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Original Research Paper

Study of Soil Moisture Dynamics in Relation to Microtopography in the Loess Region of Northern Shaanxi, China

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ABSTRACT

Soil moisture is the primary limiting factor of vegetation restoration and rehabilitation in the loess region of northern Shaanxi Province, China. A 5-year study was conducted in a microtopographically diverse landscape of Chinaô's loess region on the dynamics (monthly variations, vertical distribution, spatial variability) of soil moisture content in representative microtopographical units (including undisturbed slope as a control) as part of a long-term observational experiment at the Wuqi Ecological Station of Beijing Forestry University. One goal was to improve the efficiency of the use of soil moisture through a reasonable spatial distribution of planted vegetation. According to the 5-year average monthly variations in soil moisture content, we divided soil moisture conditions in the study area into four stages: slow moisture loss (March to May), moisture depletion (June to August), slow recovery (September to October), and stabilization (November to February). From January to December, soil moisture content varied with microtopography as follows: gullies > gently sloped terraces > collapsed soils > undisturbed slopes (control) > furrows > scarps. In terms of vertical distribution, soil moisture content varied obviously and was stratified; it also increased with increasing soil depth. Specifically, soil moisture content was generally low at 0-20 cm deep, varied considerably at 20-100 cm deep and the variation of soil moisture increased significantly at 100-160 cm deep. Spatial variability of soil moisture content in relation to microtopography can be categorized as follows: scarps > undisturbed slopes > furrows > collapsed areas > gentle-sloped terraces > gullies. These results provide reference information for implementing microtopographical and tree-oriented near-natural afforestation and optimizing vegetation selection for diverse microtopographical units of the loess region of northern Shaanxi.

INTRODUCTION

Soil moisture is a crucial factor of the soil-plant-atmosphere continuum, which serves as the carrier of nutrient cycle and flow in soil system and integrally reflects climatic factors (e.g., precipitation) and soil characteristics (Fortin et al. 1989, Tansey et al. 1999). Soil moisture not only directly affects soil properties and plant growth, but also indirectly affects plant distribution and ecosystem microclimate (Walker et al. 2001, Cârdei et al. 2010, Srivastava et al. 2012). Researching spatial distribution patterns of soil moisture content is of importance to understand the conditions of vegetation, the relationship of vegetation and soil, and the spatial distribution patterns of vegetation (Chen et al. 2008). In recent years, natural-simulating artificial afforestation and vegetation construction in the loess region have encountered a series of problems related to the low survival, conservation, and growth rates of forests and grasses, small-old trees, low-yield low-function forests, and dried soil layer (Qiu et al. 2010). Soil moisture is the limiting factor for the above issues, which becomes the primary limiting factor for plant growth and vegetation restoration in the loess region (Henderson-Sellers 1996).

Research related to microtopography has been conducted in a number of countries. The effects of microtopography on vegetative ecology (Alpert 2008), vegetation type (Moser et al. 2007), and soil texture (MartinezTuranzas et al. 1997) have been studied in the United States. Scholars from Japan investigated the relationship between microtopography and vegetation structure (Hara et al. 1996), spatial tree distribution patterns in relation to microtopography (Enoki 2003), differences in vegetation and resource allocation in microtopographical units of lower slopes (Kikuchi & Miura 1991), effects of microtopography on forest structure (Kikuchi & Miura 1993), tree mortality (Nagamatsu et al. 2003), landscape pattern of vegetation (Sakai & Ohsawa 1993), and microtopographical changes in soil-plant systems (Tokuchi et al. 1999). In China, studies have been reported on soil moisture characteristics and soil distribution patterns by analysing microtopographical units of sunny, dry slopes (Zhao et al. 2010). However, previous studies have investigated soil moisture mainly at the regional, watershed and slope scales (Hu et al. 2010, Hawley et al. 1983, Nagamatsu & Miura 1997, Western & Blöschl 2010), while few reports are available on soil moisture characteristics at a microtopographical scale. Additionally, existing research on the distribution of soil moisture in microtopographical units is largely limited to 1 or 2-year periods, without long-term monitoring data, so the evidence presented in earlier research is relatively weak.

