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Characteristics of soil moisture in relation to microtopography in the Loess region of Northern Shaanxi, China

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Abstract

Soil moisture is the primary factor limiting plant growth and vegetation rehabilitation in the loess region of northern Shaanxi, China. This 5-year (2008–2012) study investigated methods of selecting appropriate microsites for vegetation restoration based on efficient use of soil moisture; 5-year data were compared with 56 years of precipitation data using standardized precipitation index. In addition, the effects of microtopography on the spatiotemporal variations of soil moisture were analyzed at the Wuqi Ecological Station of Beijing Forestry University. Results showed that average annual precipitation during last 5 years fell by 12.4% during the growing season compared with 1957–2012 data and soil moisture content at depth of 0–160 cm under went dramatic changes and became relatively low in July and August. Soil moisture content varied in different microtopographical units as follows: gullies > gently-sloped terraces > collapsed soils > undisturbed slopes (control) > furrows > escarpments. The vertical distribution of soil moisture content in different microtopographical units showed dramatic changes at depth of 0–40 cm. Soil moisture content of gently-sloped terraces, gullies, collapsed areas, furrows, and undisturbed slopes was highest at depth of 80–160 cm with a level of instability at depth of 40–80 cm. For gently-sloped terraces and gullies, soil moisture content followed the order of 40–80 cm > 0–40 cm; for collapsed areas, furrows, and undisturbed slopes, soil moisture content follows the order of 0–40 cm > 40–80 cm. For escarpments, soil moisture content varied with depth in a different pattern: 0–40 cm > 80–160 cm > 40–80 cm. This study is of theoretical significance and will help guide the sustainable development of ecological restoration and vegetation rehabilitation in the Loess region.

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Introduction

The combination of low precipitation, a dry climate, high evaporation rates, and sparse vegetation forms a fragile ecosystem in Loess region (Zhao *et al.,* 2010). In particular, intense sunlight and strong evaporation on sunny and semi-sunny slopes causes a serious soil moisture deficit, making vegetation restoration and rehabilitation difficult (Famiglietti *et al.*, 1998; Fang *et al.*, 2013; Western *et al.*, 1999). In recent years, attempts to naturally reforest the landscape in the loess region have encountered problems related to low survival rates, conservation efforts, and slow growth rates of forests and grasses resulting in areas of small-old trees, low-yield, low-function forests, and a dried soil layer (Qiu et al., 2010). Soil moisture is the limiting factor for all of the above issues (Henderson-Sellers, 1996), because it is the primary factor limiting plant growth and vegetation restoration in the loess region.

Although previous attempts to implement ecological restoration measures (e.g., returning farmland to forest or grassland and exclosure protection for natural restoration) have mitigated the problems related to water and soil loss, severe soil erosion continues to be a problem in the loess region. Water erosion not only shapes various eroded gullies, it also fragments slopes into diverse microtopographical units, such as collapsed areas, gullies, furrows, gently-sloped terraces, and escarpments (Zhu *et al.,* 2011). The presence of these microtopographical units enables redistribution of precipitation by regulating infiltration of precipitation and evaporation from the soil. The resulting changes in soil moisture and plant growth in different microtopographical units allows formation of different microhabitats, leading to varied vegetation distribution patterns based on microtopography (Zhu *et al.,* 2011). Thus, research related to the loess region regarding precipitation characteristics and spatiotemporal variability in soil moisture in relation to microtopography is of theoretical significance and provides guidance to land managers attempting to make reasonable selections of vegetation for use in ecosystem restoration, to use water efficiently, and to restore vegetation in an ecologically sound manner on the Loess Plateau.

Currently, research related to soil moisture distribution has mainly been conducted at the regional, small catchment and watershed and slope scales (Hu *et al.,* 2010; Nagamatsu and Miura, 1997; Western and Blöschl, 1999). On the Loess Plateau, Yang *et al.* (1998) analyzed mean soil moisture content data in a multi-year study and revealed its relationship to land desertification. Qiu *et al.* (2001) studied the spatial variability of soil moisture and factors influencing soil moisture in a small watershed of a loess hilly area. They showed that both the mean values and spatial heterogeneity of soil moisture content have distinct patterns of cross-sectional and temporal variation and that the spatial heterogeneity of soil moisture content is a result of joint interaction of site, slope and watershed scales. In a study of the distribution of soil moisture at depths of 0–5 cm on sloped areas associated with different land use types, Famiglietti *et al.* (1998) demonstrated that variability of soil moisture content in relation to topography and soil properties changes over time. In addition, Sun *et al.* (2005) conducted a field study on distribution of soil moisture in sloped areas of the loess hilly and gully zone in western Shanxi Province, China. This study indicated the direction, degree and position of slope all have important effects on the slope-scale distribution of soil moisture, and summarized the cross-sectional variations and temporal dynamics of soil moisture content under different site conditions.

