

Soil moisture dynamics under different land uses on karst hillslope in northwest Guangxi, China

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Abstract Temporal and spatial dynamics of soil moisture are little known on karst hillslope with shallow soil in subtropical region. The objectives of this paper were (1) to investigate the temporal dynamics of soil moisture at depth of 0–10 cm under different land uses; and (2) to understand the relationship between mean and coefficient of variation (CV) of moisture contents on karst hillslope in northwest Guangxi, China. Soil moisture contents had a moderate variation (CV 17.5–30.3%) over an 8-month period and they had a significant difference among different land uses at the 0.01 level with a decreasing order: native scrubland > abandoned cropland and sloping cropland > economic forestland. There were higher mean and lower CV of moisture contents in rainy season than those in drought season. Mean and CV of moisture contents had a significant negative linear relationship except in abandoned cropland with higher soil and vegetation heterogeneity. This suggested that spatial variability of soil moisture within sampling sites would decrease when soils were wet and increase when soils were arid. Compared with rainy season, more soil samples may be needed and the interval for sampling should be shortened in drought season. Such

information provided some insights to better understand the dynamics and variability of soil moisture at a larger scale in karst region of southwest China.

Keywords Soil moisture dynamics · Land use · Topography · Hillslope · Karst region of southwest China

Introduction

Surface soil moisture plays a crucial role in hydrological and ecological processes at the land surface, including infiltration, runoff, erosion, solute transport, and land–atmosphere interactions (Western and Blöschl 1999; Qiu et al. 2001; Daly and Porporato 2005). It exerts a high degree of variability in space and time and is influenced by a number of factors, such as topography, soil, vegetation, land uses, precipitation and other meteorological conditions (Famiglietti et al. 1998; Gómez-Plaza et al. 2001; Fu et al. 2003). However, the importance of these factors can vary with seasonal variations in soil moisture content (Grayson et al. 1997; Famiglietti et al. 1998; Ridolfi et al. 2003). Although numerous studies have characterized soil moisture, there is no agreement as to whether soil moisture variability is positively (Robinson and Dean 1993; Famiglietti et al. 1998; Martínez-Fernández and Ceballos 2003) or negatively (Hupet and Vanlooster 2002; Choi et al. 2007) correlated to mean soil moisture content. Moreover, the factors which control soil moisture content in humid environments may differ from those in semiarid areas even at the hillslope scale (Gómez-Plaza et al. 2001). Consequently, space–time soil moisture dynamics are still poorly understood due to the complexity of hillslope topography as well as hydrology (Western et al. 1999; Ridolfi et al. 2003).

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Karst regions are landscapes characterized by caves and sinkholes formed by the dissolution of highly soluble carbonate rock. Soils are often thin and rocky with relatively high permeability, while fissures, gaps, and channels enlarged by solution in the underlying bedrock facilitate the rapid transport of surface water to groundwater. These features result in an uneven distribution of permeability in karst systems and surface and subsurface hydrological conditions. Local high permeability at shallow depth in mature karst regions leads to an ecology associated with a soilless and water-scarce surface environment (LeGrand and Stringfield 1973; White 2002). Therefore, to investigate soil moisture dynamics may be helpful to better understand the hydrological and ecological processes in karst ecosystems.

Many ecosystems of tropical and subtropical latitudes suffer water stress, which is in turn controlled by the temporal fluctuations of soil moisture (Rodriguez-Iturbe et al. 2001). The karst ecosystems in southwest China are ecologically fragile and have been degraded with shallow soil and high cover of exposed bedrock in recent years (Yuan 2001; Cao et al. 2004). Although the precipitation is abundant in this area, the seasonal drought occurs often which heavily inhibits plant establishment and growth. In order to restore the degraded ecosystems in karst region, most cultivated sloping lands have been abandoned or converted to artificial forestland since the latter 1990s. However, compared with other regions, the mosaic of rock outcrops and thin soils increases the complexity of topography and the diversity of microhabitats in karst region (Wang et al. 2004). This kind of particular mosaic may

have an important effect on soil moisture dynamics and play an active role in hillslope hydrology (Conn and Snyder-Conn 1981; Crowther 1982; Descroix et al. 2001). However, soil moisture dynamics in space and time are still unclear under different land uses in karst region of southwest China.

