Effect of shrub land on soil carbon storage in the Loess Plateau

Yao Zhong, Yifan Gong, Jianjun Cao

College of Geography and Environmental Science, Northwest Normal University, Lanzhou, Gansu province, China

Abstract. With the increasing atmospheric CO$_2$ concentrations in the current years, afforestation implemented on lands with poor fertility is considered to be an effective measure for mitigating CO$_2$ emissions. However, little studies have focused on the comparison of effects of different shrub lands on soil carbon storage. In this case, 16-year-old *Caragana Korshinskii* K. (CK) land and 16-year-old *Hippophae rhamnoides* L. (HR) land were investigated in Huining County, Gansu Province, to explore the differences in soil carbon storage between them. The results showed that the total soil carbon storage at the 1.0 m soil depth for the CK land and HR land was 46.55 Mg·ha$^{-1}$ and 56.73 Mg·ha$^{-1}$, respectively, with a significant difference in total soil carbon storage between them. The soil organic carbon (SOC) decreased with the soil depth, and was significantly negatively correlated to soil bulk density, but positively correlated to STN. However, SOC showed no significant correlations with soil pH, STP and soil moisture content. The SOC arising was not significant affected by the interactions between land use type and soil depth, demonstrating that the SOC is generally affected by soil either depth or stand type, rather than both in this area. This study expects to advance new understanding of the relationships between soil carbon storage and shrub land in the Loess Plateau, and it could also have wider implications for other regions where land use and land cover change is being addressed by afforestation options.

1. Introduction

Climate change is growly affecting the distribution of soil carbon storage (SCS) because of its close relationship with terrestrial ecosystems [1]. Estimatedly, about two-thirds of the terrestrial ecosystems’ organic carbon was fixed by forests (trees and shrubs), and thus, forests play an important role in global carbon cycle [2, 3]. In recent years, forest plantation, has been considered as a better way to reduce the negative consequences of global warming, and have been received widespread attention [4-6]. In China and many other countries, afforestation is prevalent on former agricultural lands, marginal croplands, wasteland and deserts that have poor soil fertility and productivity, to prevent ecosystems from degradation and improve environmental quality [7, 8].

Due to transitional geographic position and climate, complex topography and high degree of human activity, the ground vegetation and soil was destroyed seriously in the Loess Plateau, and thus this area became a key ecological restoration area by “Grain for Green Project” (GGP) put forward by Chinese government in 1999 [9]. With the implement of it, the area of forest plantations on the Loess plateau has rapidly increased [4, 5]. To accommodate drought, different afforestation species such as *Populus tremula* L., *Salizmatsudana* K., *Robinia pseudoaccacia* L., *Prunus armeniaca* L., *Hippophae rhamnoides* L. and *Caragana Korshinskii* K., appeared successively in the Loess Plateau, and their
physiological process of photosynthesis were intensively studied [10-12]. Also, effects of different species plantations on SCS were explored [13-16], but no consistent conclusion was reached [17], and thus it is still needed to study on the specific location through the ground truth observation in order to fully understand the connection between the plantation ecosystem and soil C in the Loess Plateau [18, 19].

Huining County, a representative area in the Loess Plateau, also has implemented this project, and Hippophae rhamnoides L. (HL) and Caragana Korshinskii K (CK) were widely planted by the GGP (Figure 1). The present paper aims to investigate the influence of the stand types on SCS. Our hypothesis was that carbon sequestration capacity of C. korshinskii is higher than that of H. rhamnoides. This study expects to advance new understanding of SCS based on stand type in the Loess Plateau, and it could also have wider implications for other regions where land use and land cover change is being addressed by afforestation options.

Figure 1. The sampled land (A: Caragana Korshinskii K.; B: Hippophae rhamnoides L.).

2. Materials and methods

2.1. Study area
Huining County (104°29'-105°31'E, 35°24'-36°26'N) is located in the central of Gansu Province at the Northwest Loess Plateau at an average altitude of 2025m extending over an area of about 6,439 km². Annual average temperature is 6 °C to 9 °C with an annual rainfall of 180-450 mm, mainly attributable to a temperate semi-arid climate. The region is characterized by complex tectonic structures, most of which are based on metamorphic rocks and granites.

