Hydrological Sciences Journal

ISSN: 0262-6667 (Print) 2150-3435 (Online) Journal homepage: http://www.tandfonline.com/loi/thsj20

Spatio-temporal variability of surface soil water content and its influencing factors in a desert area, China

Pingping Zhang & Ming'an Shao

To cite this article: Pingping Zhang & Ming'an Shao (2015) Spatio-temporal variability of surface soil water content and its influencing factors in a desert area, China, Hydrological Sciences Journal, 60:1, 96-110, DOI: 10.1080/02626667.2013.875178

To link to this article: http://dx.doi.org/10.1080/02626667.2013.875178

Published online: 20 Dec 2014.

Hydrological Sciences Journal – Journal des Sciences Hydrologiques, 60 (1) 2015
http://dx.doi.org/10.1080/02626667.2013.875178

Spatio-temporal variability of surface soil water content and its influencing factors in a desert area, China

Pingping Zhang[1] and Ming'an Shao[1,2]

[1]*State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A & F University, Yangling, China*
mashao@ms.iswc.ac.cn

[2]*Key Laboratory of Ecosystem Network Observation and Modelling, Institute of Geographical Science and Natural Resources, Chinese Academy of Sciences, Beijing, China*

Received 9 May 2013; accepted 29 October 2013

Editor D. Koutsoyiannis; **Associate editor** D. Gerten

Abstract Knowledge of the variability of soil water content (SWC) in space and time plays a key role in hydrological and climatic modelling. However, limited attention has been given to arid regions. The focus of this study was to investigate the spatio-temporal variability of surface soil (0–6 cm) water content and to identify its controlling factors in a region of the Gobi Desert (40 km^2). The standard deviation of SWC decreased logarithmically as mean water content decreased, and the coefficient of variation of SWC exhibited a convex upward pattern. The spatial variability of SWC also increased with the size of the investigated area. The spatial dependence of SWC changed over time, with stronger patterns of spatial organization in drier and wetter conditions of soil wetness and stochastic patterns in moderate soil water conditions. The dominant factors regulating the variability of SWC changed from combinations of soil and topographical properties (bulk density, clay content and relative elevation) in wet conditions to combinations of soil and vegetation properties (bulk density, clay content and shrub coverage) in dry conditions. This study has important implications for the assessment of soil quality and the sustainability of land management in arid regions.

Key words surface soil water; spatial variability; influencing factors; statistical analysis; geostatistics; arid area

Variabilité spatio-temporelle de la teneur en eau superficielle des sols et facteurs d'influence dans une zone désertique en Chine

Résumé La connaissance de la variabilité de la teneur en eau du sol (TES) dans l'espace et le temps joue un rôle clé dans la modélisation hydrologique et climatique. Cependant, les régions arides ont fait l'objet d'une attention limitée. L'objectif de cette étude était d'étudier la variabilité spatio-temporelle de la teneur en eau superficielle du sol (0–6 cm) et d'en identifier les facteurs de contrôle dans une région du désert de Gobi (40 km^2). Les résultats montrent que l'écart-type de la TES diminue de manière logarithmique avec la diminution de la teneur en eau moyenne, et que le coefficient de variation de la teneur en eau moyenne affiche un profil convexe vers le haut. La variabilité spatiale de la TES augmente aussi avec la taille de la zone étudiée. La dépendance spatiale de la TES change au fil du temps, avec des structures d'organisation spatiale plus fortes dans les conditions d'humidité du sol plus sèches et plus humides, et des structures aléatoires dans les conditions intermédiaires. Les facteurs dominants qui régissent la variabilité de la TES vont de combinaisons de propriétés pédologiques et topographiques (densité apparente, teneur en argile et élévation relative) dans les conditions humides, à des combinaisons de propriétés de sol et de végétation (densité apparente, teneur en argile et couverture arbustive) dans les conditions sèches. Cette étude a des implications importantes pour l'évaluation de la qualité des sols et la durabilité de la gestion du territoire dans les régions arides.

Mots clefs eau superficielle du sol ; variabilité spatiale ; facteurs d'influence ; analyse statistique ; géostatistique ; zone aride

1 INTRODUCTION

The water content in surface soils plays a critical role in hydrology, agrology and ecology, and strongly controls various natural processes, such as energy fluxes of the land surface, soil degradation, land–atmosphere interactions, and conservation and restoration of vegetation (Charpentier and Groffman 1992, Wang *et al*. 2012, Jia and Shao 2013).

