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Changes in soil organic carbon and nitrogen capacities of *Salix cheilophila* Schneid along a revegetation chronosequence in semi-arid degraded sandy land of the Gonghe Basin, Tibet Plateau

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Abstract

The Gonghe Basin is a sandified and desertified region of China, but the distribution of soil organic carbon (SOC) and total nitrogen (TN) along the cultivation chronosequence across this ecologically fragile region is not well understood. This study was carried out to understand the effects of afforestation with *Salix cheilophila* for different periods of time (6, 11, 16, 21 years) to test whether it enhanced C and N storage. Soil samples, in four replications from seven depth increments (every 10 cm from 0 to 30 cm, every 20 cm from 30 to 50 cm and every 50 cm from 50 to 200 cm), were collected in each stand. Soil bulk density, SOC, TN, aboveground biomass and root biomass were measured. Results indicated that changes occurred in both the upper and deeper soil layers with an increase in revegetation time. The 0–200 cm soil showed that the 6-year stand gained 3.89 Mg C ha^{-1} and 1.00 Mg N ha^{-1}, which accounted for 40.82 % of the original SOC and 11.06 % of the TN of the 0-year stand. The 11-year stand gained 7.82 Mg C ha^{-1} and 1.98 Mg N ha^{-1} in the 0–200 cm soil layers, accounting for 58.06 % of the SOC and 19.80 % of the TN of the 0-year stand. The 16-year stand gained 11.32 Mg C ha^{-1} and 3.30 Mg N ha^{-1} in the 0–200 cm soil layers, accounting for 66.71 % of the SOC and 21.98 % of the TN of the 0-year stand. The 21-year stand gained 13.05 Mg C ha^{-1} and 5.45 Mg N ha^{-1} from the same soil depth, accounting for 69.79 % of the SOC and 40.47 % of the TN compared with the 0-year stand. The extent of these changes depended on soil depth and plantation age. The results demonstrated that as stand age increased, the storage of SOC and TN increased. These results further indicated that afforestation with *S. cheilophila* has positive impacts on the Gonghe Basin and has increased the capacity of SOC sequestration and N storage. Shrub's role as carbon sink is compatible with system's management and persistence. The findings are significant for assessing C and N sequestration accurately in semi-arid degraded high-cold sandy regions in the future.

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1 Introduction

Arid and semi-arid regions cover ~30 % of the terrestrial land around the globe and desertification affects over 250 million people (Lal, 2001, 2009; Reynolds et al., 2007; Allington and Valone, 2010). In the largest developing country, China, the most typical and serious form of land degradation is desertification. China is the country with the largest area of desertified or sandified lands in the world. According to statistics, China has a total desertified land area of 26.237×10^5 km^2 covering 27.33 % of the national territory and a total sandified land area of 17.311×10^5 km^2 covering 18.03 % of the national territory and which are under threat of land degradation by the end of 2009 (State Forestry Administration, 2011). Desertification is the degradation of land in arid, semi-arid and sub-humid dry areas resulting from various factors, including climatic variations and human activities (UNEP, 1994). It results in soil degradation and severe decreases in land potential productivity. With the exception of land degradation, desertification promotes atmospheric emission of soil C and N as greenhouse gas (Breuer et al., 2006). Measures such as artificial reforestation and grass plantation have worked to improve the ecological benefits of sandstorm control to reduce the damage from sandstorms. Revegetation of degraded land is a major global issue, which has been shown to improve and restore some of the ecosystem services both of the physical and biological processes. It has been widely recognized that revegetation is an effective measure for soil and water conservation, increasing C and N storages and improving land productivity (Grünzweig et al., 2003; Cao et al., 2008, 2011; Hu et al., 2008; Lal, 2009; Li et al., 2012). In desertified areas of northwest China, establishing artificial vegetation and bans on grazing are commonly adopted measures for combating desertification and restoring vegetation. It not only resists the spread of desertification but also restores ecosystem processes that could potentially yield significant gains in nutrients storage (Zhao et al., 2007; Huang et al., 2012). Therefore, land use and management practices to sequester soil organic carbon (SOC), including afforestation and revegetation, are the driving forces that could determine the transition of desertification regions from a C source to a C sink or vice versa. For this reason, the effects of revegetation on soil C and N contents in degraded land have become a concern in recent years.

Revegetation on a large-scale in degraded arid and semi-arid lands is likely to have far reaching consequences on the global C cycle and climate change (Lal, 2009). To know the changes in soil C and N content is not only critical to determining the soil physiochemical properties but also to quantifying the influence of changing rates of C and N cycling and storage (Liu et al., 2002). It has been reported that chronosequence or successional stage may be a critical factor affecting changes in C stock and allocation among the different ecosystem components (Li et al., 1997; Zhang et al., 2005; He et al., 2012). Wang (2009) observed that a significant difference in SOC occurred in a semi-arid grassland of an undisturbed steppe, a 28-year crop land and a 42-year crop land and the changes depended on soil depth and land age. Chen (2010) and Li (2012) reported that SOC and N increased significantly in different depths with plantation age of Mongolian pine in semi-arid degraded sandy land. Zhou (2011) investigated the dynamics of soil C and N accumulation over 26 years under controlled grazing in a desert shrubland. Su (2005) found that after planting the shrubs *Caragana microphylla* Lam. and *Artemisia halodendron* Turcz. ex Bess on shifting sand dunes, SOC and N significantly increased in two upper soil layers (0–5 and 5–20 cm) in semi-arid Horqin sandy land. Information on SOC and N concentration in a long-term revegetation chronosequence is necessary to identify the strategies of degraded land recovery. Despite an increasing number of related studies, the effect of *Salix cheilophila* on soil improvement still remains poorly understood.