The objectives of this study were (1) to investigate the temporal dynamics of soil moisture under different land uses; and (2) to understand the relationship between mean and coefficient of variation (CV) of moisture contents on karst hillslope in northwest Guangxi of southwest China.

Materials and methods

Site description

The study was carried out in a typical peak-cluster depression area of Guzhou catchment ($24^{\circ}54'–24^{\circ}55'N$, $107^{\circ}56'–107^{\circ}57'E$) in Huanjiang County, northwest Guangxi in southwest China (Fig. 1), which belonged to the Huanjiang Observation and Research Station for Karst Ecosystems under the Chinese Academy of Sciences (CAS). The catchment consists of a broad depression flanked by steep hills. This area has 1.87-km² lands with an elevation ranging from 375 to 816 m above sea level, and has 0.17-km² cultivated lands mainly located in the depression. The study site has a mean annual temperature of 16.5–20.5°C, and a mean annual rainfall of 1,389.1 mm, mainly falling from May to September. The discrete soils containing few rock fragments have been developed from

Fig. 1 Schematic map of sampling sites under five land use types on hillslope with contour lines at 25-m interval in Guzhou catchment in Huanjiang County of Guangxi, China. *NS* Native scrubland, *AC* abandoned cropland, *SC* sloping cropland, *CF* chestnut forestland, *PF* pigeonpea forestland

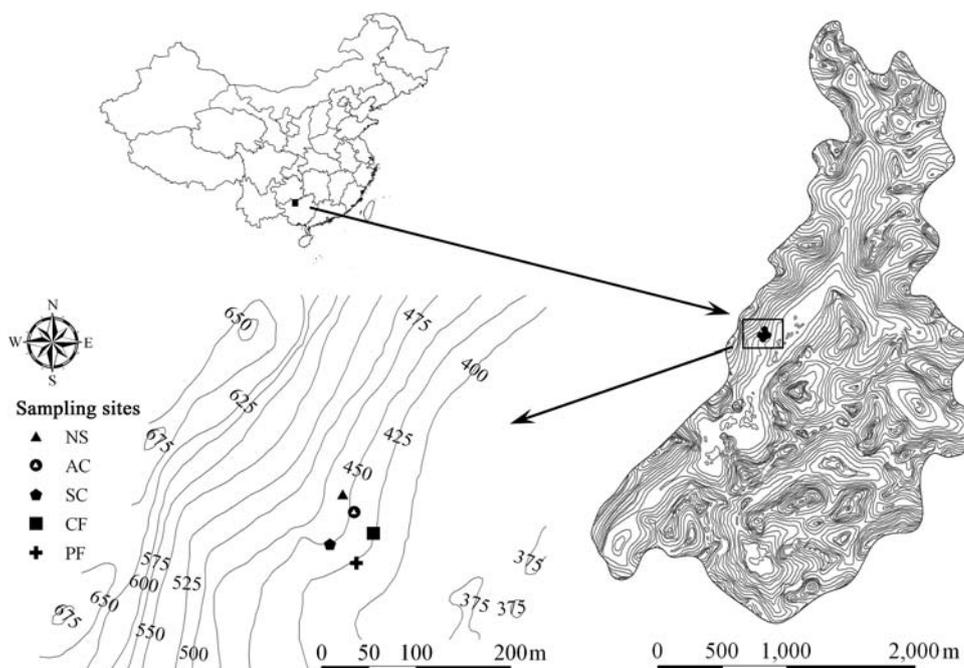




Fig. 2 View on the study area. Some sloping croplands were abandoned at the end of 1996, and chestnut and pigeonpea were planted in the other sloping croplands in late 2002

limestone, and have an average depth of 50–80 cm in the depression and 10–30 cm on hillslope.

