REVEGETATION USING THE DEEP PLANTING OF CONTAINER SEEDLINGS TO OVERCOME THE LIMITATIONS ASSOCIATED WITH TOPSOIL DESICCATION ON EXPOSED STEEP EARTHY ROAD-SLOPES IN THE SEMI-ARID LOESS REGION OF CHINA

Short title: DEEP PLANTING TO OVERCOME TOPSOIL DESICCATION LIMITATIONS

Xingkai Zhao[1], Zengyao Li[1], Danhong Zhu[2], Qingke Zhu[1*], Michael D. Robeson[3], Jia Hu[3]

[1] *School of soil and water conservation, Beijing Forestry University, Beijing 100083, China*

[2] *Planning and Design Institute of Forest Products Industry, State Forestry Administration, Beijing 100010, China*

[3] *Profile Products LLC, Fort Collins 80528, USA*

Abstract: Exposed, steep earthy road-slopes (ESERs) in the semi-arid loess region of China are prone to soil erosion and are difficult to revegetate. Topsoil desiccation (TSD) leads to land degradation, which limits the revegetation success. In this study, TSD was assessed on south-facing ESERs (with slopes of 45-55 degrees, 55-65 degrees, 65-75 degrees and >75 degrees), and a revegetation method using the deep planting of container seedlings (DPCS) of 3 species (both native and introduced species) was designed to overcome the problems associated with TSD. Plant growth was evaluated by measuring plant height and diameter of the stem base after 4 growing seasons. The following results were obtained: (1) TSD occurs on south-facing ESERs and persists after the rainy season. The thickness of the TSD layer remained at approximately 15 cm (< 20 cm for all studied slope grades) on the slopes with a formation time of approximately 3 years as of the beginning of this study, and the thickness increased to 35-40 cm on the control slope after 4 years of the study. (2) Using the DPCS method, plant roots can completely penetrate the TSD layer. The selected native species (*Caragana korshinskii* Kom. and *Tamarix chinensis* Lour.) and introduced species (*Caryopteris clandonensis* 'Worcester Gold') all survived; among them, *Tamarix chinensis* Lour. exhibited the best growth and the best adaptation to changes in slope grade. The applied method can also effectively inhibit further increases in TSD and can be used in semi-arid loess regions and similar areas.

Keywords: semi-arid loess region; steep earthy road-slope; topsoil desiccation; deep planting; revegetation

* Correspondence to: Q.K. Zhu, School of soil and water conservation, Beijing Forestry University, Beijing 100083, China.
E-mail : zhuqingke@sohu.com

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/ldr.2988

Introduction

The Loess Plateau in China suffers from serious soil erosion and is one of the most severely affected regions worldwide. With increasing social and economic development, the construction of infrastructure (e.g., houses and roads) in this region is often accompanied by excavations that result in the formation of exposed, earthy road-slopes over large areas, the majority of which are either steep or extremely steep, with gradients of greater than 45 degrees. Exposed, steep earthy road-slopes (ESERs) lack vegetation cover and are susceptible to soil erosion and slope instability (Matesanz *et al*., 2006), which increase sediment yield and accelerate soil degradation (Jimenez *et al*., 2013). As a result, ESER areas in this region are prone to ecological (Latocha *et al*., 2016) and geological disasters (Huang *et al*., 2007).

Establishing vegetation is an important ecological measure used to mitigate soil erosion on slopes (Bochet *et al*., 2010; Tang *et al*., 2013). Vegetation cover can enhance the aggregate stability and soil shear strength of shallow soil (Fattet *et al*., 2011), and providing vegetation cover is considered an effective method for stabilizing slopes. The diameter and distribution of vegetation roots play important roles in slope protection, and in general, shrubs are superior to herbaceous plants in root diameter and distribution and are more conducive to slope protection (Stokes *et al*., 2009). Vegetation cover can also intercept rainfall (She *et al*., 2012) and weaken splash erosion caused by raindrops (Huang *et al*., 2006). Furthermore, vegetation cover can weaken overland flow velocity (Liu *et al*., 2014), thus increasing the infiltration time and infiltration amount of rainwater (Huang *et al*., 2010) and reducing runoff (Liu *et al*., 2014). These effects reduce slope erosion due to runoff (Zhao CH, *et al*., 2016). Therefore, vegetation cover plays an important role in soil and water conservation (Pan *et al*., 2016) and can also improve soil nutrient status (Gong *et al*., 2006; Li *et al*., 2016; Wang *et al*., 2012). The improvement of soil water and nutrient conditions can promote the growth of vegetation; therefore, revegetation on ESERs can be mutually beneficial for the soil and the plants (Chen *et al*., 2016) and can inhibit soil degradation, promote the development of soil, and improve the regional ecological environment.

