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Carbon sequestration capacity of shifting sand dune after establishing new vegetation in the Tengger Desert, northern China

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HIGHLIGHTS

- Carbon sequestration capacity and potential of restoring desert system are assessed.
- The contribution of different components to TOC is quantified.
- The TOC significantly increased over time in the restoring desert areas.
- Restoring desert ecosystems may accumulate more TOC compared to natural vegetation.
- SOC represented the largest carbon pool for restored systems.

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ABSTRACT

Reconstructing vegetation in arid and semiarid areas has become an increasingly important management strategy to realize habitat recovery, mitigate desertification and global climate change. To assess the carbon sequestration potential in areas where sand-binding vegetation has been established on shifting sand dunes by planting xeric shrubs located near the southeastern edge of the Tengger Desert in northern China, we conducted a field investigation of restored dune regions that were established at different times (20, 30, 47, and 55 years ago) in the same area. We quantified the total organic carbon (TOC) in each ecosystem by summing the individual carbon contributions from the soil (soil organic carbon; SOC), shrubs, and grasses in each system. We found that the TOC, as well as the amount of organic carbon in the soil, shrubs, and grasses, significantly increased over time in the restored areas. The average annual rate of carbon sequestration was highest in the first 20 years after restoration (3.26×10^{-2} kg·m^{-2}·year^{-1}), and reached a stable rate (2.14×10^{-2} kg·m^{-2}·year^{-1}) after 47 years. Organic carbon storage in soil represented the largest carbon pool for both restored systems and a system containing native vegetation, accounting for 67.6%–85.0% of the TOC. Carbon in grass root biomass, aboveground grass biomass, litter, aboveground shrub biomass, and shrub root biomass account for 10.0%–21.0%, 0.2%–0.6%, 0.1%–0.2%, 1.7%–12.1% and 0.9%–6.2% of the TOC, respectively. Furthermore, we found that the 55-year-old restored system has the capacity to accumulate more TOC (1.02 kg·m^{-2} more) to reach the TOC level found in the natural vegetation system. These results suggest that restoring desert ecosystems may be a cost-effective and environmentally friendly way to sequester CO_2 from the atmosphere and mitigate the effects of global climate change.

1. Introduction

Arid and semiarid areas occupy approximately one-third of the land surface worldwide (Reynolds, 2001; Reynolds et al., 2007; Lal, 2004a). These areas are particularly prone to desertification as a result of climatic changes and human activities (Wang, 2003; Schlesinger et al., 1990; Puigdefábregas and Mendizabal, 1998). As a result, the vegetation and soil structure in these areas are degraded, which in turn decreases the capacity of regional ecosystems to store carbon and leads to the release of carbon into the atmosphere (Helldén and Tottrup, 2008). A recent estimate suggests that deserts and semi-deserts cover nearly 22% of the Earth's land surface (Janzen, 2004). However, arid and semiarid areas are spreading because of the desertification occurring in the farming-pastoral transition zone that borders these areas. Historically, it has been estimated that global desertification has caused total carbon

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losses in arid and semiarid ecosystems in the range of 19–29 Pg (Lal, 2001). However, these losses suggest that terrestrial ecosystems may have a large capacity (both in soil and vegetation) to sequester CO_2 from the atmosphere if appropriate management practices are followed. In recent years, constructing vegetation in desert and desertified areas has become an increasingly important management technique to protect soils, mitigate desertification, and improve the ecosystem resilience of a region (Castillo et al., 1997; Miao and Marrs, 2000; Reynolds, 2001; Zeng et al., 2009; Chen et al., 2010). It also has been regarded as an effective way to mitigate the effects of global climate change (Fang et al., 2001; Lal, 2004b). For example, constructing vegetation in arid and semiarid regions through planting trees has great potential to increase organic carbon sequestration (Keller and Goldstein, 1998; Nosetto et al., 2006; Lal, 2009). However, a sufficient water supply may be crucial for successful afforestation or reforestation. Jackson et al. (2005) indicated that tree plantations have greater water and nutrient demands than land containing grasses and shrubs, and increasing the carbon sequestration arising from biomass involves tradeoffs with water use. The irrigated afforestation areas in the Sahara and Australian deserts, in which eucalyptus forests were planted, can indeed sequester carbon from the atmosphere, but such efforts are expensive (Ornstein et al., 2009; Manfready, 2011).

In China, an extensive vegetation construction project called the Three-North Shelterbelt Program was implemented in arid and semiarid regions by the Chinese government, in the early 70s and continues today (Li et al., 1995; Wang et al., 2004). Limited by natural conditions, especially precipitation, two main forms of vegetation are used in construction. One form is forest shelterbelts in areas that receive sufficient moisture or have high groundwater levels. These forest shelterbelts effectively store a large amount of carbon in their biomass (Fang et al., 2001). The other form of vegetation is xerophytic shrubs that are planted to stabilize shifting sand dunes along highways and railways, especially in regions with low annual precipitation (<200 mm) (Wang et al., 2010). One such successful example of this type of restoration is located at the southeastern edge of the Tengger Desert. In this area, sand-binding vegetation, first established in 1956 and then further established in 1964, 1981, and 1991, successfully controlled shifting sand dunes, allowing the Baotou–Lanzhou Railway to be built. The railway has been operating smoothly for over half a century. The regional ecological environment, including the physical and chemical properties of the soil as well as the diversity of the animal and plant species, has been significantly improved since the sand-binding vegetation was established (Li et al., 2005b). Without human intervention, the sand-binding vegetation has gradually transformed into no-irrigated natural vegetation (Li et al., 2005b). Accordingly, many vegetation restoration efforts have been successfully applied to deserts and desertified areas in China. Studies on such areas have investigated the relationship between vegetation and soil properties (Li et al., 2004c; Li, 2005), vegetation and soil moisture (Li et al., 2004a; Wang et al., 2007), and ecological and hydrological processes (Li et al., 2004b; Li et al., 2005a,b; Pan et al., 2008). However, there is little information regarding how sand-binding shrubs introduced to sand dunes affect carbon sequestration in these areas. Therefore, we aimed to determine whether an ecosystem formed from sand-binding vegetation has the ability to increase organic carbon sequestration. If so, the expanses of desert and desertified areas around the world may provide a platform to improve organic carbon sequestration.

The objectives of the present study were (1) to evaluate how much organic carbon is stored in restored shifting sand dune areas, located at the southeastern edge of the Tengger Desert, whereby sand-binding vegetation was established at different times; and (2) to determine the relative contributions of different types of biomass, namely shrubs, grasses, and soil, to the TOC of the ecosystem. We hypothesize that establishing sand-binding vegetation in a shifting sand dune will significantly increase the carbon storage capacity of the dune, and that the amount of carbon stored will increase with the age of the vegetation.

