Spatial variability and patterns of surface soil moisture in a field plot of karst area in southwest China

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ABSTRACT

A field plot (100 m × 50 m) was chosen in a karst depression area of Huanjiang County, Guangxi Province of southwest China, with the aim of characterizing the variability and patterns of upper 15 cm soil moisture. Soil moisture content was measured at 5 m intervals by gravimetric method during dry and rainy seasons in 2005. Results indicated that the surface soil moisture presented a strong spatial dependence at the sampling times in the field scale. The variability of soil moisture by *CV* values and sill decreased with the increasing mean field soil moisture content either in dry or rainy season. In the dry season, mean soil moisture had a little influence on the sill owing to the previous tillage. But, in the rainy season, a heavy rain event could decrease the variability of soil moisture. The anisotropy characteristics were found that the variance was lower in 0° direction than that in 90° direction based on the northeast axis, and the range had opposite trend except for the sampling on March 15, 2005. The mosaic patterns of soil moisture exhibited the variability and its anisotropy visually. The rainfall (mean soil moisture), topography and micro-relief (rock outcrops) had important influence on the variability of soil moisture. To better understand the variability of soil moisture in the karst depression area, more soil samples should be required in the dry season and in a field with more rock outcrops.

Keywords: geostatistics; anisotropy; mean soil moisture; rock outcrops; depression area; Karst

Soil moisture near the land surface affects a wide variety of earth system interactions over a changing spatial and temporal scale. Surface soil moisture plays a critical role in the interaction between land surface and the atmosphere, as well as in hydrological and ecological processes (Peters-Lidard et al. 2001, Zhu and Shao 2008). It exerts a major control on the partitioning of net radiation into latent and sensible heat and on the conversion of rainfall into runoff and infiltration (Pan et al. 2008). Given the importance of surface soil moisture to land surface system, quantification of its variability and patterns received increasing attention in recent years (Famiglietti et al. 1998, Western et al. 1998, Hupet and Vanclooster 2002, Koster et al. 2004, Brocca et al. 2007, Tang and Piechota 2009).

Using geostatistics is feasible to characterize and quantify the spatial variability of soil variables, perform rational interpolation, and estimate the variance between the point values sampled in a spatial field. The central concept of geostatistics

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is the experimental variogram, which represents the variance as a function of distance between measurement points. Its main feature is range; this is defined as the distance at which the variogram levels off (the sill) and beyond which point observations appear to be independent (Western et al. 2004, Brocca et al. 2007). A particularly important geostatistical technique is Kriging, which is a linear interpolation procedure with a best linear unbiased estimator, and widely used to characterize the spatial pattern of soil variables, and its values at non-sampled sites (Feng et al. 2004).

The karst area in southwest China covers a land of 550 000 km^2 (Yuan 2001), about one fifth of which suffered from severe degradation issues, i.e. rocky desertification, soil erosion, drought and shortage of available water (Wang et al. 2002, Zhang et al. 2006a). In the process of rocky desertification, soil moisture plays a key role in the decline of soil functions including productivity and stability of mediating the nutrient and water flow (Chen and Wang 2008). The soil coverage and soil moisture are major controls in the structure, function and succession of the karst ecosystem (Wang et al. 2004, 2005). In karst depression area, the soils are often scarce, thin and rocky with relatively high permeability and fissures, gaps, and channels enlarged by solution in the underlying bedrock facilitate the rapid transport of surface water to groundwater (Chen et al. 2010). Furthermore, rainfall is the only source of soil moisture in the local area. These features result in an uneven distribution of hydrological conditions. Thus, knowledge of the variability of soil moisture is of great importance to assess the hydrological responses, watershed management and vegetation restoration process in karst depression area.

The aims of this study are: (1) to characterize the variations of surface (0–15 cm) soil moisture content in a field plot of karst depression area; (2) to compare the differences of variability and patterns of soil moisture in dry and rainy seasons, and (3) to discuss the effect of rock outcrops on soil moisture content and its variability. To achieve them, techniques from both classical statistics and geostatistics were used in this study.

