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Soil desiccation for Loess soils on natural and regrown areas

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Abstract

In the Loess Plateau, soil desiccation has become a serious problem for forest and grass vegetation. Soil desiccation leads to the formation of a dried soil layer (DSL). This paper presents the results of research carried out in the central part of the Loess Plateau. The objective of the research was to produce a statistically supported set of indicators for evaluating soil desiccation of forestlands, to present a heuristic idea for soil desiccation and to supply scientific support for replacing farmland with forest or grass in the Loess Plateau and other regions of China. Here, we suggest that more attention should be paid to soil desiccation and its effects on the ecosystem of the region in the future. The results showed that natural *Quercus liaotungensis* forestlands (NQF) retained more water content than regrown *Robinnia pseudoscacia* forestlands (RRF). Significant DSLs were formed in the RRF but not in the NQF. A possible reason for no formation of DSL in NQF could be due to the presence of an arbor–shrub–herb stand structure and large humus and litter accumulation, which increased the natural forest's (NF) adaptability to the environmental conditions. Soil water content in the north-facing slope was significantly larger than in the south-facing slope. DSLs formed in the 0–500 cm layer of the south-facing slope. When slope gradient was greater than 25°, soil water content deceased sharply and showed significant difference compared with 9°, 15° and 20° ($P < 0.05$). So, we conclude that plant species, aspect and slope angle could be the predicators for the formation of DSLs. The analysis on soil physical properties of 0–60 cm layer indicated that plant species, aspect and slope angle also have significant effects on bulk density, porosity, plant-available capacity, and hydraulic conductivity, especially in the 0–20 and 20–40 cm layers. In the NQF and RRF with north-facing slope, soil physical properties were improved.

Keywords: Soil desiccation; Dried soil layer (DSL); Natural forest; Regrown forest; Slope aspect; Slope gradient; Soil physical property

1. Introduction

Li (1983) acknowledged soil desiccation as a serious problem in the central Loess Plateau of China. Extensive, long-term soil desiccation not only prevented the return of farmland to forestland, but also brought negative impacts on hydrological conditions. A direct consequence of soil desiccation is the formation of a dried soil layer (DSL), which can lead to soil degradation, regional microclimate environment aridity, poor renewal by natural germination, failure of afforestation and reduction of vegetation (Yang, 1996). Several researches have addressed soil desiccation attention (Yang and Yu, 1992; Sun et al., 1998; Fu et al., 2000; Wang et al., 2000; Li, 2001; Shangguan and Zheng, 2006). Yang and Yu (1992) provided a conceptual framework for soil desiccation, combining with the information about soil water shortage and vegetation functions.

In the Loess Plateau, soils are largely barren ecosystems characterized by a droughty climate with infrequent precipitation, damaged plant populations, restricted biological activity, high soil and water loss and the pressure of human activities. If drought conditions occur with excessive water consumption by vegetation, soil water loss occurs not only in the 0–200 cm soil layers, defined here as the shallow soil layer, but also in deeper layers >200 cm. This soil water loss can be partly replenished by rainfall in wet seasons, but without full replenishment, the moisture in deep soil layers may remain small for several years. The deep layers are then called dried soil layers (DSL). Yang and Yu (1992) stated that DSL have three characteristics: (1) extension to deeper soil depth, mainly in deep layers and sometimes reaching 1000 cm; (2) having water contents near or below the permanent wilting point; (3) occurring for significant time durations. Soil desiccation can be defined as a drying

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process in which soil water contents decrease to permanent wilting point by evapotranspiration. Desiccation is often exacerbated by forest and grass vegetation or other non-native species which can remove large amounts of water from not only the shallow soil layer but also from the deep soil layer (>200 cm) where moisture is less likely to be replenished by rainfall. Few studies have identified quantitative indices of soil desiccation. Yang and Yu (1992) showed that the range of soil water in DSLs is from less than or equal to the permanent wilting point (lower limit) to less than or equal to a stable field capacity (upper limit) at which soil water remains stable or soil capillaries break. Wang et al. (2004) proposed the concept of ‘‘stable soil water-holding capacity in woodlands’’ as an upper limit to determine the formation of DSL in natural and regrown forestlands. So a clear quantitative upper limit of soil desiccation remains controversial. Yang (1996) considered vegetative factors as the major causes of soil desiccation. He found that inappropriate uses of vegetation types, improper community density and excessive community productivity could result in soil desiccation. For example, some arbor species were planted in areas which were better suited for growing shrubs; some species, which consume plenty of water, were planted in areas which were better suited for growing species well adapted to drought. Also, people planted species for economic benefits at a density which exceeded the regional carrying capacity, and caused soil water to be exhausted. Wang et al. (2001) stated that drought, an infrequent precipitation and serious soil erosion could also be responsible for soil desiccation.

There are limited data relating soil desiccation and changes of soil physical properties such as bulk density and porosity, particle composition and specific surface area, hydraulic properties, and the effects of soil water infiltration on soil desiccation. In this study, soil water contents were mainly surveyed for the natural *Quercus liaotungensis* and different regrown *Robinnia pseudoscacia* forestlands. We stipulate that a dried soil layer (DSL) is formed if gravimetric water content is less than 8% that is equal to 40% of field capacity (20% in Yan’an area). We investigated natural and regrown forests and grasses, slope aspect and gradient effects on soil desiccation. Soil physical properties were investigated for different lands under soil desiccation. One specific objective of the study is to determine soil physical property changes after soil desiccation. A purpose is to produce a statistically supported set of indicators for evaluating soil desiccation of forestlands and grasslands, to present a heuristic description of soil desiccation and regional-level management of the soil water system, and to supply scientific support for replacing farmland with forest or grass[1] in the Loess Plateau and other regions of China.