The Gonghe Basin, located in the northeast Tibet Plateau (35°27′ to 36°56′ N, 98°46′ to 101°22′ E), is one of the most seriously desertified and ecologically fragile high-cold regions in the Qing Hai province of China. Arbitrary land use and several decades of overgrazing have led to land degradation and desertification. Frequent sandstorms happened and desertification occurred during the last century. Semi-arid steppe, sandland and shrubland are widely distributed in the Gonghe Basin. Based on the geographic-ecological similarity, one effective approach to improve the fragile ecological environment and control for desertification is to select shrub species that have excellent adaptability and characteristics under natural ecological conditions. Large areas of trees and shrubs have been planted in this region since the 1980s. *Salix cheilophila* is one of the shrub species growing well in degraded land and it can be used for multiple shelterbelts and desertification control. *S. cheilophila* Schneid. is a member of the Salix Family (Salicaceae), is a Chinese endemic species which adapts well to windy and sandy environments and is widely distributed throughout the Northwest of China, especially in the Qing Hai province and Tibet. Because of its adaptability in harsh environmental conditions, *S. cheilophila* is widely cultivated in revegetation programs to control desertification in the Gonghe Basin. The metabolic activities of *S. cheilophila* have been extensively studied by H. Liu (2012) and L. Liu (2012) however, there remains little knowledge about *S. cheilophila* enhancing soil SOC and N along a chronosequence in this region. It was hypothesized that SOC and N allocation changes with increasing stand age of *S. cheilophila* and soil fertility significantly increases over time. The objectives of our study were to investigate the soil physicochemical properties and quantify the effects of vegetation restoration on the SOC and N in *S. cheilophila* plantations and in lowland among sandy dunes of the Gonghe Basin. Results from this study can provide base data for the parameterization of regional models that can be used to determine SOC and N storages under *S. cheilophila* plantations and provide the basis for soil improvement of high-cold sandy land ecosystem services.

2 Materials and methods

2.1 Study area

The study was conducted at the Gonghe Desert Ecosystem Research Station (latitude 36°19′ N, longitude 100°16′ E and altitude 2871 m), which was constructed by the Chinese Academy of Forestry and the Desertification Combating Station of Qinghai Province (Fig. 1). It is one of the stations in the Chinese Desert Ecosystem Research

Network located in the Gonghe Basin on the northeast part of the Tibetan plateau. The area has a strong continental semi-arid climate. The growing season is from June to September. The mean annual precipitation is ~246.3 mm, more than 75 % of which falls during the growing season, and the mean annual air temperature is 2.4 °C. The mean annual potential transpiration is 1716.1 mm, the mean annual number of windy days is 50.6 d and the primary wind direction is north-northwest. The mean annual wind speed is 2.7 ms^{-1} and the mean length of the frost-free season is 91 d. The vegetation in the desertified sandy land is generally dominated by psammophytes including grasses (e.g., *Leymus secalinus*, *Orinus kokonorica*, *Stipa capillata* and *Thermopsis lanceolata*) and shrubs (e.g., *Caragana intermedia*, *Salix cheilophila* and *Tamarix chinensis*). *C. intermedia*, a leguminous shrub, is the dominant shrub species on semifixed and fixed sandy dunes. *Salix cheilophila* is the dominant shrub species on land between dunes. Both of them adapt well to the sandy environment, and have been widely used in vegetation re-establishment programs, such as artificial shelter belts, since the 1980s. Four stands of *S. cheilophila* of different ages (6, 11, 16, and 21 years) were identified. A plot (0 years old) between dunes was used as a control. All of the stands located in the land between dunes had only rarely been disturbed by human activities and had naturally regenerated after revegetation. The main type of soil in the research region is sandy loam, and clay exists at different soil depth.

2.2 Soil sampling and laboratory analysis

The field measurements and sampling were completed in the growing season of 2011 and 2012 (June to August). Three 20 m × 20 m plots were randomly selected in each stand. In each of the plantation plots, tree basal diameter and average tree height for all of the live *S. cheilophila* were recorded using a diameter tape, and canopy height was estimated using a clinometer for all trees within each plot. Five 1 m × 1 m subplots were randomly established within each plot and sampled for both accumulated litter and understory plant biomass. During the study, four trees representing the respective stand-specific basal diameter and height range were selected. A depth of 0–200 cm was divided into seven layers, (every 10 cm from 0 to 30 cm, every 20 cm from 30 to 50 cm and every 50 cm from 50 to 200 cm) and samples were taken with a 6 cm diameter soil core on the edge of the south crown of each standard tree. Therefore, in every plot, a total of 28 composite soil samples were obtained for each soil layer with a total of 112 samples across all plots. The samples were sealed in plastic bags and transported to the laboratory. Soil bulk density (BD) of each depth increment for every sampling site was measured using the core method (stainless steel cylinders with a volume of 100 cm^3). All soil samples were air dried and visible plant material was removed, then they were sieved to 0.5 mm for SOC and TN measurements. In each plot, roots of four samples were excavated manually from each of the soil layers. All root samples were transported to the laboratory, and carefully washed on a 60 mm sieve to separate the roots from the soil at once. All washed roots were weighed after oven drying at 65 °C for 48 h. Total SOC was determined by loss on ignition at 500 °C (Storer, 1984). Total N concentration was measured by the Kjeldahl procedure (Bremner et al., 1996).

