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Spatial structure of surface soil water content in a natural forested headwater catchment with a subtropical monsoon climate

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SUMMARY

The surface or near-surface soil moisture at the interface between atmospheric and terrestrial environments has significant implications for the complex interactions between hydrological processes and ecosystems. Although a number of previous studies have reported the spatial patterns and structures of surface moisture in pasture environments based on large sample sizes, information regarding the detailed spatial patterns and structure of surface moisture in a natural forest environment is still sparse, particularly for steep headwater catchments due to the labor intensity involved and the difficulty of making field measurements. In this study, we measured the detailed surface soil water content at depths of 0–12 cm and 0–20 cm at 470 measurement points using the TDR (time domain reflectometry) method. Thirteen surveys were conducted within 1 year in a steep natural forested headwater catchment with a subtropical monsoon climate in Taiwan. The sample and model variograms were used to evaluate the spatial structure of the surface soil moisture. We also compared the spatial structures of surface moisture in this study with those in a similar study conducted in a flat pasture catchment (Western et al., 1998). For the results at our site, exponential model variograms with the nugget effect well fitted sample variograms, indicating an obvious regional dependence of surface moisture and stationary spatial structures in all surveys. The geostatistical structural characteristics of the nugget varied between 22.70 and 47.40 $(\% \text{ V/V})^2$; the sill varied between 54.99 and 98.51 $(\% \text{ V/V})^2$; and the range varied between 10.20 and 58.65 m. The nugget, sill, and range all increased with an increase in soil moisture. The notable anisotropy under dry conditions was attributed to the year-round surface runoff pathway. The sample variograms that represented the spatial structure of soil moisture and reliably estimated the nugget, sill, and range required a sample size of at least 235 at our 0.15-ha site (i.e., a measurement resolution of at least 6.4 m^2 per sample). The pattern of soil moisture was relatively stationary in two gullies and on the side of a hillslope, but it varied on the valley-head hillslope depending on whether conditions were dry or wet. In contrast to previous results for a flat pasture catchment (Western et al., 1998), our results produced a right-skewed histogram of soil moisture under dry or moderately wet conditions, variograms that tended to increase with an increase in soil moisture, anisotropy of soil moisture structure under dry, but not wet, conditions, a need for a 55 times higher measurement resolution associated with the large sample size, and a larger nugget effect in the steep natural forested headwater catchment. This study identified the spatial structure and patterns of surface soil moisture as the primary step in understanding hydrologic processes in a natural forested headwater catchment.

1. Introduction

Although the overall quantity of soil moisture is small (~0.05%) in the global hydrological cycle (Dingman, 2002), soil moisture provides water that can be used by animate and vegetative life, and it should be considered crucial for ecohydrological processes and an important natural resource (Lin, 2010). In the critical zone, the surface or near-surface soil moisture at the interface between the atmospheric and terrestrial environments has significant implications for the complex interactions between hydrological processes and ecosystems. Therefore, the spatial distribution of or temporal variations in surface soil moisture are of interest and have been extensively studied.

There are many techniques to measure spatial and temporal changes in surface moisture, which have been extensively reviewed in the literature. Several review papers (Western et al., 2002; Robinson et al., 2008; Vereecken et al., 2008) have presented conceptual diagrams showing the estimated spatial and temporal extent of measurements. They noted the capacity of measurements relative to the scales at which hydrological process can be observed and emphasized the importance of linkages or combinations of

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specific methods. Two major classes of methods have been employed for measuring surface soil moisture: remote-sensing (contact free) and ground-based (contact based) measurements (Western et al., 2002; Robinson et al., 2008; Vereecken et al., 2008). Western et al. (2002) reported that remote sensing provides excellent spatial coverage over large areas but only provides measurements for shallow depths, with the influence of the vegetation canopy and the relatively infrequent repeat cycles making data use problematic. In contrast, ground-based measurements can be made at any depth and can be accurately calibrated and logged at any time scale. However, they are essentially point measurements, which may make spatial interpretation difficult. This suggests that a large sample volume is necessary when measuring spatial patterns of soil moisture using ground-based methods.

With regard to data analysis, spatial patterns of surface soil moisture in situ are difficult to capture using common descriptive statistics and histograms. Geostatistical analysis using a variogram is more effective to characterize the spatial structure of regional dependence or the correlation between two points (McKillup and Dyar, 2010). Variogram analysis consists of the sample variogram, which is calculated from the data, and the model variogram, which is fitted to the sample variogram. Three parameters of the model variogram, i.e., the nugget, sill, and range, are usually used to describe the geostatistical characteristics of data structure (Kanevski and Maignan, 2004). The nugget (or nugget effect) indicates the variance between two points at zero distance and represents micro-scale variation and measurement errors. The sill is the value at which the variance plateaus at its maximum height. The sill of the variogram is the statistical variance under the stationary hypothesis. The range is defined as the distance at which the variance reaches about 95% of the sill. When the distance is greater than the range, the data are no longer autocorrected. Thus, these three parameters can be used to evaluate the spatial structure of data belonging to the regional dependence or the random field, which are widely used in analyses of spatial and temporal variations in soil moisture (Loague, 1992; Western et al., 1998; Zhao et al., 2011).