2. Materials and methods

2.1. Site description

The study was performed in the Yangou catchment of Yan’an County, which is located in the central Loess Plateau, 350 km north of Xi’an, the capital city of Shaanxi province of China. The longitude is E109°20′–109°35′ with latitude N36°28′–36°32′. To keep similar site conditions, investigations were conducted within a limited area with distances not exceeding 10 km. The study area is approximately 47 km^2. The landform is a typical Loess hilly landscape with relative elevations of 200–400 m and altitudes of 980–1400 m. The climate is semiarid with an annual average temperature of 9.8 °C and average annual precipitation of 560 mm, of which more than 70% falls from June to September (Xu and Sidle, 2001). The natural biome is the northern extended area of deciduous broadleaf forest and zonal climax vegetation is oak forest dominated by *Quercus liaotungensis* (average height 1055 cm and 90% cover) that has developed more than 100 years succession and become the natural secondary forest. However, the natural oak forest accounted for less than 10% of total catchment area because of denudation and estrepement during the last 100 years. The regrown forests (including economic trees, such as apple and pear) dominated by *Robinnia pseudoscacia* and *Populus* spp. that were planted in the late 1970s, accounted for 18.6% of the total catchment area (Liu et al., 2005). The soil is calcareous silt loam (Calcic Cambisols) belonging to the Entisol order according to the USDA texture classification system, derived from Loess with generally more than 50 m depth.

2.2. Soil sample collection and analysis

The sampling plots were 1 ha with 20 m × 20 m for forestlands and 10 m × 10 m for grasslands subplots being used for vegetation investigations. The sampling strategy was comparable across sites with similar aspects, similar slope and altitude. However, sometimes a few sites varied slightly in certain respects because exact sites could not be found. Three replicates of all measurements were obtained in each sampling plot. All measurements were done at the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, China.

In situ altitude, longitude and latitude were determined by double frequency RTK-GPS. Slope inclination and direction were determined by compass. The age of forests was estimated according to the whorls of trees. A probing was made in order to count tree rings, and a regression was performed between the height of trees and the number of rings.

In May 2006, the erosion plots were established to measure the surface runoff and erosion rate in the different lands with 2 replicates. The size of each erosion plot was 5 m × 20 m. The plots were bordered with 40 cm height PVC boards, and the half of the height of boards was embedded into soil. In the bottom of runoff plots, runoff buckets (made by iron) were installed to collect runoff through PVC tubes with diameter of

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[1] From the late 1990s, the Chinese Central Government has enacted the policy of ‘‘Replacing Farmland with Forest or Grass’’ for the restoration of vegetation, which plans to update and readjust crop production structure, actively develop green agriculture, return the related farmland (especially slope farmland) to forest and grassland and stop new reclamation for agricultural use.

10 cm at the outlet of each runoff plot. The size of runoff buckets were designed according to hydrological data derived from Yan'an meteorological station, which is 60 cm diameter and 100 cm height. The ditches were dug in top of erosion plots to prevent runoff of other places running into plots. After each runoff event, the water level in runoff buckets was measured to calculate the runoff volume; and after mixing, sediment samples from runoff buckets were collected in 1-l bottle. Next, the sediment samples sat overnight, and the excess water was poured from the bottles. Then, the sediment samples were placed in an oven at 105 °C until the sediment was dry. The dry sediment weight was then taken to calculate the erosion rates.

Infiltration rates for the different lands were determined in the field by two methods, disc tension permeameter (Perroux and White, 1988; Schwartz and Evett, 2002; Wang et al., 2007) and double rings (Xu et al., 2002).

Soil samples were obtained in October 2006 just before harvest. At each sample location, soils were obtained with a soil auger (4 cm-diameter) to measure profile water contents in 10 cm layers to a depth of 200 cm and in 20 cm layers between the depth of 200 and 500 cm. Soil water content was determined by oven-dry samples of 105 °C.

Each humus (if have) at each sampling location was collected and weighed by an electronic scale. Here, humus refers to surface accumulations of organic matter including litter and mor. Humus that incorporated into soils will be classified into soil organic matter (SOM) and measured by chemical method. Soil organic carbon (SOC) was measured on an Elementar Vario EL element analyzer and soil organic matter (SOM) was obtained by multiplying SOC content values by 1.723.For soil physical properties, undisturbed soil samples were obtained from the 0–60 cm soil layer. To measure bulk density and soil saturated hydraulic conductivity (K_s), three replicates of intact soil cores were obtained by ring knife (5 cm in diameter and 5 cm in height) at every 20 cm in the 0–60 cm soil layer. K_s was measured by the constant hydraulic head method (Klute and Dirksen, 1986; Jury and Horton, 2004). Intact saturated soil cores were fixed within a permeameter and supplied with water at the top, using a Marriote bottle to keep a stable hydraulic head of 10 cm. K_s was calculated using Eq. (1):

$$K_s = \frac{QL}{(At \cdot \Delta H)} \tag{1}$$

K_s is the saturated hydraulic conductivity (mm min^{-1}); Q the water volume (mL); L the length (mm) of soil core; A the cross-sectional area of the soil core (mm^2); t the time (minutes), and ΔH the difference of hydraulic head (mm).

Following K_s measurements, bulk densities were determined on the cores. Soil total porosity was calculated using Eq. (2), based on measured bulk density and assuming a soil particle density of 2.65 g cm^{-3} (Jury and Horton, 2004). Soil capillary porosity was measured using the same intact soil core before K_s measurement. Each soil core was obtained to absorb water through capillary action via filter paper until it reached a steady weight, usually 12 h later. Then, this soil capillary water capacity could be measured. Soil capillary porosity was subsequently calculated using Eq. (3) by bulk density and soil capillary water capacity data. The core samples did not swell.

$$P_t = \left(1 - \frac{B_d}{d_s}\right) \times 100 \tag{2}$$

P_t is the total soil porosity (%); B_d the soil bulk density (Mg m^{-3}); d_s the soil density (Mg m$^{-3)}$:

$$P_c = \frac{W_c \times B_d}{V \times 100} \tag{3}$$

P_c is the soil capillary porosity (%); W_c the soil capillary water content (w–w, %); V the volume of soil core (m^3).

