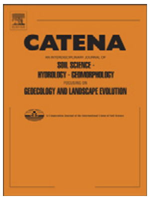
Catena 115 (2014) 123–133

Contents lists available at ScienceDirect

Catena

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



Response of temporal variation of soil moisture to vegetation restoration in semi-arid Loess Plateau, China

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ARTICLE INFO

Article history:
Received 9 May 2013
Received in revised form 5 December 2013
Accepted 7 December 2013

Keywords:
Soil moisture
Soil desiccation
Ecological restoration
Introduced vegetation
Temporal stability

ABSTRACT

Soil moisture is fundamental to ecosystem sustainability in semi-arid regions, and characterizing the response of temporal soil moisture variation to different vegetation types is important for assessing the sustainability of vegetation restoration. In this study, the soil moisture among eight typical types of vegetation is investigated and compared during three rainy seasons. The temporal variations of soil moisture in the near-surface (0–0.4 m), sub-surface (0.4–1.0 m), and deep layers (1.0–2.0 m) are explored to evaluate the ecohydrological effect of vegetation restoration in the semi-arid Loess Plateau of China. The results show that soil moisture content decreases drastically after vegetation restoration, with no significant difference in near-surface soil moisture among the vegetation types but significant differences in the sub-surface and deep soil layers. Introduced vegetation is the main factor affecting the soil moisture deficit below near-surface layers. Secondly, soil moisture is temporally stable in the sub-surface and deep layers, especially in introduced vegetation. This indicates that introduced vegetation consumes excessive amount of soil moisture and induces temporally stable soil desiccation. Soil desiccation with temporal stability cannot provide enough available soil moisture for plants and will inevitably threaten the sustainability of vegetation restoration and the associated ecosystem services. Lastly, high planting density is the main cause of severe soil moisture deficit on a long-term temporal scale. Our study results suggest that the current planting density of introduced vegetation is too high in specific cases and should be optimized with local soil moisture conditions in semi-arid regions.

1. Introduction

Water is fundamental to the biophysical processes that sustain ecosystem functions, particularly in arid and semi-arid regions where tight coupling exists between ecosystem productivity, surface energy balance, and water source availability (Wang et al., 2012a). Specifically, the moisture stored in different soil layers is recognized as an important driver of the productivity and sustainability of semi-arid terrestrial ecosystems (Legates et al., 2011; Porporato et al., 2002). Because vegetation strongly affects the water cycle, the interactions between vegetation and soil moisture are fundamental for ecological processes in semi-arid regions. This issue is particularly crucial in ecohydrology, and has recently been investigated in many studies. For example, Hupet and Vanclooster (2002) found that vegetation plays an important role on the temporal dynamics of soil moisture through evapotranspiration based on intensive measurements. In addition, the results of Chen et al. (2007) showed that vegetation type have a significant influence on soil moisture dynamics. Vivoni et al. (2008) revealed that vegetation can mediate the soil moisture response to precipitation and change the spatial distribution of soil moisture, and Yang et al. (2012a) found that plant growth conditions can change the spatial pattern of shallow and deep soil moisture in semi-arid regions. Vegetation can significantly influence soil moisture and its spatiotemporal patterns.

Researchers have more recently focused on understanding the relationship between spatiotemporal variation of soil moisture and soil texture, soil organic matter, topographic factors, and other factors (Meerveld and McDonnell, 2006; Qiu et al., 2001; Western et al., 1999). Temporal variations of soil moisture are important, particularly in arid and semi-arid environments, and have been widely investigated in various ecosystems (Brocca et al., 2007; Grassini et al., 2010; Sala et al., 1992; Wendroth et al., 1999). Research shows that different plant species can lead to different rainfall–runoff responses, and thus lead to temporal variation in soil moisture (Aranda et al., 2012; Cubera and Moreno, 2007; Jost et al., 2012). Furthermore, the temporal pattern of soil moisture was found to vary at different soil depths (Mohanty et al., 1998). Similar studies have been conducted in the Loess Plateau of China. For instance, a decline of soil moisture in the 0–1 m layers was found during the process of ecological restoration, and the soil moisture replenishment by rainfall during the rainy season was not sufficient to recharge the soil moisture storage (Chen et al., 2010).

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0341-8162/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.catena.2013.12.005

In the Chinese Loess Plateau, the "Grain-for-Green Program" was implemented on a large scale by the central government in 1999, with the goal of controlling serious soil erosion (Chen et al., 2010). Afforestation and the introduction of new grasses and shrubs have been the main types of vegetation restoration in this region. Consequently, the newly introduced vegetation has become the dominant vegetation type (Liu et al., 2008). The newly introduced vegetation usually consumes more soil moisture than native plants and thus rapidly depletes local soil moisture resources (Cao et al., 2011; Yang et al., 2012b). The high soil moisture consumption has had negative impacts, decreasing ecosystem services (Chazdon, 2008; Liu et al., 2008; Wang et al., 2011). It is possible that the large-scale vegetation restoration project is limited by the availability of soil moisture resources (Cao et al., 2011; Chen et al., 2008). The groundwater in the Loess Plateau is too deep and thus unavailable for soil evaporation and/or plant transpiration (Mu et al., 2003). For this reason, the soil moisture stored in different depths is critical for plant growth and serves as a key water source for sustaining ecosystems in this region (Chen et al., 2008; Yang et al., 2012b). The temporal variations of soil moisture at different depths may have varying responses to vegetation and play different roles in sustaining vegetation growth.