Despite the fact extensive studies have been conducted relation to the distribution of soil moisture and its variability at different scales, few relevant reports address the characteristics of soil moisture in relation to microtopography. For example, Wang *et al.* (2011) conducted a one-year study on the characteristics of soil moisture in relation to microtopography in a sunny dry slope area of the loess region in northern Shaanxi, which indicated that seasonal variations in soil moisture content of some microtopographical units lag behind seasonal variations in regional precipitation. Similarly, Zhao *et al.* (2010) conducted a one-year study of soil moisture characteristics from a sunny dry slope area on the Loess Plateau, demonstrating microtopography has a strong influence on soil moisture content. Because several have studies analyzed short time periods (1- or 2-year), long-term monitoring data are generally unavailable in existing research on the distribution of soil moisture in relation to microtopography and the evidence presented is often relatively weak.

In the present study, the spatiotemporal variations and variability of soil moisture in different microtopographical units in the loess region was investigated. The aim of the research was achieved through a comprehensive and systematic analysis of regional precipitation characteristics using long-term experimental field data (2008–2012). This work lays a solid foundation for environmental rehabilitation, as well as provides information designed to guide the production practices of local residents and decision-making by regional governments.

Materials and Methods

The study site is located in the Hejiagou watershed Wuqi County, Yan'an City, Northern Shaanxi Province, China, at an elevation of 1233–1890 m. The region has a semi-arid temperate continental monsoon climate. Average annual temperature was 7.8°C, and the annual accumulative temperature was ≥10°C was 2817.8°C. Average annual sunshine was 2400 h, with a frost-free period of 96–146 days. Average annual precipitation is 478.3 mm, while average annual evaporation is 400–450 mm (Lu *et al.*, 2009). A light-loam-textured loessial soil covers 97.16% of the 3791.5 km^2 watershed. 97.64% of the watershed (3702.2 km^2) has experienced soil erosion resulting in increased runoff and decreased available water in the soil.

Grazing exclosure protection was implemented in 1998 to restore the natural vegetation, composed of a forest-steppe to steppe transition type. Naturally regenerated vegetation was dominated by herbaceous communities. Small shrubs and trees seedlings were scattered across the steppe, with a few species of trees widely scattered along the bottom of gullies. The type of plant community found at any particular microsite coincides the community age. Despite the presence of certain differences in coverage, spatiotemporal variations in soil moisture distribution was obviously affected by variations in vegetation coverage.

Determination of soil moisture: In 2008, five representative microtopographical units and one undisturbed slope (control) were selected based on their microtopographical features (e.g., degree and direction of slope) with careful consideration of the sampling scale while selecting representative sites (Fig. 1). Correspondingly, six long-term observation stations were set at the selected points as indicated (Fig. 2). At each observation point, a 2-m long, 45-mm inner-diameter polyvinyl chloride pipe was buried vertically. During 2008–2012, volumetric soil moisture content was measured at the observation points using a TRIME®-HD portable handheld meter (IMKO, Ettlingen, Germany) based on high-precision time-domain reflectometry. Measurements were made from the ground surface downward to 160 cm deep at 20 cm intervals. For each depth interval, soil moisture content was measured three times by rotating the probe 120° each time, and mean of the three measurements were taken as the soil moisture content of that particular depth interval. The measurement was carried out every 10 days, plus measurements after rain events. Data were recorded both manually and

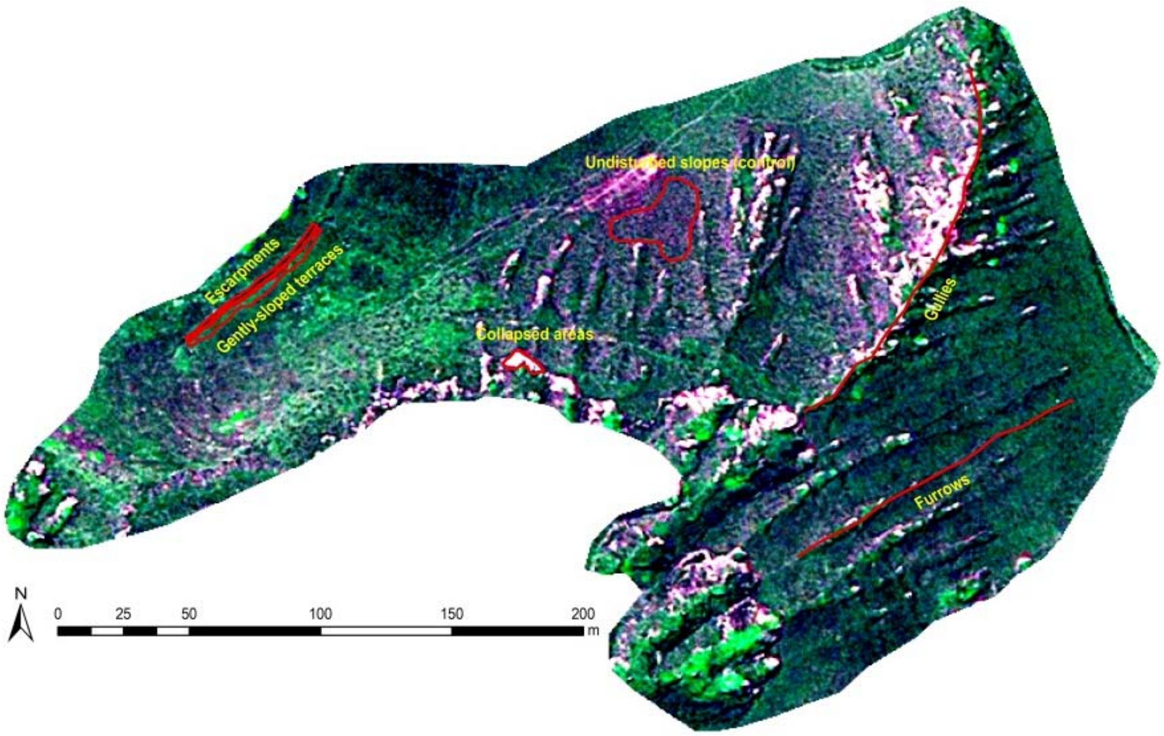


Fig. 1 : A sketch of the study site microtopography (Digital Orthophoto Map from Quick Bird Image)

