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Temporal stability analysis of surface and subsurface soil moisture for a transect in artificial revegetation desert area, China

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SUMMARY

Temporal stability analysis is a statistical approach for describing the persistence of spatial patterns and characteristic behavior of soil moisture. Using temporal stability method, we aimed to identify statistically stable locations to estimate mean soil moisture content and examine the feasibility of confirming temporally stable locations by using other properties that were themselves relatively temporally stable. The temporal stability of near-surface soil moisture contents were investigated at three depths at the hillslope scale in an artificial revegetation desert area, China. Soil moisture were measured at soil depth of 0–6, 0–15 and 0–30 cm, using temporary frequency-domain reflectometry (FDR) and time domain reflectometry (TDR), at ten locations along a hillslope with relatively homogeneous soil properties and vegetation cover but contrasting topography during May to September in 2006. Summary variables were determined at corresponding locations. Results indicated that strong temporal persistence existed at three depths, and the temporal stability was more pronounced at deep soil layer than at soil surface. The temporal stability characteristics were relatively lack in a state of transition from wet to dry. Identified statistically stable locations at three depths represented well for the mean soil moisture content; the offset values were 0.011, 0.002 and 0.001 $m^3\,m^{-3}$ at 0–6, 0–15 and 0–30 cm depth, respectively. The representative site for 0–6 cm soil layer can serve as a good indicator of soil moisture at other depths. Elevation and soil properties were the leading factors affecting the spatial and temporal distribution of soil moisture at the hillslope scale. The mean soil moisture contents at different depths can be predicted by other topographic and edaphic factors. This study is expected to be useful in characterizing mean soil moisture content in soil profiles on a hillslope scale, which helps to a good management of soil water on sloping land in desert areas.

1. Introduction

Soil moisture plays a significant role in determining the amount of energy exchange between atmosphere and earth's surface (Joshi et al., 2011); it is the principal limiting factor in semi-arid ecosystems for vegetation restoration (Hu et al., 2009), controlling the spatial and temporal distribution pattern of vegetation by regulating complex dynamics in the climate–soil–vegetation system (Porporato et al., 2002). Soil moisture in the near-surface is broadly acknowledged as a crucial control on several hydrological and geomorphic processes (Penna et al., 2013). However, soil moisture is highly variable in time and space across different scales (Manfreda and Rodriguez-Iturbe, 2006; Famiglietti et al., 2008; Penna et al., 2009; Brocca et al., 2007, 2010; Heathman et al., 2012). Understanding such a variability is essential for a thorough comprehension of the processes it is related to (Penna et al., 2013), and presents one of the major challenges in modern hydrology (Vereecken et al., 2008). The spatial variability characteristics of soil moisture had been widely researched in farmland, forest, grassland, wetland and desert ecosystems. The research scale has also been further expanded, from field scale covering a few square meters and a few hundred square meters to large scale of hundreds of thousands of square meters (Hawley et al., 1982; Ladson and Moore, 1992; Loague, 1992; Robinson and Dean, 1993). A major concern during the past years has been the identification of factors controlling spatial and temporal soil moisture variability (Western et al., 1999; Entin et al., 2000; Pan et al., 2008; Pan and Wang, 2009) and the quantification of this variability at different scales (Seyfried, 1998; Skøien et al., 2003). Both local controls, such as vertical dominant fluxes governed by soil hydraulic properties and vegetation, and non-local controls, such as lateral processes induced by topography or climate variability, affect spatio-temporal fields of soil water contents (Grayson et al., 1997). At the small

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scale, spatial and temporal soil moisture variability can be inducedby the heterogeneity of soil, vegetation and topography. At larger scales, atmospheric processes superimpose moisture dynamics on small scale effects and make reliable estimates of mean soil moisture even more difficult (Schneider et al., 2008). Knowledge about the spatial variability characteristics of soil moisture was still lacking so far because it was influenced by a large number of environment factors (Famiglietti et al., 2008; Penna et al., 2009). Researches on temporal stability of soil moisture were more scarce compared with spatial variability characteristics.