Composite samples of about 1 kg were collected from each sampling location and then air-dried and passed through a 1 mm sieve. The sieved soil was out to measure plant-available soil water capacity (water held between 0.03 and 1.5 MPa suction), soil particle composition, and soil organic matter (SOM). Plant-available soil water capacity was measured in the laboratory by a high-speed centrifuge (R21G/CR22G, made by Hitachi Company). Hence, the measured values of 0.03 MPa water content would be smaller than field measured values or using undisturbed soil. Soil structure can be damaged with a consequent reduction of B_d, particularly for well-structured soils. Such low-tension values are positively correlated with soil macroporosity (Zhu, 1983). However, to a variable extent, our results should also reflect an overall tendency in changes of soil plant-available water capacity. Particle composition was measured by the laser diffraction technique using a MasterSizer 2000 (Malvern Instruments, Malvern, England), equipped with a low-power (2 mW) Helium-Neon laser with a wavelength of 633 nm as the light source. The apparatus has active beam length of 2.4 mm, and it operates in the range 0.05–1000 μm. The sample obscuration was adjusted to an optimal value of 45%. Air-dried soil was passed through 2 mm sieves before analysis and large roots and other fresh organic materials were removed by hand. Approximately 5 g of soil was added to the water reservoir of the machine that contained approximately 2 L of tap water. The water–soil mixture was circulated at high constant speed (2500 revolutions per minute) past the measurement cell (Liu and Huang, 2005). Particle size distribution was obtained by a MasterSizer 2000 analysis.

Soil specific surface area (SSA) is a property that synthesizes particle composition characteristics. SSA was not measured directly. Ignoring SOM, SSA for mineral soil was calculated using Eq. (4) for the sand (2–0.05 mm), silt (0.05–0.002 mm), and clay (<0.002 mm) fractions, based on Foster et al. (1985):

$$\text{SSA} = 0.05(\text{Sa\%}) + 4.0(\text{Si\%}) + 20.0(\text{Cl\%}) \tag{4}$$

SSA is the specific surface area (cm^2 g^{-1}) for mineral soil; Sa, Si and Cl the percentage of sand, silt, and clay in soil, respectively.

Table 1
The soil gravimetric water contents in forestlands of different species

Soil depth (cm)	Natural forestlands		Shrubs	Regrown forestlands	
	Populus davidiana	*Armeniaea sibiriea*		*Caragana microphylia*	*Hippophae rhamnoides*
0–200	8.8^{a} (0.64)	8.0^{a} (0.51)	7.7^{a} (0.48)	5.4^{b} (0.42)	6.0^{b} (0.53)
200–500	9.9^{a} (0.45)	8.5^{a} (0.39)	9.3^{a} (0.25)	6.1^{b} (0.26)	5.6^{b} (0.21)

Means with the same letter in the same row are not significantly difference at the 0.05 level (Duncan's test). Data in the parentheses are standard deviations.

2.3. Statistical analysis

Mean values, standard deviations and standard errors are reported for each of the measurements. One-way ANOVA was used to assess the difference of the measured variables. When ANOVA indicated a significant F-value, Duncan's test at $P < 0.05$ was performed to compare means of soil variables. The SPSS software package (2003) was used for all of the statistical analyses.

3. Results and discussion

3.1. Species and water content

3.1.1. Comparison of natural and regrown forestlands

Gravimetric water content profiles in regrown *Robinnia pseudoscacia* and natural *Quercus liaotungensis* forestlands with same aspect (*S*) and slope (15°) are shown in Fig. 1. The regrown *R. pseudoscacia* forestland (RRF) had smaller soil water contents than the natural *Q. liaotungensis* forestland (NQF) of all depth ($P < 0.01$). The average water contents from RRF and NQF were 5.1% (0.53) and 8.7% (0.75) for the 0–200 cm layer, and 5.5% (0.43) and 9.8% (0.40) for the 200–500 cm layer, respectively. This indicated that (1) the water content difference between RRF and NQF was more significant in deeper soil than in shallow soil; (2) DSLs were formed not only in the shallow layer but also in the deep layer from RRF; (3) there was almost no formation of DSL in NQF and only a few depth in shallow layer had water contents less than 8%.

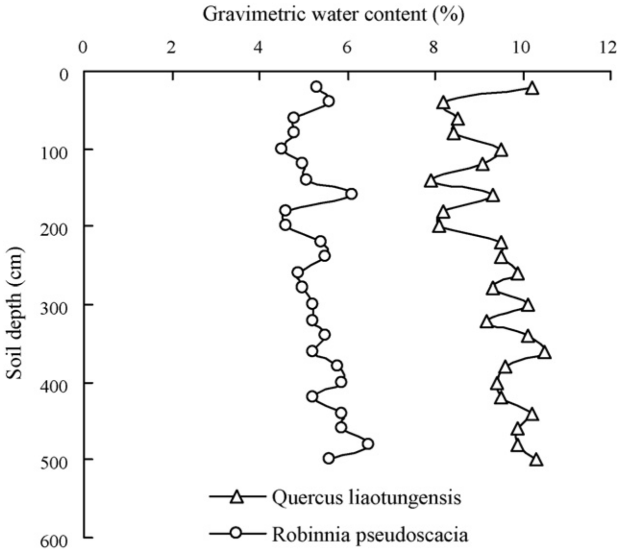

Fig. 1. Comparison of water content between the natural and regrown forestlands with south aspect (S) and 15° slope.

The water content from other natural and regrown species lands were also surveyed, and Table 1 shows their average values for the 0–200 cm layer and the 200–500 cm layer. As shown, the differences in deeper soil layer were more significant ($P < 0.05$) between natural and regrown forestlands, which indicated that regrown species tend to consume more deep soil water compared with the natural species.