Because of the overpopulated pressure, sloping lands at the middle and bottom of hillslope have been cultivated intensively with high cover of exposed bedrock ranging from 40 to 80%, and forest coverage is as low as 13% (Fig. 2). From top to bottom of hillslope, rock outcrops often decrease with increase in soil depth. At the end of 1996, some villagers moved outside and a part of sloping croplands were abandoned due to the project of “Grain to Green”. However, in late 2002, in order to gain economical benefits, chestnut (*Castanea mollissima* Bl.) and pigeonpea [*Cajanus cajan* (L.) Millsp.] were planted gradually on another part of sloping croplands. The dominant vegetation is euphorbiaceae (*Sapium rotundifolium* Hemsl.), leguminosae [*Bauhinia championii* (Benth.) Benth.], and firethorn [*Pyracantha fortuneana* (Maxim.) Li] in native scrubland, and is contorted tanglehead [*Heteropogon contortus* (L.) Beauv.] and sedge (*Carex* spp.) in abandoned cropland. In order to investigate

temporal dynamics of soil moisture, five dominant land use types were selected on hillslope (Fig. 1). Sloping cropland was re-cultivated again from abandoned cropland in early 2003, and the main plants were pumpkin (*Cucurbita moschata* Duch.), red pepper (*Capsicum annuum* Linn.), and tobacco (*Nicotiana tabacum* Linn.). Table 1 shows vegetation cover, topography, and some soil properties at 0–15 cm depth in five land use types. The soil texture is often silty clay in native scrubland, and loam in chestnut and pigeonpea forestland.

Soil sampling and data collection

Soil moisture contents were measured every other week on hillslope under five land uses from May 6 to December 22 in 2004. Soil samples were collected randomly at depths of 0–5, 5–10, 10–15, and 15–20 cm with ten replications in a 20 × 20 m area using a 2 cm diameter hand auger.

Due to shallow soils, it was not always possible to collect samples at depths of 10–15 and 15–20 cm at each location so moisture contents at depth of 0–10 cm were analyzed. Once extracted from the ground, soil samples were placed quickly in aluminum cans with tight-fitting lids. Shortly thereafter, the gravimetric moisture content of each sample was measured with oven-drying method (10 h, 105°C). Rainfall data were obtained from a rain gauge installed in the depression.

Results and discussion

Descriptive statistic analysis of soil moisture contents

Some main statistical parameters, including description of the mean, standard deviation (SD), CV, and extreme maximum and minimum values of soil moisture contents at depth of 0–10 cm under five land use types, were analyzed and the results are shown in Table 2. Mean comparisons were made using the least significant difference (LSD)

Table 1 Vegetation cover, topography, and some soil properties at depth of 0–15 cm in five land use types on hillslope

Land use	Vegetation cover (%)	Rock outcrop ^a (%)	Slope gradient (°)	Soil depth ^b (cm)	Organic matter content (%)	Bulk density (g/cm ³)	Soil particle size USDA (%)		
							Sand	Silt	Clay
Native scrubland	70–80	60–80	35–45	5–20	5–10	0.9–1.1	5–10	40–50	40–50
Abandoned cropland	50–70	50–70	25–40	5–30	3–5	1.0–1.2	5–10	50–60	30–40
Sloping cropland	40–60	50–70	25–35	10–40	3–5	0.9–1.1	5–10	50–60	30–40
Chestnut forestland	20–40	40–60	20–30	15–40	2–4	1.1–1.3	15–25	40–50	20–30
Pigeonpea forestland	20–40	40–60	20–30	15–40	2–4	1.1–1.3	15–25	40–50	20–30

^a Taking no account of vegetation cover

^b Depth to bedrock or petrocalcic horizon

Table 2 Descriptive statistic analysis of soil moisture contents at 0–10 cm depth in five land use types on hillslope from May 6 to December 22, 2004