MATERIAL AND METHODS

Study area description. This study was carried out in a typical peak-cluster depression area (24°54'–25°55'N, 107°56'–107°57'E) of Huanjiang County in northwest Guangxi, southwest China. In this area, feasible tillage fields are only about 0.17 km^2 (less than one tenth of the total land area) and mainly distributed in the depression area. The mean annual temperature is about 16.5–20.5°C, and the mean annual rainfall is about 1389 mm, occurring mainly from May to September (the rainy season). In contrast, dry season is from October to April, and the drought poses a serious threat to local agriculture. The thin and discrete soil is developed from limestone and distributed among the whole depression area (Chen et al. 2010). The elevation varied from 376 m (the depression area) to 816 m (the peak). The depression area contains numerous limestone fragments, and has a relatively thinner soil depth compared with red soil region of southwest China. Cropland is the most intensively disturbed system, cultivated with maize (*Zea mays*) for more than 100 years in the depression area. The maize is grown without irrigation; since there is no irrigation project in this area. The soil is loam developed from limestone.

Sampling and measurements. A 5 m × 5 m grid was established over a field plot (100 m × 50 m) in the depression area, and 231 points were fixed in total (Figure 1). The position of each point was marked by a bamboo stick (80 cm height and 8 cm width). The soil moisture content was measured at the depth of 0–15 cm on March 15 and 27 (in the dry season), and on June 14 and July 19 (in the rainy season) during the maize growing season of 2005. Each time of soil sampling was completed within one day using a 5 cm diameter soil auger. Soil moisture content was determined gravimetrically (Gardner 1965). The rainfall data were observed from a rain gauge installed in the centre of depression area. The field plot was cultivated by steel hoe to a depth of 20 cm on March 9, followed by maize seeding, and it was harvested on July 22. The southern part of the plot had scattered rock outcrops; while the northern part had few such outcrops (Figure 2). The bare rock ratio of each

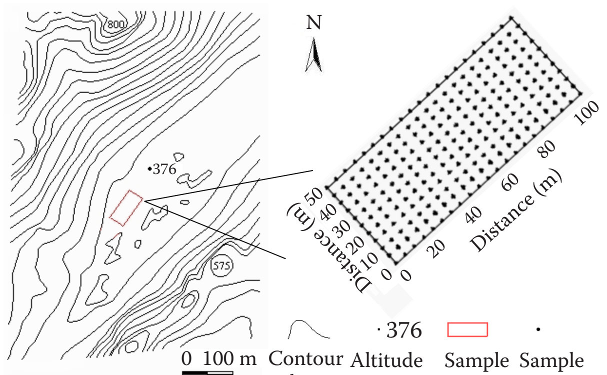

Figure 1. Sketch of sampling sites in the research area

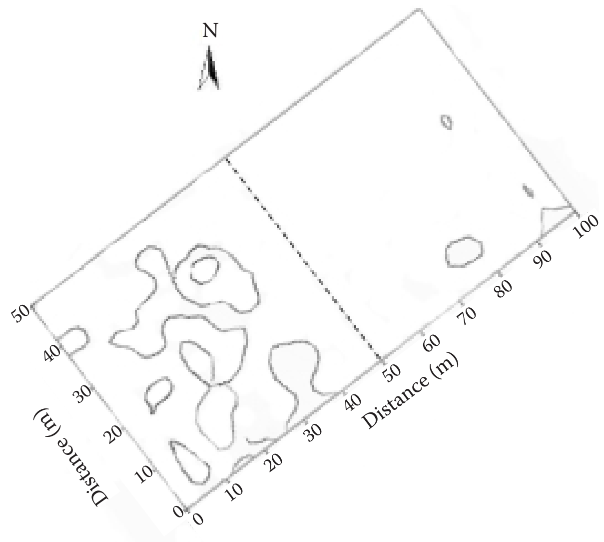

Figure 2. Distributıon map of rock outcrops in the study area

sampling point was calculated by the rock outcrops area to the whole area in 2 m × 2 m square around the bamboo sticker.

