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Spatial continuity and local conditions determine spatial pattern of dried soil layers on the Chinese Loess Plateau

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Abstract

Purpose Many efforts of restoring vegetation have ignored the feedbacks between biotic and abiotic factors that have developed in water-limited ecosystem. Dried soil layers (DSLs) have formed extensively on the Chinese Loess Plateau (CLP). The objective of this study was to identify the primary factors controlling spatial pattern of DSLs on the CLP.

Materials and methods Two DSL indices (DSL thickness (DSLT) and soil water content in a DSL (DSL-SWC)) were estimated by measuring SWC to a depth of 5 m at 86 sites along a south-north transect on the CLP in 2013. The correlation between the spatial pattern of DSLs and environmental factors was determined with redundancy analysis (RDA).

Results and discussion DSLs had formed at most of the sites (66 of the 86 sites) along the transect. The sites without DSLs were primarily in an irrigated agricultural zone. DSLT was >400 cm and generally increased from south to north, and DSL-SWC was 2.54% (*v*/*v*) in the semi-arid zone of the transect. The connected features of DSLs between connected neighboring sampling units exhibited a much wider extent. A total of nine environmental variables were the primary contributors to the spatial pattern of the DSLs, explaining approximately 47.3% of the variability. Local conditions were responsible for the higher proportion of explained variability than climatic factors. In addition, field capacity was the most important factor in all environmental factors, which may have influenced water-holding capacity.

Conclusions This study concludes that spatial continuity and local conditions determine the spatial pattern of DSLs at a regional scale. Understanding the characteristic of DSLs is useful for efficiency of vegetation restoration and soil water management.

Keywords Dried soil layer · Feedback · Spatial continuity · The Loess Plateau · Water-limited region

1 Introduction

The Chinese Loess Plateau (CLP) is well known for its soil erosion and water deficits (Yang 2001; Han et al. 2010). More than 20.7 million ha of abandoned farmland have recently been afforested with the "Grain-for-Green" project, which aims to restore the historical environmental conditions of an ecosystem (Shi and Shao 2000; Liu et al. 2008; Shangguan 2009; Lu et al. 2015). This project, however, ignores changes in biotic factors and the feedback between biotic and abiotic factors (Hobbs and Norton 1996; Prach et al. 2001; Willems 2001; Suding et al. 2004; Suding and Hobbs 2009). For example, intensive invasion of exotic species has depleted deep soil water in water-limited regions, so the soil rarely receives water in its deeper layers, and most biotic processes are confined to the upper soil layers (Schlesinger et al. 1990). These problems have led to the desiccation of the deep soil layers, further strengthening a more widespread and intensive occurrence of

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dried soil layers (DSLs). The most widespread of DSLs further intensify soil degradation, low-productivity of the vegetation, and die-off in water-limited region, which have considerably altered the eco-hydrology process of the region (Bakker and Berendse 1999; Zedler 2000; Breshears et al. 2005; Ponce Campos et al. 2013). The presence of DSLs differs from the more general process of soil desiccation, which only seasonally extends into the surface soil and are confined to deep layers for a long time (Chen et al. 2008; Wang et al. 2010a).

Numerous studies on the CLP have demonstrated that DSLs are mainly caused by the excessive depletion of deep soil water by introduced vegetation, high transpiration, and long-term insufficient rainwater supply (Li 1983; Shi and Shao 2000; Yang 2001; Chen et al. 2008; Li and Huang 2008; Shangguan 2009; Wang et al. 2010b; Jin et al. 2011). The effects of various factors on DSLs, however, remain controversial, not only for the cause of formation but also for the magnitude of estimated DSL indices. Yan et al. (2015) showed that DSLs were obviously affected by climatic and vegetation factors. Wang et al. (2010b) concluded that the rate of formation and thickness of DSLs largely depended on the type of vegetation at a regional scale and plant age at a site scale. Yelenik and D'Antonio (2013) reported that dominant exotic species were persistent due to internal self-reinforcement, which would lead systems to alternative stable states. These different assessments among studies may be due to different scales, which involve complex geographical features and constraints of the external environment. On the other hand, the extent and location of DSLs remain unclear. The relationship between spatial pattern of DSLs and hydrological behavior, which will change as continuous patterns changes, is quite important. For example, incorporating local DSL pattern into connected dry soil water patterns has a dramatic effect on hydrologic processes, even if the continuity (the spatial correlation structure or variogram) is unchanged (Grayson et al. 1997; Bronstert and Bardossy 1999). For example, Western et al. (2001) demonstrated that patterns with large amounts of small-scale variability have little continuity, the correlation lengths are small, whereas correlations over large scale are characteristics of smooth, highly continuous pattern, which lead to preferred flow paths. Runyan et al. (2012) studied that persistent drought stress will determine whether an irreversible shift has occurred for large areas. Similarly, Scheffer et al. (2012) reported that a high level of connectivity may cause a network as a whole to change abruptly. Estimating the effect of connected features or convergent features has been a main task (Journel and Huijbregts 1978), not focus only on the change of spatial correlation structure.