Land use	The whole observation period (May 6 to Dec. 22)					Rainy season (May 6 to Sep. 8)					Drought season (Sep. 9 to Dec. 22)				
	Mean (%)	Max (%)	Min (%)	SD (%)	CV (%)	Mean (%)	Max (%)	Min (%)	SD (%)	CV (%)	Mean (%)	Max (%)	Min (%)	SD (%)	CV (%)
Native scrubland	38.5a	47.6	25.0	6.7	17.5	43.1a	47.6	37.1	2.9	6.8	32.5a	40.1	25.0	5.3	16.4
Abandoned cropland	26.8b	36.2	17.3	5.9	22.0	30.3b	36.2	24.3	4.1	13.4	22.1b	29.0	17.3	4.6	20.7
Sloping cropland	27.7b	37.1	15.6	6.1	22.1	31.0b	37.1	26.1	3.7	11.9	23.6b	33.6	15.6	6.3	26.8
Chestnut forestland	19.0c	28.8	9.8	5.8	30.3	22.6c	28.8	17.2	4.3	19.1	14.5c	21.2	9.8	3.9	26.7
Pigeonpea forestland	18.4c	25.6	10.4	4.8	26.4	21.5c	25.6	17.8	2.9	13.3	14.4c	21.1	10.4	3.8	26.5
<i>F</i> value	30.42**					51.07**					16.71**				

Values in each column with the same letter are not significantly ($p < 0.01$, LSD) among different land uses

** Significant at the 0.01 level

method with $p < 0.01$. Soil moisture contents had a moderate variation (CV 17.5–30.3%) under five land use types from May 6 to December 22, 2004. During the whole observation period, mean moisture contents had a significant difference ($p < 0.01$) among different land uses with a decreasing order as follows: native scrubland > abandoned cropland and sloping cropland > chestnut and pigeonpea forestland. However, the CV values seemed have the opposite trend. Native scrubland had the highest mean moisture content (38.5%) and the smallest CV value (17.5%) because of high vegetation and litter cover. Chestnut and pigeonpea forestland had the smallest mean moisture contents (19.0 and 18.4%) and the highest CV values (30.3 and 26.4%) due to low vegetation cover and high evaporation. This suggested that some soil moisture conservation measures should be carried out during the early growth period of artificial plants.

Moisture contents had a close relationship with rock outcrops when land uses were the same (Conn and Snyder-Conn 1981; Noy-Meir et al. 1991). Conn and Snyder-Conn (1981) found that areas immediately adjacent to the outcrops had higher soil moisture than areas away from the outcrops, which could provide greater runoff, shading, and soil temperature stability. Noy-Meir et al. (1991) discovered that soil moisture was significantly higher than elsewhere at the sampling points close to or between rocks, in particular tall smooth rocks. However, Cousin et al. (2003) suggested that the high calorific characteristics of the rock fragments would lead to heating of the soil and therefore to a decrease of its water content under strong evaporation conditions. Therefore, land use may still be the dominant factor affecting the differences of soil moisture contents on hillslope in karst region. In order to better understand soil moisture dynamics under various land uses, topography,

rock outcrops, soil, and vegetation conditions should also be integrated into consideration in the forthcoming research.

Temporal dynamics of soil moisture contents

Soil moisture contents had apparent seasonal changes and were fluctuant with rainfall process from May 6 to December 22, 2004 (Fig. 3a, b). The change process of moisture contents had no significant differences among five land use types. During the observation period, the total rainfall was 1,178.5 mm, but most fell from May 12 to September 8, which was 1,067.8 mm and covered the total by 90.6%. Therefore, moisture contents increased from May to June and then kept relatively stable with high values from June to September. Subsequently, they decreased with the decrease in rainfall in October but there was an increasing trend due to rainfall between November and December. According to the rainfall process, the whole observation period could be divided into two stages: rainy season (May 6 to September 8) and drought season (September 9 to December 22). There were higher mean and lower CV of moisture contents in rainy season than those in drought season under five land use types (Table 2). This implied that more soil samples were needed in drought season than those in rainy season. In general, increased moisture contents appeared after heavy rainfall but there was a lag effect following a rainfall event. The highest daily rainfall was 109.5 mm on July 20, but the following mean moisture contents on July 23 were not the highest under five land use types. The second highest rainfall (80.7 mm on May 12 and 81.2 mm on July 31) also did not lead to the corresponding highest moisture contents on May 23 and on August 9, respectively. Furthermore, the time for the occurrence of the peak value of moisture

