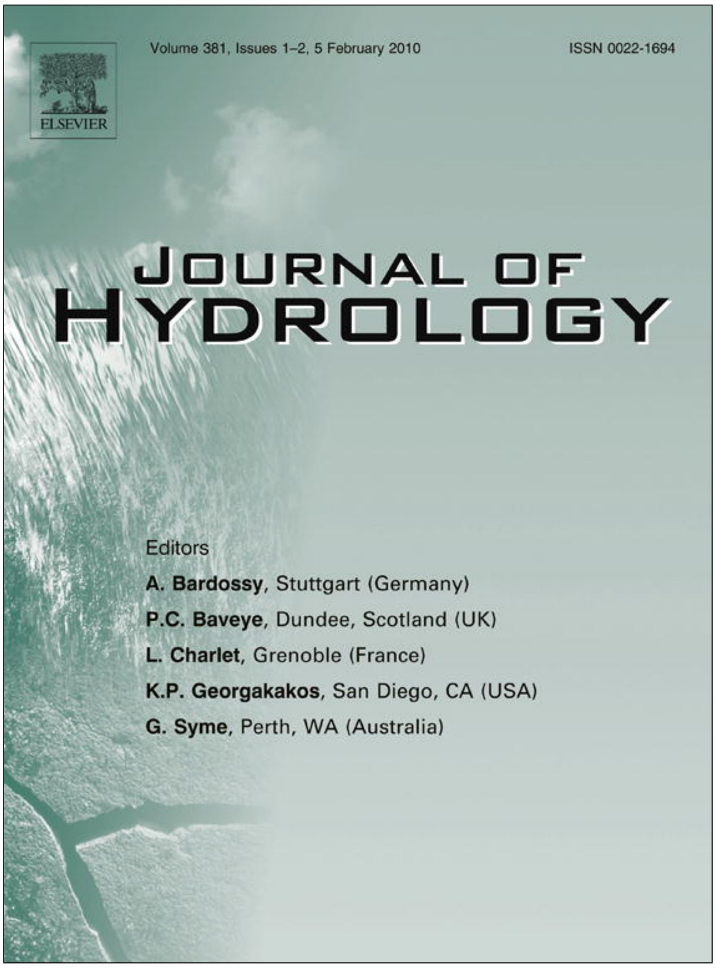
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A preliminary investigation of the dynamic characteristics of dried soil layers on the Loess Plateau of China

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S U M M A R Y

Serious soil desiccation, resulting from climatic conditions and poor land management, may lead to the formation of a dried soil layer (DSL), which can negatively affect ecological and hydrological processes. To mitigate these effects through management, it is necessary to understand property interactions within DSLs, compared with those in the whole soil profile, and DSL formation processes under different land uses. We investigated the relationships between soil water content (SWC) and plant root indices, and other soil properties, under various land uses in the Liudaogou watershed on the Loess Plateau, China. We also studied the development of DSLs as a function of the growth age of two vegetation types. Rate of formation and thickness of DSLs were dependent on vegetation type: DSLs formed after 2 years of alfalfa (*Medicago sativa*) growth and 3 years of *Caragana korshinskii* growth; after 4 years of growth, DSLs under alfalfa were thicker than those under *C. korshinskii*, but after 31 years the DSL thickness under *C. korshinskii* (4.4 m) exceeded that formed under alfalfa (3 m). The more persistent DSLs occurred below a 100 cm thick upper soil layer that was seasonally dried and replenished by rainfall under both vegetation types. The degree of soil desiccation under natural vegetation was generally less than that under non-indigenous plant species, and was similarly less over a period of about 30 years for a natural plant succession sequence than for an artificial one. Thus, the use of natural vegetation succession management principles would possibly reduce soil desiccation during vegetative restoration. Densities of root length, weight, and surface area, and the average root diameter of soybean (*Glycine max*), alfalfa, *Stipa bubgeana*, and *C. korshinskii* all decreased with increases in soil depths below 20 cm. Correlations between SWC and root indices, and various soil physical and chemical properties, were generally weaker within the DSL layers than within the whole soil profile. The only significant correlation was between soil organic carbon and SWC under alfalfa ($r = 0.627$, $P < 0.05$). Soil desiccation may thus interfere with these typical interrelationships occurring within the whole soil profile. Our findings may provide a helpful base reference for the control and restoration of DSLs occurring on the Loess Plateau and in similar arid and semi-arid regions.

Introduction

The Loess Plateau of China (35–41°N, 102–114°E), situated in the upper and middle reaches of the Yellow River, covers a total area of about 630,000 km^2, has an elevation of 1200–1600 m above sea level, and is predominantly covered by loess deposits ranging from 30 to 80 m in thickness (Zhu et al., 1983; Chen et al., 2008a). This region has been prone to serious soil erosion that is a consequence of both natural factors (e.g., the unique geology and landforms, climate conditions, and low vegetation coverage due to water resource constraints) and anthropic factors (e.g., poor land use management, including cultivation of marginal lands and destruction of natural vegetation) (Qiu et al., 2001). Intensive soil erosion has resulted in the decline of land productivity, environmental degradation, and the elevation of the riverbed in the lower reaches of the Yellow River due to sedimentation (Shi and Shao, 2000; Chen et al., 2007; Lacombe et al., 2008). Establishing forests and grassland can be an effective measure to control serious soil

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erosion that is widely supported by many scientists, land managers, and policy-makers. However, intensive vegetation restoration over large areas might also aggravate soil water scarcity. Excessive use of limited soil water resources can lead to soil desiccation, and to the formation of a dried soil layer (DSL) in the soil profile. Generally, the presence of a DSL is the definitive indicator of severe soil desiccation on the Loess Plateau of China (Li, 1983; Wang et al., 2007; Wang et al., 2008a,b; Zhu and Shao, 2008).

