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Spatio-temporal variability of root zone soil moisture in artificially revegetated and natural ecosystems at an arid desert area, NW China

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ABSTRACT

Soil moisture is a major component of the hydrologic cycle, being highly variable and nonlinear in space and time. Knowledge of soil moisture regime, especially at the root zone, is critical to the management of water resources and restoration of vegetation. As such, techniques that allow identifying and reducing the number of samples for soil moisture analysis are required. In this study, a spatial variability and temporal stability analysis were used to analyze the volumetric soil moisture content of root zone collected by neutron probe at 36 days during three years in Shapotou, China. The specific concern was to investigate the temporal stability of soil moisture at different depths in the soil profile, determine the effects of soil and vegetation characteristics on temporal stability, and to conduct such a study in an area larger than 1 km^2. Additionally, we aimed to determine whether temporally stable sites are invariable at different depths, and compare with temporally stable shallow layer (0–6, 0–15, 0–30 cm) sites that are previously identified by Wang et al. (2013b) in the same study area. Results showed that the mean soil profile moisture demonstrated a moderate spatial variability which decreased with increasing soil moisture content at 0–60 cm depth; however, the variability of soil moisture and CV were both low and no significant correlations were found at 0–300 cm depth. A high temporal stability existed at two deeper soil layers compared with the soil surface observed by Wang et al. (2013b). The sampling locations, representative of the dry conditions in the field, were always more temporally stable. Identified representative locations at two depths well-represented the mean soil moisture content in our study area larger than 1 km^2. Furthermore, strong correlations at two soil layers revealed that spatial patterns of sampling points were preserved for all depths and that time stability of shallow measurements was a good indicator of deep soil layer time stability. Soil texture was the primary influence factor on soil profile moisture temporal stability and the dependence of soil moisture temporal stability on soil texture was consistent among different soil depths. Knowledge of the underlying stable soil moisture distribution could provide a useful basis for precise water management in arid areas.

1. Introduction

Soil moisture is a key variable controlling hydrological and energy fluxes at different spatio-temporal scales (Brocca et al., 2009; Heathman et al., 2009), which controls the exchange of water and energy between the land surface and atmosphere through evaporation and transpiration, determines the partitioning of precipitation into runoff, infiltration, and surface storage, as well as the partitioning of incoming solar radiation and long wave radiation into outgoing long wave radiation, latent heat, ground heat, and sensible heat fluxes (Pachepsky et al., 2003; Baroni et al., 2013). Soil moisture in arid environments is also crucial in limiting seed germination rates and vegetation growth, serving as the main constraint on permanently controlling desertification (Berndtsson et al., 1996; Jia et al., 2013), and largely determines the carrying capacity for vegetation and the organization and function of ecosystems (Rodriguez-Iturbe et al., 1999). Hence the patterns of soil moisture in arid environments are very important for the conservation and restoration of vegetation. However, the amount of soil moisture is a result of interactions among a series of variables, such as topography, soil properties, vegetation, water-routing processes, depth of water table and meteorological conditions (Western et al., 1999; Gómez-Plaza et al., 2000), making it highly variable over time and space across different scales (Albertson and Montaldo, 2003; Manfreda and Rodriguez-Iturbe, 2006; Famiglietti et al., 2008; Brocca et al., 2007, 2010;

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Penna et al., 2009, 2010; Zhang and Shao, 2013). Understanding such a variability characteristic is essential for a thorough comprehension of the water-related processes.