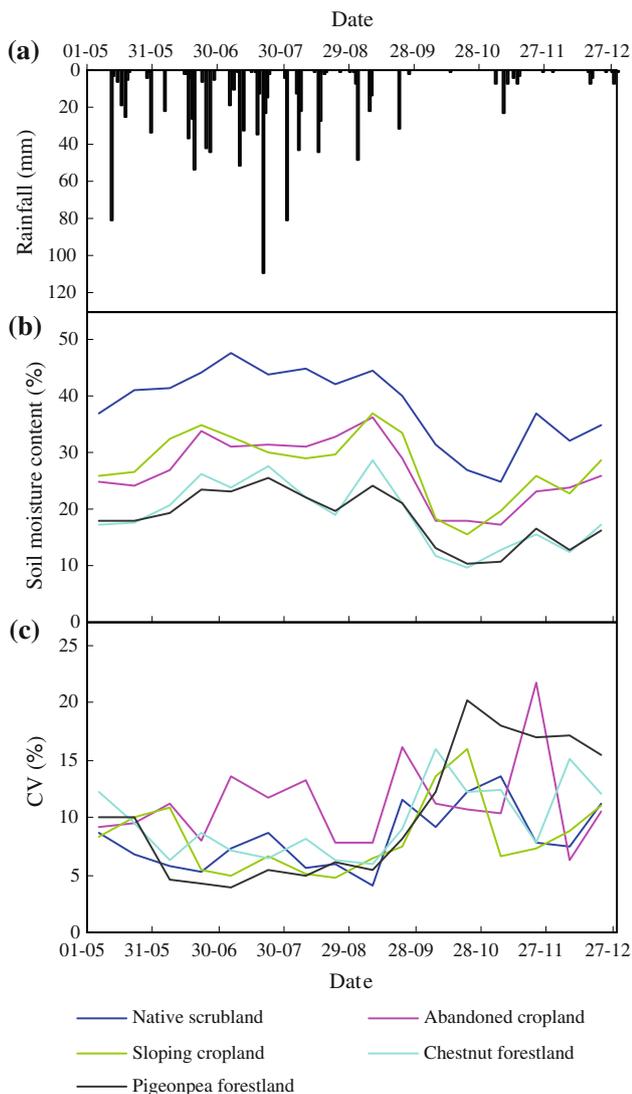


Fig. 3 Daily rainfall (a), and temporal change in mean (b) and CV (c) of moisture contents at depth of 0–10 cm under five land uses from May 6 to December 22, 2004

contents was not consistent under five land use types. This suggested that surface soil moisture changed quickly and the sampling interval should be decreased to about once every week on hillslope in karst regions.

The relationship between mean and CV of moisture contents

The CV of soil moisture contents at depth of 0–10 cm during each measurement was also fluctuant with rainfall process (Fig. 3a, c). However, the temporal dynamics of CV values were more complex than mean moisture contents and they were different among five land use types. The peak values of CV occurred in drought season but they did not appear simultaneously with the lowest mean