Soil water content is an important variable responding to rainfall distribution and water–vegetation interactions. It is necessary to consider why water content showed significant difference between RRF and NQF, and severe DSLs were formed in RRF under similar climate conditions. There was a manifest difference of stand structure between the natural and regrown forests. Natural *Q. liaotungensis* forest (QF) showed a typical arbor–shrub–herb structure, while the stand structure of regrown *R. pseudoscacia* forest (RF) was very simple. As shown in Table 2, arbor layer, the shrub layer and herbaceous layer from QF had 6, 21 and 32 species, respectively. Arbor species were mainly *Q. liaotungensis*, *Populus davidiana,* and *Betula platyphylla*; shrub species included shade-tolerant plants such as *Spiraea pubescens*, *Acer ginnala*, *Viburnum schensianum*, and *Rosa hugoni*. This indicated that after more than 100-year succession, QF became a multistoried, multi-forb species community. While the corresponding values from RF were 1, 2 and 40 species, respectively. The only arbor species was *R. pseudoscacia*; shrub species were shade-intolerant plants such as *Periploca sepium*, *P. uniflora*. It is likely that relatively lower coverage (70%) of RF facilitated the heliophytes. This indicated QF was still being an early seral single storied condition that had high herb species diversity (Table 2). Due to the typical and stable forest structure, QF could adapt to a variety of environmental factors (including soil water content) and adjust the species competition very well. As emphasized by Perry (1995) (1) species may not need to

Table 2
The spatial distributions of family, genus and species number of natural and regrown forests

Forest types	Items	Arbor layer	Shrub layer	Herbaceous layer	Total
Q. liaotungensis	Family	6	9	16	31
	Genus	6	18	20	44
	Species	6	21	32	59
R. pseudoscacia	Family	1	2	20	23
	Genus	1	2	28	31
	Species	1	2	40	43

compete when their growth is largely influenced by predation, disturbance, or climate perturbation (e.g., soil water shortage); (2) competing species may actually benefit each other by either decreasing or eliminating the adverse effects of plant competition (e.g., by improving the soil or microclimate, reducing the influence of other competing plants, catalyzing beneficial components in the root zone, and attracting pollinators) (Hunter and Aassen, 1988); (3) trees may avoid competition through specialization (e.g., early-colonizing N-fixing plants competing for resources, but later benefiting each other by increasing soil fertility). While *R. pseudoscacia* forest (RF) showed a poor adaptability to environmental factors because of its simple forest structure. For example, when water shortage occurred in the shallow layer, *R. pseudoscacia* tended to consume the water storage of the deep soil layer and resulted in the formation of DSLs.

Secondly, a large amounted humus and litter accumulated in the surface of NQF, but not in the RRF. Surface humus and litter accumulations may not only provide some necessary nutrients but also contribute to moisture retention and water storage (Rode, 1999). By interception activity, humus and litter can reduce runoff and increase infiltration, thus improve the water content in the forest soils (Geng and Wang, 2000; Fan et al., 2006). Wu et al. (1998) reported that litter and humus can capture 25% of total rainfall, and finally some of captured rainfall infiltrate into soil and redistribute. Also due to high quantity of organic matter in the humus and litter, soil physical and chemical properties were improved, such as aggregate stability (Fan et al., 2006), soil water retention (Rode, 1999), soil water availability (Leuschner and Rode, 1999), and soil respiration rate (Raich and Tufekcioglu, 2000) that all are helpful to ameliorate the water content in the central area of Loess Plateau. In this study, even though we did not make a detailed analysis on the relationship between humus/litter and water content from NQF, we can still find some evidence to favor the humus/litter function on the water content. For example, natural seedling germination and growth was ubiquitous in the NQF but little was found in the RRF, which is consistent with the report by Prescott et al. (2000a,b) that surface humus accumulations may conserve soil water for natural seedling germination. Therefore, humus and litter may play an important role in preventing the formation of DSLs in the NQF.

3.1.2. Comparison of natural and regrown grasslands

There were two types of natural grasslands in the Yan'an experimental area. One was sagebrush grassland, mainly dominated by annual *Artemisia gmelinii* (average height 56.1 cm with 91% coverage), and the other was mixed grassland dominated by several biennial and perennial plants like *A. capillaries*, *A. giraldii* and *Stipa bungeana* (average heights of 65.1, 29.6, and 22.5 cm and with average coverage of 54%, 24, and 16%, respectively) interspersed with the undershrub *Lespedeza davurica* (average height 48.8 cm with 8% coverage). In the two natural grasslands, sample sites having average water content more than 60% of field capacity in the 0–500 cm soil layer accounted for 65%, and others had average water content more than 40% of field capacity.

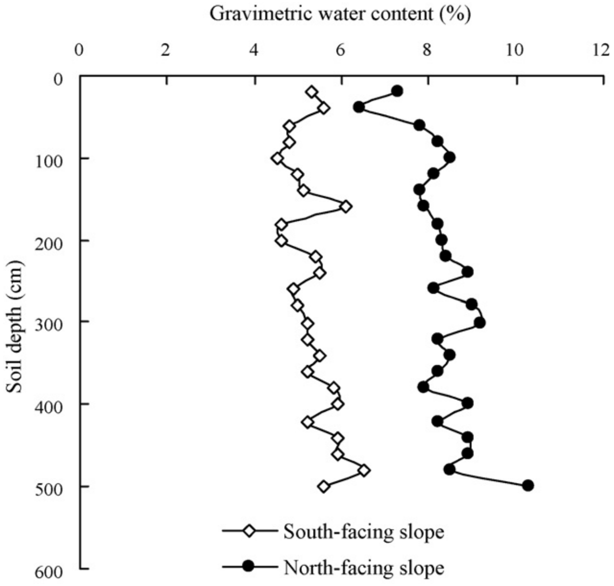

Fig. 2. Comparison of water content between north- and south-facing slope regrown with *Robinnia pseudoscacia*.

