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Identifying a suitable revegetation technique for soil restoration on water-limited and degraded land: Considering both deep soil moisture deficit and soil organic carbon sequestration

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A R T I C L E I N F O

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A B S T R A C T

Revegetation is an important means to improve the ecosystem services delivered by degraded land; however, inappropriate revegetation can result in severe soil desiccation and ecosystem degradation in water-limited regions. Here we evaluated seven common revegetation techniques by considering both deep soil moisture deficit and soil organic carbon (SOC) sequestration on the Loess Plateau of China, attempting to identify a suitable method for soil restoration of severely degraded ecosystems. The seven revegetation techniques considered were: two single-species shrub plantations (*Caragana korshinskii* and *Hippophae rhamnoides*), two single-species tree plantations (*Platycladus orientalis* with terracing and *Robinia pseudoacacia*), and three mixed plantations (*P. orientalis/H. rhamnoides* with terracing, *R. pseudoacacia/H. rhamnoides*, *R. pseudoacacia/P. orientalis*). A 12-year-old abandoned cropland served as the control. The results showed that the single-species plantation of *P. orientalis* with terracing had the lowest soil moisture deficit in deep layers (200–800 cm) but also had the lowest SOC sequestration. In contrast, the mixed plantation of *R. pseudoacacia/H. rhamnoides* had the highest SOC sequestration but also had significant deep soil moisture deficit. In contrast, the mixed plantation of *P. orientalis/H. rhamnoides* with terracing showed near-zero deep soil moisture deficit and significant, positive SOC sequestration. Therefore, this mixed plantation was identified as representing a suitable revegetation technique for this region. The results here suggest that appropriate mixed tree/shrub plantations with appropriate land engineering measures could deliver effective soil restoration in such environments. Our results provide an insight into revegetation in areas with degraded land.

1. Introduction

Revegetation has the potential to control soil erosion, enhance soil quality and improve livelihoods in areas with degraded land (Islam and Weil, 2000; Chazdon, 2008; Fu et al., 2011). Revegetation in water-limited regions is largely dependent on soil water availability because ground water is generally inaccessible (Barbeta et al., 2015; Gao et al., 2016); this in turn influences greatly the hydrological cycle and ecosystem services in terms of soil and water conservation, wood fiber products, regulation of regional climate, and spiritual benefit, among others (Bullock et al., 2011). Considerable researches have revealed that revegetation is a double-edge sword: inappropriate revegetation can result in severe desiccation in deep soil layers and the degradation of ecological communities in semiarid and semihumid regions (Chen et al., 2008). Hence, suitable revegetation techniques are critical to deliver benefits to both humans and the environment.

A major concern relating to revegetation is its effects on soil moisture, especially in deep layers in water-limited areas. Generally, there are two methods of revegetating degraded land: natural restoration and plantations using exotic species. The introduction of exotic species, such as *Robinia pesudoacacia*, *Platycladus orientalis*, *Pinus tabuliformis*, *Caragana korshinskii* and *Hippophae rhamnoides*, increases transpiration demand and results in severe soil desiccation in deep layers (Wang et al., 2009; Yang et al., 2012; Jia et al., 2017). In addition to plant species, planting density and land engineering measures significantly change soil moisture levels down the profile. For example, terracing has been shown to increase soil moisture content to a large extent and thus has potential for mitigating deep soil desiccation

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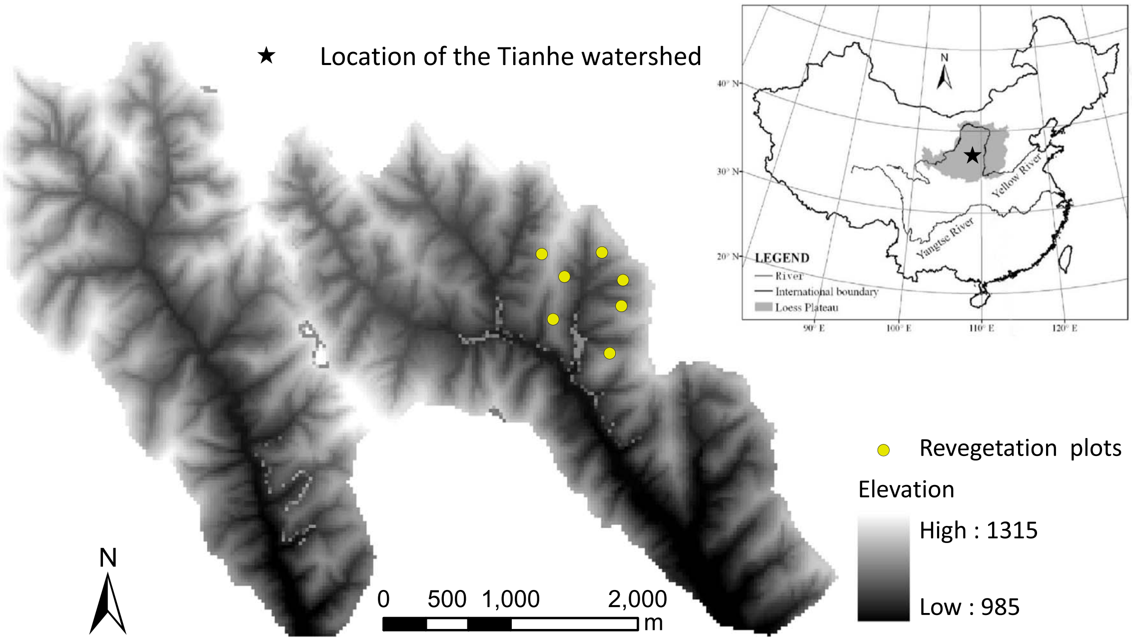

Fig. 1. The location of the study site and the distribution of revegetation plots in the watershed.

