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# Comparison of deep soil moisture in two re-vegetation watersheds in semi-arid regions

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SUMMARY

Soil moisture stored below rainfall infiltration depth is a reliable water resource for plant growth in semi-arid ecosystems. Along with the large-scale ecological restoration in Chinese Loess Plateau, identifying the ecohydrological response to human-introduced vegetation restoration has become an important issue in current research. In this study, soil moisture data in depth of 0–5 m was obtained by field observation and geostatistical method in two neighboring re-vegetation watersheds. Profile characteristics and spatial pattern of soil moisture was compared between different land use types, transects, and watersheds. The results showed that: (1) Introduced vegetation drastically decreased deep soil moisture when compared with farmland and native grassland. No significant differences in deep soil moisture were found between different introduced vegetation types. (2) An analysis of differences in soil moisture for different land use patterns indicated that land use had significant influence on deep soil moisture spatial variability. Land use structure determined the soil moisture condition and its spatial variation. (3) Vegetation restoration with introduced plants diminished the spatial heterogeneity of deep soil moisture on watershed scale. The improvement of land use management was suggested to improve the water management and maintain the sustainability of vegetation restoration.



## 1. Introduction

Soil moisture is one of the primary limiting factors for plant growth in semi-arid regions. It also plays critical roles in many terrestrial ecosystem processes (Legates et al., 2011; Porporato et al., 2002). Soil moisture exhibits a tremendous heterogeneity in space and time even in small watersheds (Gómez-Plaza et al., 2001; Western et al., 2004). Characterizing soil moisture variations across a range of spatial and temporal scales is important for both theoretical and practical applications on runoff, soil erosion, agriculture, and ecological restoration.

Scientific literatures indicated that soil moisture on watershed scale was affected by dozens of environmental factors, such as land use/vegetation, topographic factors, soil properties, and others (Brocca et al., 2007; Cantón et al., 2004; Gómez-Plaza et al., 2000). Among these factors, soil properties and topography can be considered relatively constant in short term, while land use and climate are the dominant variables (Montenegro and Ragab, 2012; Wei et al., 2009). In fact, land use can disrupt the surface water balance and the partitioning of precipitation into evapotranspiration, runoff, and groundwater flow (Foley et al., 2005; Sun et al., 2006; Vose et al., 2011; Shi et al., 2013). Land use/vegetation controls the soil moisture distribution pattern in many ecosystems (Ferreira et al., 2007; Vivoni et al., 2008). On the other hand, soil moisture in different depth may have different response to influencing factors (Meerveld and McDonnell, 2006; Venkatesh et al., 2011).

Soil moisture stored in deep layers (below annual rainfall infiltration depth, usually below 1–2 m) is a reliable water resource for plant growth in semi-arid regions (Ferreira et al., 2007). Specifically, because of the thick loess soil (nearly 100 m in thickness) and loose soil structure (Mu et al., 2003), nearly little groundwater in Chinese Loess Plateau can be used by plants. Because of this reason, deep soil moisture has become an important water source for this region (Yang et al., 2012). Due to the large-scale implementation of "Grain to Green Program" initiated by central government since 1999, introduced vegetation has become the main vegetation type for the purpose of decreasing serious soil erosion in this region (Chen et al., 2010). However, introduced vegetation usually consumes more soil moisture than native plants and cannot obtain sufficient water for its growth due to limited rainfall amount. These plants are forced to develop deep root system to utilize deep soil moisture (Chen et al., 2008a). Recent studies have found that introduced vegetation in this area affect lots of hydrological processes

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and ecosystem services (Chen et al., 2008b; Liu et al., 2008), such as decreasing deep soil moisture, changing the spatial pattern of deep soil moisture, decreasing the potential water yield production.

The correlations between land use and surface soil moisture variability have been identified by previous studies in loess regions (Fu et al., 2003; Qiu et al., 2001). Since the functions of deep soil moisture on local ecosystems in Loess Plateau were realized in last decades, the influence of land use/land cover change on deep soil moisture was highlighted in recent studies. For example, Wang et al. (2011b) found that land use have significant influence on deep soil desiccation on regional scale. However, the relationships between land use structure and deep soil moisture are poorly documented in literatures. Thus, it is urgent to evaluate the influence of vegetation restoration on deep soil moisture variability in this area. The objectives of this study are: (1) to compare the soil moisture content in different soil layers between different land use patterns; (2) to find the relation between land use structure and soil moisture variability; (3) to elucidate the response of spatial variation in soil moisture to human-introduced vegetation restoration.