2.3 Calculations and data analysis

The SOC and TN at each depth were obtained by the sum of organic C and N stocks of the seven depths. The SOC mass per unit surface area ($\mathrm{kg\,m^{-2}}$) of a profile is calculated as the weighted average of the SOC mass density of every depth, where the thickness of the horizon is the weighting factor, multiplied by the reference depth (Meersmans et al., 2008; Han et al., 2010). For each depth interval, SOC and TN stocks were calculated with the following equation:

$$S = \mathrm{EC} \times \mathrm{BD} \times T \times k \times 10^{-6} \qquad (1)$$

where S is the element stocks ($\mathrm{kg\,m^{-2}}$), EC is the element concentration ($\mathrm{g\,kg^{-1}}$), BD is the bulk density ($\mathrm{g\,cm^{-3}}$), T is the thickness of the horizon and k is the area multiplier.

This study did not involve replicated stands of the same age with a similar stand composition, soil type and environmental conditions, because of the complexity of the study site in this area. Data were analyzed to provide mean and standard error for each variable measured at every depth in each stand. Analysis of variance was performed using the MIXED procedure in SAS that computes Wald-type F-statistics using generalized least squares (GLSE) based on restricted maximum likelihood estimates of the variance components (Littell et al., 1996). In the case of significant differences in the Wald-F-statistic at $P < 0.05$, treatment means were compared using a two-sided t test. The regression model was determined with Matlab 8.0 software. All statistical analyses were conducted with the SAS software package (SAS, Institute Inc. 2000).

3 Results and discussion

3.1 Soil bulk density

Soil BD plays a critical role in the assessment of SOC contents. Table 1 shows that the BD values are significantly different in different stand ages and marked differences were found among the different soil depths. This indicated that the soil BD of the 21-year stand was lower compared with other stand ages in each of the seven depths (i.e. 1.49, 1.39, 1.47, 1.46, 1.47, 1.52 and 1.53 g cm^{-3} in the 0–10, 10–20, 20–30, 30–50, 50–100, 100–150 and 150–200 cm depths, respectively). The mean BDs decreased with the extension of restoration time. At 0–10 cm, the 16- and 21-year stands were significantly different to the other stand ages but not from each other. The 11-year stand was significantly lower than the 6 and 0 year stands but there was no significant difference between the 0- and 6-year stands. At 10–20 cm, the 21-year stand was significantly lower than any other stand and the 16-year stand showed no significant difference compared with the 11-year stand but was significantly lower than the 6- and 0-year stands, which in turn were significantly different from each other. At 20–30 cm, the 21-year stand was significantly lower than the other stand ages and there was no significant difference between the 6-, 11- and 16-year stands. The 11-year stand showed no difference with the 0-year area but the 6- and 16-year areas were significantly lower than the 0-year area. At 30–50 cm, the only difference from 20–30 cm was that there was no significant difference among the 6-, 11-, 16- and 21-year areas; however, all of them were significantly different from the 0-year area, which showed the same changes at 50–100 cm.

In subsoil, significant differences in soil BD were also exhibited among the different stand ages. The 21-year stands showed no significant differences from the 16-year stands but were significantly lower than the other stand ages. There was no significant difference among the 0-, 6- and 11-year stands at 100–150 cm. At 150–200 cm, significant differences existed among the stand ages. The 21-year stand was significantly different to all stand ages except 16 years and there was no significant difference among the 0-, 6-, 11- and 16-year stands. The results indicated that vegetation restoration could affect the soil BD, possibly because of the plant roots (Ryan and Law, 2005).

It is also widely believed that soil BD declines with an increase in soil organic matter because of the increase in porosity volume (Whalen et al., 2003). Therefore, the linear relationship between soil BD and SOC was established in various ecosystems. Prior to this study, no data existed on the relationship between BD and SOC for soils in High-Cold Sand land of the Gonghe Basin. The relationship in the *S. cheilophila* chronosequence was modeled with SigmaPlot 2011, and it was found that there was a linear relationship that can be described by the following equation (Fig. 2):

$$\mathrm{SOC} = 39.129 - 22.187\mathrm{BD}\,(R^2 = 0.247, P < 0.001). \tag{2}$$

3.2 Root biomass and aboveground biomass

The data in Table 2 clearly show that revegetation led to significant differences in both aboveground and root biomass, and that root biomass in the deep soil layers also increased significantly with the extension of restoration time. The root biomass in differently-aged stands changed significantly with an increase in depth. The aboveground biomass increased along the chronosequence, and was 776.40 g m^{-2} for the 6-year, 1011 g m^{-2} for the 11-year, 2098 g m^{-2} for the 16-year and 2963 g m^{-2} for the 21-year stands. Additionally, the root biomass also showed an increasing trend:

281.64 $g\,m^{-2}$ for the 6-year, 363.04 $g\,m^{-2}$ for the 11-year, 811.54 $g\,m^{-2}$ for the 16-year, and 1120.61 $g\,m^{-2}$ for the 21-year stands; this was significantly different at different soil depths. The aboveground biomass was nearly three times as large as the root biomass. Therefore, both the aboveground and the root biomass were the dominant source for soil C input in semi-arid degraded sandy land of the Gonghe Basin.

The significant increase in total C input with restoration time in the semi-arid degraded sandy area indicated that afforestation is an effective option to sequester C, which could further increase C influx through more efficient plant use of resources for primary production (Nosetto et al., 2006; Li et al., 2012). Therefore, the increase in SOC and N input will subsequently result in increased SOC and N storage.

3.3 Soil organic C and N concentration

The SOC and N storage increased significantly with plantation age but there were different changes as soil depth increased (Fig. 3). The mean was highest but most variable in the topsoil layer and dropped significantly in the subsoil layer (> 100 cm). For the total study area, the SOC concentrations peaked at 0–10 cm except at 6 and 0 years, which have the highest amount of SOC at 10–20 cm. For the TN concentration, the 16- and 21-year stands peaked in the surface soil and 0-, 6- and 11-year stands have the highest amount at 10–20 cm. The SOC and TN concentrations were markedly altered by the extension of restoration.

In the top 10 cm, SOC was significantly greater in the 21-year stand than in the other stands and the SOC increased significantly with the extension of restoration time. At 10–20 cm, there were no significant differences between 16- and 21-year stands, but the SOC content was significantly greater in both of these than in the other aged stands. Although the SOC content in the 6-year stand was also significantly greater than in the 0-year stand, there was no significant difference between the 6- and 11-year stands. At 20–30 cm, the SOC content of the 21-year stand was significantly greater than that of any other and the 11-year stand showed no significant difference from the 0-year stand, but was significantly lower than the 6-year stand. At 30–50 cm, the SOC content in the 21-year stand was not significantly different from the 16-year stand but was significantly greater than for the other ages. There was no significant difference among the SOC contents of the 6-, 11- and 16-year stands, which were significantly greater than the 0-year stand. At 50–100 cm, the SOC content of the 21-year stand was significantly greater than that of the 11-year stand, but was not significantly different from that of the 16-year stand. There was also no significant difference between the SOC contents of the 16- and 11-year stands, which were significantly higher than those of the 6- and 0-year stands.

The SOC storage in the deep soil showed a significant difference. The SOC in the 21-year stand showed no significant difference from the 16-year stand, and both of them were significantly higher than those in the 6- and 0-year stands, which showed the same changes at 150–200 cm. There was no significant difference among the SOC contents of the 11-, 6- and 0-year stands at 100–150 cm and that of the 11-year stand was significantly different to the other stand ages at 150–200 cm.

The patterns for TN concentration were not substantially different from those for SOC (Fig. 4). In particular, although the 0–10 cm layer showed the same variation trend as SOC, there were significant differences in each stand. The TN in the 21-year stand was significantly greater than in the 16-year stand and there was no significant difference among the 11-, 6- and 0-year stands, which were significantly lower than the 16-year stand. At 10–20 cm, there was no significant difference in TN among the 16-, 11- and 6-year stands, which were significantly greater than that in the 0-year stand and lower than that in the 21-year stands. The 20–30 cm and 30–50 cm layers showed the same changes in TN as the surface layer. At 50–100 cm, the TN content of the 21-year stand was significantly greater than those of the other stands, which were not significantly different from each other. At 100–150 cm, there was a significant difference between the TN of the 11-year and other stands and the 16- and 21-year stands were significantly greater than the 6- and 0-year stands. At 150–200 cm, there was no significant difference in TN content among the 11-, 16- and 21-year stands, which were significantly greater than those of the 6- and 0-year stands.

The higher SOC and TN content in the upper soil layer than the subsoil layer could be explained by the root growth and decay process. It is widely accepted that plant roots play an important role among the various factors influencing soil structural porosity, especially the fine roots. Most of the roots were located in the upper soil. With the extension of restoration times, the vertical distribution and biomass of the roots increased, soil N was usually moved by roots from subsoil layers to the surface during plant growth, and the soil C and N were retained when the roots died, which resulted in increased C and N concentrations. It was found that the vertical distribution at 21 years could reach 200 cm. Moreover, the growth of the root system led to the changes of BD, which could promote the soil organic matter storage and total nitrogen content. Therefore, models simulated the changes of SOC and BD with the extension of stand age and depth were established (Fig. 5), using the SOC as the dependent variable (z), the BD and stand age as independent variable (x) and (y) respectively, the regression model was established as follow:

$$z = -180.253 + 1.2x + 255.136y - 0.011x^2 - 0.474xy - 89.186y^2 (R^2 = 0.458, P < 0.01) \tag{3}$$

when used the BD (x) and depth (y) as independent variable, the model was described as:

$$z = -359.406 - 0.193x + 518.887y + 0.003x^2 + 0.078xy - 182.25y^2 (R^2 = 0.521, P < 0.01) \tag{4}$$