The relative importance of the environmental variables responsible for DSLs at a small scale is unlikely to be effectively resolved. Our view of their importance is consistent with the observed spatial scale. Traditional DSL indices have large uncertainties because their parameters vary in space and time. For example, the importance of soil properties varies with the intensities of eco-hydrological and soil processes, which are strongly scale dependent (Biswas and Si 2011; Gao et al. 2012). The temporal scale over which plant-soil feedback is irreversible will vary depending on the environmental variables (Li et al. 2015). Many confounding factors such as climatic factors (e.g., precipitation, temperature, and evaporation), however, can mask the heterogeneity of related local conditions (Runyan et al. 2012). Jia et al. (2013) reported that parameters of DSL indices weakened with soil depth, where temporal persistence was much stronger. Jia et al. (2015) concluded that spatial pattern of DSLs demonstrated good regional temporal persistence. Therefore, spatial pattern of DSLs did not change at various scales. To explore the spatial pattern of DSLs and the factors influencing it can improve the efficiency of vegetation restoration and soil water management.

Here, we investigated an 860-km transect across semi-arid and dry sub-humid regions in China. We integrated the regional environmental variables that may influence the characteristics of DSLs to address the changes and to prioritize the potential factors at a regional scale. As connected features or convergent features exhibit a hydrologically relevant spatial pattern, we hypothesized that the interplay between DSLs formation at single and continuous sampling site would strengthen impacts of eco-hydrological process. The main objectives of our study were to investigate (1) the key factors determining the spatial pattern of DSLs in complex ecological zones and (2) the relative contribution of the factors.

2 Materials and methods

2.1 Site description

The study was conducted in the typical CLP (33°43′ to 41°16′ N, 100°54′ to 114°33′ E), which covers a total of ca. 430,000 km^2 (Fig. 1). The area has complex topography, with plains, sub-plateaus, hills, and gullies and altitude ranging from 380 to 1600 m. The climate is predominantly arid and semi-arid continental, with mean annual temperature of 6.8 °C in the north and 12.3 °C in the south, mean annual precipitation ranging from 400 to 620 mm, and with 55–78% of rainfalls concentrated between June and September, mostly in the form of thundershowers and rainstorms. The study area is subject to severe soil and water loess, causing land degradation and loss of soil fertility (Li et al. 2016). The natural environment of most of this region of the CLP is being progressively restored. Soil water deficit is a crucial limiting factor for vegetation restoration.

In order to perform a comprehensive sampling at a large geographical scale, we therefore chose a south-north transect (ca. 860 km) to determine the key factors that influence spatial heterogeneity of DSLs at regional scale. The south-north transect was divided into four zones based on the geographical and hydrological features of local soil water distribution using stepwise