Although vegetation cover on the Loess Plateau was significantly improved after the Chinese "Grain for Green" program, which helped control severe soil erosion and limit soil degradation (Zhang BQ, *et al*., 2016; Ning *et al*., 2015; Miao *et al*., 2012), ESERs remain the primary and most difficult areas for revegetation in the study area. Several studies on the methods used to revegetate slopes have been performed in recent years. Spray seeding (Wu *et al*., 2000) and hydroseeding (Gilardelli *et al*., 2016; Tormo *et al*., 2007) have been widely used in the revegetation of slopes; however, their revegetation results are unsatisfactory for slopes of greater than 45 degrees because of long periods of drought and concentrated intense rainfall (Bochet and Garcia-Fayos, 2004). Yang F, *et al*. (2016) and Shao *et al*. (2014) achieved good revegetation of highway slopes and rock slopes using straw-mat and geotextile as covering materials, respectively. Cao *et al*. (2010) used air bricks to revegetate road-slopes in Hubei Province, China, increasing the vegetation cover of sloped land. Vegetation has been established by drilling on steep, rocky slopes (Wang *et al*., 2009) and decomposed granite roadcuts (Lee *et al*., 2013); however, it is unclear whether the specifications of the planting holes are limited by local environmental conditions (e.g., precipitation, evaporation and soil moisture conditions).

The loess region in north-western China is located in the marginal area of the monsoon climate (Zhang HL, *et al*., 2016). The summer monsoon is severely weakened in this region due to its deep inland location and hindering by the Qinling Mountains (Yang *et al*., 2016). Therefore, there is relatively little precipitation in this region, which has an annual precipitation typically between 300 and 600 mm; thus, the region is a typical semi-arid region. The main factor limiting vegetation restoration in the semi-arid loess region is the low soil water content (Zhu *et al*., 2012), and precipitation is the main mode of soil water recharge. In this region, the slopes formed by engineering construction are consistently steep. For steep slopes, slope grade influences rainfall infiltration because the precipitation received on each unit slope area is small (Song *et al*., 2005; Sheng *et al*., 2016) and the precipitation infiltration time is short (Zhao *et al*., 2014) during rain events, thus limiting the contribution of precipitation to the soil water content. In addition, high-intensity solar radiation accelerates the evaporation of water in semi-arid loess regions, with potential evaporation (865-1274 mm) far exceeding the precipitation level (Li Z, *et al*., 2012), such that soil water consumption far exceeds supply. Therefore, we speculate that the surfaces of ESERs will have a shallow layer of drying soil and that the soil water content can thus be less than the lower limit of the effective soil water content for plant growth (wilting humidity), particularly on south-facing slopes. In addition, topsoil desiccation (TSD) causes land degradation and can affect the process of revegetation; however, this form of land degradation has not yet been reported and addressed in previous studies.

On ESERs, revegetation is often most difficult on the south-facing slopes (Bochet and Garcia-Fayos, 2004; Gong *et al*., 2007; Guerrero *et al*., 2016). Seeds are susceptible to low soil moisture in the slope during germination (Bochet et al., 2010). TSD affects the germination of plant seeds and the early growth of plants because of the extremely low soil water content and greatly reduces the natural recovery ability of ESERs; thus, artificial revegetation is necessary. Therefore, studying artificial revegetation techniques in the ESERs of semi-arid loess regions is of great significance. Considering the water scarcity and high intensity solar radiation on the slopes, container seedlings were used to avoid the damages to seedlings by low soil moisture and strong solar radiation during the seed germination and seedling growth periods, thus promoting survival (Close et al., 2010; Li GL, et al., 2012; Xu et al., 2013, Jimenez et al., 2017). Moreover, native plant species are the first choice for artificial revegetation in various regions (Skousen and Venable, 2008). In this study, a revegetation method using deep planting of container seedlings (DPCS) suitable for the restoration of ESER vegetation was proposed under the premise of the preliminary exploration of TSD on the south-facing slopes in the semi-arid loess region.

The purposes of this study were to (1) determine whether TSD exists, (2) test the DPCS method on ESERs, and (3) analyse the revegetation effect of the DPCS method and its inhibitory effect on TSD.

1 Materials and methods

1.1 Study region

The loess region in northern Shaanxi is located in the central area of the Loess Plateau, and the study area lies in Wuqi County, Shaanxi Province, China (36°33′33″-37°24′27″N, 107°38′57″-108°32′49″E) (Figure 1). Wuqi County is known as the "Demonstration County of Grain for Green" and belongs to a semi-arid loess hilly and gully region of the Loess Plateau. Monthly mean precipitation and temperature data during 1957-2015 (Figure S1A) show that the rainy season occurs within the summer period (from May to September, also the main plant growing season) with high temperatures in the study region each year. The precipitation in the rainy season is 378.3 mm, accounting for more than 80% of the annual precipitation (467.8 mm).

In total, 170 non-repeating south-facing road-slopes were selected along the main roads of Wuqi County. The grades of the road-slopes ranged from 45 to 86 degrees. The percentage distribution of the slope grades is shown in Figure S1B.

1.2 Data collection

1.2.1 Soil water content

Four south-facing slope sections with different slope grades (45-55 degrees, 55-65 degrees, 65-75 degrees and >75 degrees) on the same continuous ESER, with a horizontal distance of 32.5 m (a slope section), an average slope length of approximately 8 m, and a formation time of approximately 3 years were selected as the representative target slopes. The soil texture was sandy loam, and the soil bulk density of the surface layer was between 1.39 and 1.49 g cm^{-3}. Samples were collected for soil water content assessment from the target slopes after the end of the rainy season (the beginning of October 2012). According to the actual length of the slope, we conceptually divided each of the target slopes into three sections (upper, middle and lower zones) and then collected samples using a soil auger, respectively. Samples were taken at intervals of 2.5 m in the horizontal direction (Figure 2), for the soil layer of 0-60 cm with an interval of 5 cm. A total of 504 soil samples were collected from each target slope. The soil water content of samples was measured after oven dried under the temperature of 105°C for at least 8 h until a constant weight was achieved.