The formation of a DSL is a hydrological phenomenon typical of semi-arid and semi-humid regions. It mainly results from the excessive depletion of deep soil water by non-indigenous or natural vegetation through excessive evapotranspiration combined with long-term insufficient amounts of rainfall (Jipp et al., 1998; Chen et al., 2008b). Many studies have reported DSL formation as a phenomenon typical to the Loess Plateau of China (e.g., Li, 1983; Yang, 2001; Han et al., 1990; Wang et al., 2008a; Chen et al., 2008b). However, there are also reports that similar cases of desiccation in deep soil layers have been observed in other regions of the world such as Russia (Yang and Han, 1985) and eastern Amazonia (Jipp et al., 1998). Possibly soil desiccation on the Loess Plateau is more serious and typical than that occurring in other regions due to the unique nature of the region's low rainfall combined with large water losses due to intense runoff, deep loess deposits, low water tables, topography and, to some extent, both past and present poor land management.

The DSL has been described as having the following three characteristics: (1) located at a certain soil depth, mainly in deeper layers that may extend to 10 m below the soil surface; (2) persistence, both spatially and temporally; and (3) having a soil water content (SWC) range between the permanent wilting point and the stable field capacity (SFC) (Li, 1983; Yang, 2001; Wang et al., 2008a). Generally, 60% of the field capacity (FC) has been considered to be equivalent to the SFC based on the textures of soils found on the northern Loess Plateau and a soil layer with a SWC lower than the SFC would thus be considered to be a DSL (Wang et al., 2004; Yang and Tian, 2004), although some studies have suggested that a SFC of 50% of the FC might be more appropriate for these soils (Yang and Han, 1985; Chen et al., 2008b). Using these criteria, many studies have reported that DSLs are widely distributed across the Loess Plateau (Han et al., 1990; Li, 2001; Wang et al., 2008a; Chen et al., 2008b). The presence of a DSL differs from the more general process of soil desiccation, in which the drying process may extend from the soil surface down into the profile rather than being confined to a deep layer, and usually only occurs seasonally or for short periods of time.

The presence of a DSL can potentially impact the soil-plant-atmosphere water cycle by blocking water interchanges between upper soil layers and the groundwater (Chen et al., 2008a). In addition, DSLs may lead to soil degradation, regional microclimate environment aridity, and further loss of land productivity. Afforestation may fail due to the lack of water at deeper depths resulting in reductions of vegetation biomass or stunted growth, localized and/or regional vegetation die-off, and poor renewal by natural germination (Breshears et al., 2005; Hou et al., 1991; Yang, 1996; Wang et al., 2004, 2008a).

To control the negative impact of DSLs by gaining an understanding of the phenomenon, many studies have been conducted in the Loess Plateau region (e.g., Han et al., 1990; Yang, 1996, 2001; Huang and Gallichand, 2006; Li, 2001; Wang et al., 2008a). In particular, assessments of the basic characteristics of DSLs have been undertaken (Chen et al., 2008a; Han et al., 1990; Huang and Gallichand, 2006; Li, 2001; Shangguan, 2007; Wang et al., 2008a,b), so that great progress has been made in defining and classifying them based, for example, on their spatial distribution and persistence within the soil profile (Chen et al., 2008b; Li, 1983; Shangguan, 2007; Yang and Tian, 2004). Studies on the mechanisms of DSL formation have identified the relationship between environmental aridization and SWC, from the aspect of the soil water energy status and soil water physical characteristics, by integrating the two dominant causal factors, i.e., poor land management and climate (Yang et al., 1999). Associations between vegetation and DSL indicated that the plant species was important in addition to other factors such as the age of the plantation, and the aspect and position of slopes, etc. (Han et al., 1990; Li, 2001; Yang, 1996). For example, Wang et al. (2008a,b) found that a substantial DSL was formed under an artificial *Robinnia pseudoscacia* forest but not under an indigenous *Quercus liaotungensis* forest, and that the SWC on the north-facing slope was significantly larger than on the south-facing slope.

Chen et al. (2008b) proposed some practical countermeasures to reduce DSL formation and made suggestions for accelerating vegetation rehabilitation. The possibility of soil water recharge under an appropriate land management system has also been suggested by others (e.g., Huang et al., 2004; Li and Huang, 2008; Wang et al., 2004). Simulations using the Simultaneous Heat and Water Transfer (SHAW) model indicated that a SWC recovery time would vary from 6.5 to 19.5 years (average = 13.7 years) for the 0–10 m soil layer, and from 4.4 to 8.4 years (average = 7.3 years) for the upper 0–3 m soil layer, for a soil that had been under an apple orchard for 32 years and that was then converted to winter wheat (Huang and Gallichand, 2006).

However, there remains the need for studies on the dynamics of the formation of, and changes to or within, DSLs under different succession periods for artificial and natural vegetation. This especially applies to analyses of the relationships between SWC and plant root indices or other soil properties within the DSLs. A better understanding of these processes should be helpful in order to prevent or alleviate the occurrence of DSLs, and also to effectively recover DSLs.

Therefore, the objectives of this study were: (1) to demonstrate the formation and development processes of DSLs on the Loess Plateau of China; (2) to explore the seasonal differences in the soil water profile under artificial and natural vegetation succession sequences; and (3) to analyze the correlations between SWC and plant root indices and/or soil physical and chemical properties within the DSLs.

Materials and methods

Study site description

The study was conducted in the Liudaogou watershed (110°21′–110°23′E, 38°46′–38°51′N), located 14 km west of Shenmu County, in Shaanxi Province, China (Fig. 1a). The watershed has an area of 6.89 km^2 and altitudes between 1081 m and 1274 m. The region has a semi-arid, continental climate with an average annual precipitation of 437 mm, 70% of which falls between June and September. According to data available for 1957–1989, the mean annual air temperature is 8.4 °C, the coldest being −9.7 °C in January and the warmest being 23.7 °C in July, and the annual accumulated temperature above 10 °C is 3200 °C. The annual average wind speed is 2.2 m s^{-1} and the mean desiccation degree is 1.8 with 135 frost-free days (Kimura et al., 2007).

