$_4$ oxidation method described by Walkley and Black (1934). SIC was calculated as the difference between total soil carbon and soil organic carbon (Chang et al. 2012; Liu et al. 2015).

The LF-SOC was ground to pass through a 0.075 mm sieve and the organic carbon of the light fractions was determined using a Vario EL III elemental analyzer (Elementar, Germany). The organic carbon of the heavy fractions was also determined using the K$_2$Cr$_2$O$_7$–H$_2$SO$_4$ oxidation method as described by Walkley and Black (1934), because SIC may be contained in HF-SOC.

Data calculation and analysis

$$\text{Soil carbon stock per unit area (Mg ha}^{-1})$$
$$= 0.1 \times D \times B \times C \qquad (1)$$

where *D* is the soil depth (cm), *B* is the soil bulk density (g cm^{-3}), and *C* is the soil carbon content (g kg^{-1}).

$$\text{Accumulation rates of soil carbon (Mg ha}^{-1}\,\text{a}^{-1}) = (SC - SC_0)/n$$
$$(2)$$

where SC is soil carbon per unit area in forested land (Mg ha^{-1}), SC$_0$ is soil carbon per unit area in bare land (Mg ha^{-1}), and n is planting years.

SPSS 13.5 software was used for all statistical analysis. Comparisons were examined using a one-way analyses of variance and the least significant difference test at a significance level of 0.05.

Results

Changes to soil carbon stock after afforestation

Afforestation significantly enhanced soil carbon stock (Fig. 1). In *R. pseudoacacia* plantations, TSC reached 51.6 Mg ha^{-1}, and was significantly higher than under *H. rhamnoides* plantations (39.9 Mg ha^{-1}) and on bare land (24.5 Mg ha^{-1}). No significant differences were found
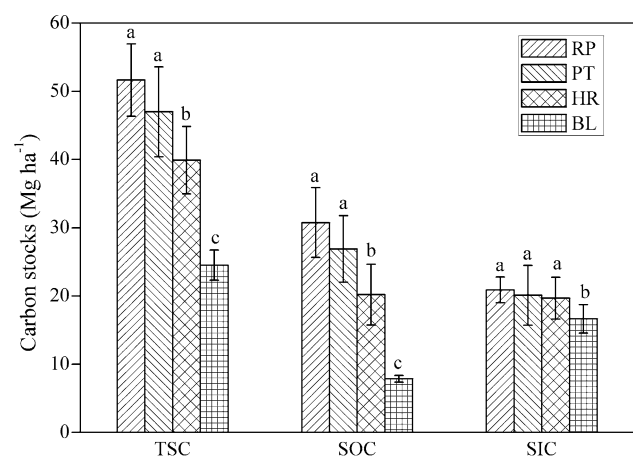
Fig. 1 Total soil carbon (TSC), soil organic carbon (SOC) and soil inorganic carbon (SIC) in *Robinia pseudoacacia* (RP), *Pinus tabuliformis* (PT), and *Hippophae rhamnoides* (HR) plantations, and on bare land (BL) (mean ± standard deviation). Means with letters are significantly different at the 0.05 level of significance ($p < 0.05$)

between *R. pseudoacacia* and *P. tabuliformis* plantations. Both SOC and SIC were increased by tree cover. SOC under *R. pseudoacacia* and *P. tabuliformis* plantations showed no significant differences but were higher than under bare land (7.9 Mg ha^{-1}). SOC under *H. rhamnoides* plantations was 20.2 Mg ha^{-1}, 12.3 Mg ha^{-1} higher than under bare land. SIC under *R. pseudoacacia*, *P. tabuliformis* and *H. rhamnoides* plantations were 25.4, 20.7 and 18.2% higher than under bare land (16.7 Mg ha^{-1}), respectively.