The model of SOC and TN with the extension of stand age and soil depth also established (Fig. 6), using the SOC as the dependent variable (z), the TN and stand age as independent variable (x) and (y) respectively, the regression model was established as follow:

$$z = -2.611 + 75.486x + 0.613y + 1867.623x^2 - 6.634xy - 0.011y^2 (R^2 = 0.392, P < 0.01) \quad (5)$$

when used the TN (x) and depth (y) as independent variable, the model was described as:

$$z = -3.668 + 368.861x - 0.009y - 2186.34x^2 - 0.965xy + 0.001y^2 (R^2 = 0.427, P < 0.01) \quad (6)$$

The results indicated that afforestation could affect the BD and especially the shrub could reduce it evidently, the difference in the BD can be caused by the root. Moreover, the content of SOC and TN increased with the BD decreased.

3.4 Soil organic C and N stocks or losses and gains of salix

Table 3 shows the gains and losses of the SOC and TN in different stands relative to the 0-year stand, based on calculations in which the BD variability, SOC, TN contents and depth were taken into account. The results indicated that the 6-year stand gained 3.89 Mg C ha^{-1} and 1.00 Mg N ha^{-1} in the 0–200 cm soil layers, which accounted for 40.82 % of the original SOC and 11.06 % of the TN of the 0-year stand. The 11-year stand gained 7.82 Mg C ha^{-1} and 1.98 Mg N ha^{-1} in the 0–200 cm soil layers, accounting for 58.06 % of the SOC and 19.80 % of the TN of the 0-year stand. The 16-year stand gained 11.32 Mg C ha^{-1} and 3.30 Mg N ha^{-1} in the 0–200 cm soil layers, accounting for 66.71 % of the SOC and 21.98 % of the TN of the 0-year stand. The 21-year stand gained 13.05 Mg C ha^{-1} and 5.45 Mg N ha^{-1} from the same soil depth, accounting for 69.79 % of the SOC and 40.47 % of the TN compared with the 0-year stand.

Although the SOC and TN increased with stand age, different stages showed differences with soil depth. These results indicated that the 11-year stand lost

$0.02\,\mathrm{Mg\,C\,ha^{-1}}$ at 20–30 cm, decreased 4.5 % compared to the 0-year stand. The soil has strong heterogeneity in arid and semi-arid regions. The root, which could be considered as the "bio-management" in the harsh environment, was the primary cause lead to the contents accumulation and consumption of the SOC and TN in different depth and stand age. Laclau (2003) and Li (2012) found that because of the biomass accumulations, soil organic matter increases with the extension of the revegetation time, in semi-arid areas. The present results are consistent with the findings of Su and Zhao (2003), who reported higher SOC in stands of C. *microphylla* shrub than in active sand dunes. Wei (2010) compared the distribution of SOC and N in soils under canopies and in outer tree canopies in semi-arid areas and found that dry climate, low C soils had a potential for C sequestration after grassland to woodland conversion. Hu (2008) documented a significant potential for soil C sequestration with afforestation in Horqin Sandy Land and Li (2012) revealed that Mongolian pine plantations in Horqin Sandy Land have a great potential to sequester C, which agreed with the present research. The Gonghe Basin has experienced intensive desertification in recent decades. *S. cheilophila* also has a great potential to sequester C. Therefore, it is important to comprehensively evaluate the effects of these plantations on ecosystem C sequestration in the Gonghe Basin. Although depth research on soil C studies varies (Guo and Gifford, 2002; Post and Kwon, 2008; Fu et al., 2010), many studies have only considered SOC changes in the upper soil layers to investigate the impacts of land use change on soil properties and C storage. The subsoil also has a large SOC storage capacity (Jobbágy and Jackson, 2000; Knops and Bradley, 2009; Carter and Gregorich, 2010; Chang et al., 2012). Therefore, more studies focusing on the subsoil SOC are necessary to accurately evaluate the changes in soil C pools following afforestation. The present results showed that significant responses occurred in the subsoil layer because of root distributions. In light of global warming, scientists have recognized the potential of soil as a C sink to counteract the increasing trend of atmospheric CO_2 concentration (Grace, 2004). Therefore, revegetation of degraded land, especially in desertified or sandified lands such as those in the Gonghe Basin, is an effective way not only to combat desertification but also to provide a C sink. Understanding the impact of revegetation and afforestation on the SOC storage and increasing the capability of soil C sequestration is a challenge for the future.