The study area is located in the center of a region of intensive erosion on the Loess Plateau. Erosion caused alternately by water and wind, and by gravitation occurs all year round. The natural climax vegetation is a shrub steppe community dominated by *Stipa bubgeana*. The climatic conditions and poor land management have led to severe soil desiccation, and the occurrence of DSLs and stunted or "small-aged" trees are distributed widely over the study area (Hou et al., 2000).

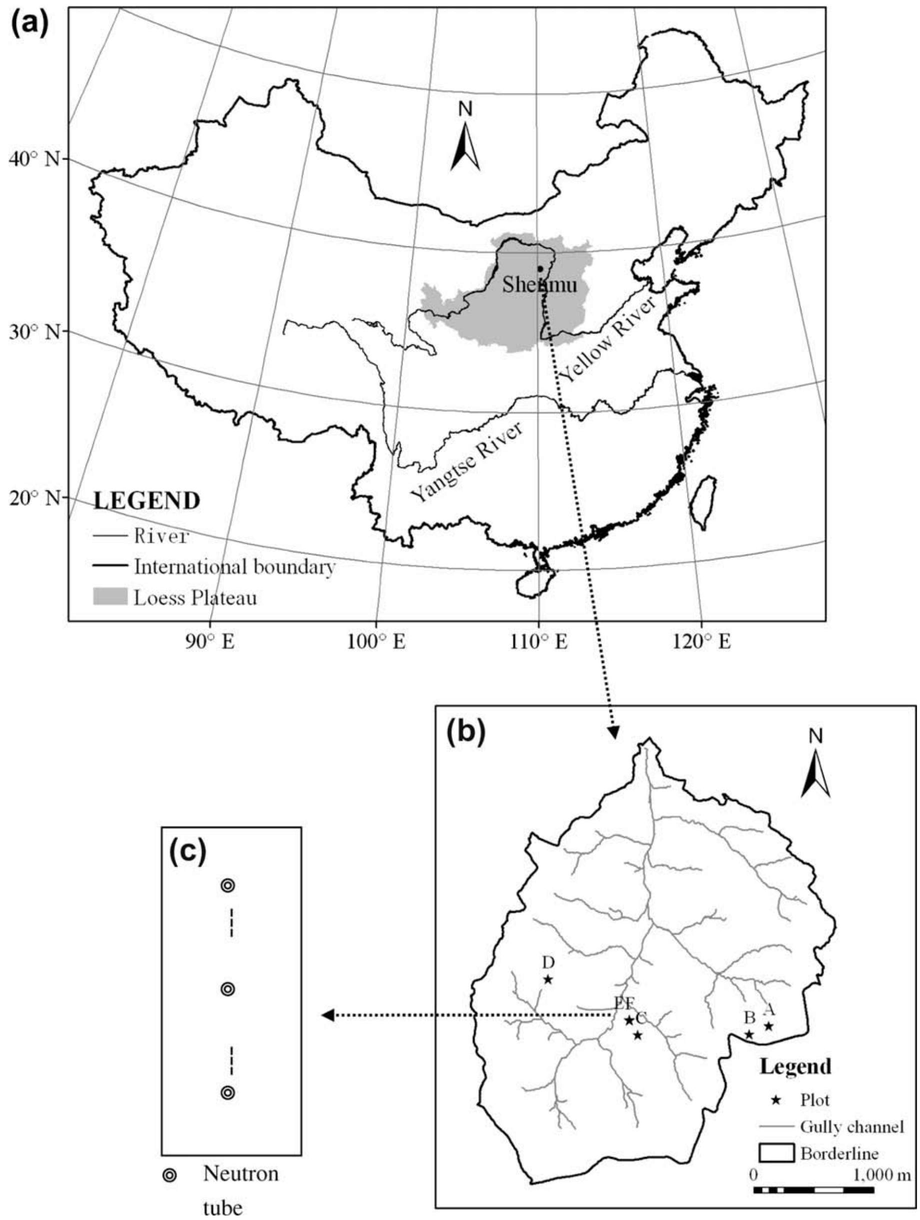

Fig. 1. Location of the study area on the Loess Plateau: (a) and of the plots (b) of the four vegetation types grown for different lengths of time: (A) soybean (*Glycine max*) (1 year), (B) alfalfa (*Medicago sativa*) (31 years), (C) *Stipa bubgeana* (30 years), (D) *Caragana korshinskii* (31 years), (E) alfalfa (4 years), and (F) *C. korshinskii* (4 years), and (c) shows the plot layout for neutron probe access tubes.

Experiment design

In the study area, we selected four representative vegetation types that had been established for various numbers of years: soybean (*Glycine max*) (1 year), alfalfa (*Medicago sativa*) (31 years), *S. bubgeana* (30 years), and *Caragana korshinskii* (31 years). Among these growths of vegetation we established four plots (5 m × 20 m) denoted as plots A, B, C, and D, respectively (Fig. 1b). In each plot, no fewer than three aluminum access tubes, used for soil water determinations using a calibrated neutron probe, were installed at intervals along the central length of the plot (Fig. 1c), and were considered as replicates. We measured SWC to a depth of 400 cm for soybean, alfalfa, and *S. bubgeana*, and to a depth of 600 cm for *C. korshinskii*. These depths were considered sufficient for assessing the homogeneity of soil-water retention characteristics on the Loess Plateau (Morgenschweis, 1984; Li and Huang, 2008). We measured the SWC under the four vegetation types from October 11 to 19 in 2007.