Afforestation elevated the LF-SOC and HF-SOC stocks (Fig. 2). LF-SOC stock under the bare land was 0.3 Mg ha^{-1} and significantly increased to 0.9, 12.0 and 5.2 Mg ha^{-1} under *H. rhamnoides*, *P. tabuliformis*, and *R. pseudoacacia* plantations, respectively. HF-SOC stock on bare lands was 7.5 Mg ha^{-1}; afforestation remarkably elevated it by 11.7 Mg ha^{-1} for *H. rhamnoides*, 7.1 Mg ha^{-1} for *P. tabuliformis* and 17.7 Mg ha^{-1} for *R. pseudoacacia*. Additionally, afforestation varied the proportions of LF-SOC and HF-SOC accounting for the SOC under the *R. pseudoacacia* and *P. tabuliformis* plantations (Table 2). The proportion of LF-SOC in SOC increased from 4.2% under bare land to 44.7% under the *P. tabuliformis* plantation and 17.0% under the *R. pseudoacacia* plantation, while the proportion of HF-SOC in SOC
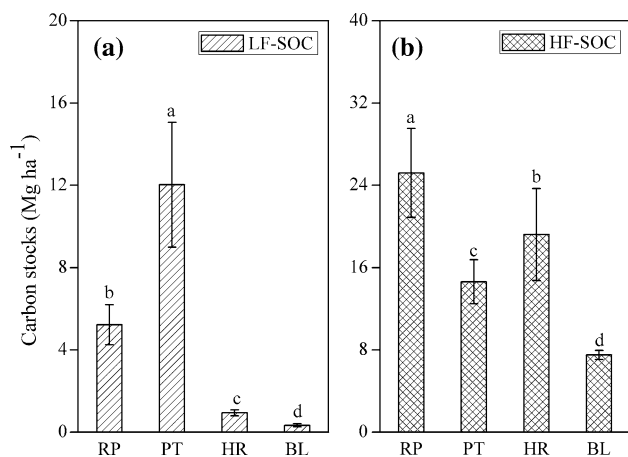
decreased from 95.4% on bare lands to 54.4% under *P. tabuliformis* plantations and 81.9% under *R. pseudoacacia* plantations.

Accumulation rates of soil carbon under different forest plantations

Afforestation of bare lands resulted in a greater increase in soil carbon stocks from land not planted with trees. The accumulation rates of TSC, SOC, SIC, HF-SOC and LF-SOC under different afforested lands are shown in Table 3. The accumulation of TSC within the upper 20 cm of soil under *R. pseudoacacia* reached 159.5 g m^{-2} a^{-1}, 55.6% higher than that under *H. rhamnoides* and 41.9% higher than that under *P. tabuliformis*. Compared to the *H. rhamnoides* plantation, the accumulation of SOC under *R. pseudoacacia* and *P. tabuliformis* was enhanced by 63.6% and 15.7%, respectively. The *P. tabuliformis* plantation had the highest accumulation of LF-SOC, followed by *R. pseudoacacia* and *H. rhamnoides*. But the accumulation of HF-SOC under *P. tabuliformis* (35.6 g m^{-2} a^{-1}) was the lowest. The rankings of accumulation of HF-SOC was *R. pseudoacacia* > *H. rhamnoides* > *P. tabuliformis*.

Contribution of soil carbon fractions to total soil carbon

The contribution of LF-SOC, HF-SOC and SIC to increased TSC after afforestation is shown in Fig. 3. In the *P. tabuliformis* plantation, the proportion of LF-SOC, HF-SOC and SIC in accumulated TSC reached 52.0, 31.7 and 15.3%, respectively; in the *H. rhamnoides* plantation, the LF-SOC, HF-SOC, and SIC made up 4.0, 76.2 and 19.7% of the accumulated TSC, respectively; in the *R. pseudoacacia* plantation, they occupied 18.0, 65.2 and 15.6% of the newly formed TSC, respectively. In addition, Fig. 3 also showed that more than 70% of the accumulated SOC was occupied by HF-SOC both under *R. pseudoacacia* and *H. rhamnoides*. In *P. tabuliformis* plantations, this proportion was less than 40.0%, and 61.4% of the accumulated SOC was accounted by LF-SOC.

Discussion

Effect of afforestation on soil organic carbon and its fractions

The results of this study indicate a significant increase in SOC (soil organic carbon) after planting *Robinia pseudoaccaia*, *Pinus tabuliformis*, and *Hippophae rhamnoides* on bare land (Fig. 1). Our results are supported by Qiu et al. (2010), Wang et al. (2011) and Jiao et al. (2012), and these

Fig. 2 LF-SOC and HF-SOC stocks in *Robinia pseudoacacia* (RP) plantations, *Pinus tabuliformis* (PT) plantations, and *Hippophae rhamnoides* (HR) plantations, and bare lands (BL) (mean ± standard deviation). Means with different letters within each treatment are significantly different at the 0.05 level of significance ($p < 0.05$)

Table 2 The distribution of organic carbon in different fractions (%)

Plantations	HF-SOC	LF-SOC	Others
R. pseudoacacia	81.9	17.0	1.1
P. tabuliformis	54.4	44.7	0.9
H. rhamnoides	95.1	4.7	0.2
Bare land	95.4	4.2	0.4