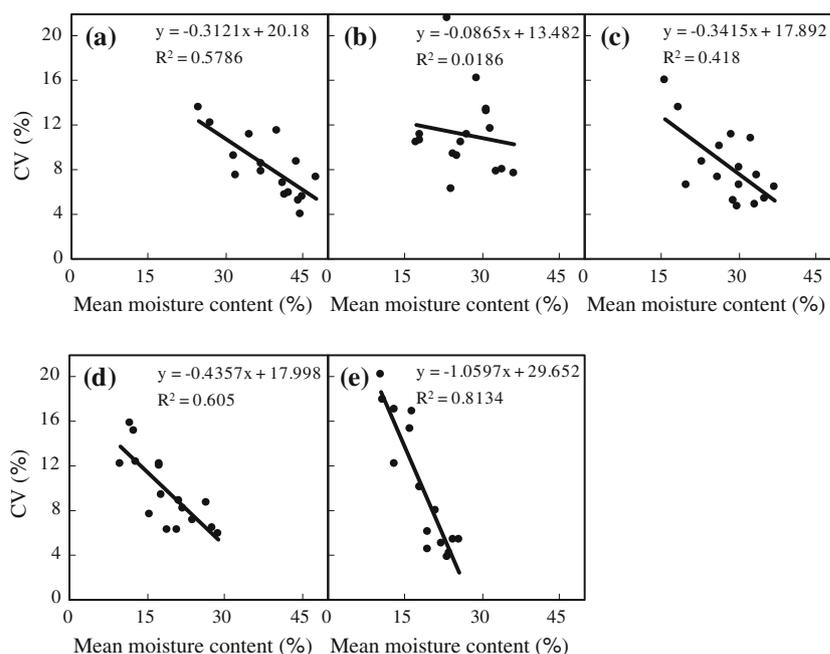
moisture contents during the whole observation period. In general, the higher mean moisture contents complied with lower CV values in rainy season, especially from June to September. This suggested that the CV values probably had the trend to decrease with increasing mean moisture contents. Figure 4 shows that mean and CV of moisture contents have a significant negative linear relationship except in abandoned cropland with higher soil and vegetation heterogeneity.

The negative linear relationship between mean and CV of soil moisture contents implied that the increase in mean moisture contents would reduce the differences of surface moisture contents within the sampling areas. Consequently, the spatial variability of surface soil moisture within sampling sites would decrease when soils were wet in rainy season and increase when soils were arid in drought season. This result was different from those obtained by Robinson and Dean (1993) and Famiglietti et al. (1998) but was consistent with those reported by Hupet and Vanclooster (2002) and Choi et al. (2007). Famiglietti et al. (1998) found that variance generally decreased with decreasing mean moisture contents, because soil heterogeneity exerted major impacts on infiltration and runoff during heavy rainfalls or storms on hillslope. However, in karst regions, soils and underlain rock had relatively high permeability and overland flow was small with runoff coefficient <10% (Chen and Wang 2008). Therefore, in rainy season, most rainwater infiltrated into soils and the spatial variability of surface soil moisture would be small following heavy rainfall. Sub-surface flow also had a negligible influence on surface soil moisture at depth of 0–10 cm because most rainwater was transported through the underlying bedrock with high permeability. In drought season, surface soil moisture would be strongly influenced by soil heterogeneity and the spatial variability would become larger.

Conclusions

Soil moisture contents at depth of 0–10 cm had a moderate variation (CV 17.5–30.3%) and mean moisture contents had a significant deference at the 0.01 level from May to December, 2004. Soil moisture is the highest in native scrubland, but the lowest in economic forestland. This suggested that some soil moisture conservation measures should be carried out during the early growth period of artificial plants. Mean and CV of moisture contents had a significant negative linear relationship except in abandoned cropland with higher soil and vegetation heterogeneity. This suggested that spatial variability of soil moisture within sampling sites would decrease when soils were wet and increase when soils were arid. In order to better

Fig. 4 The linear relationship between mean and CV of moisture contents at depth of 0–10 cm under five land use types (a native scrubland, b abandoned cropland, c sloping cropland, d chestnut forestland, e pigeonpea forestland) from May 6 to December 22, 2004



understand soil moisture dynamics, rock outcrops, soil depth, micro-landform and vegetation should also be considered in the forthcoming research.

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