2. Materials and methods

2.1. Site description

The study area is located near the southeastern edge of the Tengger Desert in northern China (37°33′N, 105°01′E) at an altitude of 1320 m a.m.s.l. (Fig. 1), which is a transitional zone between the desert and an oasis, and it also lies within the transitional belt from a desert steppe to a steppified desert. Based on the meteorological data collected over a period of 50 years at the Shapotou Desert Experimental Research Station of the Chinese Academy of Sciences, the study area has a mean annual precipitation of 186 mm that primarily falls between May and September (Li et al., 2005b). The average air temperature in the region is 9.6 °C, reaching an average maximum temperature of 24.3 °C in July and an average minimum temperature of −6.9 °C in January. The annual potential evaporation is ~3000 mm (Li et al., 2005a, 2012), and the average wind velocity is 2.9 $m \cdot s^{-1}$ in a predominantly northwesterly direction. Soils in the shifting sand dune field are blown sand soils. Their sand content is 99.7%, and their silt and clay content is 0.3%. Soils in the study area are classified as aeolian sandy soil. Groundwater is deep (~80 m) and cannot be utilized by the natural vegetation. The predominant plants at the study area include shrubs and semi shrubs (*Artemisia ordosica* Krasch, *Caragana korshinskii* Kom., *Hedysarum scoparium* Fisch. and C.A. Mey., and *Ceratoides lateens* (J.F. Gmel) Reveal et Holmgren) as well as grasses (*Allium mongolicum* Regel, *Artemisia capillaris* Thunb, *Allium polyrhizum* Turcz. ex Regel, *Chloris virgata* Sw., *Setaria viridis* (L.) Beauv, and *Bassia dasyphylla* (Fisch. and C.A. Mey.) Kuntze). Various shrubs and subshrubs have been significantly increased in former natural grasslands since the early 19th Century on the south-eastern fringe of the Tengger Desert, finally forming a typical natural desert steppe ecosystem (a sparse patchy natural vegetation) (Li et al., 2013).

This desert area is characterized by huge, dense, continuous reticulate dune chains, in which the main dune crest moves to the southeast at a velocity of 0.3–0.6 $m \cdot y^{-1}$ (X.P. Wang et al., 2011). To prevent erosion related to the constant extension of the sand dunes, to protect natural vegetation from being buried, and to ensure smooth operation of the Baotou–Lanzhou Railway, a no-irrigation sand-binding vegetation protective system was originally established by the Chinese Academy of Sciences in conjunction with other departments in 1956. The shrubs were selected and the sand-binding vegetation protective system was designed based on the features of natural vegetation. At first, windbreaks (mechanical sand fences) were erected to reduce wind erosion, and then straw checkerboard barriers (1 m × 1 m in area) were installed on shifting sand surfaces. Two-year-old seedlings of xerophytic shrubs (*A. ordosica*, *C. korshinskii*, and *H. scoparium*) were planted inside the straw checkerboard barriers to stabilize the surface of the sand dunes (16 individuals per 100 m^2). After establishing sand-binding vegetation, understory grass gradually developed wildly and became dominant plants (Li et al., 2004b). More sand-binding shrubs with the same species allocation and density were planted in 1964, 1981, and 1991. Therefore, the four sand-binding vegetation sites with different age in the initial stage were similar to each other. Combined, the completed protective vegetation system was 16 km long and 700 m wide along the railway (Shapotou Desert Experimental Research Station, 1991; Li, 2005; Li et al., 2007). The sites used in our study encompassed a bare shifting sand dune, the areas that were restored with sand-binding vegetation at different times (in 1956, 1964, 1981, and 1991), and an area of natural desert steppe vegetation, which is a mature and typical ecosystem in the study area.

2.2. Field investigation and experimental design

Six sites were chosen for our 2011 investigation: a shifting sand dune (sand); four different-aged sand-binding vegetation sites respectively were established in 1956 (55-year-old site), 1964 (47-year-old

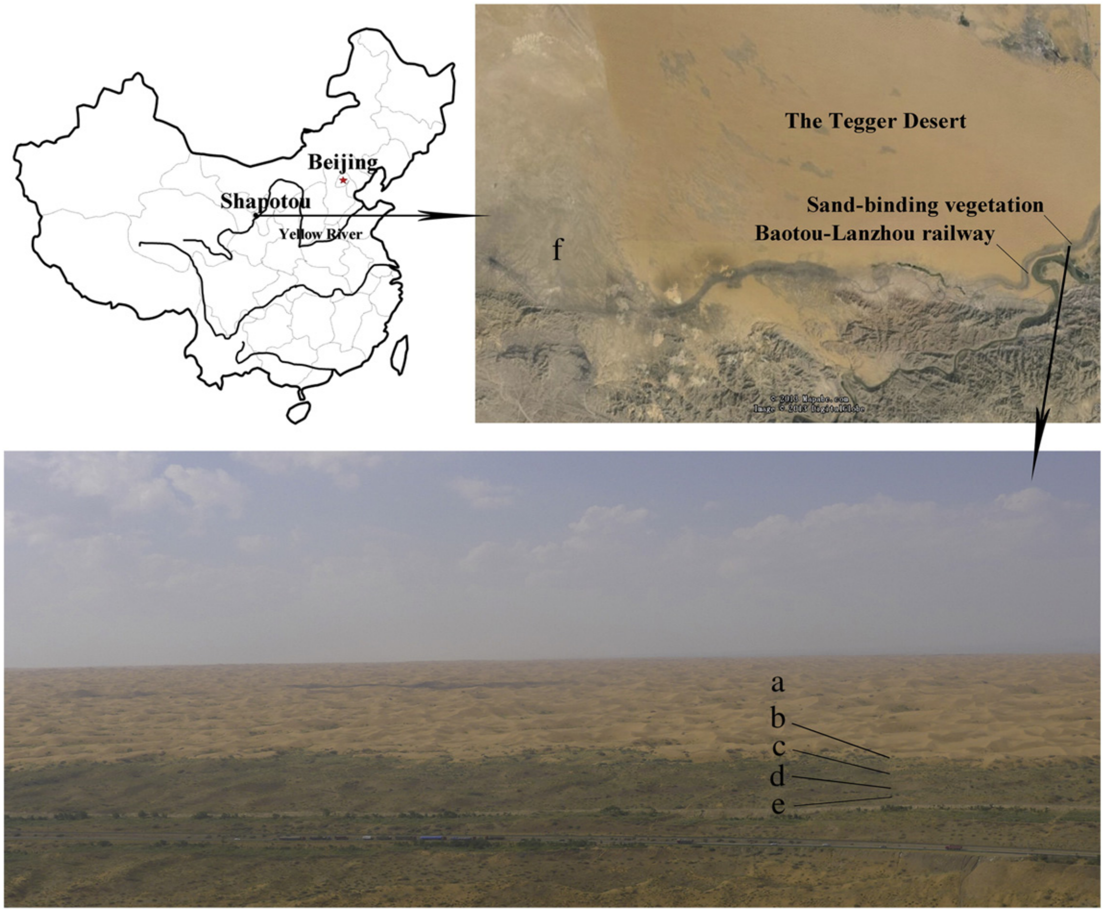

Fig. 1. Map of the People's Republic of China showing the Shapotou section of the Tengger Desert and the study sites. (a) represents the shifting sand dune site; (b), (c), (d), and (e) represent sand-binding vegetation sites established in 1991, 1981, 1964, and 1956, respectively; and (f) represents the natural desert steppe site with native vegetation.