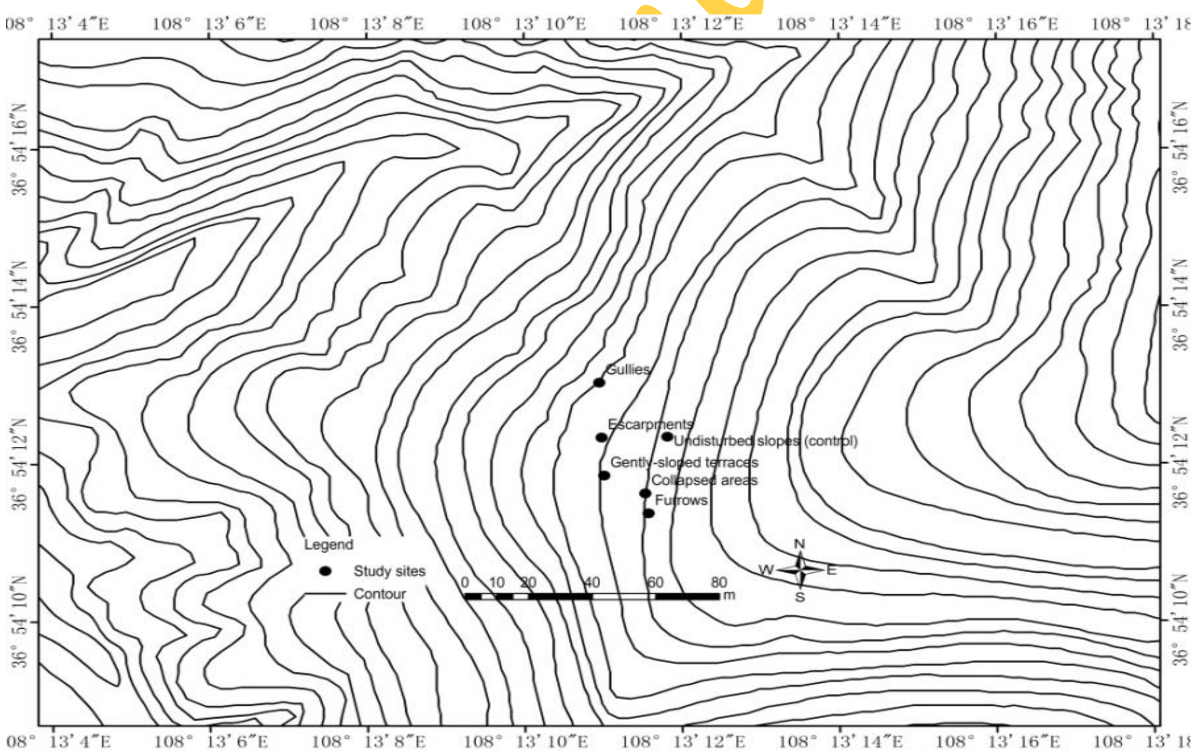


Fig. 2 : Distribution of the six observation points in the study area

automatically to ensure completeness. After field measurements, the two sets of data were processed and sorted using a computer. Precipitation and temperature data were collected from the Bureau of Meteorology, Wuqi County, Shaanxi Province, China.

Standardized precipitation index (SPI): The time scale was selected in accordance with research purposes, and the SPI values were calculated as the sum of precipitation at the selected time scale. Presently, a 12-month time scale is most commonly used for SPI calculation, which shows a high correlation with the Palmer Drought Severity Index, an annual precipitation evaluation coefficient (Logan *et al.,* 2010; Cancelliere *et al.,* 2007; Li *et al.,* 2013). In the present study, Researchers calculated the SPI values from the sum of annual precipitation, *i.e.*, 12-month precipitation, by referring to the research of Lloyd-Hughes and Saunders (Lloyd Hughes and Saunders, 2002). The SPI value is a designation of the adequacy of annual precipitation. In calculating of SPI, each precipitation value is assigned to a standard normal distribution value. When a precipitation value equals the precipitation average, SPI = 0. For evaluation of precipitation patterns (adequacy) in the loess region of northern Shaanxi, SPI classification criteria (Table 1) were proposed according to McKee *et al.* (1993).