Data analysis. The raw data of four sampling times were analyzed using the following software packages. The descriptive statistics of the soil moisture content, such as the mean, standard deviation, extreme maximum and minimum values, coefficients of variation (*CV*), skewness, kurtosis and correlation coefficients were all calculated with software SPSS11.5 (SPSS Inc., Chicago, USA). The geostatistical analysis was carried out with GS + 5.1 (Gamma Design Software, Michigan, USA). Before applying the geostatistical tests, each variable was also checked for drift, trend and anisotropy (Iqbal et al. 2005, Zhao et al. 2007). The semivariogram $\gamma(h)$ was calculated by Eq.(1):

$$\gamma(h) = \frac{1}{2N(h)}\sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \quad (1)$$

Where: $\gamma(h)$ is the sample semivariance between all observations $Z(X_i)$; $N(h)$ is the number of pairs of $Z(X_i)$ over a separation distance h.

Spherical and exponential models were best fitted to the experimental semivariograms in this study; the two models can be expressed separately as Eq. (2) and Eq. (3):

$$\begin{cases} r(h) = C_0 + C\left(\frac{3h}{2a} - \frac{h^3}{2a^3}\right) & h \le a \\ r(h) = C_0 + C & h \ge a \end{cases} \quad (2)$$

$$r(h) = C_0 + C\left[1 - exp\left(-\frac{h}{a}\right)\right] \quad h \ge a \quad (3)$$

Where: C_0 is the nugget; C is the structural component; $C_0 + C$ is the sill, and a is the range (Defeo and Rueda 2002).

Value of the proportion of $C_0/(C_0 + C)$ is a measure of the proportion of sample variance ($C_0 + C$) that is explained by the nugget variance (C_0).

Following Chien et al. (1997), the classes of spatial dependence were distinguished: strong spatial dependence ($C_0/(C_0 + C) < 25\%$, moderate spatial dependence ($C_0/(C_0 + C) > 25\%$ and $< 75\%$), and weak spatial dependence ($C_0/(C_0 + C) > 75\%$). The two-dimensional maps of soil moisture spatial distribution were produced by using software ArcGIS 8.3 (ESRI Inc., Redlands, CA, USA) for ordinary kriging interpolation.

RESULTS AND DISCUSSION

Descriptive statistics of soil moisture. The rainfall and the statistical parameters of soil moisture during the whole sampling period were presented in Figure 3 and Table 1, respectively. In the dry season, the mean soil moisture was 15.05% and 22.96% on March 15 and 27, 2005 with *CV* values of 14.39% and 9.28% correspondingly. During the rainy season, the mean soil moisture reached 27.53% and 20.71% on June 14 and July 19 with *CV* values of 8.25% and 12.07%, respectively. This meant that the mean soil moisture was higher, but with lower *CV* values controlled by the antecedent rainfall (the total rainfall during 10 days before the sampling) either in dry or rainy season. This result was in accordance with the studies of Zhang et al. (2006b) in the same depression area, and Zhu and Shao (2008) in a catchment on the Loess Plateau of China. Furthermore, a general decreasing trend of *CV* values with increasing mean soil moisture content was also observed in different experimental plots of central Italy (Brocca et al. 2007). The coefficients of skewness and kurtosis revealed that the soil moisture data of each sampling was almost normally distributed. Thus, all these sampling data were suited to proceed with the geostatistical analysis.