In view of the above issues, this study investigated soil moisture dynamics in relation to microtopography in the loess region; this was done using a long-term experiment at the Wuqi Ecological Station of Beijing Forestry University. The results provide a better understanding of soil moisture dynamics in relation to microtopography with the goal of improving water use efficiency in the study area, provide reference data for eco-environmental rehabilitation in the loess region of northern Shaanxi, and further propose microtopographical and tree-orientated near natural afforestation principles and an optimal vegetation selection model for sites with varied microtopography.

OVERVIEW OF THE STUDY AREA

The study area was the Hejiagou catchment of Wuqi County, Yan'an (36°33'33''-37°24'27'' N and 107°38'57'' - 108°32' 49'' E). The catchment stands at 1233-1890m above sea level and has an semiarid continental monsoonal climate. It has an average annual temperature of 7.8°C, an accumulative temperature (≥10°) of 2817.8°, an average annual sunshine of 2400 hours, a frost-free period of 96-146 days and an average annual evaporation of 400-450mm. Its topography is gully and hilly and its vegetation is transiting from forest steppes into grasslands. Since 1998, the catchment has been closed to facilitate its vegetation rehabilitation and now its main vegetation is herbaceous communities, accompanied by sparse undershrubs and arbor saplings as well as arbor species on valley bed lands (Zhu et al. 2011).

RESEARCH METHODOLOGY

Sample Plot Choosing and Field Investigations

In 2008, five representative microtopographic units and one undisturbed slope (control) were selected in accordance with the microtopographic features (e.g., degree and direction of slope) by taking into consideration the sampling scale and site representativeness. Fixed long-term observation stations were set at the selected points as indicated. The background information of each microtopographic unit including the undisturbed slope is given in Table 1. At each observation point, a 2-m long 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 based on high-precision time-domain reflectometry. The measurement was made from ground surface downward to 160 cm depth at 20 cm intervals. For each depth interval, soil moisture content was measured three times (probe rotated by 120° each time), and means of the three measurements were taken as soil moisture content of the depth interval.

Data Processing

Vertical division of soil moisture content: To analyse the vertical distribution of soil moisture, a cross section of soil moisture content can be divided vertically based on the inter-layer variations in soil properties. For vertical classification of the distribution of soil moisture in the loess region of northern Shaanxi, the coefficient of variation (C_v) and standard deviation (SD) are commonly used to divide vertical variations in soil moisture content along the cross section into four layers, including the rapid change layer ($C_v >$ 30%, $SD > 4$), the active layer (C_v = 20-30%, SD = 3-4), the sub-active layer (C_v = 10-20%, SD = 2-3), and the relatively stable layer ($C_v <$ 10%, $SD < 2$). In practice, however, C_v and SD may not simultaneously meet the above two division criteria. If so, C_v is taken as the sole criterion for vertical division of soil moisture content. Equations (1) and (2) show the calculations for C_v and its SD as follows (Pan et al. 2008).

$$C_V = \frac{SD}{\bar{x}} \quad ...(1)$$

$$SD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)} \quad ...(2)$$

Where $\bar{x}$ is sample (observed value of soil moisture content) average, n is the number of samples, and x_i is the i^{th} observed value of samples.

Data processing and drawing: The study employed Excel 2010, SPSS 20.0 and ArcGIS 9.3 for data processing, statistical calculations and drawing.

RESULTS AND ANALYSIS

Monthly variation in soil moisture content: In the study area, only natural precipitation recharges soil moisture. Thus, soil moisture characteristics are mainly determined by the intra-year monthly variation in precipitation. In this study, monthly variations in soil moisture content in relation to microtopography were calculated from the average monthly soil moisture content in different layers and the 5-year average monthly soil moisture content for 2008-2012.