To investigate the effect of growth age on DSL development, SWCs in an additional two plots of *C. korshinskii* (Plot E) and alfalfa (Plot F) (Fig. 1b), which had both been planted in April, 2004, were measured with a calibrated neutron probe before, during, and after the rainy season in each year from 2004 to 2007, to the depths of 600 cm and 400 cm, respectively. Since the distances between the two plots of *C. korshinskii* and, likewise, between the two plots of alfalfa were less than 1.5 km (Fig. 1b) and these plots were all located in the middle slope position with comparable slope gradients and aspects on similar soils, we considered that the SWC data for plots B and D may be representative of plots E and F after 31 years of growth. In this way, we can consider the effect of growth age on DSL development under *C. korshinskii* and alfalfa for 1, 2, 3, 4, and 31 years. In addition, seasonal changes in the DSLs under *C. korshinskii* (Plot E) and alfalfa (Plot F) were examined. Both alfalfa plots were habitually grazed by sheep.

To investigate plant root development and the soil properties within the DSL in relation to those within the whole soil profile, a 10.0 cm diameter soil auger was used to collect disturbed soil and plant-root samples close to the aluminum neutron probe access tubes from the soil layers corresponding to those used for the soil water measurements within the six plots. Undisturbed soil cores, in three replicates, were also removed from the soil surface layer (0–5 cm) and plough layer (25–30 cm) in metal cylinders (diameter 5 cm; length 5 cm).

Measurement method

A neutron probe was used to measure SWC at various times depending on the plot scheme (Li and Huang, 2008), at consecutive 10 cm increments between soil depths of 0 and 100 cm, and at consecutive 20 cm increments at depths between 100 and 400 cm, or down to 600 cm for *C. korshinskii* plots. Calibration of the neutron probe was carried out using standard methods (Hauser, 1984; Huang et al., 2004; Huang and Gallichand, 2006), and the measured volumetric water contents as determined by the neutron probe were transformed and expressed as gravimetric soil water contents.

The disturbed soil samples were air-dried and those containing roots were gently crushed and passed through a 1 mm diameter nylon mesh, permitting the roots to be removed from the mesh with tweezers. The roots were washed with water, air dried for 4 to 8 h, and scanned on an Epson flatbed scanner. Root length density, root surface area density, and average diameter were obtained using Delta-T SCAN (version 2.04nc) software. Subsequently, the root weight density was determined by drying at 65 °C (Cheng and Wan, 2002; Hao and Peng, 2005).

Each disturbed, air-dried, soil sample, separated from the root material by the 1 mm sieve, was divided into two parts. One part was passed through a 0.25 mm sieve to determine soil organic carbon (SOC) content, using dichromate oxidation with external heat applied, in two replications (Nelson and Sommers, 1982). The other part was analyzed for soil particle composition by laser diffraction using a MasterSizer 2000 (Malvern Instruments, Malvern, England) (Wang et al., 2008a).

The undisturbed soil cores were used to determine field capacity by the capillary suction method (Jiang et al., 2006) and saturated hydraulic conductivity (K_s) by the constant hydraulic head method (Klute and Dirksen, 1986; Wang et al., 2008a). After these measurements, the saturated soil water content (SSWC) and soil bulk density (BD) were determined for the same soil cores from weight loss during oven drying of the saturated samples at 105 °C (Wang et al., 2008a). The basic characteristics and physical parameters of the soil are shown in Table 1.

Primary statistical analyses, such as determinations of mean, coefficient of variation, and Pearson correlation, were performed with Microsoft Excel (version 2003) and SPSS (version 13.0).

Table 1
Plot characteristics and soil physical properties under four vegetation types.

	Vegetation type			
	Soybean	Alfalfa	S. bubgeana	C. korshinskii
Coverage (%)	30	80	85	75
Age (year)[a]	1	31	30	31
Neutron tube number	3	6	3	6
BD (g cm^{-3})[b]	1.4	1.49	1.43	1.4
SSWC (%)[b]	33.38	27.72	30.94	31.96
K_s (m min^{-1})[b]	0.034	0.014	0.032	0.031
FC (%)[c]	17	18	17	18
Clay (%)	8.37	7.92	7.79	5.23
Silt (%)	53.48	57.12	64.18	50.69
Sand (%)	38.16	34.96	28.02	44.08

[a] The growth age was surveyed value according to local aged person.
[b] The value is the mean value between 0–5 cm and 25–30 cm layers' measured data.
[c] The value is the mean value measured in 0–2 m depth.

Results and discussion

Formation and development characteristics of DSL

The profile distributions of SWC under *C. korshinskii* and alfalfa for different growth ages are presented in Fig. 2. Measurements were all made before the rainy season with the exception of the plots under 31-year-old *C. korshinskii* and alfalfa where measurements were made after the rainy season. The figure shows that SWCs under both *C. korshinskii* and alfalfa decreased gradually with the increase in growth age with corresponding changes down the profile, which implies that soil desiccation in the profile may be a function of growth age. As the plant community develops, the demands of the plants on soil water would increase.

Since we considered that 60% of FC was considered as the upper SWC limit for a DSL, based on the soil textures found on the northern Loess Plateau (Wang et al., 2004; Yang and Tian, 2004), we can easily judge whether the soil layers within the profile could belong to a DSL or not based on this characteristic alone. In Fig. 2, we found that SWCs were low enough to form a DSL under both *C. korshinskii* and alfalfa, but the formation and development characteristics under the two vegetation types were different. Under alfalfa, a DSL was formed by the second year following planting whereas under *C. korshinskii* formation occurs in the third year. This can be attributed to the differences in the plant biological characteristics, and specifically to the vigorous growth period of alfalfa that occurs earlier than that of *C. korshinskii* and to the stronger evapotranspiration of alfalfa. During the initial stages of DSL formation, the thickness of the developing DSL under alfalfa was greater than that under *C. korshinskii* such that it was about 2 m thicker under alfalfa after 4 years growth (Fig. 2). However, after 31 years, the thickness of DSL under *C. korshinskii* (4.4 m) exceeded that under alfalfa (3 m). Both vegetation types would have different impacts on the micro-biological cycle and macro-hydrological cycle through plant-root water uptake, evapotranspiration, the canopy-layer effect, soil physical and chemical properties, and the biological microclimate. However, plant-root water uptake, evapotranspiration, and canopy-layer effects are different for the same vegetation type at different growth ages (Cheng and Wan, 2002). Notably, the root systems of *C. korshinskii* become more extensive than alfalfa over time with correspondingly greater water uptake rates.