4 Conclusions

This study demonstrated the significant increases in SOC and TN over time in *S. cheilophila* plantation soils in the Gonghe Basin of Qinghai, China. The establishment of *S. cheilophila* in the semi-arid high cold sandy land had positive impacts on the soil C sequestration and N storage. Soil organic C and TN increased significantly with plantation age. The difference indicated that the inputs of aboveground and root biomass were sufficient to increase the SOC and TN with the extension of revegetation time. The responses were observed among different stand ages not only in the top soil layer but also in the deeper soil. Plant roots played an important role in soil C sequestration especially in the study area characterized by the low SOC because of the sandy soil texture. It is necessary to focus on the changes in SOC in the deeper soil layers to assess C sequestration accurately. This study identified that afforestation with *S. cheilophila* in high-cold sandy land of the Gonghe Basin is a positive way to improve soil quality and prevent desertification in these semi-arid regions.

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Table 1. Soil bulk density ($\mathrm{g\,cm^3}$) in different stand ages at different soil depth.

	Stand age (yr)				
Depth (cm)	0	6	11	16	21
0–10	1.56 ± 0.01Aab	1.54 ± 0.03ABc	1.53 ± 0.01Bbc	1.51 ± 0.01Cb	1.49 ± 0.02Cbc
10–20	1.54 ± 0.02Aa	1.44 ± 0.04Ba	1.42 ± 0.02BCa	1.41 ± 0.01Ca	1.39 ± 0.01Da
20–30	1.58 ± 0.01Ac	1.53 ± 0.01Bc	1.57 ± 0.01ABc	1.53 ± 0.03Bb	1.47 ± 0.02Cb
30–50	1.56 ± 0.02Abc	1.48 ± 0.05Bab	1.51 ± 0.02ABb	1.47 ± 0.06Bab	1.46 ± 0.01Bb
50–100	1.57 ± 0.01Abc	1.52 ± 0.02ABbc	1.50 ± 0.05ABb	1.49 ± 0.04Bab	1.47 ± 0.02Bb
100–150	1.57 ± 0.02Abc	1.55 ± 0.02ABc	1.56 ± 0.01ABc	1.53 ± 0.04BCb	1.52 ± 0.01Cd
150–200	1.57 ± 0.02Abc	1.57 ± 0.02Ac	1.57 ± 0.01Ac	1.56 ± 0.02ABb	1.53 ± 0.03Bd

Different uppercase letters indicate significant differences in different stand ages, different lowercase letters indicate significant differences in different soil depths ($P < 0.05$).

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Table 2. Aboveground and root biomass in different stand ages of *S. cheilophila*.

		Root biomass ($g\,m^{-2}$)							
Age	Above-ground residue ($g\,m^{-2}$)	0–10	10–20	20–30	30–50	50–100	100–150	150–200	total
6	776.40 ± 21.14a	55.03 ± 0.51a	60.12 ± 4.14a	54.88 ± 4.73a	45.46 ± 2.69a	36.19 ± 3.23a	30.22 ± 2.59a	–	281.64 ± 7.10a
11	1011.73 ± 18.92b	69.16 ± 3.21b	77.59 ± 2.39a	71.66 ± 2.02b	60.35 ± 2.57b	48.33 ± 2.93b	36.32 ± 2.63a	–	363.04 ± 4.81b
16	2098.19 ± 75.72c	135.50 ± 5.60c	149.19 ± 5.00b	154.92 ± 7.86c	124.67 ± 2.17c	107.49 ± 8.62c	85.12 ± 6.77b	54.92 ± 1.47b	811.54 ± 27.87c
21	2963.44 ± 58.66d	185.10 ± 2.05d	208.53 ± 25.45c	196.33 ± 11.87d	178.21 ± 11.10d	155.76 ± 8.43d	105.41 ± 5.61c	57.96 ± 4.84b	1120.61 ± 24.61d

Values are mean ± SE ($n = 4$ for aboveground plant residue, and $n = 4$ for root biomass). Significant differences between different stand ages at the same soil layers are indicated by different letters at $P = 0.05$.

Table 3. Gains and losses of soil organic carbon (SOC) and total nitrogen (TN) at different stands relative to the 0-year stand.

	6 a		11 a		16 a		21 a	
Depth (cm)	Mass (Mg ha^{-1})	%	Mass (Mg ha^{-1})	%	Mass (Mg ha^{-1})	%	Mass (Mg ha^{-1})	%
SOC								
0–10	0.32	53.87	1.13	80.3	1.32	82.63	1.34	82.81
10–20	0.18	18.79	0.01	1.44	0.57	42.39	0.61	43.99
20–30	0.21	31.01	−0.02	−4.50	0.35	42.97	0.82	63.53
30–50	0.44	38.26	0.56	44.12	0.75	51.28	1.00	58.46
50–100	1.66	59.24	2.21	66.00	2.56	69.18	3.11	73.19
100–150	0.41	25.58	1.99	62.45	2.78	69.89	2.93	71.00
150–200	0.67	38.42	1.93	64.15	2.99	73.50	3.24	75.05
0–200	3.89	40.82	7.82	58.06	11.32	66.71	13.05	69.79
TN								
0–10	0.09	16.49	0.14	23.24	0.26	36.48	0.54	54.20
10–20	0.06	11.78	0.09	16.11	0.10	17.89	0.30	38.62
20–30	0.02	4.29	0.05	8.81	0.14	20.51	0.34	39.05
30–50	0.05	6.15	0.26	24.05	0.46	36.40	0.93	53.45
50–100	0.34	15.61	0.58	23.81	0.89	32.42	1.72	48.12
100–150	0.22	10.28	0.53	21.55	0.77	28.45	1.25	39.29
150–200	0.20	9.36	0.33	14.50	0.68	25.77	0.37	15.99
0–200	1.00	11.06	1.98	19.80	3.30	29.18	5.45	40.47