The regrown species were mainly *Astragalus adsurgens* and *Medicago sativa* L. Compared with natural grasslands, the average water content in the 0–500 cm layer was significantly lower ($P < 0.05$) in the two regrown grasslands. There were 76% of the sample sites that had average water content less than 30% of field capacity, and the others had only 35–40% of field capacity. This indicated that water shortage occurred and DSLs were formed in the regrown grasslands. Similar to the arbor species, the possible reason was that regrown grass species showed poor adaptability to environmental factors compared with natural species.

3.2. Site conditions and water content

3.2.1. Aspect and water content

Fig. 2 shows the changes of water content in the south- and north-facing slope lands (with same slope gradient of 15°) regrown with *R. pseudoscacia*. In the south-facing slope land, the average water content was only 5.1% (0.53) in the 0–200 cm layer and 5.5% (0.43) in the 200–500 cm layer. The smallest value was 4.6% which was similar to the permanent wilting point (3.6% under 1.5 MPa), and the largest value was just 6.5%. This indicated that DSLs were formed not only in the shallow layer but also in the deep layer. The root system could penetrate and consume water for the deep layer because of the water shortage in the shallow layer. In the north-facing slope, the corresponding values were 7.9% (0.61) and 8.7% (0.60), respectively, which are significantly higher than that of the south-facing slope ($P < 0.05$). The smallest value was 6.4% which was similar to the largest value of the south-facing slope, and the largest value was 10.3% which was more than 50% of field capacity. There were almost no deep layer's DSLs in the north-facing slope. *R. pseudoscacia* is prone to consume much more water in the south-facing slope and result in soil water shortage.

Table 3
Some factors affected by slope aspect may influence water content

Slope aspects	Average air temperature (°C)			Average ground temperature (°C)			Moisture variation coefficient		Erosion rates (t km^{-2} a^{-1})	Runoff (m^3 km^{-2})
	Annual	June	August	Annual	June	August	0–200 cm	200–500 cm		
South-facing	10.4	23.4^a	23.1^a	12.8	27.8^a	25.3^a	0.12	0.17	926	14 881
North-facing	9.3	21.2^a	20.7^a	11.1	22.7^b	21.6^b	0.07	0.28	606	11001

Means with the same letter in the same column are not significantly difference at the 0.05 level (Duncan's test).

Our findings indicated that slope aspect had a positive effect on the formation of dried soil layer, which concurs with those of previous studies (Lee, 1963; Dargie, 1987; Oke, 1987; Badano et al., 2005; Rezaei and Gilkes, 2005) that either explicitly or implicitly state that the south-facing slopes are hotter and drier, north-facing slopes are cooler and moister from this micro-climatic difference. This suggests that soil water content is significantly affected by slope aspect, and slope aspect could be an important predictor of DSL formation in the Loess Plateau.

Slope aspect can influence temperature and moisture regimes. South-facing slopes receive more direct sunlight and are therefore warmer than north-facing slopes (in the Northern Hemisphere). Higher temperatures on south-facing slopes can increase the amount of evapotranspiration that will decrease soil water content (Dubayah, 1994). North-facing slopes are not only moister but also show less moisture variation than south-facing slopes (Geiger, 1965). Thus, soils on north-facing slopes generally dry out more slowly (Landin, 1961). Our survey data on temperature and moisture variation (Table 3) show that ground temperature on the south-facing slope was significantly larger than on the north-facing slope, and air temperature on the south-facing slope was not significantly larger than on the north-facing slope.

The north-facing slopes had smaller erosion rates than the south-facing slope. This was consistent with the results of Carson and Kirkby (1972). As for how erosion rate influence water content, we will discuss it in Section 3.2.2.

Some authors have also correlated other measurements with slope aspect, such as species diversity (Kirkpatrick and Nunez, 1980; Kutiel, 1992; Enright et al., 1994), soil nutrient status (Kutiel, 1992; Rezaei and Gilkes, 2005), soil surface cover (Kutiel et al., 1998), post-fire erosion (Marques and Mora, 1992), and weathering process and intensity (Fanzemier et al., 1969; Davis, 1976; Rech et al., 2001; Hall et al., 2005; Turkington and Paradise, 2005). Differences resulting from slope aspect may influence changes of soil water content. Further study is necessary to determine how these differences may influence soil properties that can affect water content on the Loess Plateau.

3.2.2. *Slope gradient and water content*

Table 4 presents the results of gravimetric water content under different slope gradients of regrown *R. pseudoscacia* forest lands. Generally, the greater the slope, the lower the gravimetric water content and the severer the dried soil layers. There was no significant difference between 9–15° and 15–20° ($P > 0.05$). When slope was greater than 25°, the gravimetric water content deceased sharply and showed significant difference compared with 9°, 15° and 20° ($P < 0.05$). Fig. 3 shows a contrast of water content between the maximal (33°) and minimal (9°) slope in this study. Water content in the slope 9° was larger than that in the slope 33° ($P < 0.05$). In the slopes 33° and 25°, water content was almost less than 5.5% across the whole 0–500 cm layer, and very severe dried soil layers were formed.