(Zhang et al., 2017). Furthermore, several recent studies attempted to find suitable revegetation approaches for sustainable ecological restoration based on their effect on soil moisture. For instance, Wang et al. (2015a) examined the effects of six revegetation techniques, including farmland, natural grassland and interplanting of shrubs and grass, on soil moisture from the surface to 1800 cm down and aboveground net primary productivity on the semiarid Loess Plateau, and concluded that natural grassland was the optimal vegetation in this region because it had negligible impact on soil moisture at layers below 200 cm. However, the revegetation methods examined in that study missed common tree species and mixed plantations of trees and shrubs. Compared to herbs, woody plants, particularly trees, can provide greater benefits in reducing soil erosion (Jiao et al., 2000), increasing SOC sequestration (Corre et al., 1999) and improving human livelihoods (Cao et al., 2009). Jian et al. (2015) evaluated the effects of four different woody plants on soil water storage and water balance and recommended that *C. korshinskii* and *R. pseudoacacia* were suitable species for ecological restoration on the semiarid Loess Plateau. However, they measured soil moisture at a relatively shallow depth (0–100 cm), where it can be replenished by precipitation in one growing season for the majority of plant species (Yang et al., 2012; Gao et al., 2014).

The degraded land prior to revegetation generally suffers serious soil erosion, leading to decreases in soil organic matter in semiarid and semihumid areas. The soil organic carbon (SOC) pool is the largest pool of organic carbon in terrestrial ecosystems and is one of the most important metrics for evaluating soil quality (Lal, 2004). Land use change as a result of revegetation is one of the main biotic drivers of SOC dynamics through alteration of the physical, chemical and biological properties of the land surface (Smith, 2008). Substantial evidence has been presented that revegetation of degraded land, either naturally or artificially, can increase SOC content and stocks at least in surface soils (Post and Kwon, 2000; Guo and Gifford, 2002; Don et al., 2011; Liu et al., 2011; Peoplau and Don, 2013; Zhao et al., 2015). Some research has found significantly higher SOC stock in forests than in cropland at depths deeper than 500 cm (Wang et al., 2015b), although the difference at these depths cannot be fully attributed to vegetation restoration (Gao et al., 2017). Based on the importance of SOC for soil quality and its potential for influencing global climate, it is important to consider the effect of SOC sequestration when selecting revegetation techniques for degraded lands.

The Loess Plateau in the Northwest China is one of the most eroded places on earth and the soil quality and productivity have been greatly degraded due to soil erosion (Chen et al., 2007). The Grain for Green Project (GFGP) implemented in western China is one of the largest revegetation activities in human history. By now, the GFGP has received investments of approximately US $8.7 billion and has converted around 1.60×10^6 ha of degraded cropland to plantations, bring a 25% increase in vegetation cover during the last decade (Feng et al., 2016). The annual sediment load in the Yellow river has decreased by nearly 90% percent during the last two decades (S. Wang et al., 2016). However, the expansion of plantations has consumed much more water than before and has caused severe soil desiccation, greatly restricting normal plant growth (Chen et al., 2008). In addition, the serious soil erosion before the GFGP resulted in great loss of soil organic matter, causing the SOC content in the area to be significantly lower than the national average (Liu et al., 2011). Although the effects on SOC content, density and stocks have been extensively evaluated with respect to various revegetation methods, the SOC sequestration effect, to our knowledge, has not been considered when choosing the optimal approach. Therefore, this study aimed to find an appropriate method of revegetation for ecological restoration in the degraded areas of this ecosystem by evaluating the impacts of seven common revegetation approaches on deep soil moisture and SOC sequestration. These seven revegetation methods consisted of common single-species tree and shrub plantations and mixed plantations combined with landscape engineering measures.

2. Materials and methods

2.1. Study site

The study site is located in the Tianhe watershed (109°16′ 28″-109° 24′ 59″ E, 36° 3′ 40″-36° 41′ 36″ N; Fig. 1) in the middle part of the Loess Plateau in the northern Shaanxi province of China. The elevation ranges from 988 to 1344 m. The topography of this watershed is cut by hundreds of gullies, the density of which reaches 3.4 km km^{-2}. This region has a continental climate, with mean annual precipitation of 535 mm, 73% of which falls between July and September; a mean annual temperature of 9.4 °C; a frost-free period of 179 d, on average; and mean annual sunshine hours of 2397. 3 h. The whole watershed is covered by thick loess soils with average sand, silt and clay content of 21.7, 61.6 and 16.7%, respectively. A recent land use map of Tianhe watershed was given in Fig. S1.

This area suffered serious soil erosion before the initiation of the GFGP and remains the primary sediment source for the Yellow river. At the initiation of the GFGP in 1999, the Tianhe watershed was chosen as a key demonstration area for soil and water conservation. Thereafter, a variety of plant species were introduced to replace the low-quality farmland in order to restore ecosystem services; the species included *C. korshinskii*, *H. rhamnoides*, *R. pseudoacacia*, *P. orientalis* and *P. tabuliformis*. Meanwhile, several landscape engineering measures were employed to retain water from surface runoff in order to increase the survival of plantations.