Generation of contour maps of soil moisture content : A contour map can reflect the spatial-temporal dynamics of soil moisture content very accurately. Surfer (Golden, CO, USA) is a software package often used to create color contour maps, with major functions including interpolation, graphing, calculation and analysis, and variogram modeling (Cressie, 1992). The graphing function of Surfer is widely used in spatial analysis of meteorological factors and soil moisture. Surfer's powerful graphing capability enables the generation of regular grid data from discrete data through interpolation, and simple correct data conversion into colorful contour maps, pasting maps, image maps, shaded relief maps, vector maps, wireframes, and surfaces. In this study, Surfer 8.0 was used to generate contour maps of soil moisture content for different microtopographical units and undisturbed slope. The 5-year average monthly soil moisture content for 2008–2012 was interpolated using Kriging technique (Yao *et al.,* 2013) to generate grid data and maps.

Results and Discussion

Regional precipitation characteristics: In the study area, annual precipitation for 1957–2012 generally fluctuated around the average level over a wide range. The maximal annual precipitation (787.5 mm) occurred in 1964, and the minimal annual precipitation (270 mm) in 1986, showing a great difference of 517.5 mm (Fig. 3). The 56-year average annual precipitation for 1957–2012 was 468.9 mm (SD = 109.8 mm; CV= 23.4%). The 56-year variation trend in annual precipitation is shown by the 5-year annual precipitation averages, *i.e.,* 510.5, 520.5, 494.8, 488.5, 440.6, 441.7, 460.9, 427.4, 466.7, 447.2, and 460.4 mm for the periods of 5-year intervals from 1957–1961, 1962–1966, 1967–1971 . . . to 2007–2012, respectively. In addition to the great differences in annual precipitation, monthly precipitation fluctuated widely. The maximal monthly precipitation occured in August and averaged 109 mm, accounting for 23.25% of the average annual precipitation and followed by averaged in July, September and June (Fig. 4). During the growing season (May to October), average precipitation was 410.6 mm (87.57% of the average annual precipitation). This result indicated that most of the precipitation occured during the growing season and the hot and rainy summers of this regional climate (Wang *et al.,* 2011; Zhang *et al.,* 2011; Zhu *et al.,* 2011). During the fallow period (January to April; November to December), total precipitation only averaged 58.3 mm. In few years, no precipitation fell in some months.

Although annual changes in precipitation may describe rainfall variation trends, determining the adequacy of annual precipitation is still difficult. The 56-year changes in SPI (Fig. 5) generally coincided with the above mentioned changes during the 56-year precipitation (1957–2012). According to SPI classification for the evaluation of precipitation patterns (Table 2), one year, 1986 or 2% of all years, experienced extreme drought and 2 years, 1911 and 1981 (4%), had severe drought. Six years (11%) had moderate drought and 38 years (68%) received normal amount of precipitation, accounting for the largest proportion of 56-year time interval. Six years (11%) were moderately wet while 2 years, 1958 and 1961 (4%), had very high levels of precipitation and one year (2%) was extremely wet.

Compared with the 56-year average monthly precipitation for 1957–2012, the 5-year average monthly precipitation for 2008–2012 generally showed a declining trend (Fig. 4). Specifically, monthly precipitation declined for March to August and again in December, and the declining trend was particularly evident during the rainy season in July and August, consistent with previous findings of Zhao *et al.* (2012) in northern Shaanxi province. In contrast, monthly precipitation in January to February and September to November showed an increasing trend. Average precipitation during the growing season was 378.9 mm for 2008–2012, decreasing by 31.7 mm compared with that for 1957–2012 (410.6 mm). Precipitation during the growing

Table 1 : Standardized precipitation index (SPI) classification criteria

SPI value	$\leq$2.0	-1.99 to -1.5	-1.49 to -1.0	-0.99 to 0.99	1.0 to 1.49	1.5 to 1.99	$\geq$2.0
Precipitation pattern	Extreme drought	Severe drought	Moderate drought	Normal precipitation	Moderate wetness	Severe wetness	Extreme wetness

Table 2 : The number and proportion of years (1957–2012) with different precipitation patterns in the study area

Precipitation pattern	Number of year	Proportion in the 56-year period (%)
Extreme drought	1	1.79
Severe drought	2	3.57
Moderate drought	6	10.71
Normal precipitation	38	67.86
Moderate wetness	6	10.71
Severe wetness	2	3.57
Extreme wetness	1	1.79

Table 3 : Classification of the 5-year (2008–2012) precipitation pattern (adequacy) based on the standardized precipitation index (SPI)

Year	Annual precipitation (mm)	SPI	Precipitation pattern
2008	436.8	-0.29	Normal
2009	449.8	-0.11	Normal
2010	363.8	-0.87	Normal
2011	437.0	-0.24	Normal
2012	493.2	0.38	Normal

season was of great importance to plant growth, this reduction in precipitation would inevitably affect soil moisture content, as well as plant growth and vegetation biomass Zhao *et al.* (2010); Zhao *et al.* (2012). Table 3 provides SPI values of the 5-year atmospheric precipitation for 2008–2012. SPI classification results showed that all of the last 5 years (2008–2012) showed normal precipitation patterns (SPI = –0.29, –0.11, –0.87, –0.24, and –0.38). Since 38 out of the past 56 years (1957–2012) showed normal precipitation, 5 years of 2008–2012 were in a normal state with no substantial reduction or increase of precipitation in response to global climate change.