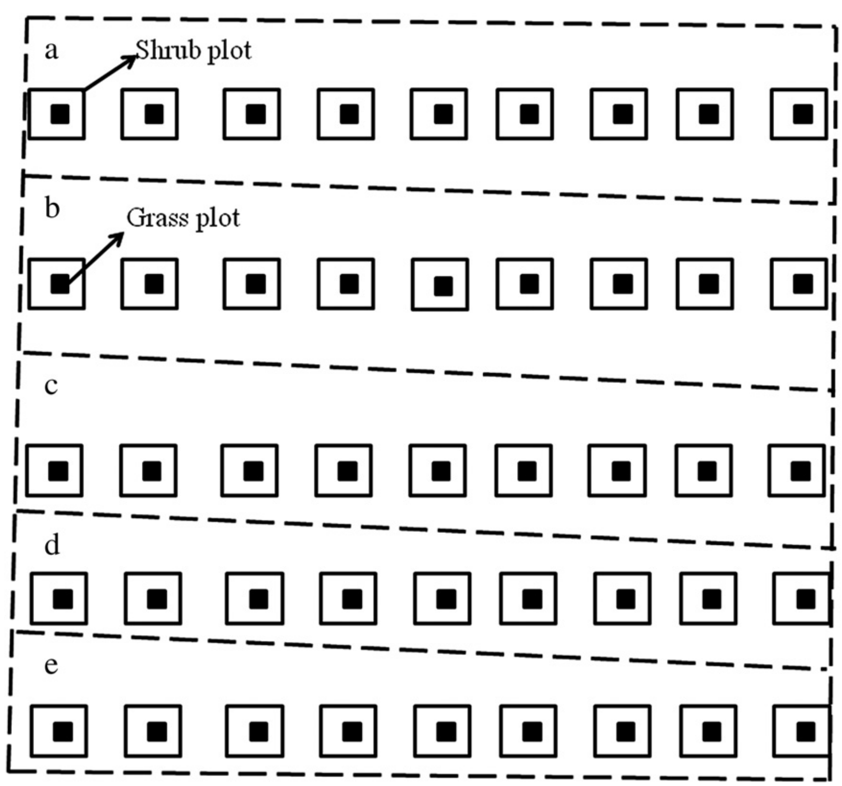

Fig. 2. The graphical layout of the shrubs and grass plots along the chronosequence. (a) represents the shifting sand dune site; and (b), (c), (d), and (e) represent sand-binding vegetation sites established in 1991, 1981, 1964, and 1956, respectively.

site), 1981 (30-year-old site), and 1991 (20-year-old site); and a site containing natural desert steppe vegetation (natural). Using the space-for-time substitution (chronosequence) method, all the study sites can be thought of as a complete succession sequence, beginning as a shifting sand dune and ending up as natural desert steppe (Johnson and Miyanishi, 2008; Li et al., 2007).

Field investigations and sampling were carried out in August 2011 at the end of the rainy season. At each restored site, a total of nine 10 m × 10 m shrub plots were chosen along 500-m-long transects spaced at random apart, depending on the distribution of the sand dune, such that three plots were sampled from each of these locations: the windward slope, the inter-dune area, and the leeward slope. Nine 10 m × 10 m plots were also set up for sampling in the bare dune site, although this site contained no vegetation (Fig. 2). For the natural site, a total of ten 10 m × 10 m shrub plots were established along 300-m-long transects spaced at least 20 m apart. A total of 55 shrub plots were set up across all study sites. In each shrub plot, a 1 m × 1 m grass plot was selected at random for sampling grass biomass.

2.3. Shrub sampling

In each shrub plot, we recorded the vegetation coverage, the richness of shrub species, and the size of each shrub (height and crown breadth). Afterwards, the aboveground biomass of individual shrubs was harvested if the shrub height did not exceed 50 cm, and half the aboveground biomass was harvested if the height of individual exceeded 50 cm. In addition, 30 individual shrubs (standard whole shrubs) per species were selected by size across the study area to represent the range of plant sizes observed in the field. Each individual's aboveground biomass was harvested using clippers and the roots were collected by excavating to determine the root/shoot biomass (R/S) ratio for each of four shrub species after the height and crown diameter were measured. The belowground biomass of individual shrubs in each shrub plot was estimated using the R/S ratio. The aboveground biomass was separated into leaves, new branches, aging branches, standing-dead, and plant litter. All samples were oven dried at 65 °C until constant weight was attained. Then, we combined and mixed the same parts of each shrub species from the same plot and determined the amount of organic carbon. We also mixed the roots of each common species and determined the amount of organic carbon in the root biomass component. Based on root/shoot (R/S) ratio per species, we separately determined the amount of organic carbon in each sample set.

2.4. Grass sampling

In the 1 m × 1 m grass quadrat within each shrub plot, the aboveground biomass was harvested and then partitioned into living biomass and litter biomass. The belowground grass biomass was sampled using an 8-cm inner diameter soil auger in each quadrat. We collected five soil cores (subsamples) from 0 to 100 cm to measure the root mass, and each core was divided into depth increments of 0–5, 5–10,10–20, 20–30, 30–50, 50–70, and 70–100 cm. From the five cores, we combined the core samples that had the same depth. The roots were sprayed with water to remove soil, and then all grass samples (living biomass, litter biomass and roots) were oven dried to have a constant weight of 65 °C.

2.5. Soil sampling

Soil samples from each plot were collected concurrently with shrub and grass samples, and they were used to measure the amount of soil organic carbon (SOC). We used a soil auger with a 5-cm-diameter core to obtain soil samples after the litter was removed from the grass plots. Five soil core samples were collected adjacent to the soil cores taken during the root collection of grass samples, as described above. All soil samples were air-dried at room temperature. Each soil sample was sieved through a 2-mm sieve to remove the root and plant residues. To determine SOC, we ground approximately 50 g of each dried soil sample into a fine powder using a ball grinder. Soil bulk density was determined in each of the seven soil layers, 0–5, 5–10, 10–20, 20–30, 30–50, 50–70, and 70–100 cm, using 100-cm^3 steel cylinders with 5 replicates. The soil samples used to determine bulk density were oven dried at 105 °C to a constant weight.

2.6. Organic carbon analyses

SOC was determined using the Walkley–Black $K_2Cr_2O_7$–H_2SO_4 oxidation method (Page, 1982). Plant samples (leaves, new branches, aging branches, standing-dead, and litter of each shrub species; living, litter, and root biomass of the grasses) taken from each study plot were ground to pass through a 0.25-mm screen. Then, the organic carbon content of the plant samples was determined using a CHNSO elemental analyzer (Elemental Combustion System 4010, Costech Analytical Technologies Inc.; Valencia, CA, USA).

2.7. Calculating the density of organic carbon

SOC density ($kg \cdot m^{-2}$) of the entire soil profile for each plot, containing all seven layers, was calculated as follows:

$$\text{SOC Density} = \sum_{i=1}^{j} C_i \times T_i \times \rho_i \times (1-\tau_i)/10 \quad (1)$$

where j is the number of layers, C_i is the organic carbon content (%) of layer i, T_i is the thickness of layer i (cm), ρ_i is the bulk density ($g \cdot cm^{-3}$), and τ_i is the volume fraction of soil skeleton >2 mm (Batjes, 1996).

We determined the organic carbon density of the aboveground shrub biomass for each species of shrub according to Eq. (2):

$$\text{SAOCDn} \left(kg \cdot m^{-2}\right) = \sum_{i}^{k} C_i \;\; M_i \quad (2)$$

where n represents the shrub species, k represents the different fractions of aboveground shrub biomass, C_i is the organic carbon content (%) of fraction i, and M_i is the biomass ($kg \cdot m^{-2}$) of fraction i. Consequently, the total amount of aboveground organic carbon (SAOCD) from all shrub species combined was calculated using Eq. (3):

$$\text{SAOCD} \left(kg \cdot m^{-2}\right) = \sum_{n}^{m} \text{SAOCDn} \quad (3)$$

where m represents the number of shrub species.

Below, Eq. (4) represents the organic carbon density of the shrub roots (SROCD) in each 10 m × 10 m plot:

$$\text{SROCD} \left(kg \cdot m^{-2}\right) = \sum_{n}^{m} C_n \;\; M_n \quad (4)$$

where m represents the number of shrub species, C_n is the organic carbon content (%) of a root of species n and M_n is the root mass ($kg \cdot m^{-2}$) of species n.