In 1999, with the national policy of returning farmlands to forest enforced, Huining County began extensive afforestation. By the end of 2015, the total area of afforestation reached up to 706.7 km², and 12.47 % of the county’s area was forest-covered. During afforestation, machines were only used for site preparation, and tree planting was done manually. Therefore, soils were little contaminated by organic pollutants, such as diesel and others [20-22]. In this case, organic pollutants were not considered in the present study. Based on our investigation in the period July to September 2017, we found that shrubs were mainly planted during 2000 to 2003. Due to relatively higher precipitation in the county’s southern region [14, 23], southern Huining was selected as the study area (Figure 2).
2.2. Experimental design and sample analysis

During the period of July to September in 2017, the site of Taiping town was selected as the sampling area, and the greater details of which are available in an earlier study of Cao et al [23]. Three 16-year-old (CK) lands and three 16-year-old (HR) land were selected on a 25° slope, and in each selected land, soils sampled were from nine 10 m × 10 m plots, arranging both up-down and on the contour at a 10 m spacing. In each plot, three 1 m × 1 m quadrats were set along the diagonal (i.e., at both ends and a midpoint), and soil profile in them were excavated to a depth of 1.0 m as this depth reflects the main root distribution of the shrub land [7]. Soil samples were taken for a profile depth range of 0-0.1 m, 0.1-0.2 m, 0.2-0.4 m, 0.4-0.6 m, 0.6-0.8 m, and 0.8-1.0 m, using a cutting ring whose volume was equivalent to $1 \times 10^{-4} \text{m}^3$ to measure soil bulk density ($\rho$) [24], gravimetric soil moisture content ($\theta$), and other soil properties, such as pH, soil organic carbon (SOC), soil total nitrogen (STN) and soil total phosphorus (STP).

Samples were dried at 105 °C for 10 hours, reweighed. The soil pH was measured with a standard pH meter using 2.5:1 water: air-dried soil ratio. The SOC (g kg⁻¹) was determined by wet dichromate oxidation of a homogenized air-dried soil subsample (0.2 g), followed by a titration with FeSO₄ [25]. STN was measured using Kjeldahl apparatus, and STP was measured using Spectrophotometer.

Soil carbon storage (SCS, Mg ha⁻¹), $\rho$ (Mg·m⁻³) and total soil carbon storage (TSC, Mg ha⁻¹) were calculated as:

$$\text{SCS}_i = [\text{SOC}]_i \cdot \rho_i \cdot T_i$$

$$\rho_i = \frac{m_i}{V_i}$$

$$\theta = \frac{m_{i_2} - m_{i_1}}{m_i} \cdot 100\%$$

$$\text{TSC} = \sum_{i=1}^{i=6} \text{SCS}_i = \sum_{i=1}^{i=6} [\text{SOC}]_i \cdot \rho_i \cdot T_i$$
where,
\[ [\text{SOC}]_i \] is the concentration of SOC in the \( i \)-th soil layer (%),
\[ T_i \] is the \( i \)-th soil layer thickness (m),
\[ V_i \] is volume of soils in the \( i \)-th soil layer \((1 \times 10^{-4} \text{ m}^3)\),
\[ m_i \] is the dry weight (mass) of soil in the \( i \)-th soil layer (g),
\[ m_{fi} \] is the fresh weight (mass) of soil in the \( i \)-th soil layer (g).

### 2.2.1. Data analysis

Data were analyzed using SPSS 22.0 statistical software (SPSS Inc. Chicago, USA) and R 3.5.1 software, and expressed as the mean ± standard deviation. One-way analysis of variance was applied to determine the statistically significant differences in the soil physical and chemical properties between the different stand types. The Least-Significant-Difference (LSD) method is used to compare the means of the variables when the results of ANOVA were significant at \( P < 0.05 \). SOC was also analyzed by two-way ANOVA with stand and soil layer as fixed factors. The Pearson’s Product Moment Correlation (r) was used to identify the statistically significant relationships between the measured variables. The Origin Pro 9.0 and R 3.5.1 software were then adopted to visualize for the data through appropriate visual and statistical diagnostic plots.

### 3. Results

#### 3.1. Vertical distribution of soil properties in different stand types

There was no difference in \( \theta \) among six soil layers in the HR land, while significant difference in \( \theta \) was found among the soil layers of 0.4-0.6 m, 0-0.1 m, 0.2-0.4 m and 0.8-1.0 m in the CK land, with the largest value being in the layer of 0.4-0.6m for both of the two land types (13.43% for HR land and 17.09% for CK land) (Figure 3A). In the CK land, the \( \rho \) at the 0-0.4 m soil layer decreased dramatically, but below 0.4 m, it did not change, and there was no difference among six soil layers in the HR land (Figure 3B); the soil pH at the 0.6-0.8 m soil layer was the largest (8.97), and was significantly larger than that at the 0-0.6 m soil depth in the CK land, while for the HR land, the soil pH at the 0-0.1 m soil layer was the lowest (8.59), and it was significantly lower than that at the 0.2-1.0 m soil layer (Figure 3C).