Consequently, during the process of managed vegetation restoration on the Loess Plateau, selection and management of an appropriate plant type is very important for maintaining the "soil water-pool" function (Li, 2001; Yang, 2001). Based on our data, soil under alfalfa would form a DSL earlier than one under *C. korshinskii*, but the extent of soil desiccation would be less than under *C. korshinskii* with increasing growth age. However, in order to prevent or reduce DSL formation under alfalfa, it would be necessary to cut back or thin the alfalfa plants after the first year of growth with the aim of reducing water losses due to plant transpiration. Li and Huang (2008) reported that soil water storage in the 0–500 cm layer decreased at a rate of 33.5 mm $year^{-1}$ after alfalfa was planted, and recommended that the optimal length of the alfalfa phase in alfalfa/crop rotation systems should not exceed 8 years since, after this time, alfalfa yields responded more vigorously to seasonal precipitation variations. In our plots, sheep

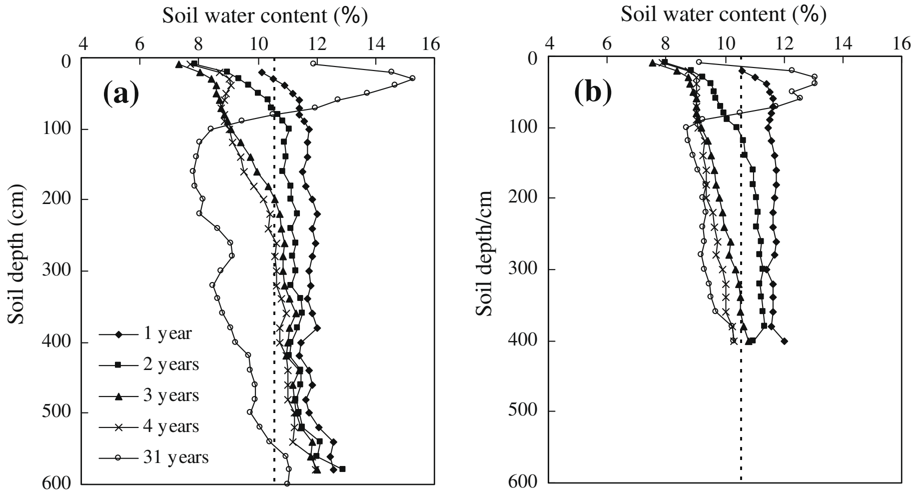

Fig. 2. Soil water content changes in soil profiles: (a) under *Caragana korshinskii* and (b) under alfalfa (*Medicago sativa*) for different plant growth years. Measurements were made before the rainy season except in the case of the 31-year-old plots, which were made after the rainy season. The dashed line represents the stable field capacity = 60% of field capacity.

grazed on the alfalfa but evidently the degree of grazing was insufficient to adequately reduce water consumption by the alfalfa in order to prevent the formation of a DSL.

The SWC under 31-year-old *C. korshinskii* and alfalfa in Fig. 2 was measured after the rainy season, which is probably why the SWC of the 0–100 cm depth was the largest observed for these plots. However, this data suggests that the replenishment depth of soil water by rainfall was about 100 cm in our study area, which was similar to that reported by Wang et al. (2007).

Seasonal changes of soil water in the profile

Seasonal changes in the SWC under *C. korshinskii* and alfalfa, both grown for three years, are presented in Fig. 3. During 2007, the SWC was only significantly changed in the upper soil layer at about 0–100 cm depth, under both vegetation types, especially when comparing the status before and after the rainy season. The SWC below 100 cm depth was not greatly affected by rainfall and remained relatively stable. This seasonal pattern of SWC in the soil profile is an indicator of the depth of rainfall replenishment, which in this area is generally limited to about 100 cm, as noted above in the preceding section.

Some researchers have suggested that DSLs could be divided into two types (Li, 1983; Wang et al., 2004; Chen et al., 2008b): (1) A temporary DSL that would typically occur at a depth below 100–300 cm under forests or grassland in semi-humid regions. Management practices, to reduce water scarcity gradually, include plowing and thinning the vegetation, thus allowing the SWC in a temporary DSL to increase through rainfall replenishment over time; (2) a permanent DSL typically occurs in a semi-arid region and is relatively stable, and has low SWCs resulting from long-term severe soil desiccation. A permanent DSL thus has relative stability and is persistent when compared with temporary DSLs, and replenishment of the SWC within a permanent DSL is more difficult to achieve due to more limited rainfall.

It should be noted that, in arid and semi-arid regions, a temporary dry soil layer with low SWC often appears in the upper part of the soil profile due to water consumption by plants, but is replen-

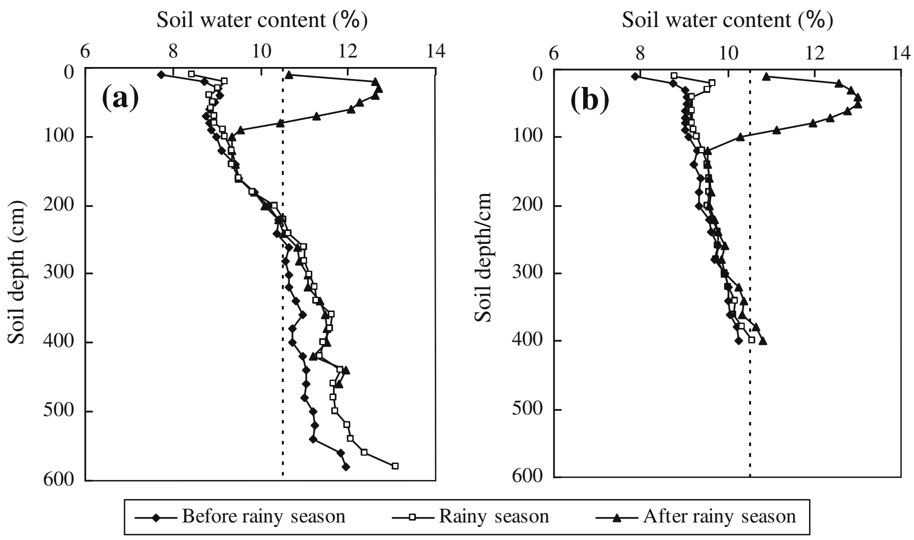

Fig. 3. Seasonal changes in soil water content in soil profiles under: (a) 3-year-old *Caragana korshinskii* and (b) under 3-year-old alfalfa (*Medicago sativa*) during 2007. The dashed line represents the stable field capacity = 60% of field capacity.