In Eq. (5), GAOCD represents the organic carbon density of aboveground grass:

$$\text{GAOCD} \left(kg \cdot m^{-2}\right) = C \times M \quad (5)$$

where C represents the organic carbon content (%) of grass and M is the aboveground biomass ($kg \cdot m^{-2}$) of grass in each 1 m × 1 m plot.

To calculate the organic carbon density associated with the grass roots (GROCD), we used Eq. (6):

$$\text{GROCD} \left(kg \cdot m^{-2}\right) = \sum_{i}^{n} C_i \;\; M_i \quad (6)$$

where n is the number of layers, C_i is the organic carbon content (%) of the grass roots in layer i, and M_i is root biomass ($kg \cdot m^{-2}$) of layer i.

We calculated the total organic carbon (TOC) density in each plot by summing all of the individual components.

2.8. Statistical analyses

The data from each site were tested for homogeneity of variance (using Levene's test) and normal distribution. Differences in SOC density, organic carbon density in shrub components, organic carbon density in grass components, and total organic carbon density among six study sites were studied using quantified by analysis of variance(ANOVA). Tukey's test was applied post hoc to distinguish between means at different sites. Correlation analysis was used to examine the relationship between SOC and root biomass carbon. Linear regression model was used to establish a best-fit relationship between total carbon density and the age (independent variable) of sand-binding vegetation. F-test was used to check the significance of regression relationship. Shapiro–Wilk test and Durbin–Watson test were used to examine the normal distribution and independence of residuals from the linear regression. The significance level was set as 0.05 in all tests. All data were analyzed using SPSS software version 15.0 (SPSS, Chicago, IL, USA).

3. Results

3.1. Soil organic carbon

Total SOC showed a sharp increase along the chronosequence samples after sand-binding vegetation was established. In the first 100 cm of soil, SOC significantly increase by 1.06 $kg \cdot m^{-2}$ 55 years after vegetation was established on the shifting sand dune ($P < 0.05$) (Fig. 3). The SOC was 0.39 ± 0.02 $kg \cdot m^{-2}$ (mean ± SE) in the bare dune site, but it was 1.45 ± 0.13 $kg \cdot m^{-2}$ for the 55-year-old site. The natural desert steppe site had a total SOC of 2.09 ± 0.20 $kg \cdot m^{-2}$. Vegetation that had been established for 20, 30, 47, and 55 years showed increases in SOC within the 0–100-cm soil layer of 72.4%, 166.7%, 203.4%, and 268.3%, respectively, compared with that of the bare sand dune (Fig. 3).

The SOC content decreased with depth in both the sand-binding vegetation and natural sites, and there were no differences between SOC in the seven soil layers in the bare dune site (Fig. 4). At a depth of 0–20 cm, the SOC accounted for 21.6%, 48.1%, 57.7%, 51.8%, 66.4%, and 34.2% of total SOC in each corresponding site's 100-cm soil profile (the bare sand dune site, the 20-, 30-, 47-, and 55-year-old sites, and the natural site, respectively) (Fig. 4). The total SOC in the natural site's soil profile was significantly greater than that of the sand-binding and sand dune sites ($P < 0.05$) (Fig. 3).

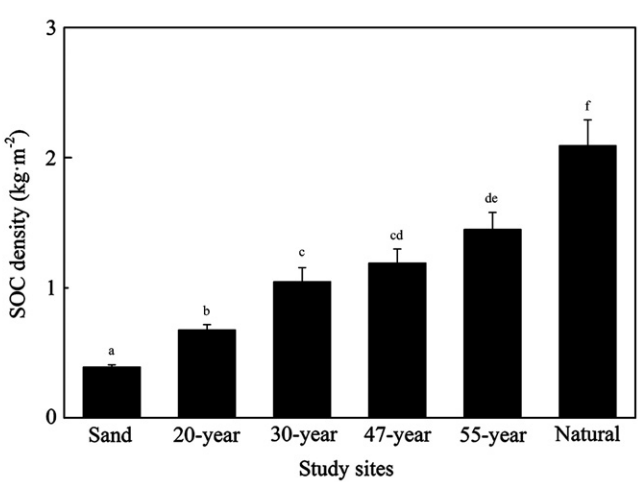

Fig. 3. SOC density at different study sites. Sand represents the shifting sand dune site; the 55-year, 47-year, 30-year, and 20-year labels represent sand-binding vegetation sites established in 1956, 1964, 1981, and 1991, respectively. Natural represents the natural desert steppe site with native vegetation. Values are mean ± SE. Letters indicate significant differences between sites ($P < 0.05$).

3.2. Carbon in grass biomass

The vegetation cover, shrub cover, aboveground biomass of shrubs and grass, litter biomass, shrub root biomass, and grass root biomass among six study sites had significant differences ($P < 0.05$) (Table 1). Shrub cover, aboveground biomass of shrubs and shrub root biomass were the largest in 20-year-old site. The vegetation cover, grass biomass, grass root and litter biomass were the largest in natural site.

The carbon density of the living and litter biomass from grass was much lower than that of the root biomass. The carbon density ratios of living/root biomass ranged from 1.3% for the 47-year-old site to 3.0% for the 20-year-old site. The carbon densities of the living, litter, and root biomass of grass were markedly higher in sand-binding vegetation sites compared with the sand dune site ($P < 0.05$), but they were all substantially lower than that of the natural site ($P < 0.05$). We found no significant differences in carbon density between living grass, grass litter, and grass roots between different-aged sand-binding vegetation (Fig. 5).

3.3. Carbon in shrub biomass

Carbon densities in the leaves, new branches, aging branches, and standing-dead material of shrubs, as well as the total carbon density of aboveground shrubs, were markedly higher in the sand-binding vegetation compared with the sand dune site ($P < 0.05$). All of these shrub components reached their maximum carbon densities 20 years after sand-binding vegetation was established. They all showed sharp decreases between 20 and 47 years after restoration, reaching a minimum, but the carbon density values increased again from 47 to 55 years after establishing vegetation, and the values were then indistinguishable from the natural vegetation site (Fig. 6).

On average, the total carbon density of shrub biomass in the natural vegetation site was similar to that of the sand-binding vegetation sites. For each aboveground shrub component, aging branches and standing-dead material contained the highest percentages of carbon density, ranging from 76.5% to 83.8%, in all sites. Leaves made up 17.0% of the carbon density in the natural vegetation site and 11.6%, on average, in the sand-binding sites. New branches had the lowest carbon density component (6.6% for the natural site and 5.1% for sand-binding sites).

The root/shoot ratios (R/S) were calculated using 30 standard whole shrubs for each species in the study area. The R/S was 0.49 ± 0.03 (mean ± SE), 0.52 ± 0.02, 0.57 ± 0.03, and 0.67 ± 0.05 for *A. ordosica*, *C. korshinskii*, *H. scoparium*, and *C. lateens*, respectively. The R/S of each shrub species was used to estimate the root biomass and carbon density at all sites. Along the chronosequence, carbon density for the shrub roots was similar to that of the aboveground biomass. We found a maximum carbon density value for shrub roots (7.48×10^{-2} $kg \cdot m^{-2}$) at the 20-year-old site and a minimum value (1.23×10^{-2} $kg \cdot m^{-2}$) at the 47-year-old site. The natural site contained a shrub root carbon density of 3.21×10^{-2} $kg \cdot m^{-2}$ (Fig. 6).