In the CK land, the SOC at the 0-0.2 m soil depth was larger, and no difference was found between 0-0.1 m (4.7 g·kg\(^{-1}\)) and 0.1-0.2 m (4.77 g·kg\(^{-1}\)) soil layers. Also, SOC at the 0.4-0.6 m (3.27 g·kg\(^{-1}\)), 0.6-0.8 m (3.12 g·kg\(^{-1}\)) and 0.8-1.0 m (2.99 g·kg\(^{-1}\)) soil layers had no difference, but the SOC at the 0-0.2 m soil depth was significant higher than that at the 0.4-1.0 m soil depth; in the HR land, the SOC at the 0-0.2 m soil layer was larger, and no difference was found between 0-0.1 m and 0.1-0.2 m soil layers. Also, no difference in SOC among the bottom three soil layers was found, and SOC at the 0-0.2 m soil layer was significantly higher than that at the 0.4-1.0 m soil layer (Figure 3D). As for the STN, significant differences were found in the STN among the 0-0.1 m, 0.1-0.4 m and 0.4-1.0 m soil layers in the HR land. However, in the 1.0 m soil depth, the STN in the CK land was lower than that in the HR land at each six soil layers; The STN of the CK land at the 0-0.1 m soil depth was the highest (0.72 g·kg\(^{-1}\)), but below 0.2 m, it decreased slightly, and no difference was found among the deeper five soil layers (Figure 3E). The values of STP in CK land and HR land fluctuated as the soil depth increased, but no difference was found among the six soil layers in CK land; while a significant difference was found between the layer of 0.4-0.6 m and other layers in HR land, but no significant difference was found among other soil layers (Figure 3F).
Figure 3. The distribution of soil properties by soil layers. Different letters indicate differences by soil layers at $P < 0.05$. Where $\rho =$ soil bulk density; $\theta =$ soil moisture content; SOC = soil organic carbon; STN = soil total nitrogen; STP = soil total phosphorus; CK land = Caragana Korshinskii K. land; HR land = Hippophae rhamnoides L. land.

Note: different lowercase letters represents a significant difference with soil depth ($p \leq 0.05$).

3.2. Vegetation and soil properties and in different stand types

The $\theta$, $\rho$ and pH in CK land were significantly greater than in the HR land. Oppositely, the STN, STP, SOC and TSC in CK land were significant lower in the HR land (Table 1). Specifically, the mean value of the $\theta$, $\rho$, pH, STN, STP, SOC and TSC in CK land was 16.05 ($\%$), 1.28 (Mg·m$^{-3}$), 8.83, 0.38 (g·kg$^{-1}$), 0.58 (g·kg$^{-1}$), 3.82 (g·kg$^{-1}$), 46.55 (Mg ha$^{-1}$), respectively; for the HR land, their values were 12.86 ($\%$), 1.20 (Mg·m$^{-3}$), 8.65 (g·kg$^{-1}$), 0.56 (g·kg$^{-1}$), 0.82 (g·kg$^{-1}$), 4.98 (g·kg$^{-1}$), 56.73 (Mg ha$^{-1}$), respectively.

Table 1. Soil and plant properties in CK and HR lands (mean ± standard deviation, $n=54$).

| Variables   | CK land       | HR land       |
|-------------|---------------|---------------|
| $\theta$ (%)| 16.05±0.02a   | 12.86±0.06b   |
| $\rho$ (Mg·m$^{-3}$) | 1.28±0.10a   | 1.20±0.08b   |
| Soil pH    | 8.83±0.26a   | 8.65±0.12b   |
| STN (g·kg$^{-1}$) | 0.38±0.15b   | 0.56±0.17a   |
| STP (g·kg$^{-1}$) | 0.58±0.11b   | 0.82±0.24a   |
| SOC (g·kg$^{-1}$) | 3.82±2.08b   | 4.98±1.57a   |
| TSC (Mg ha$^{-1}$) | 46.55±16.60b | 56.73±7.58a |

Note: The $\theta$ data of all CK land was from after rain. Different letters indicate differences by stand types at $P < 0.05$. Where $\rho =$ soil bulk density; $\theta =$ soil moisture content; SOC = soil organic carbon; STN = soil total nitrogen; STP = soil total phosphorus; CK land = Caragana Korshinskii K. land; HR land = Hippophae rhamnoides L. land.
total nitrogen; STP = soil total phosphorus; TSC = total soil carbon storage; CK land = Caragana Korshinskii K. land; HR land = Hippophae rhamnoides L. land.