Structure of soil moisture variability. The semivariograms of sampling data were shown in Figure 4 and the parameters for the best fitted model (exponential) were illustrated in Table 2. The positive nugget effect (C_0) varied from 0.07 to 0.52, which could be explained by the sampling error, short-range variability, random and inherent variability (Wang et al. 2009). The sill (C_0 + C) varied from 4.30 to 6.22, which meant that the spatial variance of soil moisture was always lower accompanied with higher mean soil moisture either in dry or rainy season. The ratio of nugget

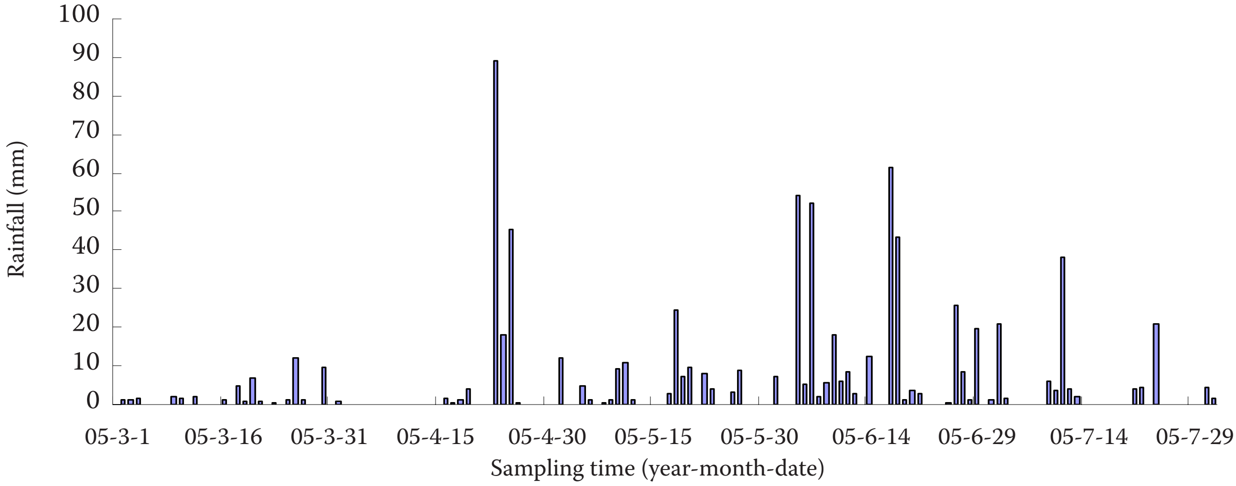

Figure 3. The rainfall of research area during the sampling period

variance to sill $C_0/(C_0 + C)$ were all below 25% during dry and rainy seasons in this study, which meant that the soil moisture had strong spatial dependence (Chien et al. 1997). Cambardella et al. (1994) suggested that the soil variables with stronger spatial dependence can be controlled by the intrinsic variability of soil, while the weaker spatial dependence can be controlled by extrinsic variability. Thus, the strong spatial dependence of soil moisture might be attributed to the soil-forming processes in this study. The range (*a*), as a measure of the spatial continuity of the soil moisture, was larger (13.2 m) with lower mean soil moisture (22.96%, on March 27) in the dry season, but smaller (6.9 m) with higher mean soil moisture (27.53%, on June 14) in the rainy season in the field plot. The difference could be explained by different processes controlling the soil moisture pattern under different moisture conditions (Grayson et al. 1997, Western et al. 1998).

The mean soil moisture had important influence on the spatial variability of soil moisture (Table 2). In the dry season, a slightly smaller sill was accompanied with higher mean soil moisture (22.96%, on March 27). The small difference of sill values might be related to the previous tillage, which could smooth some variance in the field plot. In the rainy season, a smaller sill was also found with higher mean soil moisture (27.53%, on June 14). A heavy rain event (52.2 mm) on June 6 could lead to a uniform wet condition in the whole plot. Therefore, the variability of surface soil moisture decreased when soils were wet, and increased when soils were dry in the karst field. This result was consistent with those reported by several authors (Robinson and Dean 1993, Western et al. 1998, Chen et al. 2010), which noted that the variability of soil moisture decreased with decreasing mean moisture content. But it was different from those obtained by Hupet and Vanclooster (2002), Choi et al. (2007) and Pan et al. (2008), which had the opponent trend. De Lannoy et al. (2006) found that the spatial variability increased with increasing soil moisture in the upper soil layer, while the opposite trend was found for deeper soil layers. Moreover, Famiglietti et al. (2008) found that the variability of soil moisture increased during drying from a very wet stage, reached a maximum value at specific mean moisture content, and then decreased during further drying. Therefore, these