One pioneer study of Western et al. (1998) measured surface soil moisture in a flat pasture catchment using ground-based measurements made by the TDR (time domain reflectometry) method with a large sample size and analyzed the spatial structure with variograms, which datasets have also been widely analyzed and used. The study analyzed the geostatistical characteristics of spatial and seasonal variations in soil moisture structure, finally suggesting that about 300 points are required to reliably represent the true spatial structure of soil moisture in the landscape. Further research based on the datasets of Western et al. (1998) later identified some important issues relating to spatial or temporal patterns of surface soil moisture in pasture catchments. Wilson et al. (2004) reported that the temporal variance in surface soil moisture was typically five times larger than the spatial variance in two pasture catchments. Based on four datasets in three catchments, Grayson and Western (1998) found that there were time-stable locations representing the mean areal moisture content; they suggested the possibility of a method for determining a sampling regime that could provide reliable estimates of areal mean soil moisture in complex terrain based on a limited number of sample locations. With regard to the controlling factors, the spatial soil moisture patterns could be predicted by terrain indices such as specific upslope area or a topographic wetness index that explained variability at scales from 10 m up to the catchment scale and by hillslope aspect indices, such as the potential solar radiation index, that explained variability at scales from 80 m to the catchment scale (Western et al., 1999). Additionally, the effects of spatial soil and vegetation patterns on the spatial distribution of soil moisture seemed to be of similar importance to that of topography (Wilson et al., 2004). As described above, the studies using the datasets of Western et al. (1998) reported the spatial structure, temporal variation, and the factors controlling surface soil moisture in flat pasture catchments. Similar studies have analyzed spatial patterns and the structure of surface soil moisture based on large sample sizes in pasture stands (Loague, 1992; Mohanty et al., 2000; Brocca et al., 2007; Zhao et al., 2011) and based on small sample sizes in forested stands (Nyberg, 1996; Takagi and Lin, 2011; Robinson et al., 2012). To the best of our knowledge, no studies have examined the detailed spatial structure of surface soil moisture based on large sample sizes (approximately greater than 300) in a naturally forested headwater catchment, particularly for a steep environment, due to the labor intensity required and the difficulty of making field measurements.

In this study, we measured the surface soil water content at depths of 0–12 cm and 0–20 cm at 470 points collected from 13 surveys within 1 year using the TDR method. Measurements were conducted in a steep natural forested headwater catchment with an area of 0.15 ha and a subtropical monsoon climate. As an initial step in identifying the detailed characteristics of surface soil moisture in this kind of environment, we adopted an analysis procedure similar to that used in Western et al. (1998). We attempted to clarify the spatiotemtoral structures and patterns of surface soil moisture in a steep natural forested headwater catchment as follows:

1. We used the sample and model variograms to evaluate the spatial structure of the surface soil moisture. Then, we analyzed the effects of anisotropy and sample size on the sample variograms and clarified the variations in the geostatistical structural characteristics of the nugget, sill, and range under dry and wet conditions. Finally, we determined the minimum sample size required to represent the spatial structure of the surface soil moisture at this site.
2. We compared the results in this study with those from a similar study conducted in a flat pasture catchment (Western et al., 1998), to clarify the spatiotemtoral characteristics of surface moisture in a steep natural forested headwater catchment.
3. Based on the results from this study and previous studies, we discuss the effects of topographic units and hillslope hydrological processes on the spatial patterns of surface moisture in a steep naturally forested headwater catchment.

2. Methods and materials

2.1. Study area

Observations were made at a natural forest site at the Fushan Research Center, Forestry Research Institute, located in Yilan County, northeastern Taiwan (24°45′42″N, 121°35′45″E). This area is warm temperate, and the mean annual air temperature is 18.5 °C. The climate type is a subtropical monsoon, and the mean annual precipitation is 4125 mm, distributed year-round, with no obvious dry periods and with typhoons in summer and frequent rainfall in winter due to the northeast monsoon (Lin et al., 2010). The forest is characterized as a moist subtropical mixed evergreen forest, and the families of *Lauraceae*, *Fagaceae*, and *Theaceae* are the dominant trees in the area (Wang et al., 2000). The bedrock consists of argillite (red hardish shale) and slate; the soil could be classified into yellow soil, colluvial soil, and lithosol groups or as Hapludults, Dystrochrepts, Udipsamments, and Udothents in the USDA soil classification system (Lin et al., 1996).

The study site is in a small headwater catchment located upstream of an erosion gully beside the Tsukeng stream (Fig. 1a). Surface erosion is ongoing along the Tsukeng stream, and there are a few gullies or slope failures. To obtain the microrelief of the topography under the natural forest, we used a laser