ished by the infiltration of the annual rainfall water (Li, 2001). This temporary dry layer is not the temporary DSL defined by Li (1983) and Chen et al. (2008b). In our study, the 0–100 cm depth, in which SWC was replenished by rainwater over a short time scale, can be regarded as a temporary dry layer (Fig. 3).

Therefore, we can identify the presence of a true DSL in the soil profiles in Fig. 3 as being located where the SWC was lower than the SFC and below the replenishment depth of 100 cm. Hence, the thicknesses of the DSLs were 1.2 m and 2.8 m under *C. korshinskii* and alfalfa, respectively.

The characteristics of DSL at different vegetation succession sequences

When planning large scale vegetation restoration and the sustainable development of the ecosystem on the Loess Plateau, it is important to consider the effects of vegetation succession sequences. However, little attention has been paid to the changes in DSL characteristics during various vegetation succession sequences. Therefore, we chose two vegetation succession sequences, using the existing spatial distribution of plants as a substitute for long-term experimentation, in order to compare their DSL characteristics. We chose a natural succession sequence represented by abandoned cropland (soybean) → *S. bubgeana* and compared it with an artificial succession sequence represented by abandoned cropland (soybean) → alfalfa → *C. korshinskii*.

As shown in Fig. 4, the profile distribution of SWCs under the two vegetation succession sequences indicates that SWC was significantly decreased under both the natural vegetation succession sequence from soybean to *S. bubgeana* (Fig. 4a), and also under the artificial vegetation sequence where the SWC followed the order: *C. korshinskii* < alfalfa < soybean (Fig. 4b). A DSL was formed under alfalfa, *S. bubgeana*, and *C. korshinskii* vegetation, where one did not previously exist under the abandoned cropland (soybean) (Fig. 4), and the degree of soil desiccation followed the sequence: *S. bubgeana* < alfalfa < *C. korshinskii* ($P < 0.05$). These results indicated that DSLs can form under both natural and non-indigenous vegetation, but that the degree of desiccation was worse for non-indigenous vegetation in our study area. This was consistent with previous findings (Hou et al., 2000; Yang, 2001; Cheng, 2002; He et al., 2003). Consequently, the degree of desiccation for different land use types may follow the order: cropland < natural grassland < artificial grassland < artificial shrubland according to their representative vegetation types present in our study region. Moreover, it can be inferred that the soil water conditions under a natural vegetation succession sequence were better than under an artificial vegetation succession sequence.

In the Liudaogou watershed, the primary natural vegetation succession sequence after cropland abandonment is: abandoned cropland → *Artemisia capillaries*/*Agropyron desertorum* (1 year later) → *S. bubgeana*/*Stipa breviflora* (2–4 years later) → *Caragana microphylla*/*Lespedeza davurica* (7 years later) → *S. bubgeana* (15 years later) (Cheng and Wan, 2002). At present, *S. bubgeana* is the dominant species in the watershed. To achieve sustainable restoration of the ecological environment with regard to soil water conditions, it is preferable to follow the natural vegetation succession sequence whereby SWC is higher than under non-indigenous vegetation (Fig. 4). Although artificial forest–shrub–herbaceous vegetation restoration plans do play a major role in soil and water conservation on the Loess Plateau, it should be considered that, when poorly managed, these restoration programs may themselves exacerbate soil water deficits in both vertical and horizontal directions and lead to more serious soil desiccation, a thicker DSL, and a reduction in vegetation carrying capacity (Wang et al., 2008a). Moreover, the ecosystem of the natural vegetation succession sequence probably has a greater stability than an artificially created ecosystem.

Factors related to DSL

The sequence of "plant-root water uptake → deep soil water transport upwards through the roots → water arrival in the above-ground parts of plants → water evaporating through plant transpiration into the atmosphere" is a primary mechanism of soil water loss, and consequently can lead to soil desiccation (Yamanaka and Yonetani, 1999; Cheng and Wan, 2002). However, information about the relationships between plant root indices and soil water in the interior of a DSL is scarce. Fig. 5 shows that the roots of soybean and *S. bubgeana* were predominantly distributed in the 0–100 cm soil layer while the roots of alfalfa and *C. korshinskii* may extend through the 0–300 cm and 0–640 cm depths, respectively. All root indices (length density, root weight density, root surface area density, and root average diameter) generally decreased with increasing soil depth below 20 cm. Moreover, the maximum root indices appear in the 0–30 cm layer, which was similar to the find-