Table 1. Statistical parameters of soil moisture during dry and rainy seasons

Sampling time (year-month-date)	Antecedent rainfall (mm)	Mean	Minimum	Maximum	STD	*CV*	Skewness	Kurtosis
		(%)						
05-3-15	3.8	15.05	10.34	20.53	2.17	14.39	0.289	–0.298
05-3-27	27.0	22.96	18.70	29.28	2.13	9.28	0.346	–0.064
05-6-14	154.4	27.53	19.97	33.33	2.27	8.25	0.052	0.090
05-7-19	53.7	20.71	14.48	26.25	2.50	12.07	–0.174	–0.398

Antecedent rainfall means the total rainfall during 10 days before sampling; STD – standard deviation; *CV* – coefficient of variation

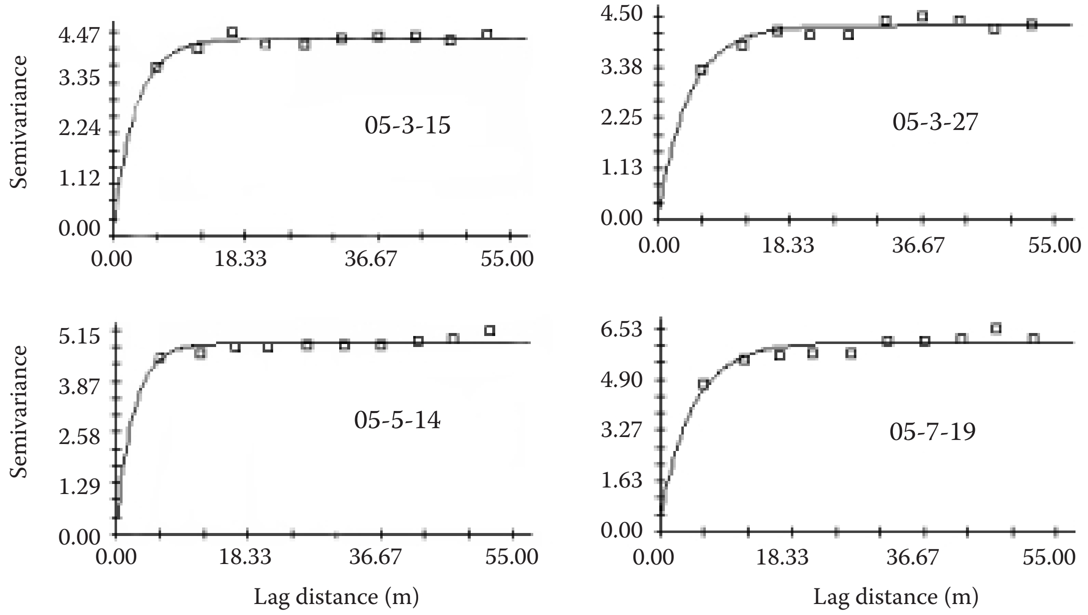

Figure 4. Semi-variograms of the soil moisture during dry and rainy seasons

differing findings could be explained by differences in climate, soils, vegetation, topography, geomorphy, sampling depth and frequency, and the status of mean moisture content, between the various field studies.

Anisotropy of soil moisture variability. In this analysis, we used principal axes with angles of 0° and 90° clockwise from the base axis, northeast. Point aligned sufficiently close to one or another of these angles was included in the anisotropic analysis for that angle. To examine the anisotropy of the spatial correlation structure of these data, the semivariogram parameters of 0° (northeast) and 90° (southwest) directions were shown in Table 3.

