Catena 124 (2015) 138–146

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Effects of vegetation restoration on the spatial distribution of soil moisture at the hillslope scale in semi-arid regions

Lei Yang, Liding Chen *, Wei Wei

State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

ARTICLE INFO

Article history:
Received 27 February 2014
Received in revised form 22 August 2014
Accepted 25 September 2014
Available online 10 October 2014

Keywords:
Soil moisture
Hillslope
Spatial variation
Vegetation restoration
Semi-arid

ABSTRACT

Soil moisture is important for plant growth in semi-arid ecosystems. In this study, spatial variations in soil moisture at depths of 0–6 m on seven hillslopes of China's Loess Plateau planted with korshinsk peashrub were analyzed based on soil moisture observations. The objective of this study was to compare the spatial patterns in soil moisture in shallow and deep soil layers at the hillslope scale under the influence of large-scale vegetation restoration. The results showed that: (1) the topographic wetness index was positively correlated with soil moisture near the surface (0–1 m), but negatively correlated with soil moisture at depths below 2 m; and (2) the negative relationship was found between biomass and soil moisture content in deep layers. Soil moisture in shallow layers was more likely to be affected by topographic factors. However, comparisons of soil moisture at different slope positions indicated that the effect of topographic factors on the variability of deep soil moisture was altered, mainly because plants with different biomasses may differ in their consumption of soil water and thus cause greater spatial variations in deep soil moisture. The introduced vegetation may alter the spatial pattern of deep soil moisture influenced by topographic factors at the hillslope scale, and the biomass may have a determining role in the spatial variation of deep-layer soil moisture content.

1. Introduction

Soil moisture is important for plant growth and plays a critical role in many surface processes in terrestrial ecosystems (Legates et al., 2011; Porporato et al., 2002). Characterizing soil moisture variations across a range of spatial and temporal scales is important for both theoretical and practical applications (Ivanov et al., 2010). Soil moisture distributions have important implications for runoff (Price, 2011), agriculture (Hebrard et al., 2006) and vegetation restoration (Engelbrecht et al., 2007). Understanding the spatial variability of soil moisture and its influencing factors will provide a basis for optimizing the spatial allocation of vegetation restoration efforts. Soil moisture and its spatial variation are closely related to vegetation (Ferreira et al., 2007; Vivoni et al., 2008). This is particularly true for ecosystems in arid and semi-arid environments (Sanchez-Mejia et al., 2014). The interaction between soil moisture and vegetation is likely to become a critical issue of great interest to researchers in hydrology, ecology, and geography.

There is growing agreement in the scientific literatures that many factors can affect spatial variation in soil moisture. In addition to vegetation attributes, topographic factors, soil depth and soil properties all play key roles (Gómez-Plaza et al., 2000; Qiu et al., 2001). Specifically, small-scale topographic variability results in significant local redistribution of precipitation and surface runoff (Crave and Gascuel-Odoux, 1997). This redistribution inevitably affects the spatial variation in soil moisture (Legates et al., 2011; Meerveld and McDonnell, 2006). For example, the topographic wetness index (TWI), which is based on topographic factors (upslope contributing areas and slope gradient), can represent soil moisture conditions under the influence of topographic factors well (Ali et al., 2010; Cantón et al., 2004; Western et al., 2004). However, soil moisture at different depths may have a different response to influencing factors in afforested land (Venkatesh et al., 2011).

The Loess Plateau of China is covered by loess soil nearly 100 m thick with a loose soil structure (Chen et al., 2007). Very little of the groundwater in this region can be used by plants due to the depth of the water table (Chen et al., 2008a). In this region, introduced vegetation has become the main vegetation type due to the large-scale implementation of “Grain to Green Program” initiated by the central government in 1999 (Chen et al., 2010). However, unlike native plants, introduced vegetation usually has a higher water demand and annual rainfall levels cannot supply sufficient water for growth (Chen et al., 2008a; Wang et al., 2010). Introduced plants in this region are thus forced to develop deep and robust root systems to utilize soil moisture in deep soil layers (Chen et al., 2008a; Yang et al., 2012a). The limited water stored below the surface layers has become a particularly important component of ecosystems in this region. Evaluation of the influence of vegetation restoration on local deep soil moisture in this area is thus urgently needed.