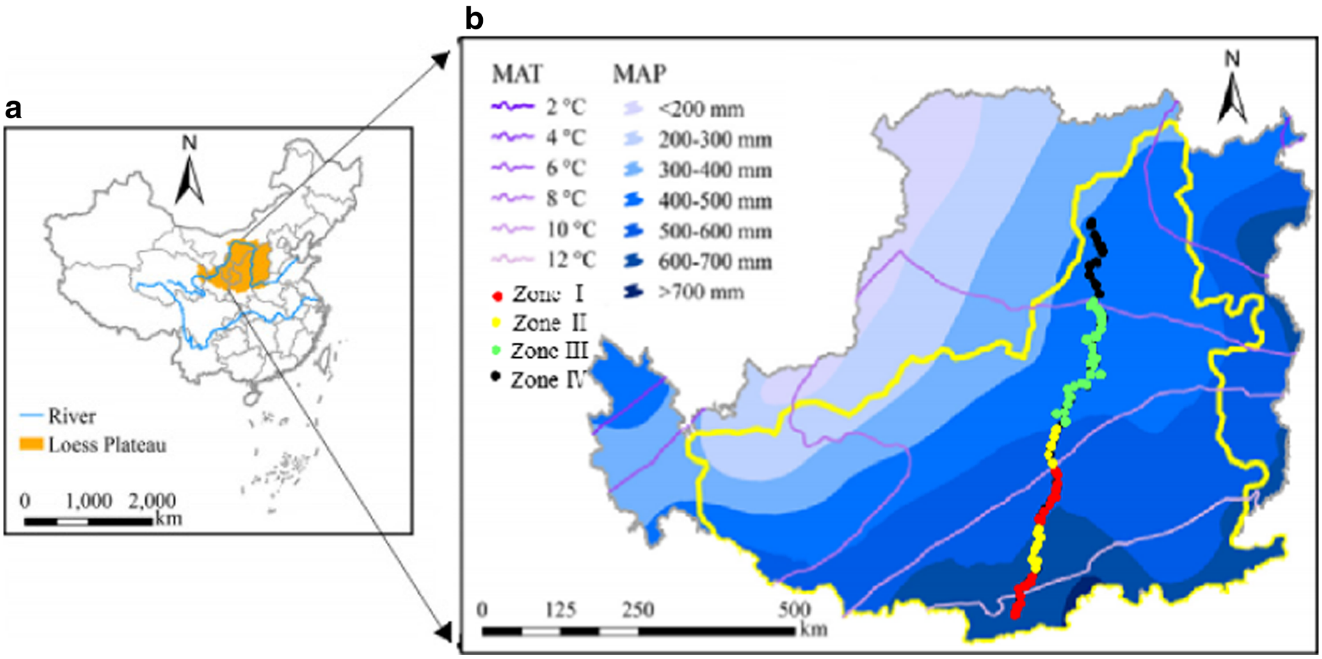

Fig. 1 Location of the Loess Plateau in China (**a**) and the 86 sample sites across a 860-km south-north transect on the plateau with the distributions of mean annual temperature (MAT) and mean annual precipitation (MAP) (**b**). Both figures were performed using ArcGIS version 9.2 (ESRI Company, USA)

discriminate analysis (Yang 2001). The transect crossed four soil water ecological zones (Fig. 1), I–IV, numbered from south to north. Soil water deficits generally increased from zone I to zone IV. The sites varied greatly; detailed information for the zones are shown in Table 1. From south to north, the land use type generally changes from cropland to forestland and then to grassland. Restoration efforts had been carried out for 15 years. All the forestlands are artificial with different tree species. The grasslands are both artificial and natural (Jia et al. 2015). The most widespread soil is clay-loam in texture, sandier soils in the north, and clayier soils in the south.

2.2 Data collection

A total of 86 soil samples were collected at intervals of 10 km along the south-north transect. Each sample site was randomly selected but represented soil water deficit of sampling unit within the four soil water ecological zones. The locations of the sites were recorded by a GPS receiver (5-m precision). Soil samples were collected at intervals of 0.1 m with 50 layers to depth of 5.0 m at each sampling site in 2013 (April–November). Then, samples were transported to the laboratory where the gravimetric soil water content (SWC) was measured.

The factors included soil, climate, and topography as possible environmental variables in subsequent analyses to identify the effect for each sample site.

2.2.1 Measurement of soil samples

Disturbed soil samples excavated at each site were divided into two sub-samples after air drying. One was sieved through a 1-mm mesh for the analysis of particle-size composition (%) by

Table 1 Characteristics of the four zones

Zone	Soil water ecological zone	Precipitation (mm)	Soil type	Aridity index	Vegetation
I	Equilibrium compensation	600–750	Loam Sandy loam	2.5	Forests, farmland
II	Semi-equilibrium compensation	500–600	Loam Silt	3.0	Forests
III	Soil water cycle deficit	400–500	Sandy Clay Loam Sand	4.0	Forests, shrubland
IV	Compensation imbalance	350–400	Loam Sand	5.0	Shrubland, grassland

laser diffraction using a Mastersizer 2000 (Malvern Instruments, Malvern, England), and the other was sieved through a 0.25-mm mesh for measuring soil organic-carbon content (SOC, g/kg) using dichromate oxidation (Nelson and Sommers 1982). Undisturbed soil samples were collected from the distance of 0.5 m at each site, using a soil auger (5 cm in diameter). The soil samples were excavated from the 0–20 and 20–40 cm soil layers at a 40 cm deep pit for measuring field capacity (FC, %), saturated soil hydraulic conductivity (Ks, mm/min), and bulk density (BD, g/cm^3). SWC at FC (volumetric SWC at −0.03 MPa) was measured from a soil water retention curve (Ratliff et al. 1983), Ks was determined using the constant-head method (Klute and Dirksen 1986), and BD was estimated by the relationship between volume and dry mass (Jia et al. 2015). The soil properties included FC, Ks, BD, SOC, and clay content (CC, <0.002 mm) were analyzed that could potentially affect the water-retention character.

2.2.2 Measurement of other main characteristics

Data for mean annual precipitation (MAP, mm) and temperature (MAT, °C) were extracted from continuous data sets via kriging collected at local meteorological stations (http://cdc.cma.gov.cn/), respectively. The precipitation seasonal distribution (PSD) in the growing season (May to September) was quantified as the coefficient of variation of the monthly precipitation (CV_{mp}):

$$CV_{mp} = \frac{\sqrt{\frac{1}{5}\sum_{i=5}^{9}\left(M_i - \overline{M}\right)^2}}{\overline{M}} \tag{1}$$

$$\overline{M} = \frac{1}{5}\sum_{i=5}^{9}\left(M_i\right) \tag{2}$$

where M_i is the mean monthly precipitation (i is calculated from May to September) and $\overline{M}$ is the average precipitation for the 5 months (May–September). The aridity index (AI) is the ratio of precipitation to evaporation (EVA). Data for EVA, PSD, and AI were also obtained for each sample site from the same data sets as for MAP and MAP, respectively.