The sill was always smaller in 0° direction than that in 90° direction in each sampling data. And the range had the similar trend except for the 05-3-15, i.e. the soil moisture had larger spatial continuity in 90° direction than that in 0° direction during the sampling periods except for the doughtiest condition. This might be related to the topography and special micro-relief in the karst field. Moreover, the sampling scale was another important factor (Western and Blöschl 1999). Short sampling distance in 90° direction, drainage lines along hill slope and rock outcrops in southern part tended to run the anisotropy in the field. Under the very dry condition of 05-3-15, the mean soil moisture approached the wilting point for plant growth (13.7%) in the depression field (Chen and Wang 2008). Meanwhile, the previous tillage might have made variance uniform across the field plot. Therefore, the soil moisture had smaller sill and larger range in 0° direction than those in 90° direction at this date. In addition, the rock outcrops in the southern part of the plot could help to generate the anisotropy by influencing the hydrologic process and soil moisture distribution.

Spatial distribution of soil moisture. Based on the kriging analysis, the two-dimensional kriged maps of soil moisture were generated in the field plot (Figure 5). The distribution maps revealed moderate positional similarity of the soil moisture in the four sampling times, with complex positional effects in the plot's interior. The spatial distribution of soil moisture was characterized by a significant difference between the dry and rainy seasons in the field plot. In the dry season,

Table 2. Parameters of semivariogram theoretical models for soil moisture during dry and rainy seasons

Sampling time (year-month-date)	Mean (%)	Nugget C_0	Sill (C_0 + C)	Nugget/sill $C_0/(C_0 + C)$ (%)	Range *a* (m)	Model	R^2
05-3-15	15.05	0.11	4.32	2.5	9.6	exponential	0.82
05-3-27	22.96	0.10	4.30	2.3	13.2	exponential	0.85
05-6-14	27.53	0.07	4.78	1.5	6.9	exponential	0.58
05-7-19	20.71	0.52	6.22	10.5	14.1	exponential	0.78

Table 3. Parameters for semivariogram for anisotropy of soil moisture during dry and rainy seasons

Sampling time (year-month-date)	Anisotropy	Nugget C_0	Sill $C_0 + C$	Nugget/sill $C_0/(C_0 +)$(%)	Range *a* (m)	Model	R^2
05-3-15	0°	2.65	4.19	63.25	19.2	spherical	0.84
	90°	3.39	4.46	76.01	15.5	spherical	0.70
05-3-27	0°	2.54	3.94	64.47	16.8	spherical	0.45
	90°	1.31	4.70	27.87	22.7	exponential	0.98
05-6-14	0°	4.22	4.95	85.25	26.5	spherical	0.74
	90°	4.05	4.94	81.98	41.3	spherical	0.70
05-7-19	0°	3.35	6.17	54.29	25.6	exponential	0.86
	90°	4.15	6.33	65.56	34.2	exponential	0.97

a very low soil moisture region was located in the southwest part of the plot with some rock outcrops, while a relatively high soil moisture area was present in the northwest (05-3-15) and northeast (05-3-27) region in the plot. However, in the rainy season, the high soil moisture area was present in northeast (05-6-14) and east (05-7-19) part of the plot, which located at the area with less rock outcrops. Meanwhile, the soil moisture showed strip-like distribution patterns under wet