Tang et al. (1998) reported that the critical slope for gully erosion is between 15° and 20°, and when slope is larger than 25°, the frequency of gully erosion can be more than 76% in the Loess Plateau. More erosion means more water loss because rainwater does not infiltrate in but flow off of slope land by runoff. Thus, water content in the large slopes will be lower than that of the small slopes. In addition, the slope angle shows normally an inverse relationship with infiltration rates because of the location of the most degraded soils on the steepest slopes (Munn et al., 1973). Zaslavsky and Sinai (1981) reported that under steady-state conditions corresponding to stable and homogeneous soils, infiltration is expected to decrease as slope gradients increase because of lateral flow. Luk et al. (1993) found that in a Loess soil that was prone to crusting, infiltration rate decreases with slope increase for longer storms. Decreasing infiltration can cause an increase of matrix suction and a decrease in water content and soil permeability in the

Table 4
The soil gravimetric water content and some possible influencing factors of regrown *Robinnia pseudoscacia* in the different slope angles

Slope gradients	Erosion rates (t km^{-2} a^{-1})	Runoff (m^3 km^{-2})	Infiltration rates (mm min^{-1})		Average water content (%)	
			By disc permeameter	By double rings	0–200 cm	200–500 cm
9°	580	10 990	1.25^a	1.31^a	5.3^a (0.28)	5.7^a (0.46)
15°	920	14 880	1.26^a	1.26^a	5.1^a (0.53)	5.5^a (0.43)
20°	1 230	15 130	1.11^a	1.18^a	5.0^a (0.38)	5.6^a (0.40)
25°	1 840	21 890	0.89^b	0.90^b	4.7^b (0.29)	5.1^b (0.45)
33°	2 180	26 250	0.78^b	0.85^b	4.6^b (0.47)	4.8^b (0.22)

Means with the same letter in the same column are not significantly difference at the 0.05 level (Duncan's test). Data in the parentheses are standard deviations.

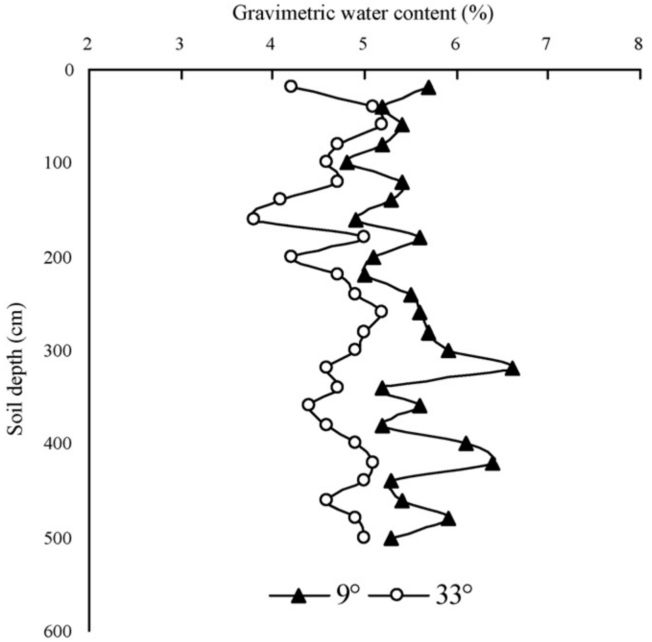

Fig. 3. Comparison of water content between the maximal (33°) and minimal (9°) slopes regrown with *Robinnia pseudoscacia*.

unsaturated soil (Ng and Shi, 1997). Therefore, slope steepness affects water content by increasing soil erosion and decreasing infiltration rate especially for the steeper slopes (more than 25°). In this study, we investigated the relationship between slope gradients and soil erosion/infiltration rates. As shown in Table 4, slope angle had a clear positive effect on erosion rates, and an inverse relationship with infiltration rates. The soils on steeper slopes have lower steady-state infiltration rates and higher erosion rates. So we can conclude that high erosion and low infiltration rate are two possible reasons for lower water contents in the large slope gradient lands, and slope angle could also be a predicator for the formation of dried soil layers.

3.3. Change of soil physical properties

3.3.1. Bulk density and porosity

Table 5 shows that (1) in the 0–20 cm layer, the difference of bulk density between NQF and RRF with north/south-facing slope was significant ($P < 0.05$). Bulk density difference was not significant between different RRFs with south-facing slope ($P > 0.05$); (2) in the 20–40 and 40–60 cm layer, there were also no significant difference of bulk density between NQF and RRF with north-facing slope. Soil bulk densities in the 0–20 cm layer were largest for RRF with 33° slope and smallest for NQF. SOM content in the surface layer for NQF (2.45%) was significantly higher than RRF, so the bulk density was generally smaller. RRF with north-facing slope (15°) in the 0–20 cm layer also had relatively small bulk density due to accumulation of litter and humus. In the 20–40 cm layer for NQF and RRF with north-facing slope, because of large coverage of perennial grass and woody plants the interaction between soil and plant roots increased, and bulk densities subsequently decreased slightly although this decrease was not significant. RRFs with south-facing slope showed larger bulk densities, which may be attributed to smaller canopy coverage, small litter and humus, and smaller SOM content in soil.

The change of total porosity and capillary porosity for NQF and RRFs had a similar pattern as bulk density. The change of soil porosity was more significant in the 0–20 cm layer, while there was no significant difference in the 20–40 and 40–60 cm layers for different lands. The ratios between capillary porosity (CP) and total porosity (TP) for NQF and RRF with north-facing slope were smaller than RRFs with south-facing slope, though the difference was not significant. This indicated that the proportion of macro-pore space in the soil for NQF and RRF with north-facing slope increased with increasing total porosity. Increased macro-pore volume implied larger hydraulic conductivities and great water-holding capacities. Such variation contributes to effective infiltration of precipitation and also

Table 5

Average values ($N = 3$) of bulk density, SOM, total porosity, and capillary porosity in the 0–20, 20–40, and 40–60 cm layers for different lands