Table 3 Accumulation of soil carbon under different forest species (g m^{-2} a^{-1})

Plantations	TSC	SOC	SIC	HF-SOC	LF-SOC
R. pseudoacacia	159.5 ± 19.4 a	134.7 ± 28.5 a	24.9 ± 5.4 a	104.1 ± 23.9 a	28.8 ± 5.3 b
P. tabuliformis	112.4 ± 24.9 b	95.2 ± 22.8 b	17.2 ± 14.3 a	35.6 ± 9.4 c	58.5 ± 14.8 a
H. rhamnoides	102.5 ± 19.3 b	82.3 ± 27.2 c	20.2 ± 8.3 a	78.1 ± 27.5 b	4.1 ± 0.6 c

Means with letters are significantly different at the 0.05 level of significance ($p < 0.05$)

TSC total soil carbon, *SOC* soil organic carbon, *SIC* soil inorganic carbon, *HF-SOC* heavy fraction of SOC, *LF-SOC* light fraction of SOC

Fig. 3 Contribution of LF-SOC, HF-SOC, SIC, and some undetected soil carbon such as dissolved organic carbon (Others), to the accumulated total soil carbon under *Robinia pseudoacacia* (RP), *Pinus tabuliformis* (PT), and *Hippophae rhamnoides* (HR) plantations
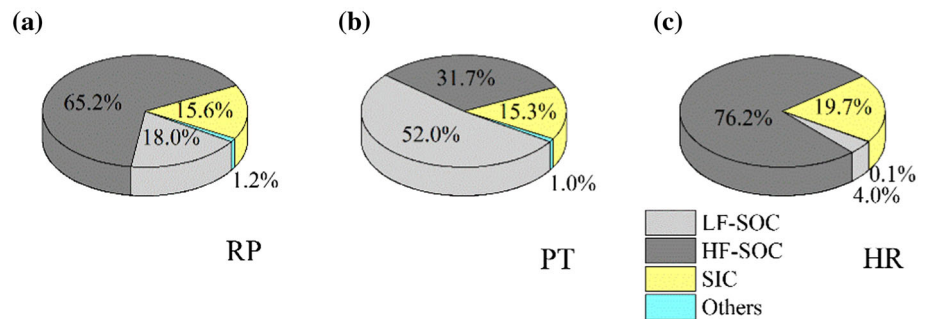
studies also illustrate the significant potential for SOC sequestration following afforestation on the Loess Plateau. A substantial carbon input, such as fine root mortality and leaf shedding, contributes to increase the SOC (Huang et al. 2012). Compared with bare lands (BL), the plantations receive more roots and litter from tree cover, resulting in rapid soil organic carbon (SOC) accumulation.

Among the accumulated SOC both under *R. pseudoacaia* and *H. rhamnoides*, HF-SOC accounted for a large proportion. Under *P. tabuliformis*, more than half of the increased SOC was accounted for LF-SOC (Fig. 3). The difference between *R. pseudoacacia* and *P. tabuliformis* plantations may be due to the different decomposition rates of forest litter. Lignin is lower in the leaves of *R. pseudoacacia* and *H. rhamnoides* than in *P. tabuliformis* needles, which cannot be rapidly decomposed by microorganisms (Berg et al. 1982; Aerts 1997). The distinction in chemical components between coniferous and deciduous leaves may result in different proportions of LF-SOC in the increased soil organic carbon. Additionally, a high percentage of the HF-SOC in the increased soil organic carbon under *R. pseudoacacia* and *H. rhamnoides* plantations may be related to the mechanical component of soil in the Loess Plateau study area. The formation of HF-SOC which is possibly hidden in microaggregates or adsorbed on the surface of mineral particles needs many silt and clay particles (Christensen 2001; Paul et al. 2008). The fine particles of the Loess Plateau were relatively abundant which is likely suitable for forming a substantial amount of HF-SOC. It is stable and not easily decomposed and can be sustained for a long time (at least decades) in soil (Golchin et al. 1995). Plantation of *R. pseudoacacia*

and *H. rhamnoides* yielded large amounts of HF-SOC, indicating afforesting with broad-leaved species on the Loess Plateau is an effective method for fixing SOC stably.