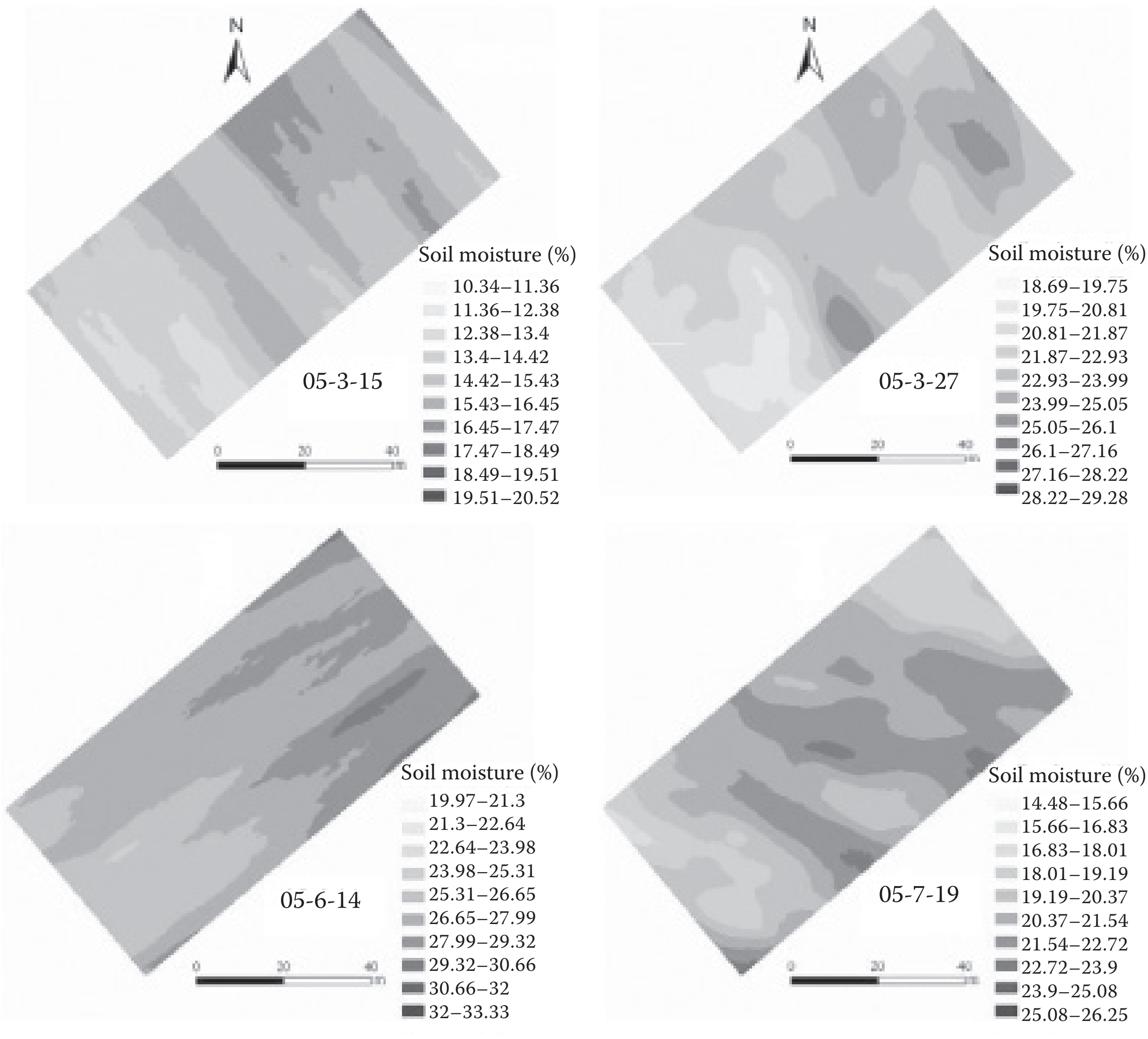

Figure 5. Spatial distribution maps of the surface soil moisture during dry and rainy seasons

conditions, which might be related to the lateral redistribution of soil moisture, especially after heavy rainfall (Western et al. 1998).