Traditional sampling methods generally assume that spatial variability patterns of soil moisture are random. However, factors controlling soil moisture exhibit non-random patterns that may persist over time (Gao and Shao, 2012). In other words, in addition to the strong spatio-temporal variability, soil moisture also shows a somewhat strong temporal stability of spatial pattern (Mohanty and Skaggs, 2001; Martínez-Fernández and Ceballos, 2005; Brocca et al., 2009, 2010; Hu et al., 2009; Zhao et al., 2010). The concept of temporal stability 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. It is a reflection of the temporal persistence of soil moisture within a spatial distribution pattern (Kachanoski and de Jong, 1988; Zhou et al., 2007; Schneider et al., 2008). This means that soil moisture at each single sampling location varies over time but the relative spatial organization of all soil moisture values is temporally preserved (Penna et al., 2013). The purpose of temporal stability study was to propose a method for reducing the number of field sampling sites while at the same time accurately characterizing the behavior of soil moisture in the study area over time. One of the most useful applications is the potential to identify sampling locations that could reliably represent the mean moisture content of the entire study area. The idea was introduced by Grayson and Western (1998) who demonstrated the existence of certain parts of the landscape which consistently represented mean behavior of soil moisture irrespective of the overall wetness of the whole study area. However, several processes can disrupt temporal stability. Joshi et al. (2011) indicated that soil texture and topography were two significant physical controls jointly affecting the spatio-temporal evolution and temporal stability of soil moisture at point and remotely sensed footprint scales; 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 temporal 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 temporal 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), and the depth of observation is also an important aspect in the study of the temporal stability of soil moisture (Martínez-Fernández and Ceballos, 2003; Starks et al., 2006). Although many authors applied Vachaud's approach over several climatic regions, a direct comparison among the achieved results is not straightforward because of the differences in the investigated area, in the sampling scheme, in the investigation depth, and in the study period (Martínez-Fernández and Ceballos, 2003, 2005; Tallon and Si, 2003; Thierdefelder et al., 2003; Cosh et al., 2004, 2006; Grant et al., 2004; Jacobs et al., 2004; Petrone et al., 2004; Pachepsky et al., 2005; Bosch et al., 2006; Starks et al., 2006; Teuling et al., 2006; Wang et al., 2013b).

There were still some deficiencies in soil moisture temporal stability analysis. Firstly, although direct measurement is the most accurate method for estimating soil moisture, this technique is expensive, time consuming and only provides point measurements which limited the study of spatio-temporal variations in soil moisture in arid environments (Gao et al., 2013). The development of modeling techniques to estimate soil moisture availability has been an area of extensive research during the past decade (Jacobs et al., 2004; Cosh et al., 2006, 2008; Starks et al., 2006; Vivoni et al., 2008). However, retrieved soil moisture products by remote sensing have focused on near surface soil moisture and very few reports refer to the whole soil profile or the relationship between surface and profile variability (Kachanoski and de Jong, 1988; Hupet and Vanclooster, 2002; Schmugge et al., 2002; Martínez-Fernández and Ceballos, 2003, 2005; Pachepsky et al., 2005; De Lannoy et al., 2006; Starks et al., 2006; Guber et al., 2008). For most practical applications, knowledge of soil moisture must be understood for layers deeper than the thin surface layers observed using remote sensing instruments. Entire soil moisture profiles provide an enhanced characterization for hydrologic applications (Western et al., 1998) and a more integral understanding of soil moisture dynamics (Bloschl and Sivapalan, 1995). The dynamics of soil moisture at deeper layers may also significantly influence surface soil moisture variability (Jacques et al., 2001). Secondly, the observation time was short for most previous studies. For a successful application of the temporal stability concept, the selected points need to represent average moisture dynamics beyond the time period they were determined for (Martínez-Fernández and Ceballos, 2003), to capture possible changes in the spatial pattern due to seasonality and to remove the influence of short-term weather patterns, samples of soil moisture should be collected on at least 13 occasions within a minimum sampling period of one year (Martínez-Fernández and Ceballos, 2005; Schneider et al., 2008). Thirdly, the concept of temporal stability has rarely been applied to desert areas (Pan et al., 2009; Wang et al., 2013b; Zhang and Shao, 2013), where rainfall is the only soil moisture source, and where soil moisture is the most crucial factor for the restoration of vegetation. To gain a deeper insight into the temporal stability of soil moisture in arid desert areas, we measured soil moisture in eight adjacent artificial revegetation desert areas and natural vegetation areas over 36 occasions from 1990 to 1992, analyzed the potential of time-stable points to estimate average soil moisture content at the field scale. The specific objectives of the study were to: (1) investigate the distribution patterns of soil moisture at different soil layers as a basis for subsequent analysis; (2) detect variations in temporal stability in soil profiles and determine whether time-stability persists between consecutive growing seasons, and (3) understand the mechanisms controlling temporal stability of soil moisture under the combined influences of vegetation type, soil depth, and soil texture. This study is expected to contribute to our understanding of soil moisture patterns in arid desert environments, which have important implications for ground sampling design, hydrologic modeling, and sustainable vegetation restoration.

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. 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 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 *Helianthemum scoparium* and *Agriophyllum squarrosum* with a cover of approximately 1–2%