In this study, we selected seven common revegetation options and evaluated their moisture deficit in deep soil layers and SOC sequestration capacity. Specifically, there were two single-species shrub plantations, i.e., *C. korshinskii* (Treatment 1) and *H. rhamnoides* (Treatment 2); two single-species tree plantations, i.e., *P. orientalis* with terracing (Treatment 3) and *R. pseudoacacia* (Treatment 4); and three mixed plantations, i.e., *P. orientalis/H. rhamnoides* with terracing (Treatment 5), *R. pseudoacacia/H. rhamnoides* (Treatment 6), *R. pseudoacacia/P. orientalis* (Treatment 7). In general, the plant species, density and land engineering measure are common on the Loess Plateau. Therefore, the seven revegetation approaches have good representativeness in this region. All of these plantations were created in 1999 or 2000 except for the *R. pseudoacacia* plantation which was planted around in 1995. A 12-year-old abandoned cropland was employed as the control to represent the natural evolution of soil moisture and SOC sequestration (Yang et al., 2012). The basic information for these revegetation plots were given in Table 1. Note that plant density varied among the seven different plantations. However, the primary objective of the study is to identify one suitable revegetation technique from existing plantations on the Loess Plateau. Among these plantations, different plantations had different plant densities when they were built according to the size and geometry of plant species; shrub species had higher plant density than tree species, and mixed plantations have greater density than single-species ones. This is common in similar studies aiming to evaluate the suitability of existing plantations (Wang et al., 2009; Yang et al., 2012; Wang et al., 2015a; Jia et al., 2017). Therefore, the experiment is sensible for our research purpose.

2.2. Field sampling and laboratory analysis

First, we selected one plot measuring 20 m × 20 m within each of the seven revegetation plantations in the middle April 2017. All seven plots were located on upper hillslopes facing north or northwest. The slope gradient, aspect and elevation of each plot were recorded. Vegetation survey and sampling of roots, soil moisture and soil cores were all conducted within these plots. Vegetation was surveyed in mid-July; the number, height, cover, diameter at breast height of the primary tree and/or shrub plants were measured and recorded as well as the total number of all plant species.

Soil moisture sampling was begun in early May and repeated every month until November. A hand auger (40-mm diameter) was used to sample soils every 20 cm within a profile from the surface to a depth of 1000 cm. The soil samples were put in a small aluminum box and then taken to the laboratory for gravimetric soil moisture determination. The drilled holes were refilled after the sampling was finished every time. For each sampling event, soil moisture sampling was repeated at three randomly selected locations within each plot. At each soil depth, the arithmetic mean of the three values was used to represent the soil moisture content of a given plot.

SOC sampling was undertaken in late July 2017. Unlike the soil moisture sampling, SOC sampling was conducted for a relatively shallow depth of 0–160 cm because the effects of vegetation on SOC are mainly within this layer in this area (Gao et al., 2017). Under each of the seven plots, a hand auger (40-mm diameter) was used to sample soils every 20 cm in the depth range 0–160 cm and repeated three times at random locations. The soil samples were stored in a plastic bag, then air-dried and passed through a 0.25-mm sieve before being taken back to the laboratory for SOC determination. The SOC content was measured using a modified Walkley and Black method, the details of which are given by Fu et al., 2010. The SOC content was then transformed to SOC density using the following equation:

$$\mathrm{SOCD}_i = \mathrm{SOC}_i \times \mathrm{BD}_i \times \mathrm{D}_i \tag{1}$$

where SOCD_i and SOC_i represent SOC density (kg m^{-2}) and SOC content (g kg^{-1}) in the *i*th layer; BD_i represents soil bulk density in the *i*th layer; and D_i represents the depth of the *i*th layer.

For root sampling, three locations, each between two adjacent main trees, were randomly selected in each plot. Soil samples were collected in the depth range 0–1000 cm using a hand auger with 75-mm diameter, in late August 2016. We did not separate coarse (> 2 mm) and fine (< 2 mm) roots because there were only a few roots in deep soils. Roots were separated by hand from soils and then washed carefully with tap water to remove all remaining soil. The separated roots were oven dried at 70 °C for 24 h to obtain dry root biomass.

Intact soil samples were collected every 20 cm from the depth range 0–100 cm by digging a vertical profile near each revegetation plot. These soil cores were oven dried at 105 °C for 24 h to measure soil bulk density. Soil texture fractions (sand, silt and clay content) were measured using disturbed soil samples from 0 to 400 cm under each plot. Meteorological variables were recorded by an automatic weather station (AR5, Rainroot Limited, China). The daily precipitation and daily air temperature during the study period are given in Fig. 2.

2.3. Evaluating metrics

For a given revegetation technique, its soil moisture deficit in the deep layers (SMDD) and SOC sequestration effect (SOCSE) relative to control values were used to assess their feasibility for ecological restoration. The SMDD and SOCSE were defined as follows.

$$\mathrm{SMDD}_{j,k} = \frac{\mathrm{SMC}_{j,k} - \mathrm{SMC}_{0,k}}{\mathrm{SMC}_{0,k}} \tag{2}$$

Table 1
Basic information of the seven revegetation techniques in terms of topography, stand features and saturated water content.

Revegetation techniques	Slope gradient (degree)	Altitude (m)	Plant density (trees hm^{-2})	Diameter at breast height (cm)	Tree height (m)	Saturated water content (%)
C. korshinskii	11	1263	–	2.0	1.38	39.15
H. rhamnoides	13	1251	–	3.1	2.19	38.31
P. orientalis with terracing	25	1275	1550	10.3	3.81	40.79
R. pseudoacacia	18	1264	2200	10.2	10.40	38.81
P. orientalis/H. rhamnoides with terracing	26	1275	1550/—	11.0/2.8	4.50/1.89	39.73
R. pseudoacacia/H. rhamnoides	23	1246	2380/—	12.2/2.5	9.80/2.10	42.46
R. pseudoacacia/P. orientalis	17	1243	1660/1400	10.5/10.8	10.30/6.20	42.23