3.3. Relationships between the measured variables

The $\theta$ showed a significantly positive correlation with soil pH ($r = 0.196, P < 0.05$), $\rho$ ($r = 0.35, P < 0.01$) and STP ($r = 0.191, P < 0.05$), but no significantly correlated with SOC ($r = -0.042, P > 0.05$) and STN ($r = -0.168, P > 0.05$). The soil pH had a significantly positive correlation with $\rho$ ($r = 0.35, P < 0.01$), but a significantly negative correlation with SOC ($r = -0.373, P < 0.01$) and STN ($r = -0.49, P < 0.01$). The $\rho$ had a significantly negative correlation with SOC ($r = -0.418, P < 0.01$) and STN ($r = -0.29, P < 0.05$), but no correlation between the $\rho$ and STP ($r = -0.186, P > 0.05$) was found. In addition, SOC had significantly positive relationships with STN ($r = 0.67, P < 0.01$), but no correlation between the SOC and STP ($r = 0.065, P > 0.05$) was found. The correlation coefficient between SOC and STN was the highest, with $r = 0.67, P < 0.01$ (Figure 4).

![Figure 4. The Pearson correlation coefficient between soil physical and chemical properties of different shrub lands. Where $\rho$ = soil bulk density; $\theta$ = soil moisture content; SOC = soil organic carbon; STN = soil total nitrogen; STP = soil total phosphorus. Blue colour: positive correlation coefficient; red colour: negative correlation coefficient. The darker is the colour, the greater is the correlation coefficient.](image)

4. Discussion

4.1. The reasons for vertical distribution of soil properties in different land use types

There was no difference in $\theta$ among six soil layers in the HR land. This may be caused by a more even distribution of shrub’s roots at different soil layer, but this needs further study. In the CK land, the $\rho$ was higher at the surface soil layers than that at the deeper soil layers, as found by Głab [26], this is because the CK land resulted from the decrease in the soil’s biological activities due to an increase in anthropogenic soil compaction [27]. However, the $\rho$ in the HR land did not change among six soil layers, which was inconsistent with the research of Ren et al [15], whose results showed that $\rho$ in the HR land in the surface soil depth was significantly lower than that in the deeper soil depth, because in their study the aboveground biomass and the biodiversity were larger, while in our study undergrowth vegetable was sparse.

The soil pH at the upper layers was lower than that at the deeper layers in both these two land types. This might have resulted from root distribution. In the Loess Plateau, fine roots are important for the absorption of water and nutrients, and about 60% fine roots of the vegetation are distributed at 0-60 cm
soil depth [28, 29]. According to Liu et al [30], in alkaline soils as the study investigated soils, plants take up more cations than anions, releasing H⁺ from their roots which reduces the rhizospheric pH and helps to maintain the charge balance [28].

Soil nutrients (SOC and STN) were generally decreased with soil depth increased in these two land types, which was in accordance with other studies [13, 31]. It might because the surface soil incorporated ground litter and created organic matter through bioturbation [13, 15], whereas, in the deeper soil layers, there was a significantly lower level of soil nutrient (Figure 3D,E) due to limited root distribution [14, 29]. As for the STP, no difference was found among the six soil layers in all the two lands, meaning that the STP was distributed evenly at each soil layer. This can be explained as follows: the distribution of tree roots caused STP even distribution at the upper soil layers, while the STP was distributed evenly at the deeper soil layer because of the higher pH, the more CaCO₃ in soil forming phosphate [32].

4.2. Factors influencing SOC and TSC

4.2.1. Soil physical and chemical properties influencing SOC and TSC. Generally, soil physical and chemical properties directly affect plant growth, microbial activities and soil nutrient cycling [33]. The HR land had a steep slope and a greater crown density (Figure1 A,B), resulting in more water rapidly loss and consumption than the CK land. Besides, the aboveground biomass and litterfall can loosen the soil and expand the soil porosity [13, 29], which is the reason for the CK land with the highest ρ.