In different microtopographical units, soil moisture content had similar seasonal variations, consistent with the variation patterns in the 5-year precipitation data (Fig. 1). However, recharge of soil moisture by precipitation during the rainy season lagged to a certain degree, and soil moisture content remained low from July to September, rebounding slightly in October. This occurred because the area experiences high temperature from July to September, with intense sunshine on semi-sunny slopes, and strong soil evaporation and plant transpiration. In addition, active vegetation growth during the most productive season is slow because water is limited. Rainwater infiltration-redistribution to a deep depth and soil evaporation-transportation also account for the decrease in soil moisture. In October, increased precipitation thoroughly recharges soil moisture; atmospheric temperature drops while sunlight intensity declines; vegetation growth enters a slow-growth stage and thus reflects the reduced soil evaporation and plant transpiration. Soil moisture recharge exceeds evaporation and transpiration consumption, accounting for the increased soil moisture content. In November, a dramatic decrease in precipitation coincides with decreased soil moisture followed by minor changes until the next February. In spring (March to April), the vegetation starts a new round of growth and development, consuming moisture and resulting in a decrease in soil moisture. During the growing season until September, soil moisture content gradually recovers to the level of field moisture capacity. Based on the above intra-year monthly dynamics of soil moisture content (Fig. 3), we divided soil moisture activity in the study area into the following four stages: March to May, slow moisture loss stage; June to August, moisture depletion stage; September to October, slow recovery stage; and November to the following February, stabilization stage.

From January to December, soil water content varied widely with changes in microtopography (Fig. 1). For example, gullies had the highest soil water content while scarps had the lowest. That is, soil moisture content varied with microtopography in the following order: gullies > gently sloped terraces > collapse soils > undisturbed slopes > furrows > scarps. This result suggests that gullies and gently sloped terraces are favourable microtopographical units for water reserve and storage, providing a reference for near-natural vegetation restoration and ecological re-construction in the study area.

Vertical distribution of soil moisture content: In the vertical cross section, various soil layers are arranged differently in different spatial locations, and thus each layer receives precipitation in a specific sequence. The effects of rainwater infiltration create an inter-layer difference in soil moisture content. The loss of soil moisture content is also affected by other factors including spatial location, soil hydraulic conductivity, and moisture uptake by plant roots. Together, the above factors contribute to the observed differences in the vertical distribution of soil moisture content among the microtopographical units (Fig. 2).

In the study area, the 5-year (2008-2012) average soil moisture content displayed different patterns of vertical distribution in relation to microtopography (Fig. 2). Across the entire soil section (0-160 cm), gullies and scarps had the highest and lowest soil moisture contents respectively, providing a reference for optimizing the re-stabilization of vegetation during the process of ecological restoration. Additionally, soil moisture content displayed obviously stratified variations in the vertical cross section and gradually increased with increasing soil depth (Fig. 2). Compared with other layers, surface soil (0-20 cm deep) had the lowest soil moisture content, possibly because strong solar radiation caused intense evaporation on semi-sunny slopes. Conversely, surface soil moisture content was relatively high for scarps, possibly because solar radiation was limited by this unique microtopographical feature compared with that received by slopes, leading to relatively low evaporation rates and thus high soil moisture content. With increasing soil depth, soil moisture content showed variable fluctuations at 20-100 cm depth. We speculate that the majority of plant roots are widely distributed within this range of soil depth, enhancing soil moisture variability through water uptake. The variations in soil moisture content at depths of 100-160 cm were increasingly significant, mainly because plant roots received little water from below 100 cm. Additionally, soil texture is more compacted than in the upper layers, preventing some movement of soil

Table 1: Background information of the study site.