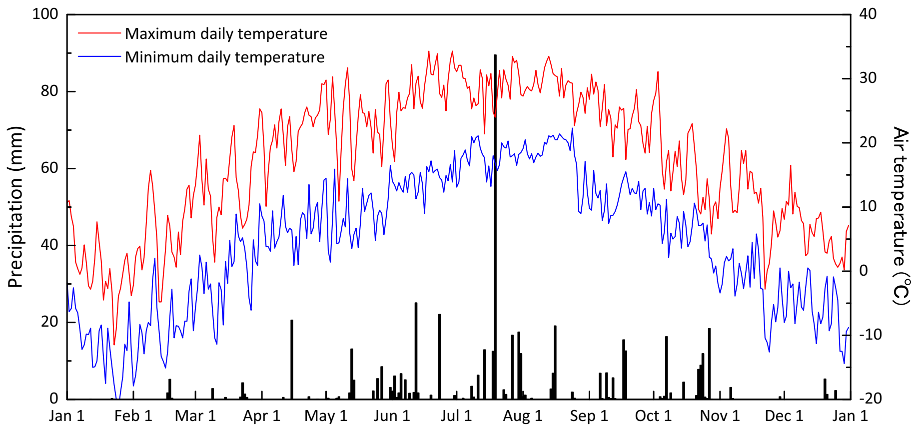

Fig. 2. Daily precipitation, maximum and minimum air temperature in the year of 2016.

and

$$SOCSE_{j,k} = \frac{SOCD_{j,k} - SOCD_{0,k}}{SOCD_{0,k}} \quad (3)$$

where $SMC_{j,k}$ and $SMC_{0,k}$ represent soil moisture content in the kth layer of the jth revegetation treatment and the control, respectively. Note that the monthly mean for each plantation was used here considering weak temporal variations of deep soil moisture within one growing season (Fan et al., 2010) and the spatial variability of soil moisture caused by the difference in sampling locations each time. $SOCD_{j,k}$ and $SOCD_{0,k}$ represent SOC density of the kth layer of the jth revegetation treatment and the control, respectively.

Soil moisture to a depth of 200 cm can generally be replenished during one growing season in the hilly region of the Loess Plateau (Gao et al., 2014; Ling et al., 2017). As a result, the top 200 cm is usually defined as the shallow layer in this region (Yang et al., 2012; Jia et al., 2017). In this study, soil moisture content in the control plot was measured down to 800 cm. Therefore, soil moisture deficit was computed for the depth range 200–800 cm. Unlike soil moisture, the effect of land use change on SOC occurs primarily in relatively shallow layers (< 100–200 cm) (Fu et al., 2010; Zhao et al., 2016; Gao et al., 2017). Therefore, SOCSE was primarily assessed for the shallow layer of 0–160 cm.

3. Results

3.1. Soil texture fractions and root parameters

Soil texture fractions (sand, silt and clay content) in the depth range 0–400 cm and root dry weight density (RDWD) in the 0–1000 cm range under different revegetation plots are shown in Fig. 3. Overall, the loess soils had similar patterns of soil texture fractions down the profile irrespective of revegetation treatment. In addition, the profile-average sand, silt and clay contents were relatively similar under different treatments, ranging from 15.4–18.6%, 57.5–59.7% and 23.1–27.1%, respectively, although the *H. rhamnoides* plot had slightly higher clay content and lower sand content over the profile compared to other plots.

Significantly heterogeneous patterns of RDWD down the profile were observed between the different treatments (see Fig. 3). *R. pseudoacacia* and its mixed plantations showed clearly higher RDWD in the 0–300 cm profile, while the *H. rhamnoides* plot exhibited clearly lower values than the other treatments. However, the RDWD seemed random at depths below 300 cm, probably because of the relatively small soil cores collected using the 75-mm hand auger. Nevertheless, roots were clearly observed in deep soils under the plots containing *C. korshinskii*, *H. rhamnoides* and the mixed plantations of *R. pseudoacacia*.

3.2. Profile soil moisture and SOC distribution

The vertical distribution of soil moisture content within the depth range 0–1000 cm and its variations during the growing season under various revegetation treatments are shown in Fig. 4. The results reveal that the revegetation treatments 2, 3 and 5 exhibited trends similar to the abandoned cropland with respect to soil moisture changes with increasing soil depth, and the highest values were observed in layers between 600 and 800 cm under these plots. The revegetation treatments containing *R. pseudoacacia*, either single-species or mixed, had clearly lower soil moisture content in the layers below 200 cm, approaching the permanent wilting point. Furthermore, deep soil moisture in treatments 2, 3, 4 and 5 exhibited greater monthly variations than the other three treatments, although these variations were relatively low.

The SOC content and density within the 0–160 cm depth range under different revegetation treatments are given in Fig. 5. The largest difference in SOC content and density was observed in the surface soil irrespective of revegetation treatment; the mixed plantation of *R. pseudoacacia/H. rhamnoides* had the highest value while the *P. orientalis* with terracing had the lowest value. Nonetheless, no significant difference was observed between the different plots. The observed difference decreased progressively with soil depth. Furthermore, mixed plantations overall showed greater SOC content and density than single-species ones throughout the profile.

3.3. Soil moisture deficit effect and SOC sequestration effect

Soil moisture deficit in the deep layers (SMDD) under various revegetation treatments is shown in Fig. 6. Note that the data from below 800 cm were not used for analysis because equivalent data were unavailable under the abandoned cropland (control). In general, deep soil moisture deficit was observed in the majority of soil layers under our revegetation plots, and the greatest SMDD was recorded in the plantations containing *R. pesudoacacia*, either single-species or mixed. Only the relatively shallow layers showed no moisture deficit under the revegetation treatments 1, 3 and 4. The soil moisture deficit was highly dependent on soil depth: soils below approximately 500 cm had clearly greater moisture deficit than the upper layers. Over the whole deep profile, as shown in Fig. 6b, the revegetation treatments containing *R. pseudoacacia* had the most severe moisture deficit while the *P. orientalis* with terracing exhibited no moisture deficit.