Characterizing the spatio-temporal variability of soil water content (SWC) is a key challenge for improving hydrological and climatic modelling and prediction (Ampofo 2006), and has thus become increasingly important in recent years, from the scale of hillslopes (Famiglietti *et al*. 1998, Zhu and Shao *et al*. 2008, Penna *et al*. 2009) and small watersheds using ground-based measurements (Hébrard *et al*. 2006, Hu *et al*. 2010, Brocca *et al*. 2012, Takagi and Lin 2012) to national and global scales using remote sensing (IGPO 1995, Lu and Shi 2012). Remote sensing is promising for the description and measurement of surface SWC on large scales, but its usefulness and interpretation require further testing due to its relatively low spatial and temporal resolution (Brocca *et al*. 2007). Data obtained from accurate on-site measurements should thus continue to be important when studying the variability of SWC (Owe *et al*. 1982). SWC in arid regions is the key resource limiting the development of vegetation and is the main constraint to permanently controlling desertification (Berndtsson *et al*. 1996). Soil water also determines the organization and functioning of the ecosystems in arid regions. Despite its importance to vegetation, soil water has received little attention in arid environments, especially in the characterization of its variability in natural deserts, due to the difficulty of data collection and the associated costs.

The spatio-temporal variability of SWC has been characterized by testing its link to field (spatial) means of soil wetness. Knowledge of this relationship is useful for determining the minimum amount of sampling needed to effectively estimate field means of water content with an acceptable error, estimating the error if the amount of sampling has been predefined, and verifying and validating remotely sensed effects of SWC (Brocca *et al*. 2007). Whether the variability of SWC has a positive or negative relationship with field means of water content, however, has not been conclusively determined (Reynolds 1970, Owe *et al*. 1982, Zhang *et al*. 2011).

The variability and distribution pattern of surface SWC in time and space can be controlled by many factors, such as soil properties, topographical characteristics and vegetation (Qiu *et al*. 2001, Hu *et al*. 2008, Zhao *et al*. 2011, Takagi and Lin 2012). However, identifying the relative significance of these individual factors is challenging because of their mutual or multiple influences on SWC. Many studies have indicated that the spatial pattern of SWC, especially in arid regions, cannot be accurately predicted by any single factor. In addition, the dominant factors may change with the chosen sites and depend on the conditions of soil wetness resulting from seasonal wetting and drying (Grayson *et al*. 1997, Famiglietti *et al*. 1998, Western *et al*. 1999, Pan and Wang 2009). For example, Famiglietti *et al*. (1998) explored the possible factors influencing the spatial pattern of SWC along the profile of a hillslope. In wetter conditions, the heterogeneity of soil properties (porosity, hydraulic conductivity) significantly contributed to the spatial variability of SWC, but in drier conditions, topographical characteristics (relative elevation and aspect) largely determined the variability of SWC. Western *et al*. (1999) showed that the indices associated with the lateral flow of water and those related to evapotranspiration were the most important predictors of distributional patterns of SWC in wet and dry conditions, respectively. Hawley *et al*. (1983) demonstrated that the variability of SWC was mainly driven by topography, but the explanatory power tended to decrease with seasonal variations of the vegetation cover. Gómez-Plaza *et al*. (2001) found that some local controls (e.g. soil texture and slope angle) were the main regulators of the distribution of SWC in non-vegetated areas, whereas the controls operating on SWC in vegetated areas were those linked to the properties of the vegetation. The factors controlling the dynamics of SWC remain quite uncertain, and much more research is needed in a variety of environments and on a variety of scales.

Soil water content and its complex spatial distribution are very important in arid regions. We therefore studied the spatio-temporal variability of surface soil (0–6 cm) water content in a typical fenced region of the Gobi Desert where precipitation is the only source of soil moisture. The main goals of the study were: (a) to quantify the spatio-temporal variability of the surface SWC, (b) to understand the relative roles of elevation, soil properties and vegetation in controlling the variability of SWC under different conditions of soil wetness, (c) to determine the amount of sampling needed to estimate field means of water content at a predefined level of statistical significance, and (d) to determine the relationship between the variability of SWC and the size of the sampling area using a re-sampling method.