3.4. Total organic carbon

In our study, the carbon density in vegetation and roots was 0 $kg \cdot m^{-2}$ for the sand dune site because it did not harbor vegetation. Consequently, we found that the total organic carbon density significantly increased after vegetation had been established on the shifting sand dune ($P < 0.05$). However, the total organic carbon densities in the sand-binding vegetation areas were still remarkably lower than that of natural ecosystems ($P < 0.05$) (Fig. 7a). Compared with the bare dune control site, the achievable increase in carbon sequestration was 0.65 $kg \cdot m^{-2}$ for the 20-year-old site, 0.92 $kg \cdot m^{-2}$ for the 30-year-old site, 1.01 $kg \cdot m^{-2}$ for the 47-year-old site, and 1.31 $kg \cdot m^{-2}$

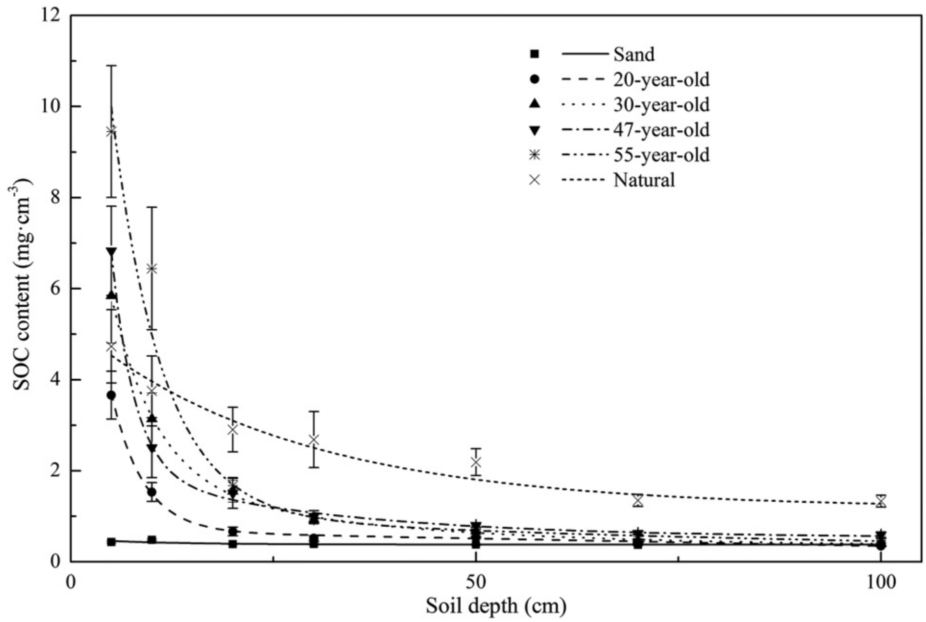

Fig. 4. The vertical distribution of soil organic carbon with soil depth.

for the 55-year-old site. The natural site showed an achievable carbon sequestration of 2.38 $kg \cdot m^{-2}$ going from the sand dune to a natural ecosystem (Fig. 7b). The TOC in the natural vegetation system is 1.02 $kg \cdot m^{-2}$ greater than that of the 55-year-old restored system. The carbon sequestration rate reached a maximum (3.26×10^{-2} $kg \cdot m^{-2} \cdot year^{-1}$) in 20 years after vegetation was established, and a minimum (2.14×10^{-2} $kg \cdot m^{-2} \cdot year^{-1}$) in 47 years, and then it increased again in 55 years (Fig. 7b).

In the study area, organic carbon was primarily stored in the soil, followed by in the grass root biomass, and then the aboveground biomass of shrubs and shrub roots. Only a small amount was stored in the living grass and grass litter biomass (Table 2). The relative contribution of soil, grass, grass roots, litter, and shrub species through different plant portions (i.e., leaves, new branches, and aging branches) to TOC in five sites are shown in Tables 2 and 3.

4. Discussion

4.1. Soil organic carbon

SOC storage is widely recognized as the largest carbon pool in terrestrial ecosystems (Schulze and Freibauer, 2005; Dawson and Smith, 2007). The results of our study indicate that SOC increased after the shifting sand dune was converted to an ecosystem containing sand-binding vegetation. Comparing to the bare dune, SOC increased by 72.4%, 166.7%, 203.4%, and 268.3% in 20, 30, 47, and 55 years after restoration, respectively. Increases in SOC were primarily caused because of the growing shrubs and grasses, which increased in biomass over time, once restoration began (Table 1). While dead shrubs and plant litter that fall onto the soil surface provide one pathways of SOC input, root turnover (Guo et al., 2007; Hertel et al., 2009) and fine-root mortality can also greatly increase SOC (Huang et al., 2012). In addition, SOC can also be provided by biological soil crusts, which colonize areas of sand-binding vegetation, because they can take in CO_2 from the atmosphere during photosynthesis (Li et al., 2012).

We found that SOC in the bare dune did not differ between soil layers. However, for areas with restored and natural vegetation, we found that SOC decreased with depth because most carbon inputs occur at the soil surface; this relationship has also been observed for other soils (Li and Zhao, 2001; Guo and Gifford, 2002). We found that SOC was primarily distributed in the topsoil, such that the first 20 cm of our 100-cm sample contained 48.1%–66.4% of the sample's SOC; soils at 30–50 cm deep contained ~20% of the SOC. Compared to other studies, we found a greater SOC distribution in the uppermost 20 cm of soil in the sand-binding and natural vegetation sites than has been seen for other soils (Jobbágy and Jackson, 2000; Li and Zhao, 2001). Guo and Gifford (2002) also found that the surface soil layer is more active in atmospheric CO_2 sequestration than deeper soil layers after changes in land use have been made. However, we did find that SOC in the natural vegetation sites was much greater than in the restored sites. These results suggest that in the restored areas studied, deeper soil layers may have the potential to store organic carbon. Longer-term observations must confirm this theory.

Our results showed that the organic carbon in ecosystems is primarily stored in soils. SOC accounted for 64.9%–85.2% of the total organic carbon in the restored ecosystems, whereby this percentage increased the longer vegetation that had been established; the average SOC contribution to TOC was 78.6% in the natural vegetation site. We found that SOC contributed about 3× the amount of carbon than biomass, which is consistent with other work (Lal, 2004b).

We found that in restored areas, SOC densities (over a 100-cm depth) ranged from 0.68 $kg \cdot m^{-2}$ (at the 20-year old site) to 1.45 $kg \cdot m^{-2}$ (at the 55-year-old site). This range is considerably less than the SOC levels commonly associated with other vegetation types in natural areas, which have SOC levels of 4.1 $kg \cdot m^{-2}$ to 40 $kg \cdot m^{-2}$ (in grassland, upland, and grass-savannah soils; paddy soils, bush, and coppice forest soils; and coniferous and broadleaf forest, meadow, and herbaceous swamp soils) (Li and Zhao, 2001; Ni, 2002). However, we found that SOC levels increased significantly after restoration efforts because the bare dune had a low initial SOC density (0.40 ± 0.02 $kg \cdot m^{-2}$). The SOC density increased by 1.06 $kg \cdot m^{-2}$ after vegetation had been established for 55 years (compared with the SOC of the bare dune). Meanwhile, the limited moisture in desert areas, particularly in years with lower precipitation, leads to a longer-term accumulation and persistence (turnover rate) of SOC due to limited rate of soil microbial respiration (Jobbágy and Jackson, 2000). Our results imply that, over the long term, more carbon can be captured from the atmosphere and stored in the study area. In addition, constructing vegetation in desert areas that get <200 mm of annual precipitation may prove to be a huge source of SOC pools because such areas are vast and widely distributed.

Table 1
Vegetation cover, aboveground biomass (shrubs and grass), litter, and root biomass (shrubs and grass) for different study sites.