Geographic coordinates (latitude, longitude, and elevation) were recorded using an RTK-GPS receiver (5-m location precision). Slope gradient (SG) and aspect (SA) were measured at each site with a geological compass. Slope position (north-south direction) and land use were observed in detail. In summary, a total of 15 parameters was chosen as factors potentially related to DSLs.

2.3 DSL indices

Two indices—dried soil layer thickness (DSLT) and SWC of DSLs (DSL-SWC)—were developed to evaluate spatial pattern of the DSLs based on the formation process of DSLs (Wang et al. 2010b, 2011). DSLT (cm) was calculated as:

$$\mathrm{DSLT} = 10 \times \sum_{i=11}^{n} S\left(\theta_i - \theta_{SFC}\right) \tag{3}$$

where

$$S\left(\theta_i - \theta_{SFC}\right) = \begin{cases} 0, \theta_i - \theta_{SFC} > 0 \\ 1, \theta_i - \theta_{SFC} \le 0 \end{cases}, (i = 11, 12, 13 \ldots, n) \tag{4}$$

$n = 50$ sampling layers within the soil profile, θ_i is the SWC of the ith soil layer, and θ_{SFC} is the SWC of stable FC (defined as 60% for the CLP). Plants generally suffer water stress when soil water is lower than θ_{SFC}, which intensifies the persistence of drought for local conditions.

2.4 Statistical analysis

The basic characteristics of the DSL indices were calculated using Excel 2003 including mean, standard deviation (SD), coefficient of variation (CV), skewness, and kurtosis. The spatial gradient of DSLs between sampling sites along the transect were performed in Origin (version 18.0). Differences in the DSL indices between zones were assessed using the non-parametric Mann-Whitney *U* test (Clarke 1993). A multivariate analysis consisted of the following steps. First, a detrended correspondence analysis (DCA) calculated an unconstrained ordination. This analysis indicated that both linear and unimodal methods should perform reasonably well, because the gradient length was <3, which suggested that the spatial pattern of DSLs exhibited linear responses to the environmental variables. Second, the possible relationships between the DSL indices and the environmental variables were examined by a redundancy analysis (RDA). All 15 measured variables were divided into two groups: climatic factors and local conditions. A partial redundancy analysis (PRDA) was used to assess their relative roles in affecting the DSLs. For data analysis, the potential factors were subsequently standardized to zero mean and unit variance to remove the different scales of measurement (Xiong et al. 2016). The DCA and RDA was performed the "Vegan" package within R 3.3.1 (http://cran.r-project.org/web/packages/vegan). Statistical significance was assessed using forward selection and a Monte Carlo permutation test (999 permutations) to determine key factors.

3 Results

3.1 Spatial distribution of DSLs

DSLs were detected at 66 of the 86 sample sites along the transect. The mean DSLT was 283.7 cm and the mean DSL-SWC was 7.73% (Table 2). The CVs for DSLT and DSL-SWC were 51 and 41.65%, respectively, indicating moderate

Table 2 Summary statistics for dried soil layer thickness (*DSLT*) and soil water content in the DSL (*DSL-SWC*) at all sampling sites

DSLs indices	Number (n)	Minimum	Maximum	Mean	SD	CV (%)	Skewness	Kurtosis	DT
DSLT	66	10	400	283.7	144.8	51	−0.82	−0.99	NN
DSL-SWC	66	2.54	17.7	7.73	3.22	41.6	0.85	0.545	NN

Significance level of normality test, $P < 0.05$

n number of samples, *SD* standard deviation, *CV* coefficient of variation, *DT* distribution type, *NN* nearly normal distribution

spatial heterogeneity. DSLs did not occur at the southern end of the transect. DSL-SWC generally decreased from zones I to IV (Fig. 2); we detected a significant difference between zones II and III ($P < 0.01$). We did not find significant difference between zones ($P > 0.05$ for all pairs) when DSLT was subjected to the non-parametric Mann-Whitney *U* test.

In Fig. 3a, DSL-SWC varied widely between sites along spatial gradient. DSL-SWC decreased greatly with increasing latitude in dry sub-humid areas, with a minimum of 3.42%, and then increased slightly at sites in semi-arid areas. More sites formed DSLs (DSLT >400 cm) along spatial latitudinal gradients between sites. Bubble size refer to DSLT; the overlapping portions in the graph indicated strong interactions between sites. The continuous sampling units overlapped least in the dry sub-humid region, moderately in the transitional region, and most in the semi-arid region. In general, soil water distinguish between the wet and dry cases quite well. The maximum depth of rainfall infiltration do not exceed 1 m; the dry soil layers at the deep soil profiles which have less water recharge are significantly joined. Figure 3b demonstrated distribution of soil water for 43–80 sampling sites within soil profile where DSLs continuous occurred. Soil water content was generally less than 6%, and much as 3%. Soil desiccation was serious and DSLT was generally greater than 220 cm. In spite of the extent with connected features have far less than range of spatial correlation structure, the DSLs are strongly influencing the eco-hydrological processes.

