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Soil moisture variations at different topographic domains and land use types in the semi-arid Loess Plateau, China

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ABSTRACT

Soil moisture plays a fundamental role in eco-hydrological processes in the semi-arid Loess Plateau. Catchments on the Loess Plateau can be generally divided into the hillslope domain and gully domain. However, the soil moisture variations linked to topographic domains and land use types remain poorly understood. Therefore, in this study, differences in soil moisture among three typical land use types (forestland, native grassland, and farmland) were investigated and compared between the spatial domains of hillslope and gully in the Jiegou catchment on the semi-arid Loess Plateau of China. Additionally, the spatial variations in the soil moisture of the 0–100 cm layers were explored in both wet and dry periods to evaluate the seasonal effects of different spatial domains and land use types. The results showed that including gully soil moisture weakly increased the spatially averaged soil moisture in the catchment but obviously increased the variability during wet periods. In contrast, the spatial means decreased weakly while the variability obviously decreased during dry periods. Soil moisture in forestland was lower than that in native grassland and farmland at all spatial domains during both wet and dry periods. The results also indicated that surface soil moisture (0–10 cm) differs between spatial domains but not land use types, which mainly due to the differences of evapotranspiration on the two topographic domains. In contrast, deep soil moisture (80–100 cm) differs among land use types but not spatial domains, which because of the differences of root water uptake among land use types. In addition, slope aspect played a more important role than slope gradient and elevation in the distribution of soil moisture at the hillslope domain. This was because the slope aspect affected the ground temperature by receiving different solar radiation, and further affected the soil evaporation and vegetation transpiration. Therefore, the results of this study indicates that both topographic domains and land use types should be considered when attempting to characterize soil moisture variability or modelling surface hydrological processes at catchment scale in heavily gullied regions.

1. Introduction

Soil moisture is a limiting factor of ecosystem development in arid and semi-arid areas (Rodriguez-Iturbe et al., 1999), where ecosystem productivity is closely related to hydrothermal conditions (Jin et al., 2011; Porporato et al., 2002; Wang et al., 2012). Soil moisture exhibits complex spatial variability that is affected by vegetation, topography, soil heterogeneity and atmospheric forcing (Biswas et al., 2014; Vereecken et al., 2007), so understanding this variability is important for the optimal management of water resources and ecosystem sustainability.

Large gullies, which occur globally, affect greatly eco-hydrological processes in gullied landscape (Gao et al., 2011). To determine the influence of large gullies on the spatial variation of soil moisture and to compare the differences of soil moisture between hillslopes and gullies, we define gully as a spatial domain. Famiglietti et al. (1998) characterized soil moisture variations in the topsoil (0–5 cm) on a hillslope; they found that soil moisture exhibits significant variability along the hillslope and that the mean soil moisture level is the major impact factor on this variability. Brocca et al. (2012) studied soil moisture variation at the catchment level; they reported that spatial variability first increases with the size of the area under consideration but then stabilizes around a constant value. Additional scientific literatures on the spatial variability of soil moisture along a hillslope (Brocca et al., 2009; Penna et al., 2009; Qiu et al., 2001) or at the catchment scale (Brocca et al., 2010; Fu et al., 2003; Rosenbaum et al., 2012) are

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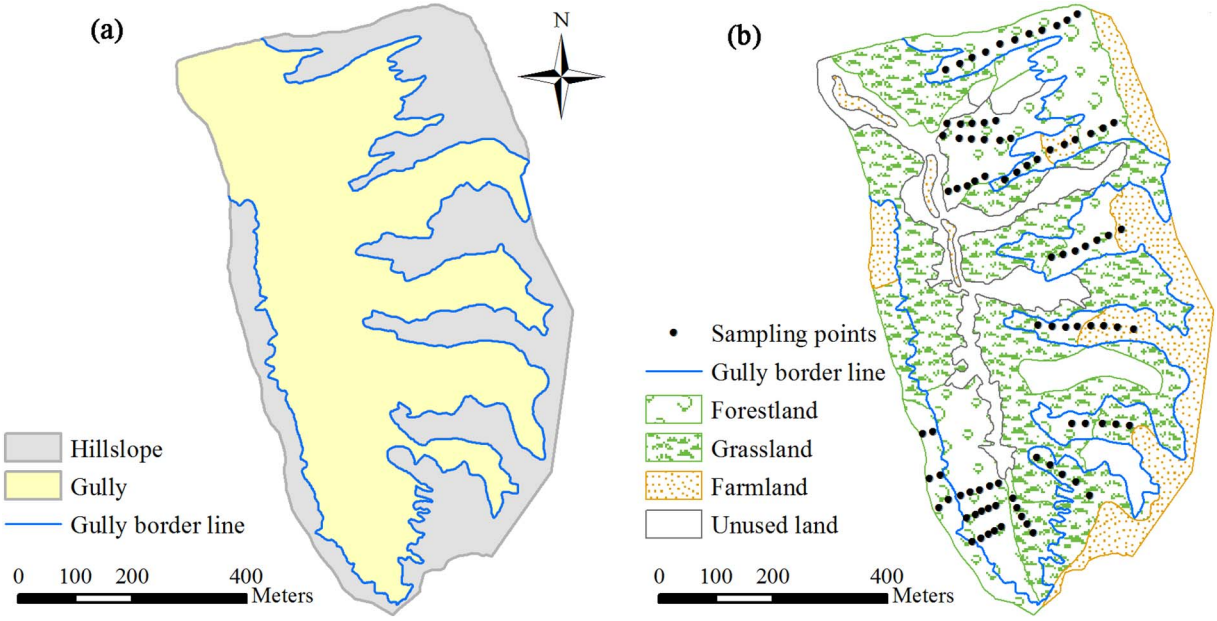