Age of site (year of vegetation construction)	Vegetation cover %	Shrub cover %	Shrub biomass (aboveground) × 10^{-2} kg·m^{-2}	Grass biomass (aboveground) × 10^{-2} kg·m^{-2}	Litter × 10^{-2} kg·m^{-2}	Shrub root biomass × 10^{-2} kg·m^{-2}	Grass root biomass × 10^{-2} kg·m^{-2}
0-year (sand)	0^{a}	0^{a}	0^{a}	0^{a}	0^{a}	0^{a}	0^{a}
20-year (1991)	23.11 ± 2.98^{c}	18.64 ± 2.01^{e}	31.70 ± 11.20^{c}	0.80 ± 0.10^{b}	0.60 ± 0.10^{b}	16.90 ± 6.20^{c}	78.20 ± 20.10^{b}
30-year (1981)	16.00 ± 2.95^{bc}	13.06 ± 1.86^{d}	18.90 ± 6.50^{bc}	1.00 ± 0.40^{b}	0.50 ± 0.10^{b}	10.10 ± 3.50^{bc}	54.80 ± 3.40^{b}
47-year (1964)	7.78 ± 1.16^{b}	$6.71 \pm 0{,}96^{b}$	5.20 ± 1.60^{b}	0.60 ± 0.10^{b}	0.40 ± 0.10^{b}	2.80 ± 0.90^{b}	74.80 ± 6.70^{b}
55-year (1956)	12.61 ± 3.01^{b}	9.44 ± 2.18^{c}	11.40 ± 4.00^{b}	0.80 ± 0.10^{b}	0.60 ± 0.20^{b}	6.10 ± 2.10^{b}	72.50 ± 8.30^{b}
Natural site	37.00 ± 2.00^{d}	11.77 ± 1.35^{cd}	13.40 ± 4.60^{bc}	3.80 ± 0.50^{c}	2.20 ± 1.70^{c}	7.30 ± 2.20^{bc}	146.40 ± 6.50^{c}

Values represent means ± SE.
[a,b,c,d]Indicate significant differences between sites ($P < 0.05$).

In general, useful management practices may improve SOC sequestration (Lal, 2004b). Many studies have shown that restoring vegetation by planting trees has greatly increased SOC (Brown and Lugo, 1990; Bashkin and Binkley, 1998; Guo and Gifford, 2002; Lima, et al., 2006; Xie et al., 2007; Fornara and Tilman, 2008; Zhou et al., 2008; Tang et al., 2010; W.J. Wang et al., 2011). However, SOC sequestration can also be achieved using sand-binding vegetation. Huang et al. (2012) found that introducing shrub plantation remarkably improved SOC in areas with annual precipitation of 200–400 mm. Furthermore, in our study we found that SOC increased the longer sand-binding vegetation (shrub plantation) that had been present. Similar results of SOC increases with time have been seen in studies on secondary forests (Brown and Lugo, 1990).

4.2. Carbon in shrub biomass

Carbon in shrub biomass is an important component of TOC in the study sites. In the first 20 years, shrub cover, productivity, and biomass at the restored sites reached a maximum level (Li et al., 2004b), which was the maximum capacity of the ecosystem (Table 1). As a result, the accumulation of organic carbon in shrubs, including five components, reached a maximum. During 20 to 47 years after establishment, the shrub cover and productivity decreased probably because the moisture content of the deeper soil layers decreased, some deep-rooted shrubs died, and grass species became more prominent (Li et al., 2004b). At this stage, the accumulation of organic carbon in shrubs decreased to a minimum. Bradley et al. (2006) also found that grass invasion into shrublands can reduce aboveground carbon stocks. Organic carbon accumulation in shrubs increased again between 47 and 55 years after restoration because the shrub cover and productivity reached stabilized (Table 3) (Li et al., 2004b), but this level remained lower than that of natural vegetation. The total shrub organic carbon made up 21.0%, 10.5%, 2.6%, and 4.6% of the total organic carbon in the ecosystem at 20, 30, 47, and 55-years after restoration, compared with 3.5% for the natural site. These results indicate that organic carbon accumulation in shrubs reaches to a natural level (the rate of organic carbon accumulation in shrubs in natural desert steppe ecosystem) over time. The carbon in shrubs' aboveground biomass was mainly stored in aging branches and standing-dead material in this study. New branches (2.9%–4.3% of shrub biomass carbon) and some of the biomass from aging branches were the main contributors that increased the carbon of aboveground biomass. The organic carbon in leaves accounted for 11.6%–16.9% of the carbon density for aboveground shrubs in study sites. Shrub leaves should be considered as an important source of SOC. Although roots were the major and direct source of SOC, there was not a significant correlation between root biomass of shrubs and SOC ($P > 0.05$). The rate of root turnover for shrubs may play a key role in determining this relationship, but this requires further research.

The relative contribution of different species, through different plant portions (i.e., branches, leaves) to TOC was different in five sites (Table 3). This arose in part from the increase of TOC and the decrease of shrub biomass carbon with time after the sand-binding vegetation was established. Another main reason for this difference was that the shrub cover and vegetation structure were different at each site (Table 1). The main shrub species in the restored sites were *A. ordosica*, *C. korshinskii*, and *H. scoparium*, and those in the natural site were *A. ordosica*, *C. korshinskii*, and *C. lateens*.

4.3. Organic carbon in grass biomass

After establishing sand-binding vegetation, grass gradually invaded the shrub-dominated restored sites, and became dominant plants (Li et al., 2004b). As a result, the carbon density in the living, litter, and root biomass from grasses was significantly higher in the restored sites than in the bare dune site. However, the carbon density from grass biomass in the sand-binding sites was notably lower than that of natural vegetation because the restored sites had lower vegetation cover and biomass (Table 1). This suggests that restored sand dune areas have the potential to accumulate carbon in grass biomass. The grass biomass carbon accumulated primarily in the roots, which was 33.5× to 80.26× more carbon than that in the aboveground grass biomass. High R/S ratios can partly explain the accumulation of SOC (Cerri et al., 1991), but the larger R/S ratios may be caused by the level of precipitation in the study area. Some annual grasses begin to grow after a rainfall, but they die during drought; as a result, aboveground grass biomass was not at a maximum level when we performed sampling for the study. Our study proves that there is a significant positive linear relationship between grass root biomass and SOC ($SOC = 0.11 \times 10^{-2}$ grass biomass $+ 0.40$, $R^2 = 0.45$, $P < 0.05$).

As the largest source of SOC, grass roots play a key role in the study area, reaching 10.5% and 21.4% of the total carbon density in the restored areas and in the natural ecosystem, respectively. Brown and Lugo (1990) indicated that grasses have high productivity (particularly from the roots), and their turnover rates input organic carbon into soil. Other studies have also found that grass roots were more important sources of SOC than the roots of woody plants, which can live longer than grass roots (Jobbágy and Jackson, 2000).

4.4. Management implications

Appropriate management strategies are important for carbon sequestration (Lal, 2004b). In the past 20 years, desertification and deforestation because of inappropriate measures or environmental factors are a significant source of atmospheric carbon (Houghton et al., 1999; Jackson et al., 2002; Wu et al., 2003; Bailis and McCarthy, 2011). Overall, about a quarter of anthropogenic carbon dioxide emissions are caused by inappropriate land use (Barnett et al., 2005). However, improved strategies (such as restoration) can increase carbon storage in terrestrial ecosystems (Houghton et al., 1999; McCarl and Schneider, 2001; Grünzweig et al., 2003; Denman et al., 2007; Hu et al., 2008; S.P. Wang et al., 2011; Chuai et al., 2012; Huang et al., 2012).