1.2.2 Wilting humidity

On road-slopes, the sampling of undisturbed soil with a ring knife can cause severe disturbances to the slope surface. Therefore, a soil auger was used to perform stratified sampling; soil samples were collected on the abovementioned target slopes (at depths of 0-5 cm, 5-10 cm, 10-15 cm, 15-20 cm, 20-30 cm, 30-40 cm, 40-50 cm and 50-60 cm) at the beginning of October 2012. Soil samples were collected on the upper, middle and lower zones of each target slope, the samples of the same depth on each target slope were then mixed with equal amounts, respectively.

After natural drying, each mixed soil sample was sieved through a 2-mm soil sieve, loaded into centrifuge rings, and compacted. The soil was allowed to absorb water for 48 h and was then centrifuged (Ren *et al.*, 2013) (H-1400pF high-speed centrifuge for soil, Kokusan Corporation, Japan). The centrifugation time of each sample was 90 minutes, and the centrifugation temperature was 20 °C. The centrifuge was operated using 9 speeds: 500, 1000, 1500, 2000, 3000, 4000, 5000, 6000 and 7000 rpm. The mass water contents of each soil sample at the set speeds were recorded individually, and the amount of shrinkage (the distance between the upper surface of the soil sample and the upper edge of the centrifuge ring, in mm) of each soil sample was measured using a Vernier calliper after each centrifugation. These data were used to calculate the soil bulk density under the corresponding speed (or soil water suction, cm H_2O) to obtain the volumetric water content of the soil sample at the corresponding speed. The transformation of rotation speed and soil suction is carried out using Equation (1) (Li, 1981):

$$H = 1.118 * 10^{-5} * r^2 * h' * \left(R_0 - \frac{h'}{2}\right), \qquad (1)$$

where H is the soil water suction (cm H_2O); r is the centrifuge speed (rpm); h' is half the length of the soil sample in the centrifuge ring (cm); and R_0 is the radius of rotation of the centrifuge at the basic water surface (cm).

Finally, the lsqcurvefit function in MATLAB (R2010b) was used to fit the van Genuchten model to obtain the soil water characteristic curve (SWCC) at different soil depths (Le Bourgeois *et al.*, 2016; Yao *et al.*, 2014; Ebrahim-Zadeh *et al.*, 2017; Zhang L, *et al.*, 2016; Pena-Sancho *et al.*, 2017). We calculated the corresponding soil permanent wilting point of each soil depth; the fitting accuracy of the van Genuchten model is very high when there are few measured data points. The van Genuchten model is expressed as follows:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha h)^n]^m} \qquad (2)$$

where θ is the soil volumetric water content (cm^3 cm^{-3}); θ_s is the saturated soil water content (cm^3 cm^{-3}), namely, the soil water content when the soil water suction is zero; θ_r is the residual soil water content (cm^3 cm^{-3}), namely, the soil water content when the derivative of the SWCC is zero; h is the soil matric potential (cm H_2O); α,n, and m are SWCC shape factors or empirical fitting parameters; and m=1-1/ n.

In practice, the soil water content at the wilting coefficient is generally considered the residual soil water content, namely, the soil water content at approximately 15,450 cm H_2O water suction (15 standard atmospheric pressures). To adapt to the current soil moisture measurement methods, after obtaining the corresponding wilting humidity (volumetric water content) of each soil layer, we converted the result to a mass water content, using the soil bulk density at 7000 rpm to replace the soil bulk density at the wilting humidity. Instead of the volumetric water content (cm^3 cm^{-3}), the mass water content (g g^{-1}) was used in this study for the following analysis.

The soil wilting humidity in each corresponding layer was calculated (and converted to the mass soil water content) based on the fitted SWCC of each soil layer (volume soil water content). Then, the mean wilting humidity of the 0-60 cm soil layer was calculated and used to judge the existence of TSD. If the soil water content in one soil layer is lower than the mean wilting humidity, it can be concluded that TSD exists in that soil layer.

1.3 Species and seedling selection

The native plant species *Caragana korshinskii* Kom. (Jian *et al*., 2015) and *Tamarix chinensis* Lour. (Yu TF, *et al*., 2017) can survive in poor water conditions; thus, they were chosen as the target plant species for this study. In addition, the introduced plant species *Caryopteris clandonensis* 'Worcester Gold', which is drought tolerant and has some ornamental properties, was also evaluated to explore its applicability for revegetation in the study region. Container seedlings were used to cultivate the target plant species for the deep-planting step. One- to two-year-old healthy container seedlings with plant heights of greater than 30 cm were planted. Similar quantities of each of the three shrubs were planted, and each species was distributed as randomly as possible over each slope.