Fig. 1. View of the different spatial domains (a) as well as the land use types and soil moisture sampling points in the Jiegou catchment (b).

common, but these studies were generally conducted on mild topographies. Fewer studies have explored the variability of soil moisture on the steep gullies (Grant et al., 2004), probably due to the difficulty of sampling (Gao et al., 2011). Nevertheless, Melliger and Niemann (2010) reported the spatial pattern of near-surface (0–10 cm) soil moisture in gullies in southeastern Colorado and they discovered that the soil moisture content in gullies weakly influenced the spatially averaged soil moisture while clearly promoting the spatial variation of moisture. Gao et al. (2016) compared the spatial variability of soil moisture at depths of 0–60 cm on hillslopes and the whole catchment on the Loess Plateau. They showed that over the whole catchment (including soil moisture measured on hillslopes and in gullies), the spatial means of soil moisture weakly increased but the spatial variability clearly increased compared with soil moisture on the hillslopes alone.

Despite the above efforts to characterize spatial variations of soil moisture in gullies, most studies have ignored the influence of land use types. Because land use strongly affects the water cycle, its influence on soil moisture is fundamental to ecological and hydrological processes, especially in water-limited environments. This is an important issue in ecohydrology that has recently been investigated by ecologists and hydrologists. For instance, based on intensive measurements, Hupet and Vanclooster (2002) reported that land use types play a critical role in the soil moisture dynamics of the superficial soil layers (0–40 cm), and Yang et al. (2012) discovered that the spatial distribution pattern of both shallow and deep soil moisture differs among land use types on the Loess Plateau. However, most of the previous researches have focused on only one spatial domain; thus, the impacts of different land uses on soil moisture variability between domains remain poorly understood. Furthermore, Grayson et al. (1997) reported that soil moisture variability is dependent on soil moisture status, and Bogena et al. (2010) found that soil moisture showed the strongest correlations with terrain attributes during dry periods rather than wet periods.

The Loess Plateau of China is typical of regions around the world with large gullies, and its catchments can generally be divided into two types: hillslopes and gullies, which are divided by the gully border line. Gullies, which have steep terrain and low altitude compared with nearby hillslopes (Gao et al., 2016), account for 42% on the entire Loess Plateau region, and this percentage can reach approximately 50–60% in the hilly gully regions. In late 1999, the Chinese government launched the “Grain for Green” project to mitigate increasing soil erosion and land degradation on the Loess Plateau (Chen et al., 2010). Since then, researchers have reported that soil moisture has been depleted more by the newly planted vegetation than by the native plants, and a dried soil layer has formed in some areas (Cao et al., 2011; Wang et al., 2010a; Yang et al., 2012). However, most investigations of soil moisture have focused on the hillslopes, which have a relatively flat terrain, and these results have been applied as representative of the entire catchment (Gao et al., 2014; Qiu et al., 2001). The variability of soil moisture among different land uses at different spatial domains was still unclear. Therefore, it is important to examine the distribution characteristics of soil moisture in relation to topographic domains and land use types, which could improve our understanding of soil moisture variations and facilitate the sustainability of vegetation restoration in seriously gullied areas.

In this study, we examined how topographic domains and land use types affect the soil moisture variations in both wet and dry periods. The objectives are (1) to examine soil moisture distributions at different spatial domains (hillslope and gully), (2) to examine the differences in soil moisture under different land use types, and (3) to identify the relationships between soil moisture and complex topography.

2. Materials and methods

2.1. Site description

The study site, the Jiegou catchment (36°56′N, 110°46′E, Fig. 1), is in the western part of Shanxi Province, China. It is a typical gullied catchment in the loess hilly region with an area of 0.49 km^2, 61% of which is covered by gullies. This region has a semi-arid continental climate, with a mean annual temperature of approximately 9.8 °C and a mean annual rainfall of 465 mm. The altitude of the catchment ranges from 1042 to 1261 m, and the landscape is highly fragmented. The hillslopes range from tens to hundreds of meters with relatively gentle gradients (< 25°). The gullies have steep slopes, generally ranging from 25° to 90°. The catchment direction extends from south to north. Most of the catchment bottom comprises a thin soil layer (< 50 cm). The entire catchment is covered by a thick, silt-loam loess soil with 27% sand, 57% silt, and 16% clay and a low organic matter content (0.5–1.1%).

There are three main land use types on the hillslopes and gullies: rain-fed farmland, native grassland, and forestland. The two types of