Species	Slope/aspect	Bulk density (Mg m^{-3})			SOM (%)		
		0–20 cm	20–40 cm	40–60 cm	0–20 cm	20–40 cm	40–60 cm
Q. liaotungensis	15°/S	1.01^a(0.10)	1.26^b(0.07)	1.29^c(0.31)	2.45^a(1.10)	1.20^a(0.46)	0.78^a(0.34)
R. pseudoscacia	15°/N	1.25^b(0.19)	1.30^b(0.11)	1.37^c(0.22)	1.77^b(1.05)	0.72^b(0.35)	0.69^a(0.29)
	15°/S	1.33^c(0.25)	1.39^c(0.23)	1.43^c(0.17)	1.46^c(0.98)	0.71^b(0.27)	0.66^a(0.21)
	20°/S	1.32^c(0.16)	1.40^c(0.19)	1.43^c(0.27)	1.35^c(0.29)	0.71^b(0.36)	0.68^a(0.18)
	33°/S	1.35^c(0.12)	1.42^c(0.21)	1.43^c(0.21)	1.26^c(0.39)	0.70^b(0.41)	0.67^a(0.36)

Species	Slope/aspect	Total porosity (TP, %)			Capillary porosity (CP, %)		
		0–20 cm	20–40 cm	40–60 cm	0–20 cm	20–40 cm	40–60 cm
Q. liaotungensis	15°/S	61.8^a (4.2)	52.6^b (3.3)	51.3^b (8.6)	48.6^a (3.2)	44.6^b (3.5)	–
R. pseudoscacia	15°/N	52.8^b (4.9)	50.8^b (5.2)	48.3^b (2.3)	42.4^b (2.6)	43.2^b (4.0)	–
	15°/S	49.7^b (2.1)	47.6^b (3.9)	46.0^b (2.7)	40.8^b (1.1)	42.5^b (0.9)	–
	20°/S	50.3^b (2.2)	47.1^b (4.4)	46.0^b (3.8)	41.5^b (2.3)	41.9^b (1.4)	–
	33°/S	49.1^b (0.8)	46.5^b (2.6)	46.0^b (3.1)	41.3^b (2.1)	40.1^b (1.0)	–

Means with the same letter in the same column are not significantly difference at the 0.05 level (Duncan's test). Data in the parentheses are standard deviations.

Table 6
Gravimetric water content at 0.03 and 1.5 MPa and plant-available water capacity of the 0–20 cm layer for different lands

Species	Slope/aspect	Gravimetric water content (%)		PAWC (%)
		0.03 MPa	1.5 MPa	
Q. liaotungensis	15°/S	23.1^{a} (0.22)	7.9^{a} (0.03)	15.2^{a} (0.18)
R. pseudoscacia	15°/N	19.2^{b} (0.37)	5.4^{b} (0.48)	13.8^{b} (0.11)
	15°/S	16.5^{c} (0.04)	3.6^{c} (0.24)	12.9^{b} (0.20)
	20°/S	16.4^{c} (0.79)	3.5^{c} (0.31)	12.9^{b} (0.40)
	33°/S	16.1^{c} (0.16)	3.3^{c} (0.19)	12.8^{b} (0.02)

Means with the same letter in the same column are not significantly difference at the 0.05 level (Duncan's test). Data in the parentheses are standard deviations. PAWC: plant-available water capacity.

aeration of deeper soil. It is then beneficial to plant-root growth and vegetation development (Li and Shao, 2006). And with slope gradient the ratios between CP and TP for RRFs with south-facing slope, there was no statistically relationship.

3.3.2. Plant-available water capacity

Changes of soil bulk density and porosity may affect soil water-holding capacity and consequently soil water conditions for different lands. Table 6 presents the results of gravimetric water content under suctions of 0.03 and 1.5 MPa, and plant-available water capacity calculated from these two values.

Results showed that 0.03 MPa water content was the largest (23.1%) for natural *Q. liaotungensis* forestland (NQF) and, as for regrown *R. pseudoscacia* forestland (RRF), the north-facing slope was larger than the south-facing slope. Water content tended to decline with slope gradient. Gravimetric water content under low suctions is usually influenced by soil structure (Zhu, 1983). In this study, measured values for disturbed soil were probably smaller than actual values for undisturbed samples, the effect being attributed to damage to soil macro-pores. However, results still partially indicate effects of soil structure amelioration. Gravimetric water contents corresponding to 1.5 MPa tension had the same variation trend as the 0.03 MPa. Water content at 1.5 MPa tension is taken as the lower limit of the plant-available water, being slightly affected by soil structure. To some extent, increased gravimetric water content at 1.5 MPa counteracts the effects of soil structure amelioration on increased gravimetric water content at 0.03 Mpa tension. This reduces the difference between gravimetric water contents at 0.03 and 1.5 Mpa tensions.

Statistical analysis of plant-available water capacity showed that RRF with south-facing and 33° slope had the smallest value of 12.8%, and that the largest value of 15.2% occurred for NQF. This trend was obviously similar to that for water contents at 0.03 and 1.5 MPa tension. The significant difference of plant-available water capacity for different lands indicated that soil water physical characteristics were affected by species, aspect and slope gradient, which consequently had influence on plant growth and vegetation reconstruction.

3.3.3. Soil particle composition and specific area

Mechanical analysis (Table 7) showed that clay content for NQF and RRF with north-facing slope was significantly larger than that of RRFs with south-facing slope ($P < 0.05$). Sand contents showed an opposite pattern. However, this difference did not induce the change of soil texture because there was no significant difference in silt content for the different lands. This textural classification of surface soil for the different lands was silt loam. SSA, ranged from 398 to 535 cm^{2} g^{-1} with C.V. of 15.4% for the different lands, showed significant difference between NQF/RRF with north-facing slope and RRFs with south-facing slope ($P < 0.05$), which indicated clay content difference has significant effect on the values of SSA. Because clay content and SSA play an important role in soil water-holding characteristics (Zhu, 1983), changes in them can be used as an indicator for variation of soil water-holding capacity attributed to soil structure.