The different shrub species can produce different soil chemical properties by their different biological processes [8]. The canopy density was higher in the shrub lands, which limited the understory vegetation development [8] and caused the lower soil nutrients in the CK land. Although we did not investigate the litter in our study, the litter can also affect the soil fertility, which was proved in other studies [34, 35]. In addition, the lower soil pH can control the soil biological activity and soil mineralization ability, and the lower ρ and more θ can increase soil permeability and infiltration rate for increasing soil fertility [36]. Besides, in our study, soil pH was negatively related to SOC (Figure 4), which is accordance with other [37, 38] but inconsistent with the findings of Cao et al [39], whose study found that soil pH was not related to SOC. This suggests that the relationship between soil pH and SOC requires further research. The θ was non-significantly positive related with SOC, which was not corresponding to the previous findings, such as Cao et al [39]. The may be due to that the soil water limited SOC accumulation. The ρ was negatively related to SOC and in the present study (Figure 4), which was consistent with the findings of Cao et al [39], whose research showed that the ρ was negatively related to SOC, but Wang et al [40] found a significant positive correlation between SOC and ρ, suggesting that the mechanisms linking these two variables must be explored further.

Also, other soil nutrients (STN and STP) can influence the SOC. The relationship between other soil nutrients and SOC (Figure 4) concurred with Cao et al [39]. The SOC were positively related to STN but not related to STP in our study. That means SOC is coupled with STN but uncoupled with STP [41]. Generally, P can be fixed relatively slowly by clay minerals, carbonates and soil organic matter as part of biochemical cycling, and a higher P could further fix N and support greater accumulation of organic matter [39]. In addition, fixation of soil N may be important factor for fixing soil C and P [42], because the increasing of the net supply of N mineralization can promote plant growth and litters increase, which can promote cycle and accumulation of soil C, N and P [43]. But our findings in present study were not accorded with these rules, demonstrating that the spatial heterogeneity of the relations between C, N and P.

4.2.2. Interactions of properties influencing SOC. Except for the above factors, biotic and abiotic interactions strongly impact SOC, because biotic and abiotic factors regulate the functions of terrestrial ecosystems [44]. In the current study, we used treatment and soil depth as fixed factors.
Many studies have explored the effects of these interactions on variables. For example, Hu et al. [45] found that leaf nitrogen and C : N (carbon: nitrogen) were significantly affected by the interaction between stand age and desertification intensity; Wu et al. [24] found that grassland community coverage and above- and below-ground biomass were related to the interaction of plant diversity and θ; Qin et al. [25] found that SOC was not affected by the interaction between soil type and slope aspect. However, research on the interaction effects between land use type and soil depth on SOC are largely absent from the literature. To the best of the authors’ knowledge, only two studies, by Menyailo et al. [46] and Zhang et al. [28], were similar to the present study. In the study of Zhang et al. [28], the interaction of land use type and soil depth strongly impact the ρ. But, in the study of Menyailo et al. [46], no interaction existed between the effects of stand type and soil depth on net N mineralization. In the current study, we found that SOC arising was not significant affected by the interactions between land use type and soil depth (Table 2). The means that the SOC capacity is generally affected by soil depth or stand type, rather than both of them in this area.

Table 2. Interaction effects between soil depth and stand type on soil organic carbon (SOC).

| Soil depth |
|-----------|
| F         |
| P         |
| df        |
| Stand type |
| F         |
| P         |
| df        |
| Soil depth × Stand type |
| F         |
| P         |
| df        |

Note: SOC = soil organic carbon. F = Fisher test (joint hypotheses test), P = probability value, and df = degree of freedom.

5. Conclusions

In this case, 16-year-old Caragana Korshinskii K. (CK) and 16-year-old Hippophae rhamnoides L. (HR) were investigated in Huining Country, Gansu Province, to explore the effects of different shrub lands on soil carbon storage. The results showed that the total soil carbon storage at the 1.0 m soil depth for the CK land and HR land is 46.55 Mg·ha⁻¹ and 56.73 Mg·ha⁻¹, respectively, and there was a significant difference in total soil carbon storage between them. The SOC decreased with the soil depth. The SOC was significantly negatively correlated to soil bulk density, but positively related to STN. Meanwhile, SOC showed no significant correlations with soil pH, STP and soil moisture content. The SOC of shrub land was not significant affected by the interactions between land use type and soil depth, demonstrating that the SOC is generally affected by soil either depth or stand type, rather than both in this area. This study would deepen the understanding of the effects of shrub lands on SOC, and then be helpful to improve the effects of afforestation policy.

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