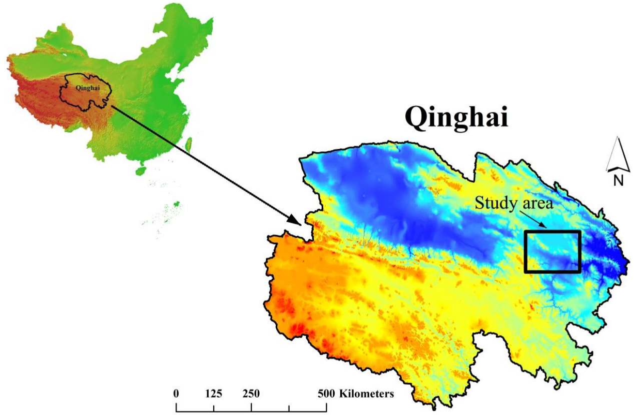

Figure 1. Location of the study area, Gonghe County, Qinghai Province, China.

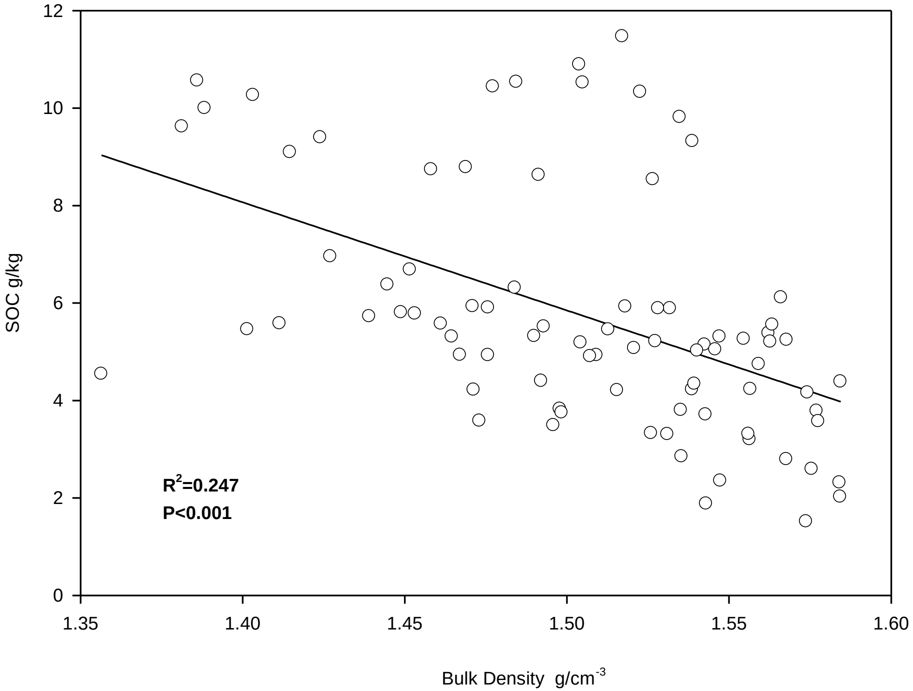

Figure 2. The relationship between soil organic carbon (SOC) and bulk density of *S. cheilophila*.

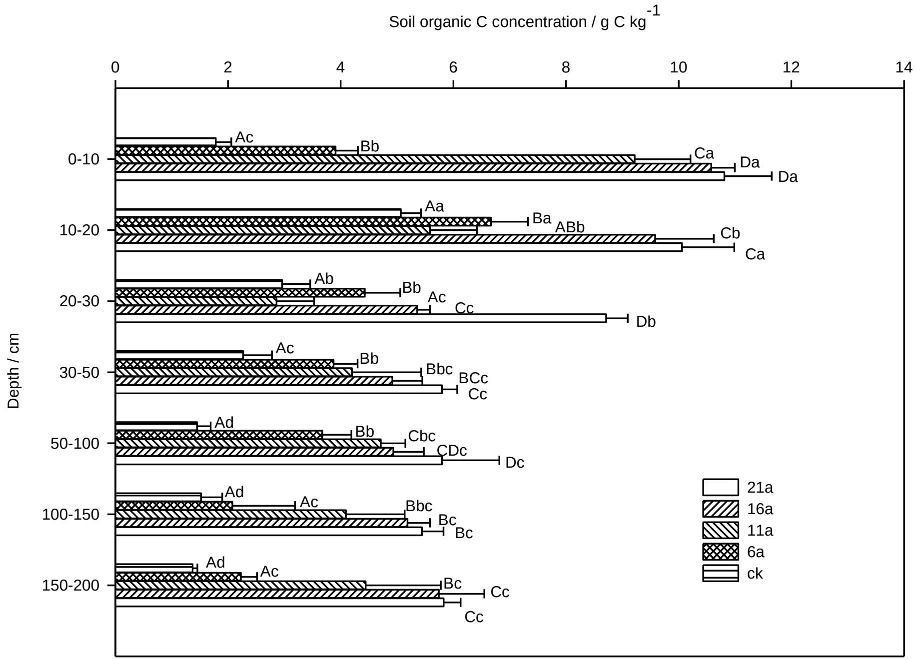

Figure 3. Variations in soil organic carbon concentration at different soil depths in different stand ages. Values are means ± SE. Different uppercase letters indicate significant differences in different stand ages, different lowercase letters indicate significant differences at different soil depths ($P < 0.05$).