Temporal and spatial variations in soil moisture content : Fig. 6 (a–f, showing gently-sloped terraces, collapsed areas, furrows, gullies, escarpments, and undisturbed slopes, respectively) provides contour maps of 5-year average soil moisture content for 2008–2012. Regarding temporal distribution, soil moisture content at 0–160 cm depth showed the most dramatic changes in July and August during the year. Seasonal variations of soil moisture content displayed similar patterns among the microtopographical units and undisturbed slope (Fig. 6), consistent with seasonal variations in precipitation but showing a time lag for precipitation recharge during rainy season (Fig. 4).

The 5-year precipitation for 2008–2012 mainly peaked in July, August, and September, whereas the corresponding soil moisture content remained low in July and August, slightly rebounding in September, consistent with previous findings of Zhao *et al.* (2010) and Lu *et al.* (2009) in dry sunny microtopographical slopes on the Loess Plateau. This is because July and August experience high temperature, intense sunshine on semi-sunny slopes, and strong soil evaporation and plant transpiration; when combined with active vegetation growth in the most productive stage of plants, rainfall infiltration-redistribution in soil is slow; soil evaporation and slow water transport to deep depths also causes the reduced soil moisture content. In September, sufficient precipitation enables a thorough recharge of soil moisture. Atmospheric temperatures drops while sunlight

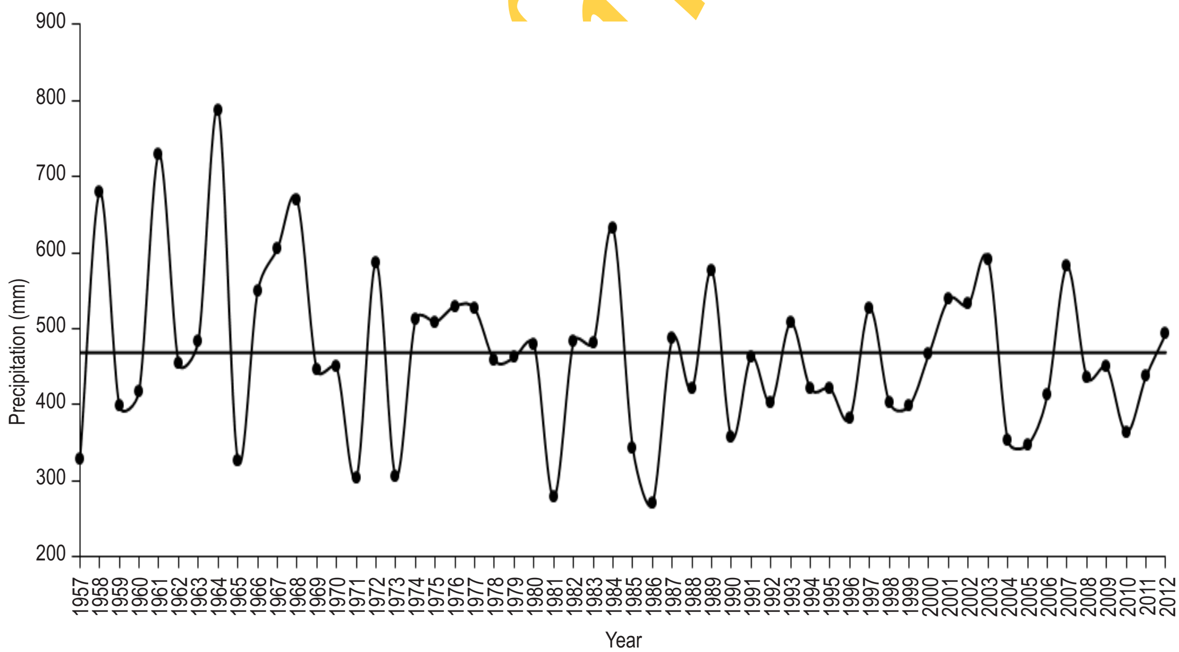


Fig. 3 : Average annual precipitation for 1957–2012 in the study area

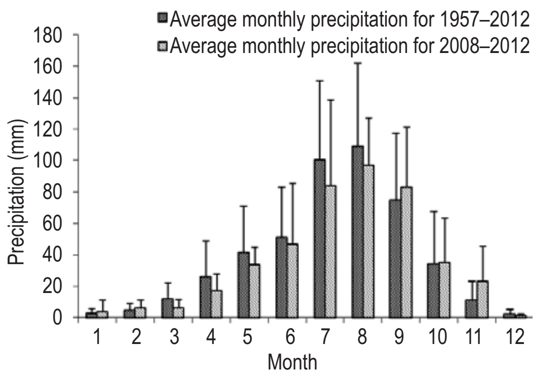


Fig. 4 : Average monthly precipitation for 1957–2012 and 2008–2012 in the study area

intensity declines. Vegetation growth enters a slow-growth stage with reduced soil evaporation and plant transpiration. Soil moisture recharge exceeds evaporation and transpiration consumption, accounting for increased soil moisture content.