The SOC sequestration effect (SOCSE) under different revegetaion treatments is shown in Fig. 7. Overall, the mixed plantations had significantly positive SOCSE values while the single-speices plantations had negative values in the majority of layers, with the exception of the *R. pseudoacacia* plot. Futhermore, the advantage of mixed plantations over single-species was primarily seen in the top 100 cm. Over the

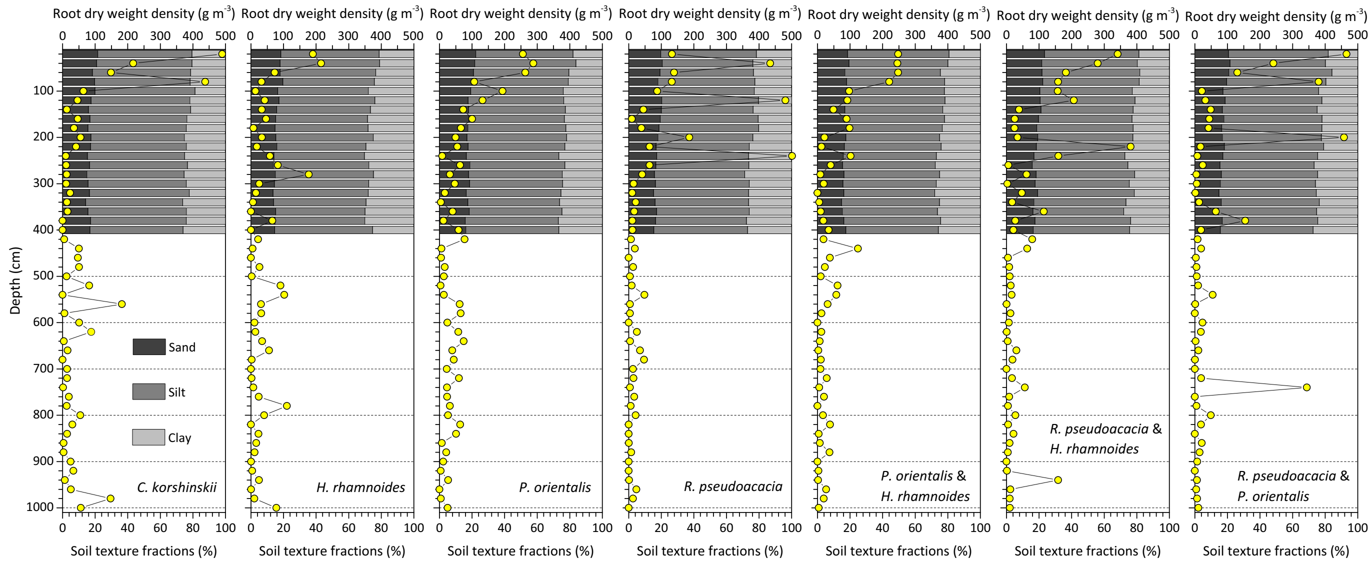

Fig. 3. Soil texture fractions (sand, silt and clay content) in the depth range 0–400 cm and root dry weight density (RDWD) in the 0–1000 cm range under different revegetation plots.

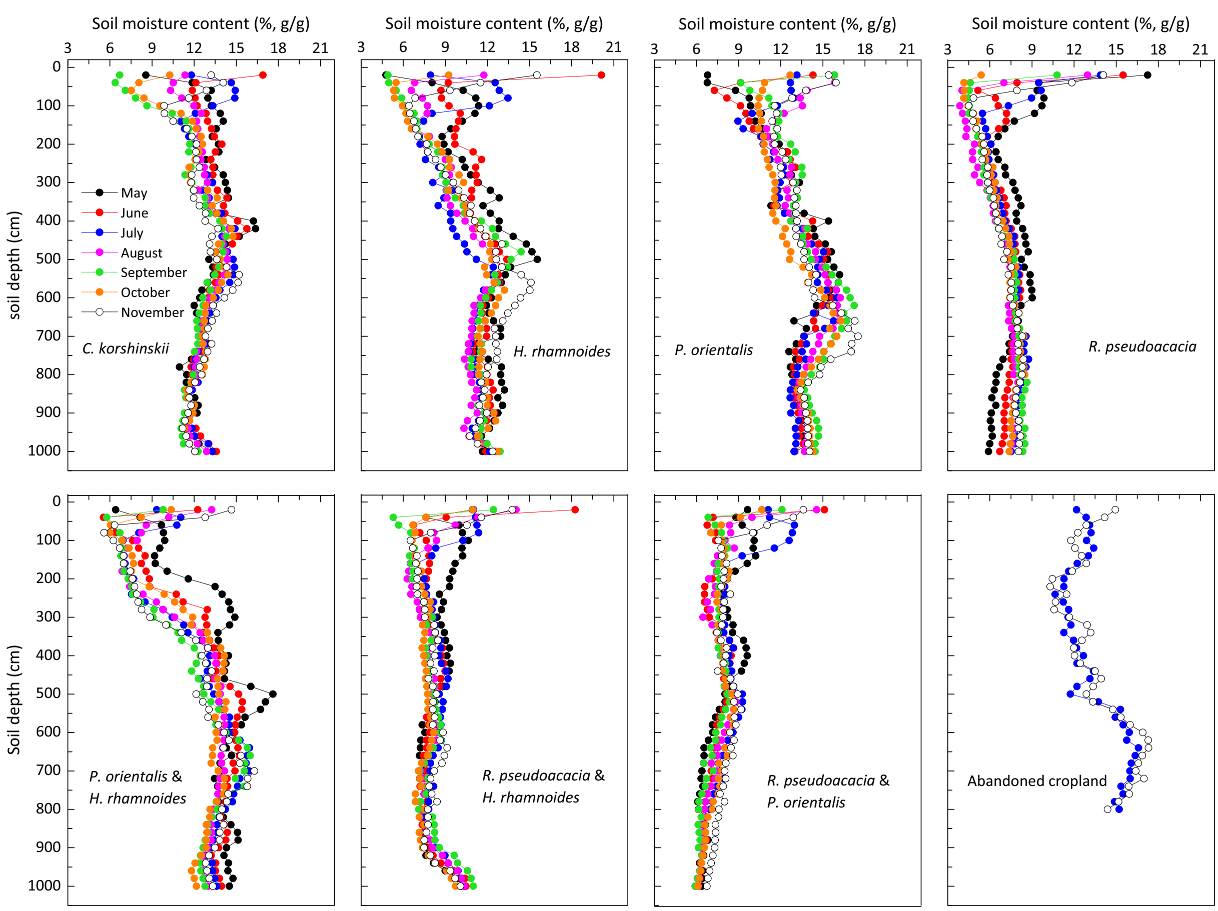

Fig. 4. The vertical distribution of soil moisture content within the depth range 0–1000 cm and its variations during the growing season under various revegetation treatments.