Microtopography	Direction of slope	Degree of slope (°)	Elevation (m)	Latitude	Longitude
Gently-sloped terrace	Semi-sunny slope	43	1385	E108°13’ 11.0’	N36°54’ 11.9’
Collapse	Semi-sunny slope	43	1399	E108°13’ 11.0’	N36°54’ 12.0’
Furrow	Semi-sunny slope	43	1391	E108°13’ 11.3’	N36°54’ 11.5’
Gully	Semi-sunny slope	30	1401	E108°13’ 11.4’	N36°54’ 12.7’
Scarp	Semi-sunny slope	40	1411	E108°132 16.23	N36°542 10.93
Undisturbed slope (control)	Semi-sunny slope	30	1405	E108°132 11.53	N36°542 12.33

moisture; as a result, soil moisture content is subjected to minor effects from evaporation (nearly none) and thus remains at relatively high levels at deeper depths (>100 cm). The above results indicate water at depths of 100-160 cm soil depth provide an important supply supporting plant growth, which should be given priority in future vegetation stabilization and afforestation efforts in the loess region.

Spatial variability of soil moisture content: Soil moisture content often undergoes dynamic spatial changes and variability caused by the effect variations in precipitation, infiltration, runoff and evaporation. In the study area, soil moisture content varied dynamically in the various microtopographical units. Even with the same microtopographical type, soil moisture content varied at different depths in the vertical cross section (Table 2). Despite its varying C_v values, soil moisture content at different soil depths had similar variation patterns in different microtopographical units. The C_v value of soil moisture content declined with increasing soil depth, showing the same effects on soil moisture content as did the external environmental factors such as precipitation and temperature. Correlation analysis showed that soil depth was significantly negatively correlated with the C_v value of soil moisture, with the Pearson correlation coefficient of -0.939 (two-tailed, $P < 0.01$) (Table 3).

Based on soil moisture data of different microtopographical units, C_v values of soil moisture content reached a maximum (30-40%) at depths of 0-40 cm; the minimal C_v values of soil moisture content (7-10%) were mainly observed at depths of 100-160 cm (Table 2). In terms of microtopography, the average C_v of soil moisture content varied with microtopography as follows: high C_v (scarp > undisturbed slope) > moderate C_v (furrow > collapse > undisturbed slope) > low C_v (gently sloped terrace > gully).

For soil moisture content of different microtopographical units, rapid changes generally occurred at depths of 0-40 cm, with substantial differences in vertical stratification of soil moisture content below 40 cm. For soil moisture content of gullies and gentle-sloped terraces, the rapid change layer was distributed in a narrower range (0-20 cm depth), with the active layer at 20-60-cm depth, sub-active layer at 60-100 cm, and the stable layer below 100 cm. Compared with the remaining microtopographical units, gullies and gently sloped terraces can provide relatively stable microhabitat conditions for vegetation growth.

Soil moisture content of collapsed areas and furrows had a moderate average C_v with similar variation patterns at 0-40 cm depth (i.e., rapid change layer for both). However, soil moisture content of collapsed areas had an active layer at 40-80 cm and a sub-active layer at 80-120 cm, entering a stable layer from 120 cm. In contrast, soil moisture content of furrows had an active layer at 40-100 cm and a sub-active layer at 100-140 cm, entering a stable layer from 140 cm. The above results indicate that collapsed areas and furrows

Table 2: Spatial variability of soil moisture content in different microtopographical units.

