Catena 172 (2019) 655–663

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Dynamic variations in profile soil water on karst hillslopes in Southwest China

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ARTICLE INFO

Keywords:
Soil moisture
Soil water storage
Time series analysis
Vertical stratification

ABSTRACT

Precipitation in the karst regions of southwest China is plentiful, however, soils are shallow and highly permeable, which results in rapid transportation of surface water through a soil profile. Therefore, the presence and amount of water stress in a soil layer can be unpredictable. This study will investigate the soil water conditions on karst hillslopes in southwest China through dynamic in situ observations of profile soil moisture (θ). Three profiles at two slope positions on two shrub-grasslands (S1 and S2) were selected, respectively. At each profile, TDR 100 probes were set at 10, 20, 30, 50, and 70 cm and for 100 cm, only on downslopes. Soil samples (undisturbed and disturbed) were collected to measure basic physical and chemical properties. Precipitation and θ were monitored manually each week between July 15, 2012 and November 25, 2014. Results show that soil properties, which have an important effect on θ, varied among slope positions and between the two hisllslopes. A higher clay content, which led to greater water holding capacity, explained a higher θ in downslopes and on S2. Shallow soil layers (0–30 cm), especially in the coarse textured soil layers of S1, were susceptible to water stress due to the limited availability of soil water. Water stress was low during water supplying (December through April) and relatively stable periods (May to June). However, during water consuming periods (July to November), profile θ decreased greatly which resulted in severe water stress for the whole profile. Although precipitation was seasonally uneven, based on weekly observations, profile θ on both hillslopes was not temporally active (coefficients of variation of θ was smaller than 20%) and the variance of each depth was similar. Generally, the effects of precipitation on θ can last two (0–50 cm) to five (70–100 cm) weeks. Nevertheless, θ of downslope deep soil, which was (or near) saturated all year round, was barely affected by precipitation. These results can provide valuable information for hydrological models and rational strategies for ecological restoration designing in karst regions.

1. Introduction

Soil moisture (θ) affects a wide variety of earth system interactions, such as hydrologic and biological processes, over a range of spatial and temporal scales in the soil-plant-atmosphere continuum (Famiglietti et al., 1998; Tromp-van Meerveld and McDonnell, 2006). Soil water stored near the surface exerts major control on the partitioning of precipitation into surface runoff and infiltration, redistribution of infiltrated rainwater and facilitation of plant transpiration demands (Daly and Porporato, 2005; Legates et al., 2011; Rivera et al., 2014; Canton et al., 2016). Observations of θ may offer unique insights into near-surface ecohydrologic processes, which can reflect the status of soil water recharge and depletion (Vereecken et al., 2008; Ries et al., 2015). Therefore, the amount of available soil water, which is essential for plant survival and growth, should be evaluated. Soil water constants, such as field capacity (FC) and permanent wilting point (PWP) are used to indicate soil water conditions and levels of water that are available for plant utilization (Yang et al., 2016b). If the values of θ are compared with FC and PWP, free water content (Lai et al. 2018) and available soil water can be determined. Given the importance of θ, quantification of its spatial-temporal behavior at various scales is receiving increased attention (Western et al., 1999; Brocca et al., 2007; Chen et al., 2010; Rötzer et al., 2015; Yang et al., 2016a). However, this task is formidable, since θ exhibits a high degree of variability in both space and time

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https://doi.org/10.1016/j.catena.2018.09.032
Received 28 October 2017; Received in revised form 12 August 2018; Accepted 18 September 2018

due to the uneven distribution of precipitation, evaporation and transpiration (Famiglietti et al., 1998; Penna et al., 2009; Zhang et al., 2011). The variability in θ is more complicated in highly heterogeneous regions, such as karst.

Karst is defined as terrain that is generally underlain by limestone or dolomite, where the topography is formed by dissolved rock (Field, 2002). Karst landscapes are widely distributed (about 550 thousand km^2) in southwest China, where karstification is the strongest (Li et al., 2002). Most weathered materials are removed by water resulting in shallow and discontinuous soil coverage in karst regions, especially on hillslopes (Wang et al., 2004). Vegetation is mainly unevenly distributed tussock grasses and shrubs (Nie et al., 2011). The subtropical monsoon climate leads to abundant precipitation in southwest China (Liu et al., 2014). While, the shallow and coarse soils on karst hillslopes, with low water holding capacity and high permeability, facilitate fast downward transportation of soil water (Bonacci et al., 2009). Furthermore, the uneven distribution of rock fragments and diverse soil depths, cause soil water storage and plant available water to vary in space (Tokumoto et al., 2014). The three questions which are important during vegetation restoration in karst regions: What is the water condition on karst hillslopes? Do plants suffer from water stress? and If there is water stress, when does it happen? are still unanswered. In the last 60 years, precipitation in southwest China has decreased at a rate of 11.4 mm per decade and the climate is gradually getting more extreme (Liu et al., 2014). It is urgent to understand the variations in θ dynamics, so as to provide a scientific basis for vegetation restoration in these areas.