1.4 Technical revegetation

In the study region, ESERs with formation times of approximately 3 years were selected as the revegetation target slopes (the other slope sections of the abovementioned continuous ESER). The slope angle ranged from 45 to 80 degrees, and the slope aspect was south facing, which is the most difficult aspect for revegetation. Based on the degree of TSD in the target slopes, a method of DPCS was attempted. The specific planting procedures were as follows:

(1) After selecting the target slopes, planting holes were established on the slopes. The depth of the planting holes was approximately 40 cm (the depth was greater than the thickness of the TSD, and below a depth of 40 cm, the soil water content was higher than the soil wilting humidity according to the measured soil water content data and the wilting humidity of each soil layer). The diameter of the planting holes was approximately 12 cm (depending on the specifications of the container seedlings' culture medium), and the spacing between the planting holes was 50 cm (the row spacing can be adjusted according to specific requirements).

(2) The container seedlings were placed into the planting holes together with their planting medium and were covered with soil (the soil that had been removed during the drilling of the planting holes); the covering depth of the container seedlings was approximately 10 cm from the slope surface; this depth was established to reserve a catchment area (Figure 3).

(3) After planting was complete, the sites were fully irrigated once.

In this study, the TSD degree was evaluated after the rainy season (the beginning of October 2012), but the DPCS method was performed before the beginning of the rainy season in the following year (the beginning of May 2013). Therefore, a further increase in TSD might have occurred in the half-year that elapsed since TSD evaluation. In consideration of this possibility, the depth of the planting hole was set to approximately 40 cm (deeper than the depth of the TSD) to pass through the TSD layer, allowing the plants to effectively use the soil water of the deeper soil layer. Such deep-planting holes can improve the stability of container seedlings, and the seedlings are protected to some extent after planting is finished. For comparison with the DPCS method, the shallow-planting of container seedlings (a planting hole depth of approximately 15 cm, within the TSD layer) and the shallow-seeding/direct-seeding revegetation method at shallow depths (pits approximately 10 cm deep in the test slope; plant seeds placed in accordance with conventional planting methods) were used as control trials.

A vegetation survey was performed after approximately 4 growing seasons (in August 2016). The slope range of the target road-slope was divided into three gradient levels: 45-55 degrees, 55-65 degrees and greater than 65 degrees. Then, the vegetation height (determined with a measuring tape) and diameter of the stem base (determined with a Vernier calliper) of three target species were measured on slopes of different grades.

In October 2016 (after the end of the rainy season), the TSD depth was measured using the same method as that described in Section 1.2 on the slope after afforestation with the DPCS method and on the blank control slope (an untreated slope near the target slope) after planting. The slope angles of both slopes were approximately 60 degrees (the average angle of the slope with the DPCS method).

1.5 Statistical analysis

One-way ANOVA (with a significance level of 0.05) was applied to determine whether there were significant differences in the soil water content (before and after planting) of each target slope (upper, middle and lower zones) and the plant height and diameter of the stem base of each target species. When necessary, the data were log-transformed before statistical analysis to meet the requirement of normal data distribution. If an ANOVA indicated a significant difference, a multiple-comparisons test (LSD, with a significance level of 0.05) was used to identify the differences. All analyses were conducted using SPSS 18.0.

2 Results

2.1 Soil water content characteristics of the target slopes

The distribution characteristics and variance analysis of soil water content on the target slopes of different grades (Figure S2) show that the soil water content increased with increasing depth within 0-60 cm. Although the soil water content among the different slope positions generally decreased in the order of lower zone > middle zone > upper zone, very few significant differences in soil water content were observed among the slope positions at each depth and slope grade. This indicates that slope position had little influence on the distribution of soil water content on the studied slopes. Thus, it was reasonable to use the average soil water content of three slope positions to represent the soil water content at each depth of the target slope.

2.2 Exploration of the TSD phenomenon on ESERs

The van Genuchten model was fitted to the soil moisture data at different soil depths within the top 0-60 cm of the target slopes after the rainy season. Each fitting parameter and the residual sum of squares (resnorm) between the calculated and the measured values of the corresponding model are listed in Table S1. Each resnorm value was less than 0.005, indicating that the accuracy of the model fitting was high and that the error was small. For brevity, Figure 4 only shows the SWCC of each soil layer of the 45–55-degree slope grade according to the curve fitting results, and all curves are represented in three stages: a rapid decline stage, a slowing decline stage and a basically stable stage. In the high soil-water suction stage (>10,000 cm H_2O), the soil moisture change rate is small, and the change in soil bulk density is also small (as inferred from the amount of soil compression during the experiment). In addition, all soil water suction levels reached approximately 15000 cm H_2O at 7000 rpm during centrifugation, as shown in Figure 4. These features confirmed the feasibility of substituting the soil bulk density at 7000 rpm during centrifugation for the soil bulk density when the soil water content reaches the soil wilting humidity.

The average wilting humidity and average measured soil water content results (Figure 5) show that the ESERs, which had a formation time of approximately 3 years, continued to have a TSD layer at the end of the rainy season. The thickness of the TSD layer was maintained at approximately 15 cm, and the severity of TSD increased with slope grade. These findings indicate that the soil water content at 0-15 cm and even 0-20 cm is very low and insufficient to support seed germination and plant growth. Such low soil water contents are expected to seriously impede the natural recovery of vegetation.