2 MATERIALS AND METHODS

2.1 Description of the study area

The study was conducted in a region of the Gobi Desert (39°24′–39°28′N; 100°08′–100°11′E) in the central reaches of the Heihe River basin in Gansu Province, northern China (Fig. 1(a), (b)). The elevation ranges from 1390 to 1470 m a.s.l., and the water table is at a depth of nearly 11–13 m (Yu *et al*. 2012). The area is characterized by low and highly variable rainfall, and has an arid desert climate. The average annual rainfall and air temperature are 117 mm year^{-1} and 7.6°C, respectively. Rainfall in brief summer showers contributes 65% of the total annual precipitation. The mean annual pan-evaporation is approximately 2390 mm year^{-1}; this is 20 times greater than the annual precipitation. The zonal soil is classified as grey-brown desert soil and is derived from diluvial-alluvial materials. The soil profile is sandy in texture, low in nutrients and has a small amount of gravels in the surface and subsoil horizons. The above-ground plant cover is discontinuous and can be described as patches of sub-shrubs surrounded by bare areas. The study area has been fenced and is protected from grazing for the purpose of revegetation and reclamation. The dominant plant species are *Nitraria sphaerocarpa* Maxim. and *Reaumuria soongorica* (Pall.) Maxim., and the accompanying plant species are mainly *Kalidium gracile* Fenzl, *Allium mongolicum* Rgl., *Bassia dasyphylla* (Fisch. and Mey.) Kuntze, *Halogeton arachnoideus* Moq., *Suaeda microphylla* (Mey.) Pall., *Caragana brachypoda* Pojark., *Salsola ruthenica* Iljin, *Asterothamnus centrali-asiaticus* and *Sympegma regelii* Bunge.

2.2 Soil sampling and data collection

A regular sampling grid (500 m × 500 m) of 187 sampling points was established over a 40-km^2 (5 km × 8 km) experimental area (Fig. 1(c)). Each sampling point was positioned with a portable Garmin GPS receiver (with a resolution of 3 m), and each point was marked by a wooden stick. The volumetric water content of the surface soil (0–6 cm) was measured with FDR probes (Type ML2x, Delta-T Devices) approximately every two weeks from 15 April to 15 October 2012. A total of 13 measurement campaigns were conducted. Measurements were taken in the same sequence to reduce the possible influence of sampling time. The probes were handled carefully to avoid touching the gravel, which can influence the measurements. To further reduce the possible influence of micro-scale variability, we averaged three measurements for each point and date. The

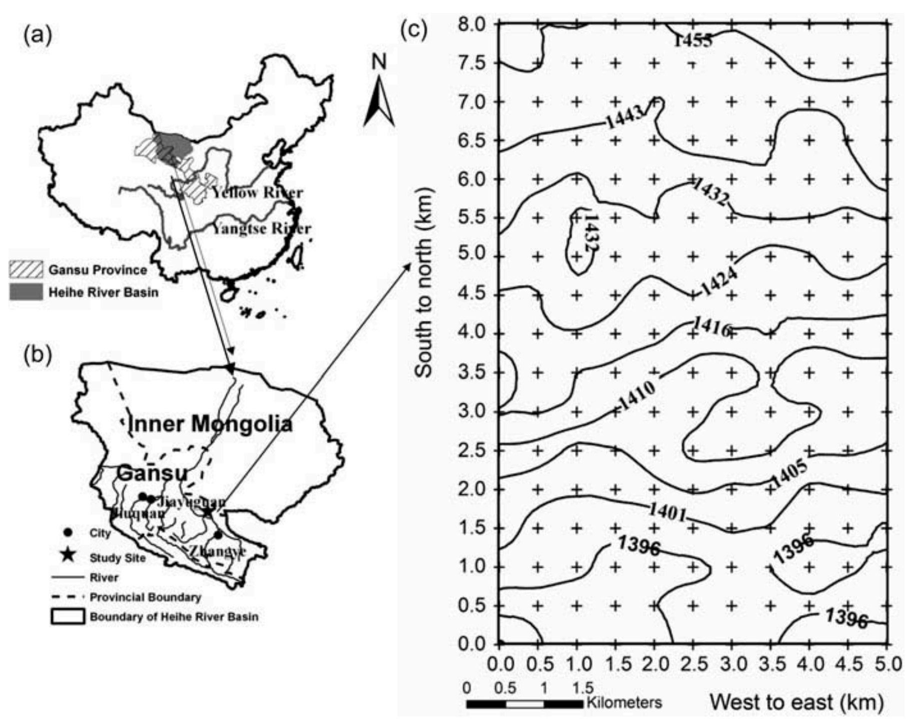

Fig. 1 (a and b) Location of the study site in northern China and (c) elevation contours and the sampling grid in the study site.

reliability of the Theta Probe was enhanced by calibrating it with a site-specific gravimetric assessment. Calibration was performed at three times of year (May, August and October) to allow for variations in soil wetness. The calibrations had a root mean squared error of approximately 1.09%, indicating adequacy.

A quantitative survey of the vegetation was performed in mid-August 2012, the period of vigorous growth of the vegetation. Quadrats of 20 m × 20 m for shrubs and 2 m × 2 m for herbaceous species were established at each sampling point to investigate species richness and the coverage of herbs and shrubs. Species richness was defined as all occurrences of species in all quadrats. The coverage of the herbs and shrubs was calculated as a percentage of the area.