3.2 Factors responsible for the DSL characteristics

The ordination biplot based on the redundancy analysis (RDA) showed the correlation between DSL indices and environmental factors (Fig. 4). The DSL-SWC was correlated positively with CLAY, MAT, and MAP, while EVA and PSD were negative. Briefly, the DSLT weakly associated with the two local conditions SG and SA.

We omitted the obvious collinearity of factors and selected only the significant properties for further analysis. These nine factors included MAP, MAT, EVA, PSD, BD, FC, saturated SWC (SSWC), CC, and SOC were key factors for explaining the total variability of DSL based on forward selection and Monte Carlo permutation tests (Table 3). Similarly, the results showed the relative importance of each environmental variable when the variable was treated separately. MAP ($R^2 = 0.695$, $P < 0.001$) and EVA ($R^2 = 0.690$, $P < 0.001$) were the largest climatic contributors which influenced the local dryness condition. Local conditions, especially FC, were the most important factors ($R^2 = 0.831$, $P < 0.001$) in all environmental variables.

All these results suggest that both the climatic factors and local conditions were responsible for the DSL characteristics. We therefore explored the relative importance of these two categories of factors further using variance partitioning.

3.3 Relative importance of regional factors versus local conditions

The relative importance of these factors was explored based on partial redundancy analysis (PRDA). The ordination of the RDA showed that these nine factors were able to explain 47.3% of the total variability and thus contributed greatly to the DSLs characteristics ($F = 4.46$, $P < 0.001$) (Fig. 5). The PRDA showed that climatic factors explained by measured

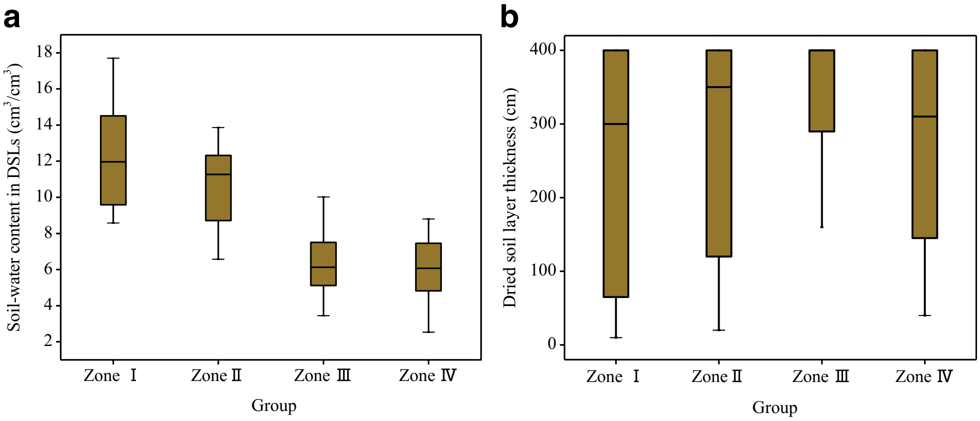

Fig. 2 Boxplots of soil water content in the DSLs (DSL-SWC) (**a**) and DSL thickness (DSLT) in the four zones (**b**). *Boxes*, *central bars*, and *solid lines* represent the interquartile range, the median, and the range of data, respectively

Fig. 3 Graphs displaying the spatial distribution of DSL-SWC along a spatial latitudinal gradient between sites (**a**). *Bubble size* corresponds to the effect size of DSLT, and the *red color* represents connected neighboring sites. The *overlapping portions of DSLs between sites* represent strong spatial interactions between two small neighbor sites. Spatial distribution of soil water content within the soil profiles for connected sampling sites 43–80 (**b**). Soil water content was measured at intervals of 0.1 m to a depth of 5 m