2.3 The growth of target plants using the DPCS method

The vegetation survey results (Figure 6) showed that both the survival rate and the preservation rate of the ESER were maintained at high levels, indicating that the DPCS method can effectively improve the vegetation cover of ESERs. The results of plant growth analysis showed that the height (Figure 6A) and diameter of stem base (Figure 6B) of each of the 3 species decreased with rising slope grade. For *Caragana korshinskii* Kom., plant height and diameter of the stem base differed significantly depending on slope grade ($P < 0.05$), whereas in *Caryopteris clandonensis* 'Worcester Gold' and *Tamarix chinensis* Lour., no significant difference in plant height or diameter of the stem base was observed between at least two slope grades. These results indicated that *Caryopteris clandonensis* 'Worcester Gold' and *Tamarix chinensis* Lour. are less sensitive to increases in slope grade and are more suitable for revegetation on ESERs, especially *Tamarix chinensis* Lour., and as an introduced species, *Caryopteris clandonensis* 'Worcester Gold' can survive and form landscapes in the study area.

Both the shallow-planting method using container seedlings and the shallow-seeding/direct-seeding revegetation method (Figure S3) failed to achieve satisfactory plant establishment. The growth of vegetation with the shallow-planting method using container seedlings was very weak. The effects of these two planting methods are in sharp contrast with those of the DPCS method.

2.4 Inhibitory effect of the DPCS method on TSD

The analysis of average wilting humidity at 0-60 cm soil depth and the measured soil water content data (obtained using the same method as that described in Section 2.2; Figure 7) showed that the soil water content of the road-slope obtained using the DPCS method (DH) increased as a whole, although the TSD depth remained at approximately 15 cm. However, the TSD depth of the blank control slope (CK) reached 35-40 cm. These results demonstrate that the DPCS method can markedly inhibit TSD but cannot completely eliminate it.

3 Discussion

On the Loess Plateau, a dryland region in China, the low soil water content is considered the main factor limiting revegetation (Zhu *et al*., 2012), and revegetation is most difficult on the south-facing slopes. The topsoil water content or the available topsoil water is closely related to the revegetation success on steep slopes, and these slopes require the use of specific artificial revegetation methods (Zhao *et al*, 2018).

The present study showed that TSD occurs on south-facing ESERs and persists after the rainy season. As slope grade increases, TSD might become more severe (Figure 5), and revegetation might become increasingly difficult. Atmospheric precipitation is the main form of water recharge in the study area (Zhao XK, *et al*., 2016). According to the standardized precipitation index (SPI) (McKee et al., 1993), both the year selected to evaluate soil drying on the slope surface and the previous year were normal years (SPI_{2012}=0.36, SPI_{2011}=-0.22). Thus, the conclusion that TSD occurs on south-facing ESERs in the semi-arid loess region of China, even after the rainy season, is sound. This finding validates our conjecture.

The lack of water availability in the topsoil limits seed germination and the early growth of plants during revegetation (Bochet *et al*., 2007); hence, it is logical to believe that TSD in the studied south-facing ESERs is the main factor limiting plant establishment and vegetation recovery. The DPCS method used in this study can enable plants to completely penetrate the TSD layer and use the deeper available soil water. This method can also retain and collect slope runoff by reserving a catchment area in the planting holes, which can improve water availability and the living environment of the plants. The three target species (both native and introduced species) selected in this study showed good growth after being planted using the DPCS method.

Compared with the shallow-planting method using container seedlings and the shallow-seeding/direct seeding revegetation method, the DPCS method has the advantage of avoiding the adverse effects of low soil water content and strong solar radiation on seed germination and initial vegetation growth. In addition, although pit chiselling (the shallow-seeding/direct-seeding revegetation method) increases surface roughness, providing a more suitable environment for plant seed germination and can reduce seed loss (Bochet and Garcia-Fayos, 2004). However, the increased disturbance accelerated the erosion of the slope (Figure S3), and increased erosion accelerates the loss of seeds (Yu WJ, *et al*., 2017) following heavy rainfall during the rainy season. This process is probably another main reason for the failure of the shallow-seeding/direct-seeding revegetation method in the present study. Furthermore, considering the unsatisfactory effects of shallow-planting and the positive effects of deep-planting on vegetation recovery, it can be concluded that the phenomenon of TSD on ESERs cannot be ignored and is a more important factor causing soil degradation and unsatisfactory revegetation on ESERs. Methods of artificial revegetation (e.g., the DPCS method) that break through the drying layer can promote vegetation growth by providing access to deeper soil water, which is conducive to the survival and preservation of vegetation and thus slope protection and the mitigation of soil degradation and geological disasters.

Based on the analysis of TSD depth over the past four years (from October 2012 to October 2016), we infer that the TSD depth of ESERs will gradually increase with increasing age of the road-slope (Figure 5, Figure 7-CK), at least to a certain extent, and the difficulty of revegetation will increase accordingly. The finding that the DPCS method can markedly inhibit but not completely eliminate TSD might be related to the density of vegetation allocation and the low vegetation cover. Theoretically, the infiltration of precipitation on the target slope must increase to some extent because of the existence of the planting holes, but this contribution of infiltration by planting holes is counteracted by the water consumption by vegetation in the planting holes. Therefore, DPCS can likely play a more active role in restraining or even eliminating TSD if the vegetation density is adjusted accurately or if the vegetation cover reaches a certain level. This requires further study.