Soil depth (mm)	Gently sloped terrace			Collapse			Furrow		
	SD	Cv	Active Level	SD	Cv	Active Level	SD	Cv	Active Level
0-20	4.37	38.38	The rapid change layer	3.92	34.87	The rapid change layer	3.49	35.02	The rapid change layer
20-40	3.29	27.95	The active layer	4.29	31.32	The rapid change layer	3.47	32.73	The rapid change layer
40-60	3.19	23.25	The active layer	3.10	24.46	The active layer	2.66	26.98	The active layer
60-80	2.49	17.15	The sub-active layer	3.16	26.66	The active layer	2.43	21.75	The active layer
80-100	1.85	13.14	The sub-active layer	2.00	15.62	The sub-active layer	2.76	23.28	The active layer
100-120	1.43	9.87	The relatively stable layer	1.38	10.16	The sub-active layer	1.80	13.93	The sub-active layer
120-140	1.26	8.50	The relatively stable layer	1.30	9.06	The relatively stable laye	1.92	13.79	The sub-active laye
140-160	1.19	7.93	The relatively stable layer	1.30	8.62	The relatively stable laye	1.46	9.88	The relatively stable laye
Soil depth (mm)	**Gully**			**Scarp**			**Undisturbed slope (control)**		
	SD	Cv	Active Level	SD	Cv	Active Level	SD	Cv	Active Level
0-20	4.29	32.83	The rapid change layer	3.99	37.83	The rapid change layer	3.95	36.47	The rapid change layer
20-40	3.58	27.17	The active layer	3.54	36.01	The rapid change layer	4.58	34.92	The rapid change layer
40-60	2.80	21.09	The active layer	2.78	27.30	The active layer	3.41	26.81	The active layer
60-80	2.45	16.27	The sub-active layer	2.41	23.64	The active layer	2.88	22.93	The active layer
80-100	1.85	12.59	The sub-active layer	2.15	20.07	The active layer	2.38	18.89	The sub-active layer
100-120	1.45	9.61	The relatively stable layer	1.67	15.36	The sub-active layer	1.80	14.09	The sub-active layer
120-140	1.39	8.71	The relatively stable layer	1.52	13.87	The sub-active layer	1.65	12.27	The sub-active layer
140-160	1.16	7.06	The relatively stable layer	1.49	12.86	The sub-active layer	1.63	11.52	The sub-active layer

Table 3: Correlation analysis of the coefficient of soil moisture variation and soil depth.

Pearson Correlation Coefficient	-0.939**
N	48

Note: **Correlation is significant at $P < 0.01$.

are unfavourable for providing stable growth conditions for deep-rooted plants.

Undisturbed slopes had the average C_v of soil moisture content smaller than scarps but greater than collapsed areas and furrows. Among different microtopographical units, scarps had the greatest average C_v of soil moisture content. Neither undisturbed slopes nor scarps had a stable layer of soil moisture; that is, when compared with the remaining microtopographical units, these areas cannot provide stable habitat conditions for plant growth.

DISCUSSION AND CONCLUSION

In different microtopographical units, soil moisture content displayed similar seasonal variations as regional precipitation. The variations and soil moisture content conditions in the study area can be divided into four stages, including the slow moisture loss stage (March to May), moisture depletion stage (June to August), slow recovery stage (September to October), and stabilization stage (November to next February). From January to December, soil moisture varied with microtopography as follows: gully > gently sloped terrace > collapse > undisturbed slope (control) > furrow > scarp. The results indicate that gullies and gently sloped terraces are favourable microtopographical units for providing a soil moisture reserve and for moisture storage. This finding provides guidance to land managers attempting to optimize artificial afforestation efforts and to conduct near-natural vegetation restoration.

The vertical distribution of average soil moisture content also displayed different patterns with microtopography. Across the entire vertical section (0-160 cm), gully and scarp microsites have the highest and lowest soil moisture content, respectively. These provide reference information for the optimization of plant selection during vegetation restoration. Additionally, soil moisture content showed obviously stratified vertical variations, and it generally increased with increasing soil depth. Overall, soil moisture content was relatively low at the surface (0-20 cm deep), with unstable variations at 20-100 cm deep and significantly increasing variations at depths of 100-160 cm. Thus, the soil at depths of 100-160 cm provides the most stable water supply for plant growth.

Regarding spatial variability of soil moisture content in different microtopographical units, the coefficient of variation of soil moisture content declined with increasing soil depth. A significant negative correlation was found between soil depth and the coefficient of variation in soil moisture content. That is, with increasing soil depth, the recharge of soil moisture from precipitation declined, accounting for the increasing stability of soil water content.