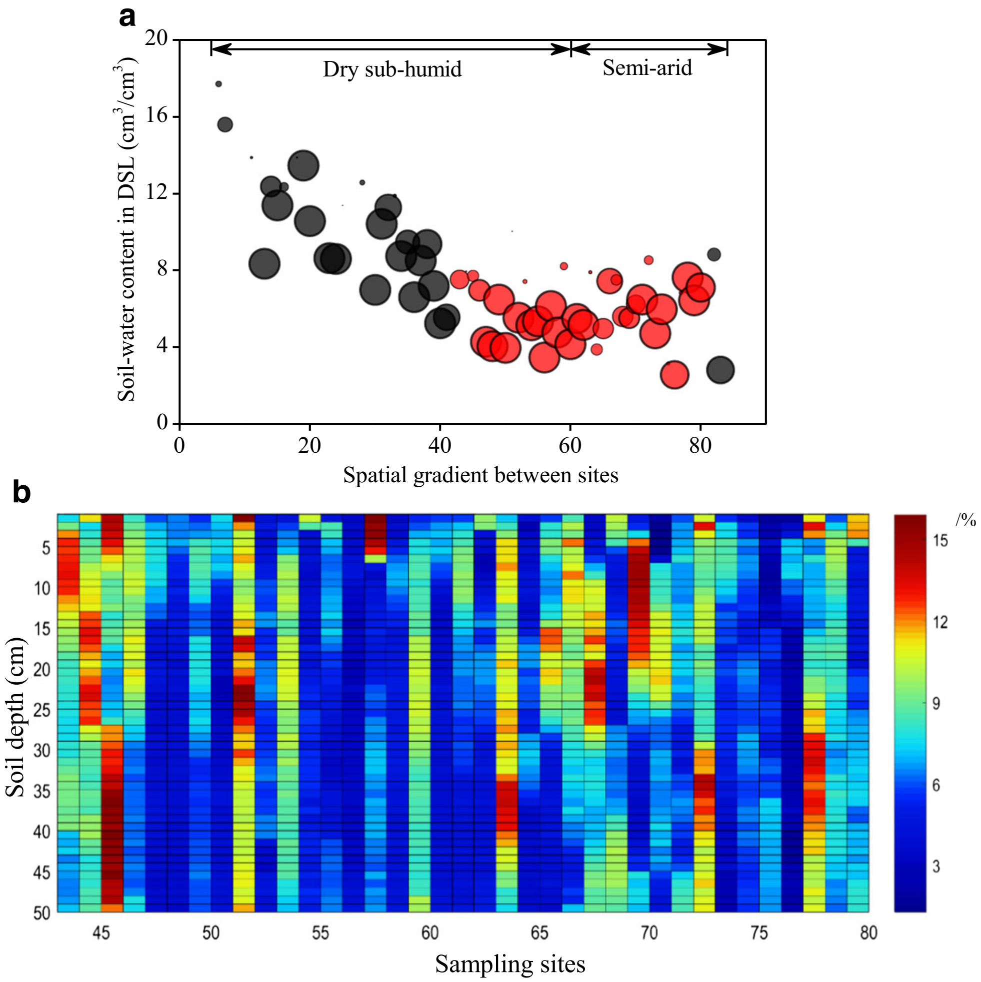

Fig. 4 The relationship between characteristics of DSLs and various environmental variables. *Arrows in red* represent characteristics of DSLs, while *arrows in black* represent measured environmental variables. *Arrows in different quadrants* denoted positive or negative relationship between environmental factor and axis

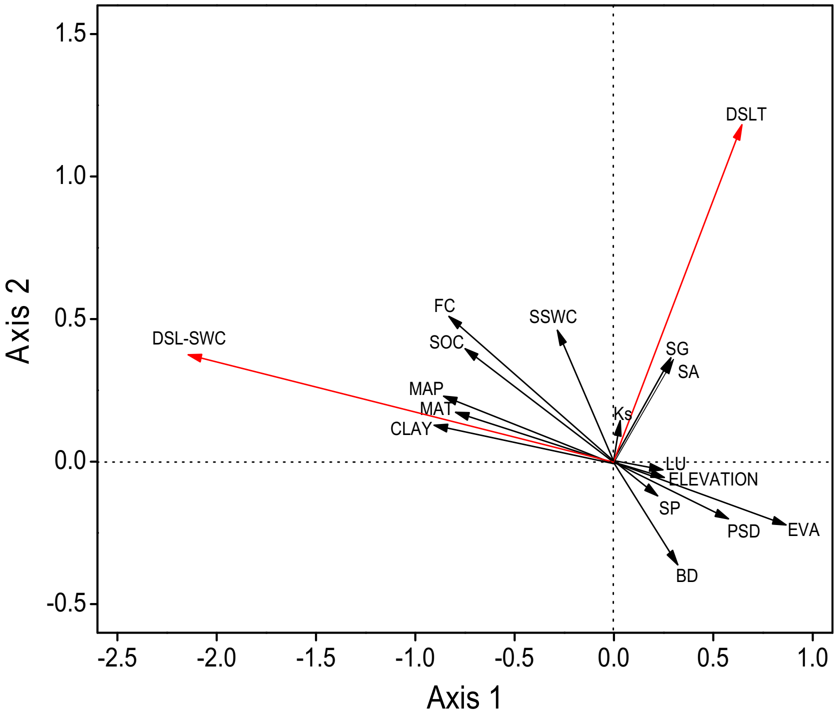

Table 3 Results of forward selection and Monte Carlo permutation tests from the redundancy analysis (*RDA*) of at all sampling sites. The *P* value indicates the significance of each variable either whether considered independently or dependently. The R^2 represents the relative importance of each environmental variable when the variable was treated separately. The selected environmental variables were listed by the order of their inclusion in the RDA model