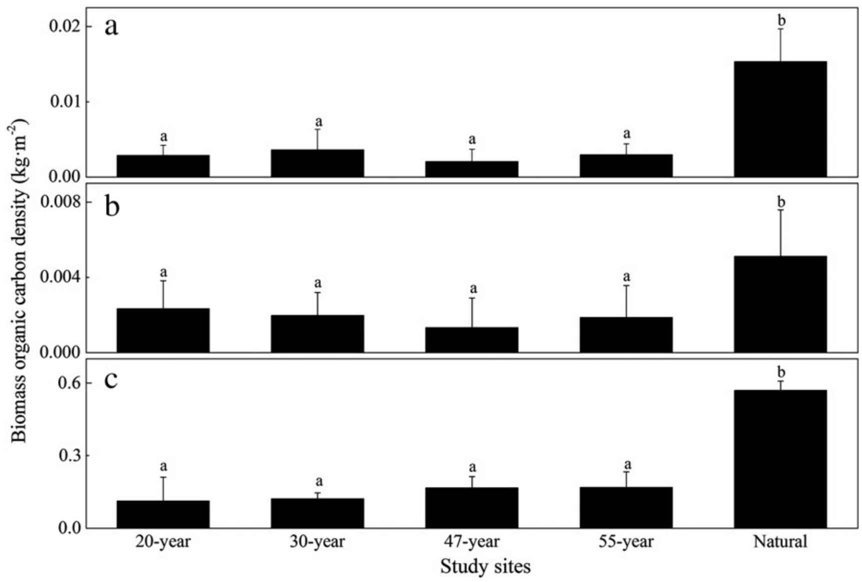

Fig. 5. Organic carbon density of (a) living, (b) litter, and (c) root biomass from grass in the restored sites and the natural vegetation site. Values are mean ± SE. Letters indicate significant differences between sites ($P < 0.05$).

The established vegetation in a shifting sand dune can stabilize the dune surface and increase the surface roughness (Li et al., 2005b), which further increases atmospheric dust deposition (Xiao et al., 1996) and creates a stable physical environment. A large number of biological soil crusts and many grass species colonize such areas when conditions are favorable (Li et al., 2005b, 2006). As a result TOC rapidly and significantly increased after sand-binding vegetation was established ($P < 0.05$). Our results proved Meyer's (2011) conclusion that shrubs in cold deserts can store significant amounts of carbon in their biomass and soil. In addition, the sand-binding vegetation system effectively prevented the desertification process, protected the railway from the shifting sand dune while also providing a stable natural ecosystem. In other words, the sand-binding vegetation system not only prevented carbon emissions from a potentially desertified land, but

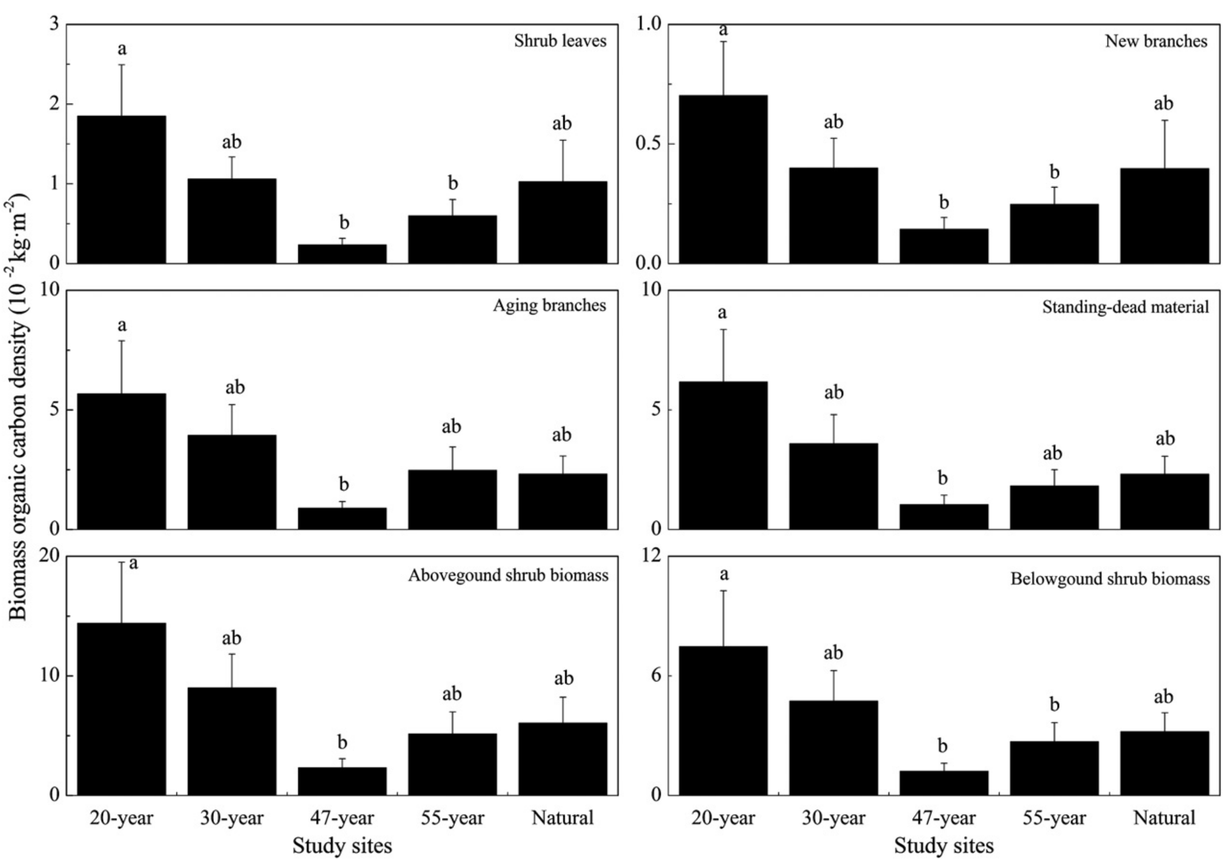

Fig. 6. Organic carbon density of (a) shrub leaves, (b) new branches, (c) aging branches, (d) standing-dead material, (e) aboveground shrub biomass, and (f) belowground shrub biomass in the sand-binding vegetation sites and the natural vegetation site. Values are mean ± SE. Letters indicate significant differences between sites ($P < 0.05$).