Presently, more studies are focused on θ dynamic variations, over short (Chen et al., 2010; Canton et al., 2016) and long-term (Penna et al., 2009; Zhang et al., 2013; Canton et al., 2016) periods of time. Through long-term θ dynamic monitoring, the presence and seriousness of water stress should be evaluated. Based on these evaluations, strategies can be developed for vegetation restoration. However, there is still a lack of research in this area, especially in karst regions. Canton et al. (2016) investigated the fluctuations in θ for 17 months on a Mediterranean karst hillslope, but they only monitored θ in the 25 cm surface layer due to the shallow soils. Zhang et al. (2013) compared the daily variations of profile θ (100 cm deep) in a dolomite and limestone depression, respectively. However, they did not investigate the water condition and their results do not represent the variations in θ on hillslopes. Soil properties, land cover and evaporation may vary depending on the hillslope position. This variability would have an important effect on θ (Kidron and Zohar, 2010; Canton et al., 2016). Therefore, systematic studies that focus on the dynamic variations in profile θ on different karst hillslope positions need to be conducted.

We analyzed the dynamic variations of profile θ along different slope positions on two shrub-grasslands in karst regions in southwest China. Specifically, the objectives of this study were to (i) investigate soil water conditions by dynamic monitoring of profile θ, and (ii) discuss the effects of precipitation on θ variations with time on the two hillslopes.

2. Materials and methods

2.1. Site description

The study area is a small catchment with an area of approximately 1.14 km^2 located in the Huanjiang Observation and Research Station for Karst Ecosystems of the Chinese Academy of Sciences in Huanjiang County of northwest Guangxi, southwest China (Fig. 1). This region is dominated by a subtropical mountainous monsoon climate with annual rainfall of 1389 mm and temperature of 18.5 °C (Song et al., 2010). The wet season lasts from late April until the end of September and provides > 60% of total annual rainfall (Yang et al., 2012). A pronounced 4–6 months' dry season in winter/spring provides only 20%–30% of total annual rainfall. The catchment is a typical karst (dolomite) area with a flat depression surrounded by mountains on three sides and an outlet in the northeast. This area experienced severe deforestation from 1958 to the mid-1980s and has been under natural restoration for over 30 years. Tussock grasses and shrubs dominate most hillslopes. Secondary forest is only found on the continuous dolomite outcrops and on deep soils at the foot of hillslopes (Nie et al., 2011).

Elevation in this catchment ranges from 272 m to 647 m and hillslopes are steep, with approximately 60% being > 25°. Areas with bare rock account for 30% of this region, and the relative soil depth in this area is 10–30 cm. The shallow and discontinuous soils are mostly underlain by weathered dolomite. Fractures are widely distributed in the epikarst zone and most of them are filled with soil or regolith materials (Yang et al., 2016b). The soil depth decreases as rock fragment content increases from upslope to downslope (Chen et al., 2011). Soils on hillslopes are in highly permeable with steady-state infiltration rates of 42–126 mm h^{-1} (Chen et al., 2012a). Overland flow on hillslope is rare, with a runoff coefficient, which is often < 5% (Chen et al., 2012b).

2.2. Soil profiles selection and samples collection

Two shrub-grasslands (S1 and S2), which have similar vegetation and slope aspect, were selected for this study. S1 soils were relatively thinner and coarser with higher rock fragment content than that of S2. Springs occur at the footslopes of both S1 and S2. The S2 spring is perennial while S1 is intermittent, which occurs from the middle of the wet season to the dry season (mainly from May to November). Three soil profiles at two slope positions were selected on S1 and S2 (as shown in Fig. 1), respectively. Each profile was excavated to bedrock. Soil profiles were about 70 cm upslope and 100 cm downslope on both hillsides. Downslope profiles on both hillslopes were about twenty meters away from their springs. Stratified (0–10, 10–20, 20–30, 30–50 and 50–70 cm and 70–100 cm only on the downslope) disturbed and undisturbed soil samples were collected. Disturbed soil samples were used for particle distribution (clay, silt and sand contents) and soil organic carbon content (SOC) determination while undisturbed samples were used for bulk density (ρ_b), saturated conductivity (K_s) and water retention curves measurements. Capillary porosity (CP) and non-capillary porosity (NCP) were calculated during K_s measurement; FC and PWP were calculated during water retention curves measurements.

The characteristics of these basic soil properties were shown in Table 1. Generally, ρ_b increased while CP, NCP, FC, PWP and SOC decreased with increasing soil depth in both positions on the hillslopes. CP and NCP of each soil depth were higher, and FC and PWP were lower in S1 than in S2. As a whole, soils on S1 had more sand content and higher K_s than on S2. Correlated with the highest clay content in the profiles, K_s was the lowest at 30–50 cm layer in both positions of S2.

2.3. θ and precipitation amount monitoring

To monitor θ at different depths, TDR 100 (Campbell Scientific, Logan, UT, USA) probes were inserted at 10, 20, 30, 50 and 70 cm and 100 cm only on the downslope. The soil profiles were backfilled by the original soils. Soil moisture was measured weekly from July 15, 2012 to November 25, 2014. If there was rainfall on the monitoring date, monitoring was put off. Simultaneously, precipitation amounts in the study area were measured weekly according to θ monitoring.

2.4. Data analysis

Basic statistics, including the mean, standard deviation (SD), coefficient of variation (CV), and maximum (Max), and minimum (Min) values of θ at each soil depth were analyzed. Based on CV and SD, soil water vertical variation was divided into 4 layers: rapidly changed (CV ≥ 30%, SD ≥ 4%), active (20% < CV < 30%, 3% < SD < 4), sub-active (10% < CV < 20%, 2% < SD < 3%) and relatively stable (CV ≤ 10%, SD ≤ 2%) (Chen et al., 2010). In reality, satisfying