Throughout the growing season, soil moisture content showed substantial variation in relation to microtopography (Fig. 6). Among different microtopographical units and undisturbed slope (control), gullies had the highest soil moisture content, followed by decreasing amounts for gently-sloped terraces; collapsed areas, undisturbed slopes (control), and furrows which have relatively low soil moisture content, and escarpments which have the lowest soil moisture content. This suggests that these two microtopographical units favor water reserve and storage, providing a reference for those interested in conducting vegetation restoration and rehabilitation in the study area. Spatial variation in soil moisture content in relation to microtopography diminished during rainy season, illustrating that microtopography exerts a stronger effect on soil moisture content during dry season than in the rainy season.

Regarding spatial distribution, soil moisture content at a depth of 0–40 cm underwent dramatic changes in relation to microtopography, and moisture levels were very unstable at that depth at various sites (Fig. 6). For gently-sloped terraces (Fig. 6a) and gullies (Fig. 6d), soil moisture content varied with depth in the order of 80–160 cm > 40–80 cm > 0–40 cm depth. For collapsed areas (Fig. 6b), furrows (Fig. 6d), and undisturbed slopes (Figure 6f), soil moisture content varied with depth in the order of 80–160 cm > 0–40 cm > 40–80 cm. The dramatic variation in soil moisture content at depth of 0–40 cm can be attributed to the joint influence of climatic factors such as precipitation, temperature, and wind (Lu *et al.,* 2009; Zhao *et al.,* 2010; Zhao *et al.,* 2012). During precipitation, rainwater first infiltrates into the surface layer, increasing soil moisture content rapidly. Then, a combination of surface evaporation, plant transpiration, root uptake, and capillary force- and gravity-driven downward movement leads to decreases in soil moisture at deeper depths.

At depths of 40–80 cm, soil moisture receives bi-directional recharge, through infiltration of precipitation from the upper layer and upward moving moisture drawn by surface evaporation from the lower layer. In addition, the native vegetation in areas that had previously been farmland mainly comprises herbaceous plants, with the majority of roots distributed at depths of 40–80 cm. Together the above

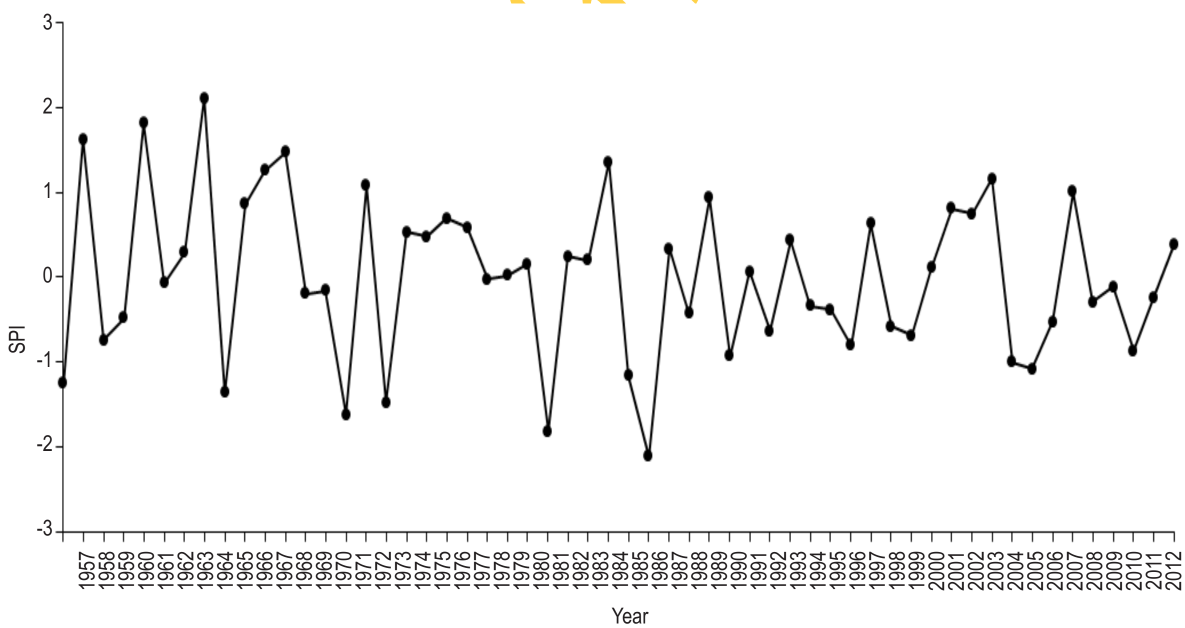
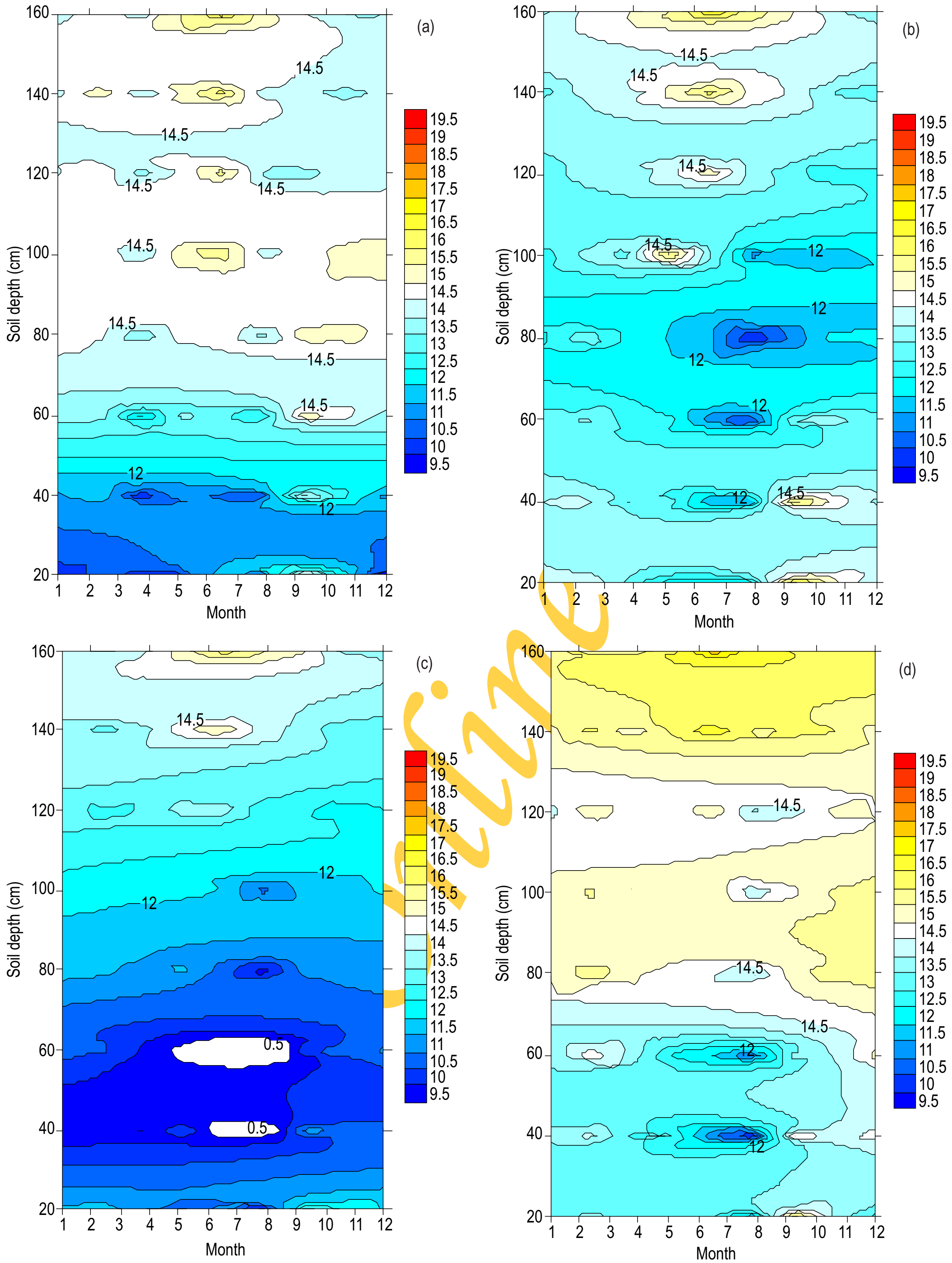