In conclusion, in the loess region of Northern Shaanxi, crisscrossed gullies form fragmented topographies and thus catchments or slopes are investigated as individual units for artificial vegetation restoration; but diverse microtopography, which the fragmented topographies and ground coverage act together to form, have different microhabitats resulting in such commonly ignored problems as poor vegetation growth (stunted trees) and low vegetation survival rates. The study put forward the vegetation distribution-optimizing model of matching microtopography against proper trees and developed the closer to nature microtopography forestation principle. Gully and gently-sloped ter-

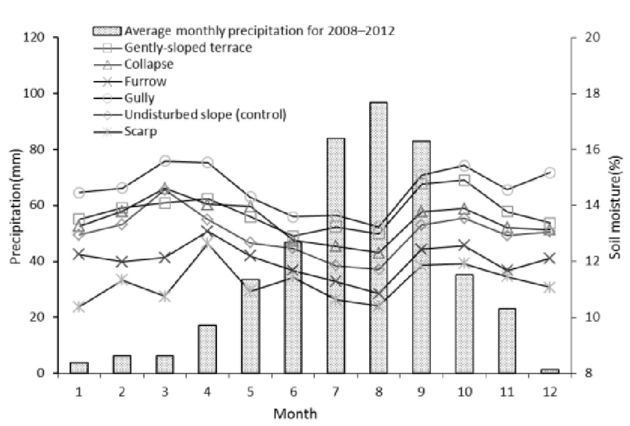

Fig. 1: 5-year average monthly precipitation and soil moisture content in relation to microtopography (undisturbed slope, control; 2008-2012).

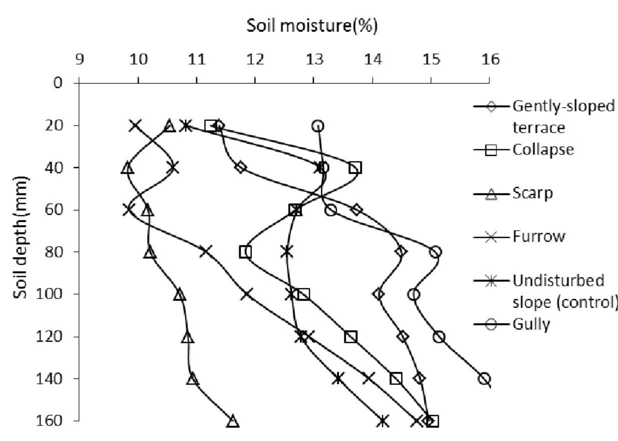

Fig. 2: Vertical distribution of the 5-year average soil moisture content in relation to microtopography (undisturbed slope, control; 2008-2012).

race had higher soil moisture content and as a result original herbaceous plants for gully should be preserved and arbors should be chosen for vegetation restoration, that is to say, the vegetation rehabilitation-optimizing model for him should be the arbor and grass combined one; the vegetation rehabilitation-optimizing model for gently-sloped terrace should be the arbor, shrub and grass combined one as well the model of artificial forestation or grass planting; the scarp had the lowest soil moisture content and as a result the vegetation rehabilitation-optimizing model for him should be the model of natural vegetation restoration (by preventing them from grazing and tree felling) instead of tree planting, which was labour, material and capital saving. The collapse, furrow and undisturbed slope (control) had moderate soil moisture content and as a result the vegetation rehabilitation-optimizing model for them should be the shrub and grass combined model complemented with the models merely relying on shrubs or grasses. In the region, study of soil moisture dynamics in relation to microtopography could provide scientific basis for closer to nature forestation, hence speeding up vegetation restorations of different microtopography in the loess region of Northern Shaanxi as well as avoiding such problems as too larger areas involved and lower vegetation survival rates while engineering measures were adopted.

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