4 Conclusions

In semi-arid loess regions, TSD occurs on south-facing exposed, steep (gradients of greater than 45 degrees) ESERs and can persist after the rainy season. TSD in the south-facing ESERs is the main factor limiting plant establishment. Use of the DPCS method on ESERs, which allows the complete penetration of the topsoil desiccation layer, can achieve satisfactory revegetation and inhibit further increases in topsoil desiccation. This method can be applied in semi-arid loess regions and in similar regions.

However, the specific formation mechanism and influencing factors of TSD on ESERs lack quantitative descriptions and require further study. The relationships between TSD on ESERs and both slope factors (e.g., slope angle, slope aspect, and formation time) and meteorological factors in the study area, as well as techniques to reduce TSD, require further study to improve revegetation methods for ESERs. Such efforts will help to reduce soil erosion and soil degradation and improve the ecological environment in the region.

Acknowledgements

This study was supported by the 13th Five-Year National Key Research and Development Project (No. 2016YFC050170502) funded by the Ministry of Science and Technology (MOST), P.R. China; the China National Scientific and Technical Innovation Research Project for the 12th Five-Year Plan (No. 2015BAD07B02) and Shenzhen Techand Ecology & Environment Co., Ltd. (THRD002).

Supporting Information

Figure S1 Distributions of monthly precipitation, temperature and the slope grade

Figure S2 Soil water content distribution on each target slope

Figure S3 Revegetation effect of the two control trials

Table S1 Fitting coefficients and the residual sum of squares of SWCC

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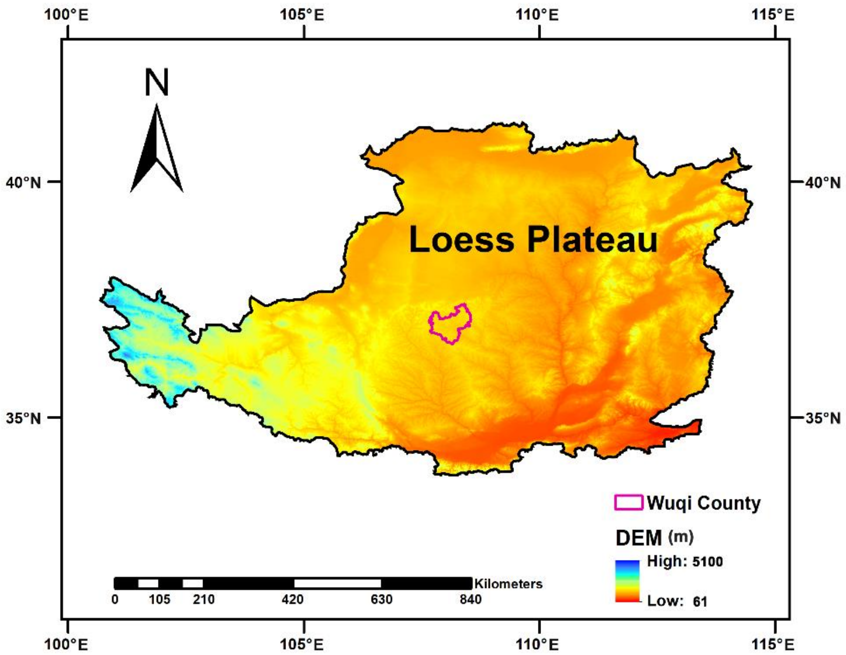

Figure 1. Location of the study area, Wuqi County, on the Loess Plateau, China

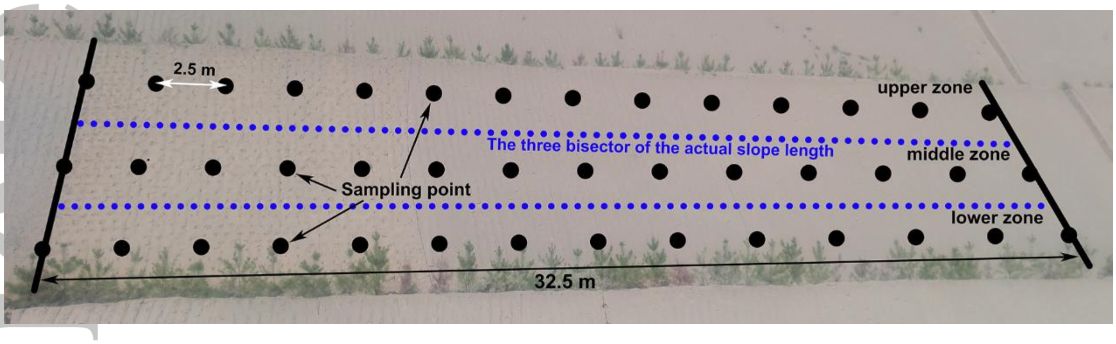

Figure 2. A schematic of the sampling design. The black lines on the left and right sides indicate the edges of the selected target slope section. The horizontal distance is 32.5 m. The blue dashed lines represent the boundaries between the slope zones, dividing the target slope into three sections. The black dots indicate sampling points and are at horizontal distances of 2.5 m. The vertical distance between the points varied according to the actual slope length.