Effect of afforestation on soil inorganic carbon

In our study, soil inorganic carbon (SIC) stocks under three different plantations were all significantly greater than under bare lands (Fig. 1). In other areas of the Loess plateau, Zhang et al. (2012) reported that the density of SIC in shrublands is higher than in grasslands and croplands. Jin et al. (2014) found that forestlands showed higher SIC contents than grasslands. Similarly, Su et al. (2010), Li et al. (2012) and Liu et al. (2015) also found vegetation rehabilitation elevated the SIC content in sandy soils. These results demonstrate that SIC in arid and semiarid areas is not permanent and can be affected by afforestation.

The mechanism of afforestation effects on varying SIC is not entirely certain. Pedogenic carbonate (PIC) formation under forested lands or carbonate erosion on bare lands may provide some answers. PIC is an important fraction of SIC and its accumulation involves two main reactions:

$$CO_2 + H_2O \leftrightarrow HCO_3^- + H^+ \tag{3}$$

$$Ca^{2+} + 2HCO_3^- \leftrightarrow CaCO_3 + H_2O + CO_2 \tag{4}$$
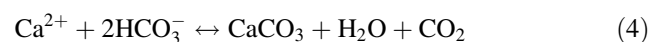
In general, an increase in soil CO_2 as a result of SOC decomposition and root respiration following afforestation (Zhang et al. 2013) would lead to production of HCO_3^-. The accumulated HCO_3^- can drive reaction (4) to the right, resulting in carbonate precipitation (Wang et al. 2015). The soil on our study site is alkaline with pH 7.9–8.3, and rich in available cations. Afforestation resulted in large

quantities of leaf litter and root input into the soil and dramatically elevated the CO_2 concentration. Under alkaline conditions, the emitted CO_2 combining with available cations may cause continuous PIC accumulation following afforestation (Meyer et al. 2014).

On the other hand, the difference of SIC stock between plantations and bare lands may be attributed to carbonate loss under bare lands. Vegetation on bare lands was sparse and provided limited soil protection, especially for the surface layer. The runoff, which contained masses of dissolved inorganic carbon, and the sediment discharge on bare lands, were much greater than for the plantations. Precipitation in the study area is not very significant but it is relatively centralized. Carbonate erosion by runoff may cause a lower SIC stock on bare lands. Overall, the plantations stored more SIC than bare lands indicating that forested lands have greater potential as an SIC sink than bare lands. The proportion of sequestered SIC in newly increased TSC exceeds 15% (Fig. 3), suggesting that the variation of SIC cannot be overlooked in assessing the effects of afforestation on soil carbon, especially in the Loess Plateau.

The accumulation rates of soil carbon

The accumulation of TSC (total soil carbon) within the top 20 cm soil layers under *R. pseudoacacia, P. tabuliformis,* and *H. rhamnoides* reached 159.5, 112.4 and 102.5 g m^{-2} a^{-1}, respectively (Table 3). Afforestation resulted in faster TSC accumulation rates than in the southern edge of the Badan Jaran Desert (Su et al. 2010) and in the southern part of the Horqin Sandy Land (Li et al. 2012), suggesting that afforestation on the Loess Plateau may have more potential for soil carbon sequestration than in other semiarid regions of northern China. Our results also provided a reference in species selection for better environmental contribution on the Loess Plateau. The accumulation rate of TSC under *R. pseudoacacia* was higher than under both *P. tabuliformis* and *H. rhamnoides*. Moreover, the accumulation rates of relatively stable HF-SOC under *R. pseudoacacia* was also highest among the three species, which was higher than that under *P. tabuliformis* and *H. rhamnoides* by 192.2% and 33.3% (Table 3). Additionally, *R. pseudoacacia* can adapt to local climate and edaphic conditions very well and be capable of covering large areas in a relatively short time. Therefore, *R. pseudoacacia*, as a rapidly growing species with high stable soil carbon accumulation rates, is the most conducive to sequester soil carbon among these three species on the Loess Plateau.

Conclusion

The results of changes in soil carbon and its fractions after afforestation demonstrated that tree planting on bare land has a high potential for total soil carbon (TSC) accumulation on the Loess Plateau. Among the newly sequestrated TSC, soil organic carbon (SOC) was the major portion. Within the newly increased SOC, the high-fraction of soil organic carbon (HF-SOC) with a slow turnover rate accounted for a considerably high percentage, suggesting that significant sequestrated carbon can be stably stored in soils following afforestation, which may be meaningful for fixing atmospheric CO_2. Furthermore, we also found that afforestation induced soil inorganic carbon (SIC) sequestration. Although its contribution to TSC accumulation was relatively less than SOC, overlooking it may substantially underestimate the capacity of carbon sequestration following afforestation on the Loess Plateau.

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