Environmental variables	R^2	P
Climatic factors		
Mean annual precipitation	0.695	0.001***
Mean annual temperature	0.580	0.001***
Evaporation	0.690	0.001***
Precipitation seasonal distribution	0.325	0.001***
Local conditions		
Elevation	0.052	0.182
Slope gradient	0.077	0.083
Slope aspect	0.077	0.084
Saturated hydraulic conductivity	0.007	0.791
Bulk density	0.176	0.003**
Field capacity	0.831	0.001***
Saturated soil water content	0.204	0.002**
Clay content	0.711	0.001***
Soil organic carbon	0.641	0.001***
Slope position	0.048	0.220
Land use	0.043	0.237

*$P < 0.05$

**$P < 0.01$

***$P < 0.001$

variables was only 3.0% of the total variability that could not be explained by local conditions. Similarly, local conditions explained 14.7% of variability that could not be explained by climatic factors. The interaction between climatic variables and local conditions accounted for 29.6% of the DSLs-environment relationship explained in the model. In summary, both the climatic factors and local conditions contributed greatly to the spatial pattern of DSLs, but the local conditions explained high proportion of explained variability and played a more important role in driving the spatial pattern of the DSLs based on multiple analyses.

4 Discussion

All feedbacks can increase or decrease in strength as the spatial scale of disturbance increases (Runyan et al. 2012). For example, small-scale deforestation in the Amazon Basin has led to local vertical instability and an increase in fire frequency (Avissar et al. 2002). While it is also likely that complete removal of the forest would increase in the fire frequency, an increase in the scale of deforestation does not necessarily coincide with a strengthening of this feedback (D’Odorico et al. 2006; Runyan et al. 2012). Similarly, plant-soil feedbacks can operate at scales as small as a tree canopy, hill-slope, or landscape (D’Odorico et al. 2007; D’Odorico et al. 2012). Therefore, the feedbacks can have larger scale effects that feedback at regional and larger scales.

We did not account for any temporal dynamics of DSLs for two reasons. Firstly, DST and DSL-SWC are very temporally persistent, so recovering historical environmental conditions will be difficult over short time periods (Hu et al. 2009; Liu and Shao 2014; Jia et al. 2015). For example, Huang and Gallichand (2006) reported that the recovery time of the same soil water content varies from 6.5 to 19.5 years, with an average of 13.7 years. Our surveys on temporal variation of DSLs showed no significant changes in 86 representative locations within 2013–2014 (Jia et al. 2015). Consequently, spatial pattern of DSLs generally demonstrate temporal stability. Secondly, the observed relationships between DSLs and environmental variables are consequently highly relevant;

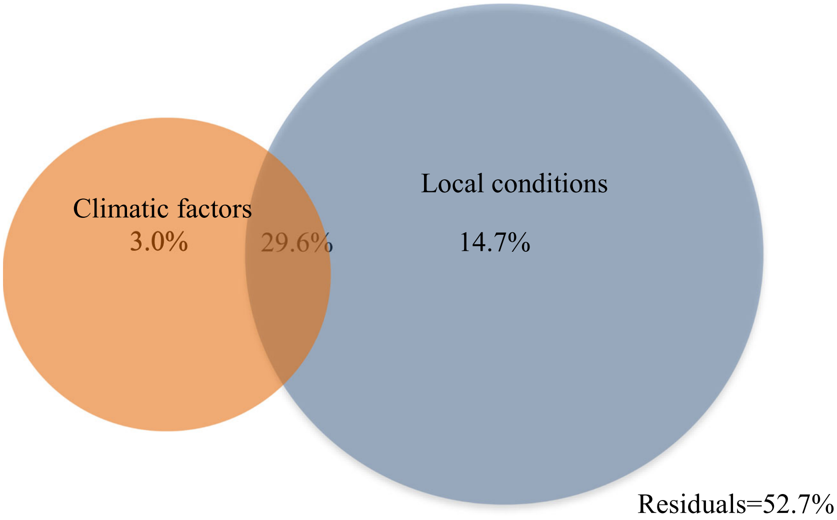

Fig. 5 Results of the variation partitioning analysis for assessing the relative contribution of climatic factors and local conditions for the spatial pattern of DSLs

environmental changes will lead to corresponding changes in DSLs at short timescales. Whether all environmental factors tend to increase in strength as the spatial scale increase is not clear. The aim of our study is to test the spatial pattern of DSLs at regional scale. Consequently, we only considered the effects of different environmental factors on geographical distribution of DSLs (i.e., spatial variation, rather than temporal variation).