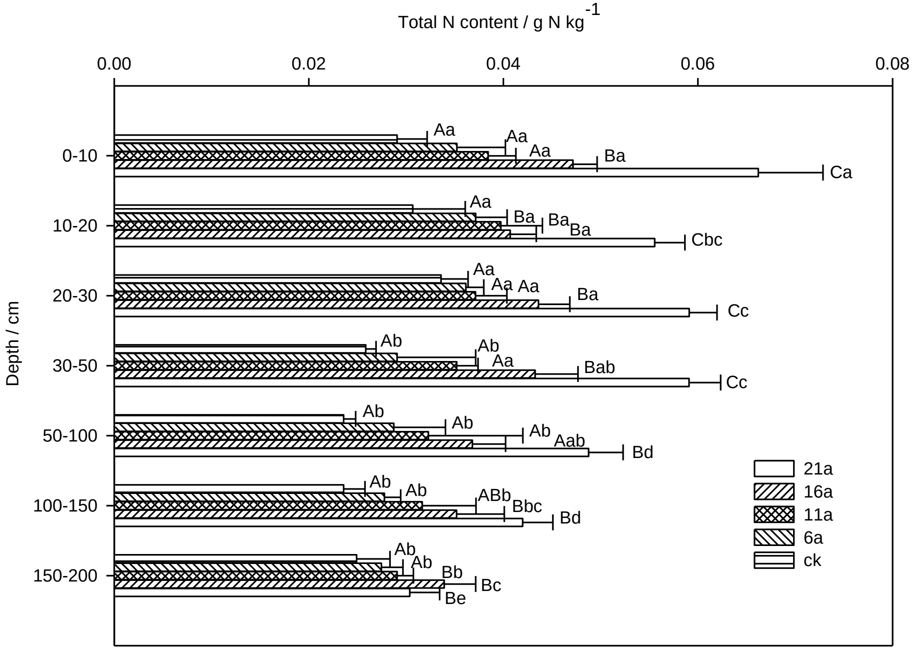

Figure 4. Variations in total nitrogen (Total N) concent at different soil depths in different stand ages. Values are means SE. Different uppercase letters indicate significant differences in different stand ages, different lowercase letters indicate significant differences at different soil depth ($P < 0.05$).

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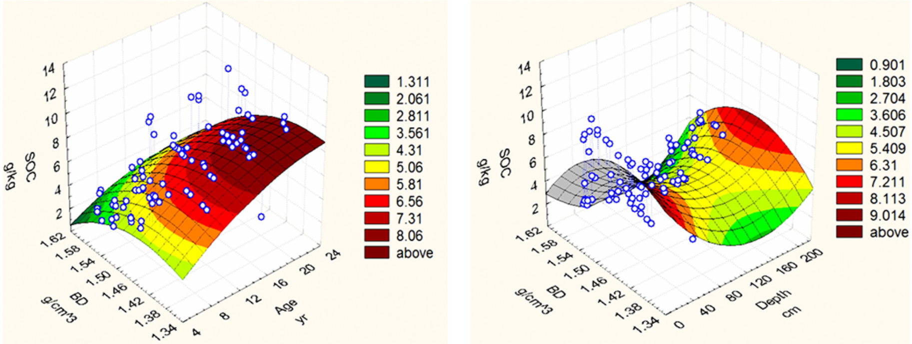

Figure 5. Regression models of soil organic carbon (SOC) and bulk density (BD) with extension of stand age and soil depth.

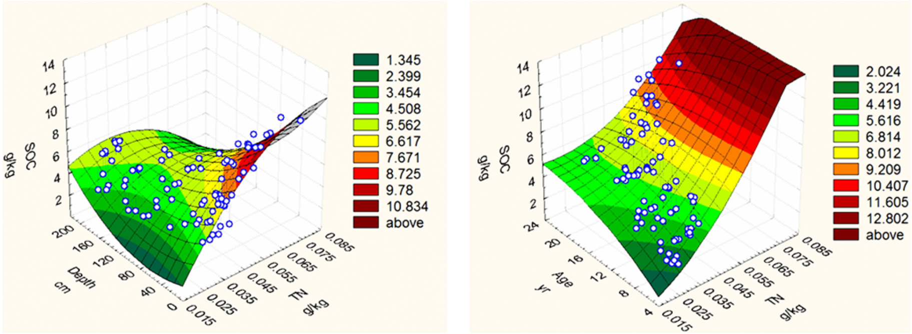

Figure 6. Regression models of soil organic carbon (SOC) and total nitrogen(TN) with the extension of stand age and soil depth.