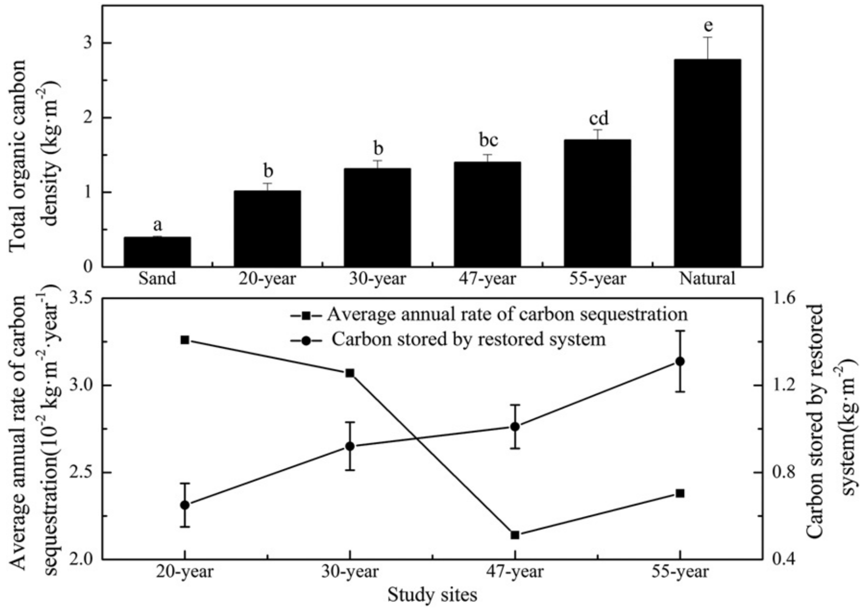

Fig. 7. (a) Total organic carbon density of all sites. Values are mean ± SE. Letters indicate significant differences between sites ($P < 0.05$), and (b) the carbon stored by sand-binding vegetation sites and average annual rate of carbon sequestration of each restored site.

also sequestered CO_2 from the atmosphere. Under the condition of no irrigation, the restoration systems by establishing windbreaks and planting xerophytic shrubs in shifting sand dune with an annual precipitation of <200 mm proved to be a successful and environmentally friendly management strategy.

The cost of this type of restoration system was about 1000 dollars per hectare today. Based on our study results, we calculated carbon sequestration by multiplying the carbon density by the study area. From this calculation, we estimate that 0.62×10^4 kg of carbon can be stored in ecosystems per hectare at 20 years after vegetation was first established on the shifting sand dune. The carbon sequestration may increase to 1.31×10^4 kg after 55 years. Considering the carbon market in China and the environmental and ecological economic benefits, restoring desert ecosystems is a cost-effective

Table 2
The relative contribution of different components to the total organic carbon density in five sites.

Study sites	Soil	Grass	Litter	Grass root	Shrub (aboveground)	Shrub root
20-year	67.61 ± 4.62	0.28 ± 0.04	0.23 ± 0.05	13.57 ± 2.36	12.08 ± 3.1	6.23 ± 1.69
30-year	79.45 ± 2.66	0.25 ± 0.06	0.15 ± 0.03	9.94 ± 1.13	6.67 ± 2.02	3.5 ± 1.09
47-year	84.75 ± 2.15	0.15 ± 0.04	0.1 ± 0.04	12.42 ± 1.4	1.68 ± 0.54	0.89 ± 0.29
55-year	84.96 ± 2.6	0.19 ± 0.04	0.11 ± 0.03	9.95 ± 0.9	3.14 ± 1.25	1.65 ± 0.65
Natural	74.79 ± 2.21	0.59 ± 0.13	0.17 ± 0.14	21.02 ± 1.66	2.24 ± 0.71	1.2 ± 0.33

Values represent means ± SE.

Table 3
The relative contribution of shrub species, through different plant portions (i.e. leaves, new branches, and aging branches) to TOC in five sites.

Study sites	*A. ordosica*				*H. scoparium*			
	A	B	C	D	A	B	C	D
20-year	0.69 ± 0.18	0.24 ± 0.07	1.55 ± 0.49	2.1 ± 0.96	0.73 ± 0.32	0.32 ± 0.12	2.22 ± 0.91	2.81 ± 1.35
30-year	0.27 ± 0.06	0.08 ± 0.02	0.7 ± 0.25	0.86 ± 0.29	0.33 ± 0.16	0.14 ± 0.07	0.87 ± 0.49	1.31 ± 0.58
47-year	0.04 ± 0.01	0.02 ± 0.01	0.15 ± 0.04	0.4 ± 0.14	0.11 ± 0.05	0.08 ± 0.03	0.39 ± 0.14	0.3 ± 0.13
55-year	0.11 ± 0.05	0.05 ± 0.02	0.26 ± 0.1	0.34 ± 0.15	0.2 ± 0.08	0.08 ± 0.04	0.72 ± 0.43	0.55 ± 0.18
Natural	0.22 ± 0.18	0.08 ± 0.07	0.32 ± 0.27	0.35 ± 0.23				
Study sites	*C. korshinskii*				*C. lateens*			
	A	B	C	D	A	B	C	D
20-year	0.15 ± 0.08	0.07 ± 0.03	0.96 ± 0.55	0.24 ± 0.15				
30-year	0.19 ± 0.11	0.08 ± 0.04	1.35 ± 0.6	0.5 ± 0.27				
47-year	0.03 ± 0.02	0.01 ± 0	0.14 ± 0.08	0.03 ± 0.02				
55-year	0.07 ± 0.05	0.02 ± 0.01	0.53 ± 0.43	0.22 ± 0.18				
Natural	0.06 ± 0.02	0.02 ± 0.01	0.32 ± 0.18	0.22 ± 0.12	0.08 ± 0.02	0.04 ± 0.02	0.22 ± 0.06	0.3 ± 0.12

Values represent means ± SE.
A, B, C, and D represent leaves, new branches, aging branches and standing-dead material of shrubs, respectively.

Table 4
Relationship between organic carbon storage and the age of sand-binding vegetation.

Relationship	Coefficient of determination	F	Significance
$y = 0.0218x + 0.1144$	$R^2 = 0.934$	47.087	$P < 0.05$

The y value represents the net increase of organic carbon, and x represents the number of years after sand-binding vegetation was established.

way to sequester CO_2 from the atmosphere and mitigate the effects of global climate change. Furthermore, as the restored areas age, their capacity to store organic carbon increases. As shown in Table 4, we found a significant best-fit linear relationship between organic carbon storage and the age of the restored site. Based on this relationship, the amount of organic carbon that can be stored in a sand dune can approach that of natural vegetation after the sand-binding vegetation has been established on the dune for 98 years. Therefore, our results clearly indicate that more carbon sequestration can be expected over time in these restored areas.

In China, the amounts of arid desert, semiarid desert, and desertified land are 58.1×10^4, 10.3×10^4, and 38.57×10^4 km^2, respectively (Wang, 2003). Furthermore, large land areas are prone to desertification. UNEP estimated that about 60% of the total land area of arid ecosystems was prone to desertification (UNEP, 1991). Therefore, we can potentially sequester significant amounts of carbon if more restoration systems are established in desert and desertification areas.

5. Conclusions

Organic carbon stored in the soil, shrubs and grass biomass (above- and belowground) markedly increased after establishing new vegetation in shifting sand dune. Furthermore, organic carbon storage increased along the chronosequence. SOC and TOC stocks were 30.8% and 36.1% lower under a 55-year-old sand-binding vegetation system than under an adjacent natural vegetation system. Despite this, the sand-binding vegetation system sequestered a significant amount of C (2.38×10^{-2} $kg \cdot m^{-2} \cdot year^{-1}$) from the atmosphere after sand-binding vegetation has been established in shifting sand dune within 55 years, especially in the top 1 m soil (1.92×10^{-2} $kg \cdot m^{-2} \cdot year^{-1}$). The average annual rate of carbon sequestration was highest in the first 20 years after restoration (3.26×10^{-2} $kg \cdot m^{-2} \cdot year^{-1}$), and reached a stable rate ($2.14 \times 10^{-2} kg \cdot m^{-2} \cdot year^{-1}$) after 47 years. Our study showed that establishing sand-binding vegetation on a sand dune may be an important strategy for mitigating the rise in atmospheric CO_2 and the effects of global climate change. Overall, regional studies that quantify the amount of organic carbon stored in ecosystems that have been converted from a desert to sand-binding vegetation areas can help improve the global estimates of carbon storage capacity. In addition, these studies may help assess the role that regional ecosystems play in the global carbon cycle.

Conflict of interest statement

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work; there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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