The vegetation in semi-arid regions consumes soil moisture not only from the surface layers but also other layers, so understanding the vertical distribution of soil moisture and the dynamics of such moisture is important for sustaining human-introduced vegetation restoration projects. The temporal dynamics of soil moisture in different layers under the influence of vegetation restoration have received limited attention. Understanding the effect of different plant species on moisture dynamics at different soil depths has several important implications. It is important for selecting optimal species for vegetation restoration efforts as well as many other scientific field and operational applications, especially in semi-arid regions. Thus, the objectives of the present study are to: (1) elucidate the influence of vegetation restoration on soil moisture content, (2) analyze the temporal variation of soil moisture under different vegetation types, and (3) identify factors responsible for soil moisture temporal variation among different soil layers.

2. Materials and methods

2.1. Study area

Longtan watershed (35°43′–35°46′N, 104°27′–104°31′E), which is located in the western Loess Plateau, covers an area of 16.1 km^2. The altitude of the watershed ranges from 1840 m to 2260 m, with a highly fragmented landscape. It belongs to a typical semi-arid loess hilly region, with mean annual temperature of approximately 6.8 °C and mean annual rainfall of 386 mm. Most rainfall occurs in the form of thunderstorms during the summer months from July to September. The potential annual evaporation (pan evaporation) is about 1649 mm. These annual averages were derived from data provided by a meteorological station that is located 0.6 km from the watershed and represent 45-year averages (1961–2006). The rainfall pattern had a uniform distribution in the watershed based on five spatially distributed auto-recording rain gauges during the 2008–2012 periods. The soil types in the study area are mainly composed of loess soil with low fertility and are vulnerable to soil erosion. The basic properties of this soil are a loose structure, high silt content (ca. 81%), soil moisture field capacity (0.180–0.240 g/g), and low organic matter content (ca. 0.2–2.9%). The wilting point in the study area is 0.054 g/g (Chen et al., 2007). Soil thickness varies from 40 to 60 m.

The predominant land use types are sparse native grassland, rain-fed farmland, introduced vegetation lands. The native vegetation in the study area is sparse native grass dominated by the following species: bunge needlegrass (*Stipa bungeana* Trin.), common leymus (*Leymus secalinus* (Georgi) Tzvel.), Altai heterpappus (*Heteropappus altaicus* (Willd.) Novopokr.), and others. The introduced vegetation types are alfalfa (*Medicago sativa*), korshinsk peashrub (*Caranana korshinskii*), Siberian apricot (*Armeniaca sibirica* (L.) Lam.), Chinese red pine (*Pinus tabulaeformis* Carr.), and other varieties. In this semi-arid area, water shortages threaten economic development, sustainable human livelihoods, and environmental quality.

2.2. Observation and analysis

2.2.1. Experimental sites design

Experimental sites were selected for three different land use groups: native natural grassland, farmland, and introduced vegetation land. For the introduced vegetation land, five typical vegetation types were selected: alfalfa (*M. sativa*), korshinsk peashrub (*C. korshinskii*), Chinese arborvitae (*Platycladus orientalis*), Chinese red pine (*P. tabulaeformis*), and Siberian apricot (*A. sibirica*).

2.2.1.1. Native grassland. Native grassland is the dominant indigenous species community in this area. The main species are native grasses and herbs that demand little water. According to interviews from local farmers and stakeholders, natural grasslands were kept from human disturbance for at least 50 years.

2.2.1.2. Farmland. There are two types of farmland: traditional and abandoned. Traditional farmland is continuously cropped (continuous farmland), such as with potatoes, which are typically planted in May and harvested manually at the end of September or beginning of October. After harvest, a fallow period is followed from October to April in the next year. The abandoned farmland has been fallowed since 2002, and has plant species of native grasses and herbs. The land can be converted back to cropping at any time if a farmer decides to do so.

2.2.1.3. Introduced vegetation land. The lands with introduced vegetation were converted from traditional farmland by planting the introduced plants on traditional farmland. These types of vegetation include grassland (alfalfa), shrubland (peashrub), and forestland (Chinese arborvitae, Chinese red pine and Siberian apricot). Alfalfa planting was started in 2003 after the initiation of the "Grain-for-Green Program". In rainfall-deficit years, alfalfa is cut only once because of its poor growth, but it is cut twice in rainfall-rich years. The korshinsk peashrubs were planted in 1984 with a planting density of $2.22 * 10^5$ plants/km^2. Chinese arborvitae, Chinese red pine and Siberian apricot were planted with a density of $1.90 * 10^5$ plants/km^2 in 1980, 1972, and 1960, respectively.

In this study, eight hillslopes with different vegetation covers were selected to measure the soil moisture content. All slopes were selected based on the upslope contributing area and flow direction. The upslope contributing area and flow direction for each sampling location were calculated using ArcGIS® 9.3 (ESRI Inc., USA) based on DEM (Digital Elevation Model) with a resolution of 10 m. Each hillslope has the same vegetation cover from the top to the foot of the hillslope along flow direction. Experimental sites on each hillslope had similar slope gradients. Three experimental sites located on the upper, middle, and downhill positions were selected on each hillslope. The upper, middle, and downhill sampling sites were at least 100 m apart (Fig. 1).

The soil properties are generally homogeneous in the entire study area. The soil moisture profile in the farmland was used as the reference to represent the conditions before human-introduced vegetation restoration. The difference in soil moisture content between the farmland and introduced vegetation reflects the response of soil moisture to the vegetation change. Soil moisture content in native grassland was used as the reference representing no human impact in the study area. Similarly, the difference in soil moisture content between native grassland and introduced vegetation indicates the degree of the soil moisture deficit relative to the initial soil moisture status.