profile of 0–160 cm, the single-species plantations including *C. korshinskii*, *H. rhamnoides* and *P. orientalis* with terracing exhibited significantly negative SOCSE values whereas the mixed plantations exhibited significantly positive SOCSE values.

4. Discussion

4.1. The effects of revegetation techniques on DSM and SOC

Revegetation is one effective avenue to improve ecosystem services on degraded land, but can result in severe soil desiccation at depth if not properly managed in water-limited regions. Since soil texture is a key factor affecting soil moisture status in both surface and subsurface

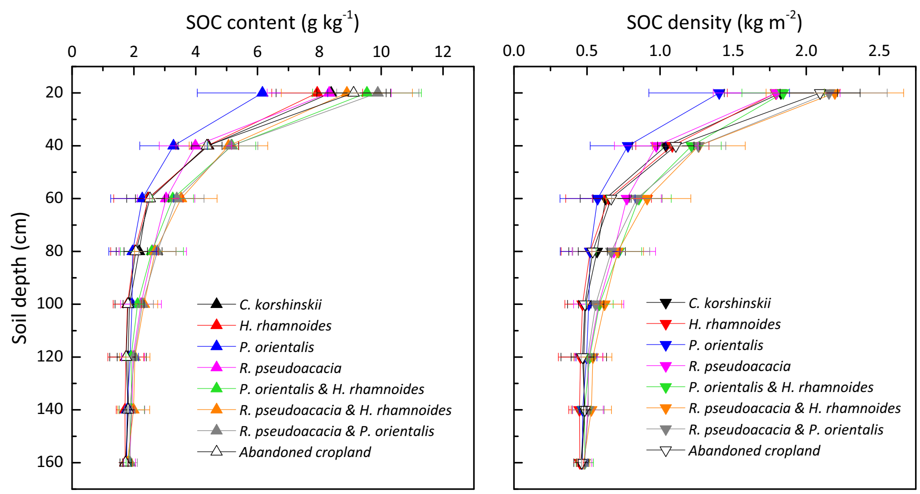

Fig. 5. The SOC content and density within the 0–160 cm depth range under different revegetation treatments.

soils (Nosetto et al., 2005; Hu et al., 2010; Gao et al., 2011; Wang et al., 2015a, 2015b), the homogeneous soil texture under our different revegetation plots allowed us to evaluate the effect of different vegetation treatments on soil moisture deficit. The low soil moisture deficit in the deep layers under *P. orientalis* and *P. orientalis/H. rhamnoides* can be attributed to the relatively low plant density (Table 1) and the creation of terracing. In general, revegetation with high plant density increases transpiration demand and soil moisture use from deep layers as shallow water is exhausted (Farnham, 2000; Yang et al., 2012). On the other hand, soil moisture in the rooting zone can be increased significantly if the plant density is reduced (Wang and Wang, 2002). Terracing on hillslopes alters surface hydrological processes and allows more water infiltration into soils. Zhang et al. (2017) found that soil water content in the top 100 cm under terraces increased by 13.7–25.4% compared to under hillslopes. The relatively high soil moisture for the *P. orientalis* with terracing can be partly attributed to the land reprofiling as well. In contrast, much lower soil moisture in deep layers was observed under the plots containing *R. pseudoacacia* and its mixed plantations with other species. First, *R. pseudoacacia* is an exotic species and has a fast growth rate (Rice et al., 2004), which occurs at the cost of high consumption of the soil water stored throughout the profile. Second, the result could be due to the relatively high plant density (Table 1) which increased profile soil water consumption and decreased water percolation into deep layers. Moreover, we observed clearly greater soil moisture deficit below 500 cm than in the upper layers. This may be primarily because the amount of water infiltration into soils above 500 cm was significantly higher than that below 500 cm. In addition, it is worth noting that relatively high soil moisture content at deep layers were observed under the *C. korshinskii* and the *H. rhamnoides* plots (Fig. 3), resulting relatively low deep soil moisture deficit there (Fig. 6). Generally, this disagrees with the findings of Wang et al. (2009) and Jia et al. (2017) who reported that these artificial species also resulted in severe soil moisture deficit at deep layers. A possible explanation is that the slope gradient of these two plantations in our site was relatively low (Table 1) and the litter layer there can increase infiltration during rainstorms, which would reduce the consumption of soil water at deep layers in dry periods.