Fig. 5 : Standardized precipitation index for 1957–2012 in the study area


(a)
(b)
(c)
(d)
Soil depth (cm)
Month
160
140
120
100
80
60
40
20
1 2 3 4 5 6 7 8 9 10 11 12
19.5
19
18.5
18
17.5
17
16.5
16
15.5
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11.5
11
10.5
10
9.5
14.5
12
0.5

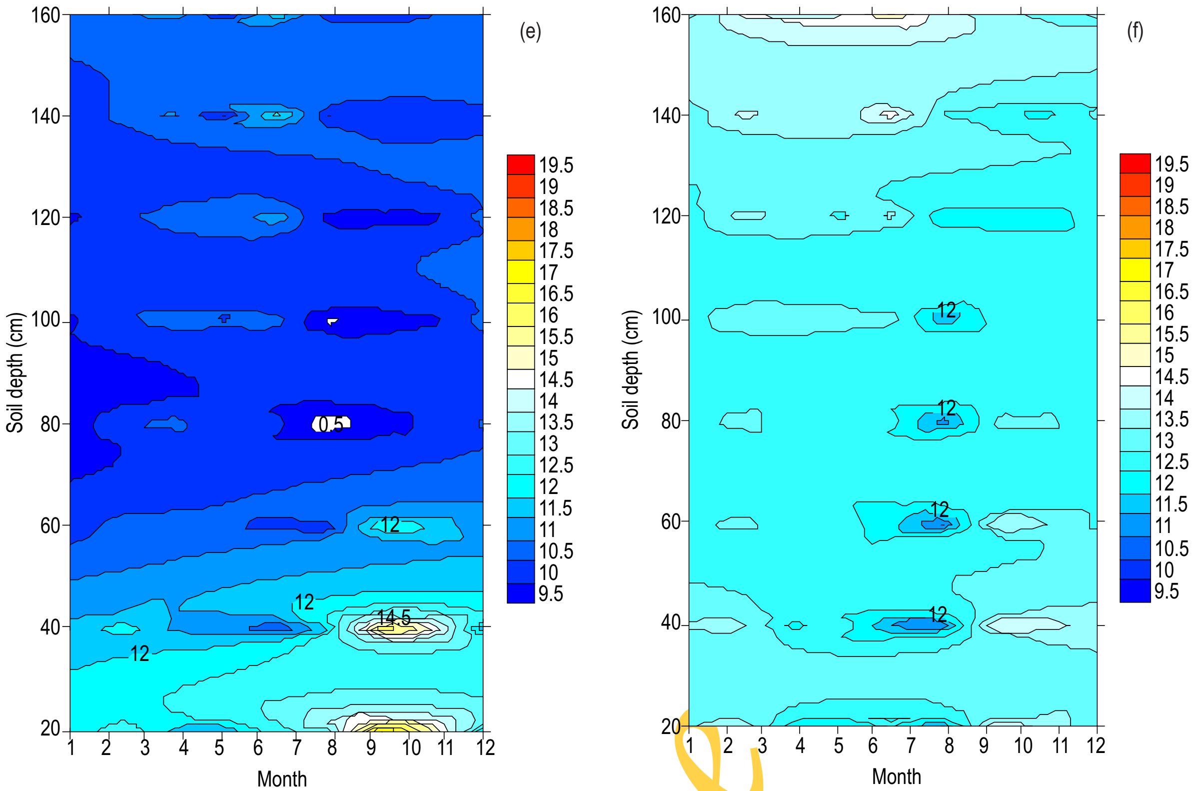

Fig. 6 : Contour maps of soil moisture content in different microtopographical units. a, gently-sloped terraces; b, collapsed areas; c, furrows; d, gullies; e, escarpments; and f, undisturbed slopes (control)

observations explain the moderate instability of soil moisture content between wetter and drier states, with either higher or lower soil moisture than that at the upper layer (0–40 cm).

At depths of 80–160 cm, soil texture becomes more compacted than that in the upper layer, thus generating greater resistance to the migration of soil moisture; soil moisture content is less affected by soil evaporation and associated precipitation recharge is slow. Under the influence of a water potential gradient, soil moisture recharge mainly comes from infiltration of precipitation through the upper layer and is unaffected by plant roots, with almost no discharge. Thus, soil moisture content at depths of 80–160 cm remains at relatively high levels with stable variations, showing high uniformity. Soil moisture not only serves as the water supply layer for existing herbaceous plants at these sites but also has implications for future forest rehabilitation.

For escarpments (Fig. 6e), soil moisture content varies with depth in a different trend: 0–40 cm > 80–160 cm > 40–80 cm. It is possible that the unique microtopography of escarpments receives less intense sunlight than slope, resulting in low surface evaporation and effectively saving soil moisture at 0–40 cm, whereas a combination of root utilization and water loss by lateral seepage accounts for the reduced soil moisture content at 40–80 cm depth.

Based on the above results, we propose land managers to consider microtopography and make tree selection carefully when simulating natural forests using artificial afforestation. This will allow the reasonable selection of species for tree-shrub-grass vegetation rehabilitation in the diverse microtopographical units in the loess region of northern Shaanxi. In gullies and gently-sloped terraces that have relatively high soil moisture content, the vegetation selected can be optimized to improve the tree-grass composite community structure. Specifically, tree species with low water consumption (e.g., *Pinus tabulaeformis* and *Robinia pseudoacacia*) can be planted and expected to thrive along the gully bases by retaining the original herbaceous plants and planted trees based on the gully shape and size. In gently-sloped terraces, the vegetation selected for planting can also be dominated by the tree-shrub-grass-based composite structure; sparse shrubs can be planted in banded patterns by retaining the original herbaceous plants at appropriate plantation density, combined with enhanced tending management. For collapsed areas, vegetation allocation should be based on a shrub-grass composite model, with scattered, shallow-rooted shrubs planted based on the actual situation and site conditions. The undisturbed slopes and furrows had similar vegetation and thus were not treated differently. However, semi-shrubs with low water consumption or herbaceous plants, at a more advanced stage of succession, could be used for furrows with long evolutionary history and sound soil moisture conditions. Considering the lowest soil moisture content exists in areas of escarpments, vegetation used here should be based on a natural restoration (enclosure protection) model, in which the existing herbaceous vegetation is protected and steep-slope silvicultural techniques are used for plant rooting, further ensuring the conservation and survival rates of plants.

Overall, research on the regional characteristics of precipitation and the spatiotemporal variations in soil moisture in relation to microtopography provides sound and rational reference data for natural-simulating artificial afforestation in the study area. The outcome would accelerate natural vegetation restoration in diverse microtopographical units of the Loess region in Northern Shaanxi; it would allow land managers to avoid problems created by implementation of engineering measures to some extent, such as use of large rehabilitation areas and low survival and conservation rates of plants previously used for vegetation cover.

The results of 56-year precipitation analysis (1957–2012) showed that with the influence of global climate change, annual precipitation stays in a normal state. Regarding spatiotemporal variations in soil moisture content, contour maps showed that soil moisture content at 0–40 cm depth underwent dramatic changes and showed high instability in relation to microtopography. In terms of temporal distribution, soil moisture content at 0–160 cm depth showed the most dramatic changes and was lowest in July and August compared to data of the other months.

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