Grayson et al. (1997) argued that soil moisture pattern was expected to be highly organized with a significant influence of topography under wet conditions, whereas in dry conditions the pattern was patchier, vegetation, soil properties and micro-relief became more important. In karst field plot, topography and micro-relief (rock outcrops) heterogeneity might control the soil moisture pattern under local environmental conditions. Furthermore, climate and vegetation would also contribute to the difference of soil moisture pattern. The spatial variation of soil moisture content, ideally expressed as maps, was valuable information not only for deriving a conceptual understanding of landscape water (Zhao et al. 2007), but also the basis for spatial discretization and parameter estimation in hydrological model in the karst area.

Effect of rock outcrops on soil moisture variability. In this study, we divided the field plot into two parts according to the bare rock ratio (Figure 2). One half of the plot (southern part) was defined as a rock distributed area for its higher bare rock ratio (about 30.0%), the other half (northern part) was the soil continuous area for its lower bare rock ratio (nearly 2.5%). The semivariogram parameters of soil moisture data in two parts were presented in Table 4. The soil moisture in rock distributed area showed lower mean soil moisture content and higher sill values compared with those in soil continuous area during dry and rainy seasons. The relationship between mean soil moisture and sill values in the two patches also confirmed the previous result. Thus, the rock outcrops could influence the spatial variability of soil moisture by affecting the mean soil moisture content.

The crock outcrops complicated the influence on soil moisture content in the plot scale. The significantly negative correlations were found (r = −0.37 and −0.41 respectively, $P < 0.05$ for both) between bare rock ratio and soil moisture content at two sampling dates in the dry season, but the correlations were not significant in the rainy season. So, in the process of soil drought, rock outcrops may have great influence on water distribution and negatively correlated with the soil moisture. Furthermore, we also found that areas immediately adjacent to a rock outcrop always had much higher soil moisture than areas away from the outcrop, especially after a heavy rain in karst depression area (Zhang et al., unpublished). This finding was in accordance to those reported by Noy-Meir et al. (1991), who also discovered that soil moisture was significantly higher at the sampling points close to or between tall smooth rocks than elsewhere. 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, the effect of rock outcrops on the surface soil moisture and its variability depended on the sampling scale, the sampling point distance from rock outcrops, the rock outcrops size and their relative position at the soil surface (Zavala et al. 2010).

In general, the study demonstrated that the variability of surface soil moisture was higher in the dry season with lower mean soil moisture, yet with lower variability during the rainy season with higher mean soil moisture in the karst field plot. The rainfall (mean soil moisture), topography and micro-relief (rock outcrops) had an important impact on the variability and patterns of surface soil moisture. More soil samples are required in

Table 4. The semivariogram parameters of soil moisture in two parts of the field during dry and rainy seasons

Sampling time (year-month-date)	Patch type	Mean (%)	Nugget C_0	Sill $C_0 + C$	Nugget/sill $C_0/(C_0 + C)$ (%)	Range a (m)	Model	R^2
05-3-15	RDA	14.47	0.42	4.77	8.81	8.37	exponential	0.99
	SCA	15.60	0.40	4.10	9.76	13.62	exponential	0.78
05-3-27	RDA	22.36	0.18	4.73	3.81	10.74	exponential	0.99
	SCA	23.60	0.38	3.70	10.27	13.41	exponential	0.92
05-6-14	RDA	26.87	0.37	4.96	7.46	6.91	exponential	0.75
	SCA	28.15	0.46	4.65	9.89	8.10	exponential	0.74
05-7-19	RDA	20.59	0.01	6.27	0.16	10.68	exponential	0.81
	SCA	20.91	0.01	5.68	0.18	11.37	exponential	0.94

RDA – rock distributed area; SCA – soil continuous area dry season and in areas with more rock outcrops, to take into account the difference of soil moisture variability between dry and rainy seasons and rock outcrops distribution patterns. Geostatistical analysis of surface soil moisture would be helpful to the soil moisture management and hydrological model in the local karst area. Future research should be focused on the soil moisture balance and its effective management, the mutual relationships of environmental factors and their effects on hydrological processes in the karst region of southwest China.

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