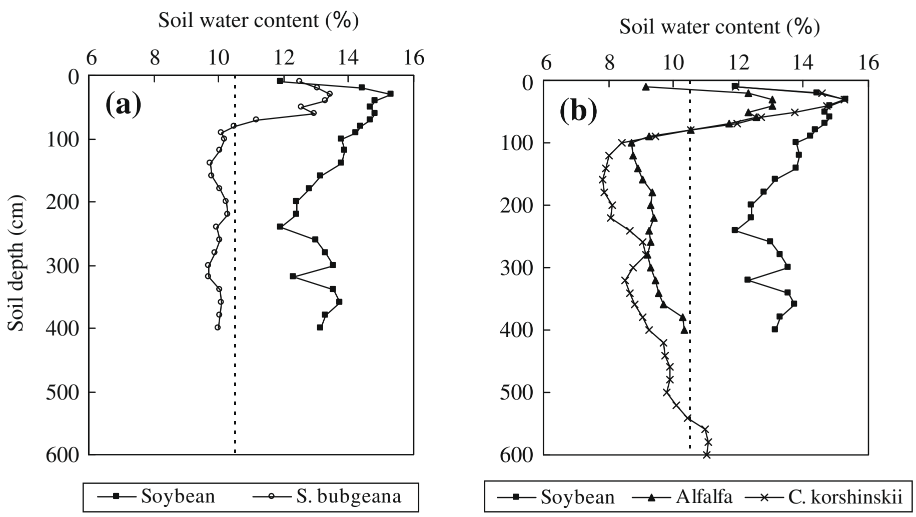

Fig. 4. Soil profile distribution of soil water content in October, 2007, for: (a) a natural succession sequence: abandoned cropland (1 year soybean (*Glycine max*)) → S. bubgeana (30 years) and for (b) an artificial succession sequence: abandoned cropland (1 year soybean) → alfalfa (*Medicago sativa*) (3 years) → *Caragana korshinskii* (31 years). The dashed line represents the stable field capacity = 60% of field capacity.

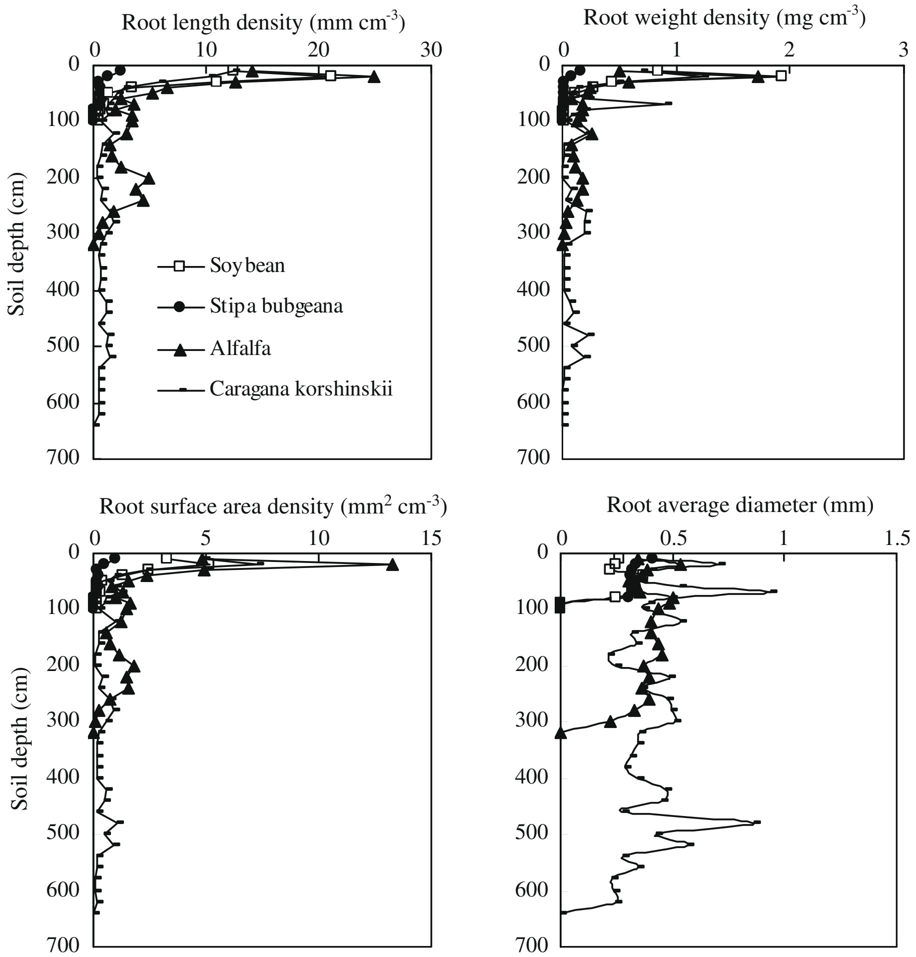

Fig. 5. Soil profile distributions of plant root length density, root weight density, root surface area density, and root average diameter in October, 2007.

ings of Wei et al. (2006). During the process of vegetation succession, plants develop their root distributions to adapt to the competition for sunshine, space, soil water and nutrition. The root distribution then feeds back to affect and change the community ecosystem, further affecting succession processes (Hao and Peng, 2005).

We analyzed the relationships between SWC and all of the measured properties within the DSLs (Table 2). In the alfalfa plots, the correlation between SWC and SOC was positive and significant ($r = 0.627$, $P < 0.05$). In addition, the average root diameter was relatively well correlated with SWC ($r = 0.261$), which may be connected with the transfer capability of water to the body of the plant. Moreover, the weak correlations found between SWC and other measured properties, imply that soil particle composition may not be the dominate factor determining the SWC level within the DSLs under alfalfa. Under *C. korshinskii*, although all the relationships were statistically non-significant ($P < 0.05$), the coefficients ranged from 0.235 to 0.317, indicating that all the measured indices may, to some extent, influence the level of SWC within these DSLs.

When the whole soil profile is considered, the only significant correlation for the alfalfa plots was between SWC and root length density ($r = 0.452$, $P < 0.05$) (Table 2). In contrast, in the *C. korshinskii* plots, the correlations between SWC and all of the measured indices, with the exception of the root average diameter, were significant. The characteristics of these correlations for the whole soil profile differ from the relationships found between SWC and the indices within the DSL. This implies that the assumption made in our study, that the interactions between SWC and the soil and plant properties should be investigated and compared within the soil profile, was valid. Table 2 also indicated that the correlations between SWC and root average diameter under *S. bubgeana*, and between SWC and SOC, and the root indices of weight, surface area, and length densities under soybean, were significant.