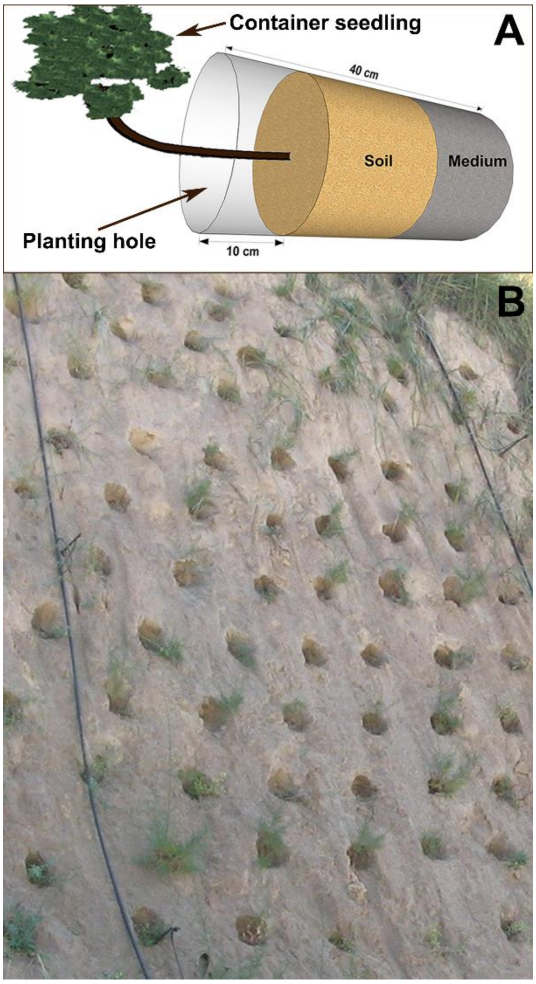

Figure 3. Schematic of the method of deep-planting container seedlings (A) and a photograph of a slope after completion (B)

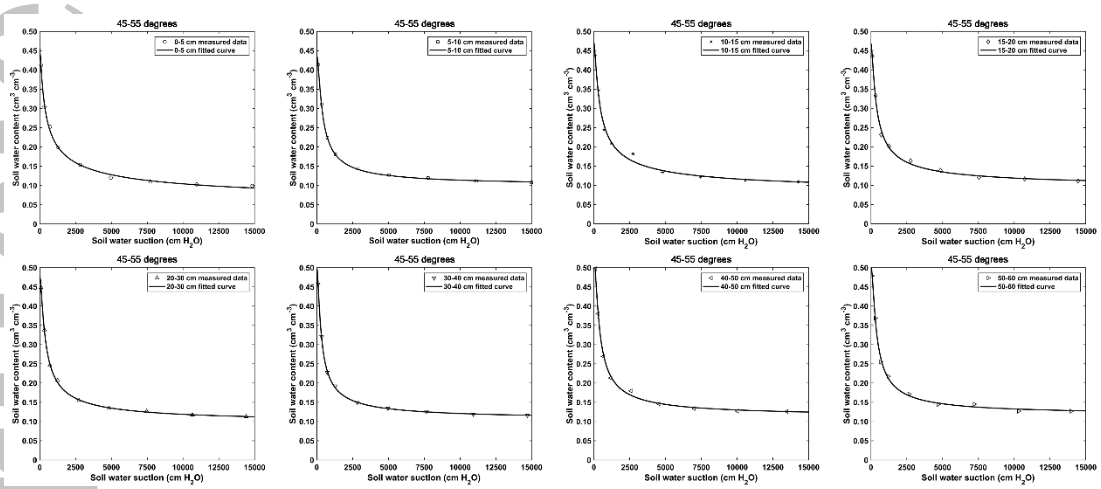

Figure 4. Soil water characteristic curves at different soil depths of the 45-55 degrees slope grade.

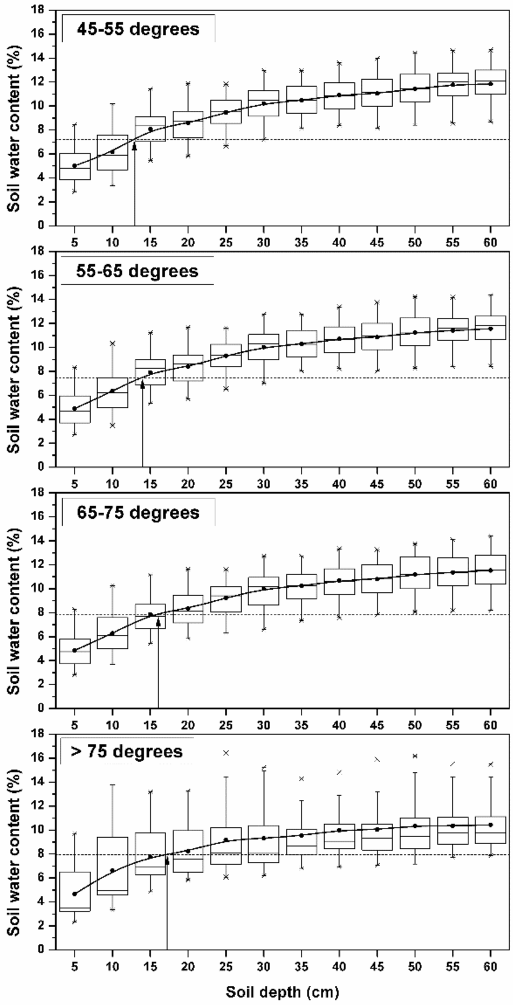

Figure 5. Topsoil desiccation (TSD) at different slope grades after the rainy season of 2012. The boxes represent the measured soil water content at all sampling points; the curve is the average value of soil water content at different soil depths; the dotted line represents the average value of soil wilting humidity within the depth range of 0-60 cm; and the arrow indicates the depth at which the TSD begins to appear.