Several recent studies have been conducted on deep soil moisture depletion (Wang et al., 2010; Yang et al., 2012a) and regional water yield reduction (Sun et al., 2006) influenced by large-scale vegetation

---

* Corresponding author. Tel.: +86 10 62943840; fax: +86 10 62849014.
E-mail address: liding@rcees.ac.cn (L. Chen).

http://dx.doi.org/10.1016/j.catena.2014.09.014
0341-8162/© 2014 Elsevier B.V. All rights reserved.

restoration in the Loess Plateau. However, these studies paid limited attention to the question of how spatial variations in deep soil moisture are influenced by vegetation restoration. Topography is a particularly important determinant of soil moisture patterns in this region (Qiu et al., 2001; Zhu and Shao, 2008). Because soil properties are homogeneous in small loess watersheds (Jin et al., 2011), the topography becomes more important in the control of soil moisture dynamics and redistribution (Qiu et al., 2001). Specifically, because deep soil moisture is an important stable water source for introduced vegetation, understanding the spatial variation in deep soil moisture is fundamental for the possible optimization of vegetation restoration.

As discussed above, soil moisture is significantly influenced by vegetation and topography in such regions. Identifying the interactions between soil moisture and vegetation/topography thus improves understanding of the mechanisms that organize vegetation structure in human-influenced ecosystems. However, the main factors affecting spatial variations in deep soil moisture under the influence of vegetation restoration still requires urgent elucidation. Due to the current observational limitations in the subsurface, most empirical studies can only focus on spatial variations in shallow surface water (Ivanov et al., 2010). The hillslope is a basic component of the landscape and is of primary importance in understanding the physical mechanisms that underline the heterogeneity of states and fluxes in simple-geometry topographic units (Ivanov et al., 2010).

This study was designed to compare the soil moisture in shallow and deep soil layers on seven separate hillslopes planted with a typical introduced vegetation, korshinsk peashrub (*Caragana korshinskii* Kom.), to support more effective restoration policies in arid and semi-arid areas. Therefore, the objectives of this study were (1) to analyze the spatial patterns of soil moisture in different soil layers on hillslopes, (2) to investigate the correlations between spatial patterns of soil moisture and vegetation/topographic features, and (3) to elucidate the main factors affecting spatial distributions in deep soil moisture at the hillslope scale.

2. Materials and methods

2.1. Study area

The study area is located in Longtan watershed (35°43′–35°46′N, 104°27′–104°31′E) in Gansu Province, and covers an area of 16.1 km^2. The altitude ranges from 1840 m to 2260 m and the landscape is highly fragmented. The study area is a typical hilly semi-arid loess region, with a mean annual temperature of approximately 6.8 °C and a mean annual precipitation of approximately 386 mm. Most of the rainfall occurs in the form of thunderstorms from July to September. The potential annual evaporation (pan evaporation) is about 1649 mm. The annual averages were derived from meteorological data provided by a meteorological station 0.6 km from the watershed and represent 45-year averages (1961–2006). Based on 2008–2012 data from five spatially distributed automatically recording rain gauges, the rainfall pattern has a uniform spatial distribution in the watershed. Loess soil with low fertility is the main soil type in this area; such soils are vulnerable to erosion. Typically they have a loose structure, a high silt content (ca. 81%), a soil moisture field capacity of 0.180–0.240 g/g, a saturated moisture content about 0.470 g/g, and contain little organic matter (ca. 0.2–2.9%). Soil thickness in the study area varies from 40 m to 60 m. The predominant vegetation types are introduced vegetation (such as korshinsk peashrub, alfalfa, Chinese red pine, and others), rain-fed crops, and sparse native grass. Water shortage is the major constraint to plant growth in this area, as is typical in semi-arid climatic zones.