Generally, these correlations are related to water uptake properties, biological characteristics, and plant root configurations, indicating that there are some intrinsic relationships among the soil characteristic indices. Comparing the correlation coefficients and the significance levels, we found that the relationships between SWC and root indices, and soil physical and chemical properties, within the DSL differed from those found within the whole soil profile by being generally weaker. Thus, we can infer that soil desiccation may interfere with these inter-relationships that would typically occur within the soil profile but in what manner remains unclear.

In summary, the plant-soil environment is a mutually-interacting system that interfaces at the plant roots, and during the life cycle of the plants the soil environment provides water, physical structural support, gaseous exchange, and nutrients to the plants, which in turn tend to stabilize the soil structure, and to add metabolites and, in senescence and death, organic matter back to the soil. This process is an important part of a natural circle whereby plant communities and the soil environment can co-evolve (Travis et al., 2003; Hodge, 2004; Malamy, 2005; Bogeat-Triboulot et al., 2007; Lambers et al., 2007; Shao et al., 2007, 2008a). The formation of a DSL is a comprehensive symptom that occurs as a result of plant-

Table 2
Pearson correlations between soil water content and all measured indices.

Index types	Impact factors	SWC within the DSL		SWC within the entire soil profile			
		Alfalfa (*Medicago sativa*)	*Caragana korshinskii*	Alfalfa (*Medicago sativa*)	*Caragana korshinskiii*	*S. bubgeana*	Soybean (*Glycine max*)
Nutrition index	SOC	0.627[a]	0.300	0.362	0.449[b]	0.453	−0.813[b]
Root indices	Weight density	0.061	0.235	0.418	0.572[b]	0.489	−0.762[a]
	Length density	−0.097	0.286	0.452[a]	0.581[b]	0.553	−0.646[a]
	Average diameter	0.261	0.317	−0.062	0.232	0.680[a]	−0.008
	Surface area density	−0.034	0.314	0.416	0.571[b]	0.569	−0.697[a]
Soil physical indices	Clay	0.035	0.268	−0.002	0.621[b]	−0.446	−0.016
	Silt	−0.089	0.251	0.012	0.37[a]	−0.518	0.195
	Sand	0.041	−0.254	−0.008	−0.431[b]	0.571	−0.114

[a] Correlation is significant at the 0.05 level (2-tailed).
[b] Correlation is significant at the 0.01 level (2-tailed).

soil environment interactions and is influenced by both plant activities, including the growing stage and the redox status, and soil properties (Sharp et al., 2004; Chen et al., 2008b; Hardtke and Torii, 2008; Shao et al., 2008a). In addition, the nature and extent of the DSL also serves as a final indicator for evaluating soil desiccation processes and the soil water status, as well as reflecting the functional root status in the proximity of the DSL for different plant communities (Tables 1 and 2; Figs. 1–4). It is possible that the DSL has a protective function in regard to the plant-soil environment system (Lambers et al., 2007; Shao et al., 2007, 2008b; Wu et al., 2007). Although the DSLs have not been systemically studied to the degree necessary (Wang et al., 2008a; Chen et al., 2008b), our results proved that co-relationships do exist among the DSL, soil properties, plant roots, vegetation types and growth ages. The results also provide new information and hold implications for the restoration and management of vegetation and soil water, and for dryland farming, on the Loess Plateau of China that may also be applicable to other arid and semi-arid areas of the world. Extensive investigations on DSLs will open up a new aspect of the plant-soil environment at different scales, contributing more to soil biology (rhizosphere biology), plant biology and hydrology. Future work should include the quantification of DSL classifications, refinement of standards, and establishment of the links among soil properties, DSL variability, root indices and aboveground plant physiological functions.

Conclusions

In this study, we investigated the formation and development of DSLs on a typical watershed on the northern Loess Plateau. The relationships between SWC and plant root indices, and soil physical and chemical properties, within both the DSL and the soil profile as a whole were compared. The following conclusions, which may provide pertinent information for eco-environmental restoration programs and for dryland farming on the Loess Plateau of China, and also for other arid and semi-arid regions in the world, can be made:

The formation rate and the thickness of DSLs were dependent on the vegetation type under which they occurred. The DSL under alfalfa formed in the second year of growth whereas under *C. korshinskii* it formed in the third year. The thickness of the DSL formed under alfalfa was greater than that formed under *C. korshinskii* after 4 years of growth; however, the DSL thickness under *C. korshinskii* (4.4 m) exceeded that formed under alfalfa (3 m) after 31 years of growth. The rain replenishment depth was about 100 cm for the soils under both the *C. korshinskii* and alfalfa. Knowing the rain replenishment depth is essential in order to identify dry soil layers, which are only temporarily and/or seasonally formed, and the depth at which a true DSL can be correctly defined within the soil profile.

The extent of soil desiccation under non-indigenous vegetation was greater than under natural vegetation. The densities of root length, weight, and surface area, and the average root diameter for soybean, alfalfa, *S. bubgeana*, and *C. korshinskii* all decreased with increasing soil depth below 20 cm. The recommendation was made to follow natural vegetation succession management principles during the process of vegetation restoration or to carefully manage artificial successions in order to prevent, control, or alleviate the occurrence of DSLs on the Loess Plateau of China, and possibly in other arid and semi-arid regions of the world.

Within the DSL, the relationships between SWC and root indices, and soil physical and chemical properties were weak, with the exception of a correlation between SOC and SWC for the DSL formed under alfalfa ($r = 0.627$, $P < 0.05$). However, the strength of the relationships between SWC and the root indices, and the soil physical and chemical properties, within the DSL differed from those within the whole soil profile, which were generally stronger, implying that soil desiccation may interfere with these inter-relationships typically occurring in the soil profile. However, the mechanism by which this occurs is not currently clear.

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