## 2. Material and methods

### 2.1. Study area

Two neighboring small watersheds, Lijiawan and Jianzicha (35°43′–35°44′N, 104°28′–104°29′E), which are located in the western Loess Plateau, covers an area of 0.94 $km^2$ and 0.30 $km^2$ (Fig. 1), respectively. The altitude of the two watersheds range from 1937 m to 2151 m, with a highly fragmented landscape. They belong to typical semi-arid loess hilly region, with mean annual temperature of approximately 6.8 °C and mean annual precipitation 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 which is located 0.6 km from the watersheds and represent 45-year averages (1961–2006). The rainfall pattern had a uniform spatial distribution in two watersheds based on five spatially distributed auto-recording rain gauges in or near the two watersheds during 2008–2013 periods. Soil types in the study area are mainly composed of loess soil with low fertility and are vulnerable to soil erosion. Soil thickness varies from 40 to 60 m. 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 study area is 0.054 g/g (Chen et al., 2010). The predominant land use types are rain-fed farmland, pasture grassland, shrubland, forestland, and native grassland. Land use structures of the two watersheds were shown in Table 1. The introduced vegetation types are alfalfa (*Medicago Sativa*), korshinsk peashrub (*Caranana korshinskii*), Siberian apricot (*Armeniaca sibirica* (L.) Lam.), 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 site designs

The native grassland, farmland (including farmland and abandoned farmland), re-vegetation lands (including pasture grassland, shurbland, and forestland) were selected in this study. Native grassland is the dominant community of native species in this region. The main species are native grasses and herbs with low water demands, including bunge needlegrass, common leymus, altai heterpappus, and others. The soil moisture profile in native grassland was used as the reference to present no human impact in study area. The farmland was planted with annual crops in a potato-corn rotation system. Crops were sown in April and harvested manually at the end of September or beginning of October. Because all the pasture grasses, shrubs, and trees were initially planted on farmland. The soil moisture in farmland can be considered as the reference value representing soil moisture conditions before vegetation restoration. Abandoned farmland has been fallowed since 2002, and has plant species of native grasses and herbs with low water demands. The re-vegetation lands were converted from farmland and planted with introduced vegetation types. In study area, pasture grassland was planted with alfalfa in 2002 after the initiation of the “Grain-for-Green Program”. Alfalfa is cut only once in rainfall-deficit year or cut twice in rainfall-rich years. The shrubland was planted with korshinsk peashrubs in 1984 with a planting density of $2.2 \times 10^5$ plants/$km^2$. The forestland was planted with Chinese arborvitae trees in Lijiawan watershed with a density of $1.9 \times 10^5$ plants/$km^2$ in 1985, and Siberian apricot trees in Jianzicha watershed with a density of $1.9 \times 10^5$ plants/$km^2$ in 1982.

Eight typical transects in Lijiawan watershed and seven typical transects in Jianzicha watershed were selected to investigate soil moisture variations. 3–5 experimental sites were located on each transect from hillslope top to bottom according to land use type and hillslope length. Experimental sites on each transect have similar slope gradient and slope aspect with a distance of 30–100 m between each other (Fig. 1). The soil properties are generally homogeneous in the two small watersheds. 32 experimental sites and 26 experimental sites in total were selected in Lijiawan watershed and Jianzicha watershed, respectively. The latitude, longitude and elevation were determined for each experimental site using a Garmin GPS60.

#### 2.2.2. Soil moisture data collection

In August 2013, soil moisture content in 0–5 m layers was measured at each experimental site. At each experimental site, three sampling profiles were randomly chosen to obtain the average soil moisture content. Soil samples in depth of 0–5 m were taken by a drill (5 cm in diameter) with 20-cm increment. A total of 25 soil samples were collected from each sampling profile. When the soil samples were taken out, the soil samples were sealed immediately in airtight aluminum cylinders and brought to the laboratory for determination of gravimetrically soil moisture content (unit: g/g). The soil moisture content was determined using the oven-dry method (24 h at 105 °C). All the field sampling and laboratory work were completed in 5 days.

Soil moisture content was interpolated by the inverse distance weighted approach (IDW) to produce the spatial distribution map in different layers in two watersheds. The ArcGIS®10.2 (ESRI Inc., USA) was used to perform IDW analyses and to produce soil moisture distribution maps. Basic statistics on interpolated soil moisture content based on IDW method were conducted by spatial analyst tools in ArcGIS.

### 2.3. Statistical methods

The soil moisture content and profile distribution of each watershed were calculated by taking the mean value of all experimental sites in each soil layer. The depth-averaged soil moisture content for each experimental site ($\theta_{ij}$) was calculated by Eq. (1)

$$\theta_{ij} = \frac{1}{i}\sum_{i=1}^{i}\theta_i \quad (1)$$

where $i$ is the number of measurement layers at site $j$, and $\theta_i$ is the mean soil moisture content in layer $i$ calculated by three random sampling profiles. In the following section, the soil moisture content was calculated for every meter, and the $j$ = 5.