DSLs had formed at only 66 of the 86 sample sites along the south-north transect on the CLP. The sites without DSLs were mostly in semi-humid regions (Table 2). DSLT was highly variable in zone I (Fig. 2b). The loss of deep soil water may have been compensated by intensive irrigation at these sites, consistent with the results by Wang et al. (2010b), who reported that irrigated areas along the Yellow River had either no or thin DSLs. Anthropogenic activity (e.g., tillage and grazing) positively affected the soil water balance. The different characteristics of spatial pattern strongly influence hydrologic behavior. There difference in hydrologic behaviors between regions is due to the one or two small connected patches combined with a few large connected patches. Dry (wet) patches therefore demonstrated a much wider range of hydrological patterns, ranging from small to large scales (Western et al. 2001). In our study, we sampled intensively at intervals of 10 km over large scales which exhibited a range of different characteristics, varying in a qualitative manner from random to highly organized (Western et al. 1998; Western et al. 1999; Bloschl and Grayson 2000). The organized patterns can include connected features or convergent features (Blöschl and Sivapalan 1995). Homogeneity and highly connected features of DSLs may widen spatially where DSLs occur and provide local adjustments to small perturbations (Scheffer et al. 2012). The interplay of DSLs at adjacent sample sites imply that hydrologic response goes beyond small scale (Scheffer et al. 2001; Zeng et al. 2004; van Nes and Scheffer 2005; Collins and Bras 2007; Eldridge et al. 2015). The degraded effects of DSLs are intensified, because spatial pattern of DSLs can exhibit a range of different characteristics, varying in a qualitative manner from random to highly organized (Bloschl and Grayson 2000; Western et al. 2001; Ravi et al. 2009). These results are consistent with those by Bronstert and Bardossy (1999) and Western et al. (2001); incorporating connectivity into neighbored moisture patterns has a great influence on hydrologic prediction, even if the continuity (the spatial correlation structure or variogram) is unchanged. The highly continuous patterns are characteristic of DSLs stationary over large scales (i.e., large correlation lengths or integral correlation scales), which further influenced the resilience of ecosystem. Our results support the hypothesis that the interaction between connected neighboring units could widen the spatial extent of DSLs. The connected features between two sampling units could characterize the degree of spatial continuity.

The nine environmental variables were consequently responsible for the DSLs characteristics before the Monte Carlo test omitted the negative factors, which accounted for 47.3% of the variability (Table 3). MAP and EVA strongly influenced local aridity, which govern SWC of DSLs. Temperature is generally highly correlated with SWC. As temperatures rise on the CLP, these arid and semi-arid areas will lose more water due to evaporation, which will further influence SWC. Our results also indicated that PSD could not be ignored. Changes in climate can alter rain patterns, so PSD can have an important effect on the spatial variation of aboveground net primary productivity in water-limited regions (Borgogno et al. 2007), which would influence the distribution of soil water. The other studies reported that pulses of precipitation can favor shrubs as dominant community species and have formed DSLs at a depth of 2 m during later stages of growth (D'Odorico et al. 2000; Liu et al. 2010). Runoff from lengthy heavy rains, however, cannot relieve local water stress in semi-arid regions as much as in drier regions, even though PSD changes. FC and CC, as local conditions, are essential for improving water-holding capacity, available soil water, and the release of water by gradient suction (Leatherdale et al. 2012).

Similar to many other studies, environmental variables dominate characteristics of DSLs. For example, Wang et al. (2011) demonstrated that BD and slope gradient were the largest contributors to DSLT. Four factors (FC, AI, latitude, and sand content) were collectively responsible for a high proportion of the explained variability of DSL-SWC. Chen et al. (2008) similarly found that regional environmental factors were the primary factors. These studies, however, used unconstrained correspondence analysis to develop models for the relationship between environmental factors and DSLs without constraining specific dimensions of the environmental variables (Gao et al. 2016; Yang et al. 2016). On the other hand, the underlying importance of climatic factors may mask or buffer the main local conditions (Scheffer et al. 2005; Brooker 2006; Saccone et al. 2010; Liancourt et al. 2013). In our study, the model separated all irrelevant climatic factors, which was an efficient way to demonstrate the relationship between the environmental factors and the DSLs characteristics in complex regions (Table 3). The interaction between climatic factors and local conditions explained a high proportion of the variation (Fig. 5). In addition, the constrained ordination demonstrated the large influences of the local conditions, which were considered conservative, especially when assessing the relative importance of environmental variables for DSLs at a certain site, indicate that local conditions mediate DSLs characteristics largely.

5 Conclusions

DSLs occurred in the semi-arid transitional zone due to a complex interplay of processes involving both rainfall patterns and local conditions. DSLT and DSL-SWC varied greatly under different soil water ecological zones. DSL-SWC decreased greatly with increasing latitude. Then, as latitude increased, the spatial pattern of DSLs, as affected by connected features in large area, can change regional eco-hydrologic processes. This result supports the hypothesis that geographical continuity of DSLs between small connected patches have an important influence. Multiple analyses identified that four climatic factors (MAP, MAT, EVA, and PSD) and five local conditions (BD, FC, SSWC, CC, and SOC) played more important roles. In addition, our study here clearly showed that climatic factors accounted for the high proportion of explained variability. The interaction between climatic factors and location conditions explained great part for explained variability, and that means local conditions rather than climatic factors are considered directly for simulating and predicting the model of DSLs. Our study also contributes to our understanding of the formation mechanism of DSLs, which are useful for the vegetation restoration and soil water management in water-limited regions.

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