2.2. Observation and analysis

2.2.1. Experimental site designs

Seven hillslopes (East-1, East-2, South-1, South-2, South-3, South-4, and North-1; Fig. 1a) in the study area were selected for investigation of soil moisture variability in different slope positions. All hillslopes were covered with korshinsk peashrub from top to bottom. Korshinsk peashrub is widely planted in the Loess Plateau to reduce soil erosion (Cheng et al., 2009). This plant has a strong taproot (Fig. 1c) and develops fine root systems, and can thus consume soil water stored at depths of more than 10 m (Chen et al., 2010; Cheng et al., 2005). The korshinsk peashrubs in the study area were planted in 1984 at similar planting densities over different sites for the purposes of decreasing soil erosion and ecological restoration. On each hillslope, five separate experimental sites were located on the upper (position 1), upper-middle (position 2), middle (position 3), middle-bottom (position 4) and bottom positions (position 5) on each hillslope (Fig. 1a, b). These five sites (from position 1 to position 5) were located along the direction of flow from upslope contributing areas. The distance between each experimental site on each hillslope was 30–70 m with the sites having similar slope aspects and slope gradients. The topographic wetness index (TWI) of each site was calculated in ArcGIS® 10.2 using a DEM (Digital Elevation Model) with a resolution of 10 m. Refer to Western et al. (1999) for more information about TWI. The experimental sites selected in this study were near to each other and affected by a unique spatially distributed precipitation.

2.2.2. Data collection

The soil moisture content (SMC) at depths of 0–6 m was observed at each experimental site in late August 2012. The SMC was measured 2 weeks after a rainfall of 22 mm, and all field work was completed in 8 days. Soil samples in 20 cm increments were taken using a drill and stored in sealed aluminum cases to prevent potential water loss prior to laboratory measurement. Measurement of SMC (units: g/g) for all soil samples was carried out using the gravimetric approach which involves oven-drying for 24 h at 105 °C. At each slope location (upper, upper-middle, middle, middle-bottom, and bottom), three sampling points were randomly chosen for triplicate samples to obtain the average SMC at each experimental site. Thirty soil samples were collected from each sampling point. The depth-averaged SMC of each experimental site was calculated using Eq. (1):

$$SMC_j = \frac{1}{i}\sum_{i=1}^{i} SMC_i \tag{1}$$

where i is the number of measurement layers at site j and SMC_i is the mean SMC in layer i calculated from the three sampling points. At depths of 0–1 m and 1–2 m there were five measurement layers, and at depths of 2–4 m and 4–6 m there were 10. For the remainder of this paper, SMC0-1 represents the SMC at a depth of 0–1 m, SMC1-2 at 1–2 m, SMC2-4 at 2–4 m, and SMC4-6 at 4–6 m.

Long-term soil moisture observations were also carried out during 2009–2012 on hillslope East-2 (including experimental sites East21, East23, and East25), hillslope South-2 (including experimental sites South21, South23, and South25), and hillslope North-1 (including experimental sites North12, North13, and North14). During 2009–2012, soil moisture measurements in the growing season (from May to October) were made biweekly (beginning and middle of each month) for the 0–2 m profile in 20 cm increments. The SMC data were also obtained using the gravimetric approach. Temporally averaged SMC data calculated from long-term soil moisture observations were used to help identify soil moisture spatial variability related to slope position.

The latitude, longitude, and elevation were determined for each experimental site using a Garmin GPS60. Slope gradients and the slope aspect of each site were determined using a compass during field investigations. Slope gradient was recorded in degrees. Slope aspect (clockwise from north), which is a circular variable, was transformed into cos (aspect). Investigation of the structure of the vegetation was conducted at each slope location. The stand density (plants/ha), canopy density (the percentage of the area covered by shrub canopy), shrub height (m), canopy length (measured along the direction of flow), and