Temporal stability analysis (TSA) is a statistical approach for describing the persistence of spatial patterns and characteristic behavior of soil moisture. The concept was first introduced by Vachaud et al. (1985), who defined it as "the time-invariant association between spatial location and classical statistical parameters of a given soil property" and suggested the ranking stability method. The concept was later expanded by Kachanoski and de Jong (1988), who described time stability of soil moisture as "the temporal persistence of a spatial pattern", potentially evaluated by using a simple correlation between successive time intervals. Information on temporal stability of soil moisture content has found multiple applications in environmental monitoring, modeling, and management (Martinez et al., 2013). Identifying representative locations that can estimate mean soil water content for an area of interest is one of the most important applications of the concept of temporal stability but typically requires extensive sampling on multiple occasions (Gao and Shao, 2012). It has been suggested that although soil moisture is highly variable, if measurements of soil moisture at the field or small watershed scale are repeatedly observed, certain locations can often be identified as being temporally stable and representative of an area average (Vachaud et al., 1985). A number of field studies had been conducted to determine footprint scale mean values based on *in situ* measurements in an effort to calibrate and validate remotely sensed soil moisture products (Njoku et al., 2002; Cosh et al., 2004, 2006). However, no conclusive results had been obtained for identifying representative locations based on related variables (Gao and Shao, 2012). Some of the research results are also controversial. For example, the research of Martínez-Fernández and Ceballos (2003) in semi-arid area indicated that temporal stability was more pronounced during dry conditions. On the contrary, Gómez-Plaza et al. (2000) and Williams et al. (2009) demonstrated that soil moisture during dry periods was characterized by more unstable patterns than during humid periods, which was later confirmed by a study from a semi-arid steppe by Zhao et al. (2010). Grant et al. (2004) found almost no changes in the spatial organization of soil moisture patterns during different soil moisture conditions. Joshi et al. (2011) indicated that soil texture and topography were two significant physical controls jointly affecting the spatio-temporal evolution and time stability of soil moisture at point and remotely sensed footprint scales (800 m $\times$ 800 m); the research of Gómez-Plaza et al. (2000) in a semi-arid environment had shown that at the transect scale, when the factors affecting soil moisture were limited to geographic position or local topography, spatial patterns showed time stability, but when other factors, such as vegetation, were taken into account, the spatial patterns became time unstable. At the point scale, and in the same areas, geographic position was the main factor controlling time stability. Meanwhile, the actual scale of observation and number of measurements affected the temporal stability analysis of soil moisture (Gómez-Plaza et al., 2000; Brocca et al., 2009; Heathman et al., 2009). Choi and Jacobs (2011) reported that soil properties and topography were the most important physical drivers across scales.

However, most of the studies reported in the literature generally assessed the temporal persistence of soil moisture patterns and their stability during wet and dry periods in gentle terrain.

The temporal dynamics and persistence of soil moisture patterns along the soil profile had not been fully analyzed on the hillslope scale, where the complex surface topography may severely affect the temporal and spatial variability of soil water distribution. In this paper, we analyzed the temporal stability of near-surface soil moisture patterns at three depths on a steep hillslope with contrasting morphology and its surface covered with biological soil crusts in an artificially revegetated desert area in Shapotou, China. The spatial distribution characteristics and main factors affecting surface soil moisture at the same study area had been studied by Pan et al. (2008) and Pan and Wang (2009). Specifically, this research aims to: (i) assess the overall time stability of hillslope scale water content distribution and indentify the primary factors responsible for temporal stability along the soil profile in a semi-arid region; (ii) identify the statistically stable locations by applying the ranking stability method at the hillslope scale; and (iii) evaluate the feasibility of identifying statistically stable locations from the readily measured soil and topographic properties.

2. Materials and methods

2.1. Experimental site description

The experiment was carried out in the desert steppe region at the Shapotou Desert Research and Experiment Station bordering the Tengger Desert at 37°32′N and 105°02′E. The average elevation is 1288 m above the sea level. The area has large and dense reticulate dune chains and the main dune crest migrates southeastward at a velocity of 0.3–0.6 m per year. According to meteorological records between 1955 and 2005 from the weather station, annual mean temperature is 10.6 °C. The lowest temperatures are observed during January, with a mean value of −6.3 °C and the highest temperatures are observed during July, with a mean value of 24.9 °C. Annual mean precipitation is 193 mm, most of which falls during the monsoon period between May and September. The annual potential evaporation is approximately 3000 mm. The growing period ranges from 150 to 180 days per year. The natural predominant plants are *H. scoparium* and *Agriophyllum squarrosum* with a cover of approximately 1–2% (Shapotou Desert Experimental Research Station, Chinese Academy of Sciences, 1991). The soil is classified as orthic sierozem and aeolian sandy soil (Li et al., 2007).

The experimental field lies in the artificially re-vegetated desert area initiated in 1956.The barchan chain is the main type of sand dunes in Shapotou area, and the geomorphic type did not changed after revegetation. The leeward, hollow and windward continues to loop on the regional scale. A desert shrub ecosystem with a dwarf shrub and biological soil crusts cover on the stabilized sand dunes has been formed. With respect to spatial heterogeneity, Our study area is characterized by patches of perennial vegetation, typically shrubs such as *Caragana korshinskii*, *Artemisia ordosica*, associated with the annual herbaceous such as *Eragrostis poaeoides*, *Bassia dasyphylla*, *Corispermum patelliforme*, *Corispermum mongolicum*, *A. squarrosum*, *Setaria viridis*, and biological soil crusts which is dominated by algae (e.g., *Euglena* sp., Hantzschia *amphioxys var capitata* Grum), lichen (e.g., *Collema tenax* Ach.), mosses (e.g., *Bryum argenteum* Hedw, *Didymodon constrictus* (Mitt)) and cyanobacteria (e.g., *Microcoleus vaginatus* Gom, *Hydrocoleum violaceum* Marten) (Li et al., 2007). The maximum thickness of biological soil crusts and sub-soil layer can reach 5.01 cm (Wang et al., 2006), with the sand content accounting for 80%, silt and clay content accounting for around 20% (Pan et al., 2008).

2.2. Experimental design and data collection

Considering the different soil surface conditions and plant occurrence at different topography location which exercises a great