Land use type or vegetation type is a key biotic factor influencing SOC distribution (Smith, 2008) by altering inputs from plant production and outputs through decomposition via complex physical, chemical

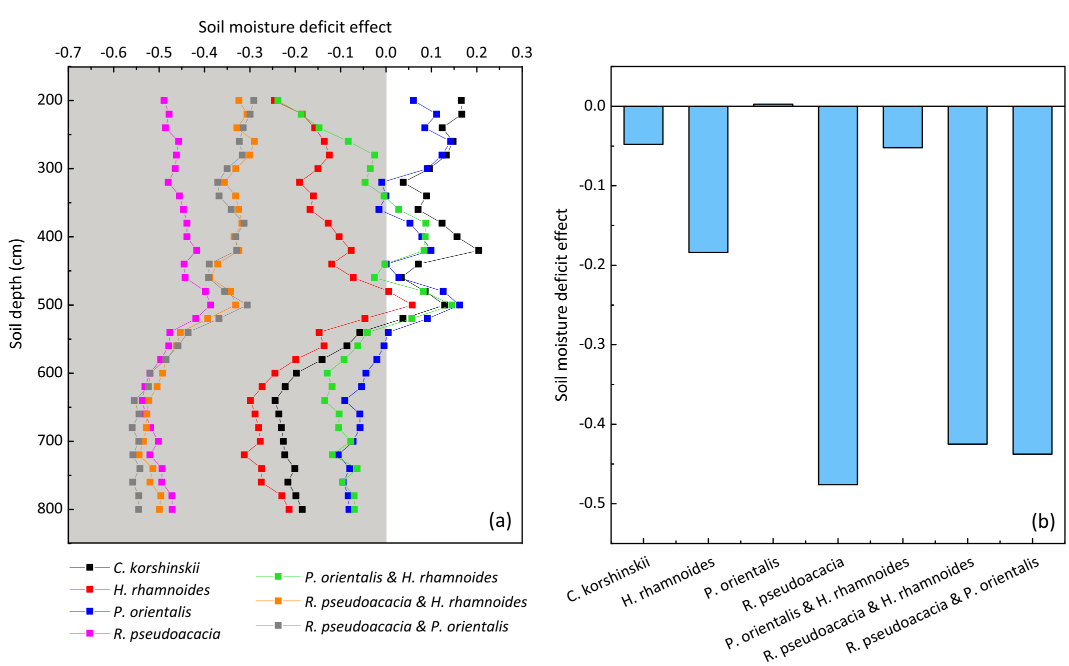

Fig. 6. Soil moisture deficit in the deep layers (SMDD) under various revegetation treatments. Shading area represents negative soil moisture deficit relative to control.

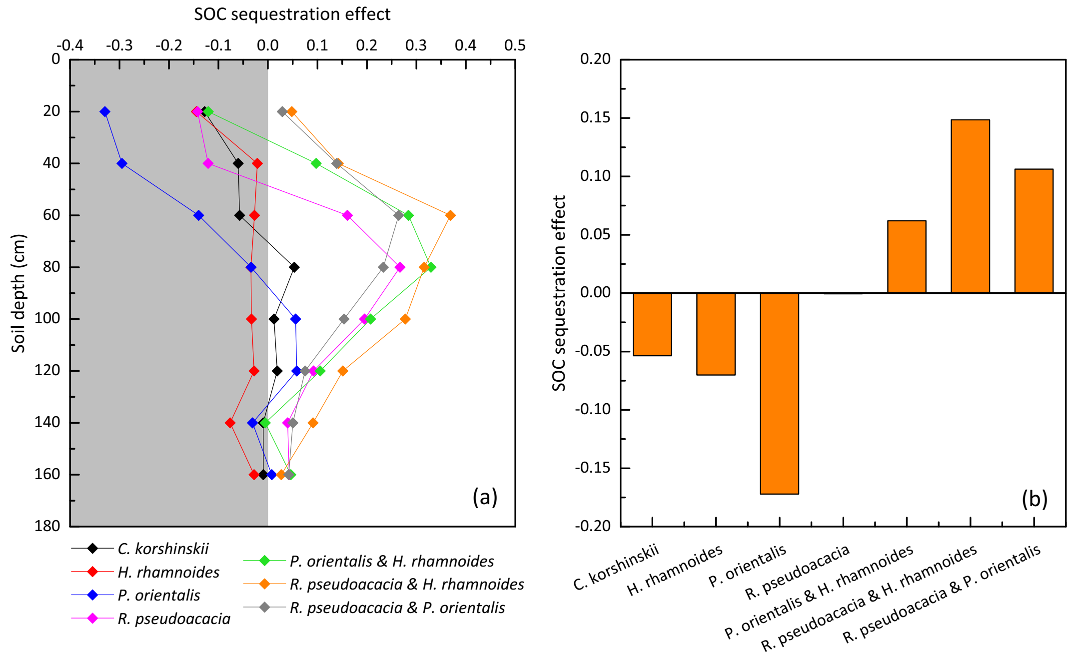

Fig. 7. The SOC sequestration effect (SOCSE) under different revegetation treatments. Shading area represents negative SOC sequestration effect relative to control.

and biological processes (Jabbágy and Jackson, 2000). First, it is noteworthy that the bulk density in the 100 cm was used to represent that in the 120, 140 and 160 cm depths based on an assumption of low vertical variation of bulk density at deep soil layers. This assumption is sensible because of the homogeneity of soil texture over loess soil profiles (Fig. 3). Therefore, we assume the uncertainty in SOCD induced by bulk density should be low. Among the single-species treatments, *R. pseudoacacia* had the highest SOC sequestration effect. This was probably because *R. pseudoacacia* is a deciduous species and was planted at high density and thus produced a relatively large amount of litter (decayed leaves and branches) so the input of organic matter into the soil was relatively greater than occurred in the other plots with single species. Furthermore, the source of SOC in subsurface soils is primarily root exudates and dead root tissues (Davidson et al., 2011; Gao et al., 2017). *R. pseudoacacia* has a well-developed root system in the top 300 cm (Fig. 1; Wang et al., 2009), which could explain to a large extent the relatively high SOC sequestration effect there. In contrast, the plot containing *P. orientalis* with terracing had negative SOC sequestration compared to abandoned cropland. One possible explanation is that *P. orientalis* is an evergreen species that was planted at relatively low density (Table 1) and hence produced relatively little litter. Furthermore, the soil moisture content under this plot was relatively high (Fig. 4), which may have resulted in an increased decomposition rate of SOC (Jabbágy and Jackson, 2000). Moreover, the mixed plantations exhibited greater and positive SOC sequestration than the single-species plantations (Fig. 7) probably because of the relatively high plant densities which produce thicker litter layers and thus a larger input of organic matter and the positive below-ground interaction between different species.