3.3.4. Saturated hydraulic conductivity

Knowledge of hydraulic properties is important for understanding water movement in soil and predicting variables that may affect many agronomic and environmental projects (Zhang et al., 2006). Table 8 shows the mean K_s values obtained using the Guelph permeameter. Values ranged from 0.12 to 0.58 mm min^{-1} for the different lands.

Table 7
Mechanical composition, texture, and specific surface area (SSA) of the 0–20 cm layer for different lands

Species	Slope/aspect	Clay (%)	Silt (%)	Sand (%)	Texture	SSA (cm^{2} g^{-1})
Q. liaotungensis	15°/S	13.2^{a} (0.9)	67.5 (0.8)	19.3^{a} (0.4)	Silt loam	535^{a} (47.2)
R. pseudoscacia	15°/N	12.4^{a} (0.7)	67.9 (0.3)	19.7^{a} (1.0)	Silt loam	521^{a} (25.8)
	15°/S	6.5^{b} (1.2)	68.3 (0.3)	25.2^{b} (0.7)	Silt loam	405^{b} (21.9)
	20°/S	6.4^{b} (0.6)	67.7 (1.2)	25.9^{b} (1.1)	Silt loam	400^{b} (37.6)
	33°/S	6.1^{b} (0.2)	69.2 (1.6)	24.7^{b} (0.6)	Silt loam	398^{b} (31.3)

Means with the same letter in the same column are not significantly difference at the 0.05 level (Duncan's test). Data in the parentheses are standard deviations.

Table 8
The initial and steady saturated conductivity (K_s) for the 0–20, 20–40 and 40–60 cm layers and the ratios for different lands

Species	Slope/aspect	0–20 cm		
		K_s-initial (mm min^{-1})	K_s-stable (mm min^{-1})	Ratio
Q. liaotungensis	15°/S	1.09^a (0.21)	0.58^a (0.22)	1.88 (1.10)
R. pseudoscacia	15°/N	0.75^b (0.13)	0.44^a (0.15)	1.70(0.81)
	15°/S	0.52^c (0.18)	0.31^c (0.33)	1.68 (0.25)
	20°/S	0.52^c (0.31)	0.29^c (0.09)	1.79 (0.69)
	33°/S	0.57^c (0.19)	0.30^c (0.16)	1.90 (0.23)

Species	Slope/aspect	20–40 cm		
		K_s-initial (mm min^{-1})	K_s-stable (mm min^{-1})	Ratio
Q. liaotungensis	15°/S	0.73^a (0.26)	0.41^a (0.36)	1.78 (0.60)
R. pseudoscacia	15°/N	0.54^b (0.31)	0.27^b (0.25)	2.00 (1.01)
	15°/S	0.42^b (0.11)	0.19^b (0.06)	2.21 (0.99)
	20°/S	0.33^c (0.16)	0.20^b (0.17)	1.65 (0.98)
	33°/S	0.40^b (0.17)	0.18^b (0.13)	2.22 (0.25)

Species	Slope/aspect	40–60 cm		
		K_s-initial (mm min^{-1})	K_s-stable (mm min^{-1})	Ratio
Q. liaotungensis	15°/S	0.35^a (0.14)	0.21^a (0.11)	1.96 (0.22)
R. pseudoscacia	15°/N	0.34^a (0.19)	0.17^a (0.09)	2.59 (0.52)
	15°/S	0.26^a (0.22)	0.13^a (0.12)	2.00(0.75)
	20°/S	0.28^a (0.21)	0.12^a (0.08)	2.33(0.89)
	33°/S	0.27^a (0.09)	0.14^a (0.07)	1.93(0.31)

Means with the same letter in the same column are not significantly difference at the 0.05 level (Duncan's test). Data in the parentheses are standard deviations.

K_s for NQF was significantly larger than that of RRF in the 0–20 and the 20–40 cm layers ($P < 0.05$), but differences were not significant in the 40–60 cm layer ($P > 0.05$). This indicated that K_s was improved in the 0–40 cm layer by the natural forest probably due to litter and humus coverage and high SOM content of surface soil. K_s for RRF with a north-facing slope was significantly larger than that of RRF with a south-facing in the 0–20 cm layer ($P < 0.05$), and slightly larger in the 20–40 and the 40–60 cm layers but not significant ($P > 0.05$). This indicated that slope aspect also has influence on K_s. There was no significant difference between RRFs with different slopes, which indicated slope gradient did not impact saturated hydraulic conductivity. Therefore, we can conclude that plant community (natural or regrown) played a more important role than aspect and slope gradient in loosening soil and improving soil structure. Our findings were consistent with previous studies that showed changes in hydraulic conductivity became apparent between cropland and native grassland, shrub and forestlands over a period of more than 10 years (Schwardz et al., 2003; Li and Shao, 2006). The initial K_s value had a similar tend as the stable K_s. The variation of the former was greater than the latter, with a typical ratio of about 2.0 and a greatest value of 2.59. This change was attributed to dispersion of aggregates and associated macro-pore-filling during the wetting process. Generally, the variation of K_s was significantly greater than the other soil physical properties discussed in this study as shown by its higher standard deviation. Data showed that K_s varied dramatically across different lands, especially for the initial K_s values.

4. Summary

In the central Loess Plateau, soil desiccation is widespread in the regrown forest and grasslands, especially with south-facing slopes. Natural species have good adaptability to the environmental factors such as soil water shortage and do not result in the formation of DSLs. Species, aspect and slope angle can affect the variation of water content and could be predicators for soil desiccation. Soil physical properties worsened in the regrown *R. pseudoscacia* forestland (RRF) compared with the natural *Q. liaotungensis* forestland (NQF). Therefore, we think regrown *R. pseudoscacia* is not suitable for planting in the central Loess Plateau because this species not only is prone to cause soil water shortage, but also worsens soil physical properties such as bulk density and hydraulic conductivity. We suggest that other species, especially native plants that have good adaptability to environmental conditions, should be used to replace *R. pseudoscacia*.

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