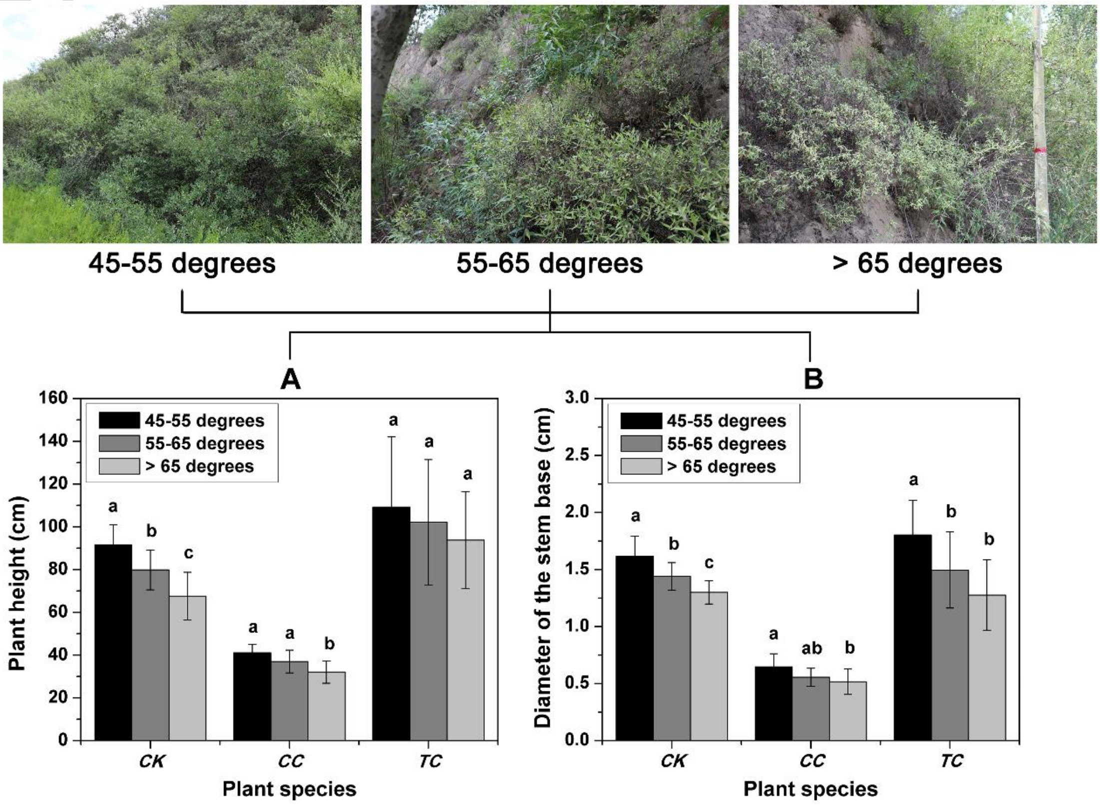

Figure 6. Revegetation effect (top row) and height (A) and diameter of the stem base (B) of 3 target species on slopes of different grades following planting with the deep-planting container seedling method. *CK* indicates *Caragana korshinskii* Kom., *CC* indicates *Caryopteris clandonensis* 'Worcester Gold', and *TC* indicates *Tamarix chinensis* Lour. Different letters above the bars within each group indicate significant differences between plots under each plant height and ground diameter density at P ≤ 0.05.

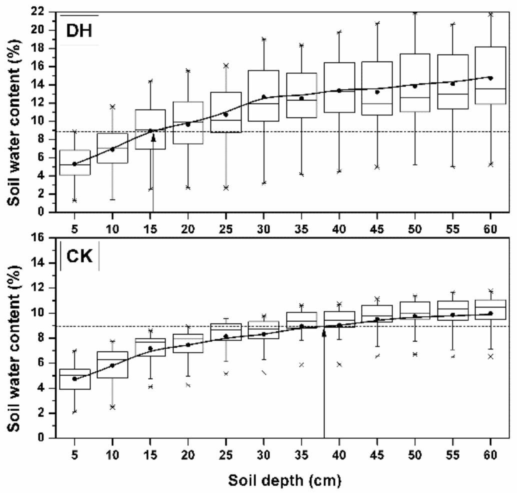

Figure 7. Topsoil desiccation (TSD) at the slope after afforestation with the deep-planting container seedling (DPCS) method (DH) and at the blank control slope (CK). The boxes represent the measured soil water content of all sampling points; the curve is the average value of soil water content at different soil depths; the dotted line represents the average value of soil wilting humidity within the depth range of 0-60 cm; and the arrow indicates the depth at which the TSD begins to appear.