4.2. Suitable revegetation techniques for soil restoration

The effect of revegetation on soil moisture status, particularly at deep layers, is of priority to be considered when judging the suitability of a given revegetation approach in water-limited regions (Wang et al., 2009; Yang et al., 2012; Wang et al., 2015a, 2015b; Jian et al., 2015). Although low soil quality exists due to severe soil erosion in degraded land (Lal, 2006; Liu et al., 2011; Dlamini et al., 2014), SOC sequestration capacity has been rarely used in finding suitable revegetation approaches in these areas. Here we found that the mixed planation of *P. orientalis/H. rhamnoides* with terracing have low deep soil moisture deficit and significant SOC sequestration capacity relative to the abandoned cropland (Figs. 6 and 7), and thus was identified a suitable revegetation technique for soil restoration on the Loess Plateau.

However, it is worth noting that the optimal revegetation method is highly dependent on the evaluation indices and the revegetation treatments under investigation. For example, Wang et al. (2015a, 2015b) found that natural grassland was the optimal land use type among six different treatments, primarily based on their effects on profile soil moisture as well as the aboveground net primary production in the semiarid region of the Loess Plateau. Indeed, *C. korshinskii* almost exhausted the soil moisture over the profile of 1800 cm and should not be considered appropriate for revegetation. However, Jian et al. (2015) argued that the *C. korshinskii* and *R. pseudoacacia* were suitable for use in ecological restoration because they had high ratios of actual evapotranspiration relative to pan evaporation, although they did not analyze their effects on deep soil moisture on the semiarid Loess Plateau. However, here we found that the *R. pseudoacacia* was not a suitable species because it created severe soil moisture deficit in deep layers (200–800 cm) although delivering relatively high SOC sequestration.

In fact, plant species (Wang et al., 2015a) and density (Yang et al., 2012) and land engineering measures (Zhang et al., 2017) can significantly influence profile soil moisture and SOC. Consistent with published studies (e.g., Wang et al., 2009; Yang et al., 2012; Wang et al., 2015a; Jia et al., 2017), planted tree and shrub species at high density overall significantly decreased soil moisture content at deep layers compared to naturally restored grassland and results in severe soil moisture deficit (Fig. 6). But the land engineering measures, such as terracing and fish-scale pits can significantly increase soil moisture content under trees even at depths down to more than five meters (Fig. 6; Li et al., 2016; Zhang et al., 2017). Furthermore, a recent regional-scale study found that soil water content in deep layers (200–500 cm) clearly increased in *R. pseudoacacia* plantation over 25 years old; and larger increases were observed in older plantations (Jia et al., 2017). This suggests that deep soil water is recovering and can be restored to the level under the abandoned cropland if the restoration period is long enough. The effects of revegetation on SOC sequestration are highly dependent of vegetation species and the results vary among studies. At local scale, a lot of literatures indicated that shrub or naturally restored grassland had higher SOC content or density than woodland probably due to much higher plant density there (e.g., Chen et al., 2007; Fang et al., 2012; Zhu et al., 2014; Zhang et al., 2013; Zhao et al., 2015; Zhao et al., 2017). But several studies reported higher SOC sequestration in woodland than in shrub and grassland (Wang et al., 2012; Wang et al., 2015a, 2015b; T. Wang et al., 2016). And Liu et al. (2005) even found that there was no clear difference in SOC content among different tree, shrub and grass species. At regional scale of the whole Loess Plateau, forestland showed overall higher SOC density in the 0–200 cm than grassland (Liu et al., 2011).

Based on the above analyses, it is clear that mixed tree/shrub plantations with land engineering measure and naturally restored grassland could be of priority in revegetation because of relative low soil moisture deficit at deep layers and high SOC sequestration in main root zone. The mixed plantation of *P. orientalis/H. rhamnoides* with terracing here represents such a mixed plantation treatment. Although naturally restored grassland has been often recommended as the optimal revegetation approach (e.g., Wang et al., 2015a), mixed plantations of trees and shrubs with land engineering measure may be a better option for revegetation in the long run under degraded ecosystems especially for developing regions based on the two reasons as follows. First, soil moisture deficit in deep layers caused by tree and shrub species potentially could be diminished to low level after several decades and longer (Jia et al., 2017). Second, mixed plantations could provide greater ecosystem services in terms of wood fiber products, greater biodiversity (trees in upper, shrubs in middle and grass in lower layers) and better economic benefit compared to natural grassland.

In addition, it is worth noting that there are tens of existing revegetation practices on the Loess Plateau, and we need to identify more than one suitable revegetation techniques for soil quality improvement. Furthermore, semiarid regions usually have deep water table depth (Barbeta et al., 2015) and both vegetation species and land engineering measure (terrace; Wei et al., 2016) here have good representativeness in water-limited areas. Therefore, the findings here could provide insights into soil restoration for other regions with degraded land.

5. Conclusions

In this study, we evaluated the effects of seven different revegetation techniques on deep soil moisture and SOC sequestration on the water-limited Loess Plateau where soil quality is relatively poor. We found that the mixed plantation of *P. orientalis/H. rhamnoides* with terracing had limited deep soil moisture deficit and significant SOC sequestration relative to abandoned cropland (control), and therefore represents a potentially valuable approach to revegetation on the Loess Plateau. This revegetation technique has the potential to be applied in other similar semiarid and semihumid regions. Furthermore, we note that plantations of *R. pseudoacacia* can be restored to an acceptable level if the restoration period is long enough, and that mixed plantations of *R. pseudoacacia* with other species exhibited significant SOC sequestration. Therefore, mixed plantations of *R. pseudoacacia* with shrub species combined with land engineering measures may be the optimal revegetation technique in the long run.

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