At each sampling point, disturbed soil samples of the surface layer (0–5 cm) were collected with a soil auger from five randomly selected positions. These samples were then pooled to produce one representative sample. The samples were air-dried, weighed and then sieved to 2 mm to separate the gravel (>2 mm) from the fine soil (<2 mm). The former was reweighed to determine the gravel content. The soil component was separated into two parts. One was analysed for particle size by laser diffraction with a Mastersizer 2000 (Malvern). The other was crushed and passed through a 0.25-mm sieve for determining the amount of soil organic carbon (SOC) with the dichromate-oxidation method (Nelson and Sommer 1982). Undisturbed soil core samples (100 cm^3) were collected from the surface layer (0.5–5.5 cm) at each point for measurement of saturated hydraulic conductivity (K_S), using the constant hydraulic head method (Klute and Dirksen 1986), and of soil bulk density (BD), based on the volume of each original soil core and the total weight of the soil after oven drying at 105°C for 48 h.

2.3 Statistical methods

To clarify the descriptions, we will first define the terms used herein:

- ‘micro-site’ is the ground location at which a measurement was taken (three measurements were done at each point);
- ‘point’ is the mean location of a group of micro-sites; and
- ‘sampling day’ represents an individual day on which several measurements were taken.

A descriptive statistical analysis was first applied to determine the overall trends and variation of the SWC. Let θ_{ijk} be the SWC at micro-site i and point j on sampling day k. The spatial mean at point j on sampling day k is then calculated as:

$$\overline{\theta_{jk}} = \frac{1}{n_p}\sum_{i=1}^{n_p}\theta_{ijk} \tag{1}$$

where n_p is the number of micro-sites at point j. The spatial mean for each sampling day k, $\overline{\theta_k}$, and the temporal mean at each point j, $\overline{\theta_j}$, can thus be given by:

$$\overline{\theta_k} = \frac{1}{n}\sum_{i=1}^{n}\overline{\theta_{jk}} \tag{2}$$

$$\overline{\theta_j} = \frac{1}{m}\sum_{k=1}^{m}\overline{\theta_{jk}} \tag{3}$$

where n and m are the number of sampling points and days, respectively.

The coefficient of variation of each sampling day in space, CV_k, and each sampling point in time, CV_j, can consequently be defined as:

$$CV_k = \frac{\sigma_k}{\overline{\theta_k}} = \frac{\sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(\overline{\theta_{jk}} - \overline{\theta_k}\right)^2}}{\overline{\theta_k}} \tag{4}$$

$$CV_j = \frac{\sigma_j}{\overline{\theta_j}} = \frac{\sqrt{\frac{1}{m-1}\sum_{k=1}^{m}\left(\overline{\theta_{jk}} - \overline{\theta_j}\right)^2}}{\overline{\theta_j}} \tag{5}$$

where σ_k and σ_j are the standard deviations in space and time, respectively.

For each sampling day, the coefficient of variation of the sampling point, CV_k^{point}, was calculated as the mean of the coefficients of variation determined for each point as:

$$CV_k^{point} = \frac{1}{n}\sum_{j=1}^{n}CV_{jk} \tag{6}$$

where CV_{jk} is the coefficient of variation of the sampling point j on sampling day k.

With an understanding of the spatial standard deviation (σ_k), we can quantify the minimum amount of sampling needed for estimating the field mean water content at a given level of confidence, which can be described by:

$$N = \lambda_{\alpha,f}^2 \left(\frac{\sigma_k}{k\mu}\right)^2 \quad (7)$$

where $\lambda_{\alpha,f}$ is the limiting value of the *t*-distribution within a level of confidence $1 - \alpha$ (α is the level of significance) and with f ($f = N - 1$) degrees of freedom, μ is the mean value of the SWC (%) and k is the permitted relative error.

One-sample Kolmogorov-Smirnov (K-S) tests were used to examine the normality of the data. Semivariograms were then constructed to evaluate the spatial dependence of SWC (David 1977). Correlation analysis was conducted for each day to evaluate the possible relationships between SWC and relative elevation, soil properties and vegetation. Stepwise linear regression analysis was subsequently carried out to detect the relative significance of these factors influencing the dynamics of the SWC. All descriptive statistical analyses used the program SPSS 16.0. The geostatistical analysis was performed with GS+ software (version 7.0, Gamma Design Software).

3 RESULTS AND DISCUSSION

3.1 Temporal dynamics of SWC

The mean SWC had apparent seasonal changes and was tightly linked to rainfall (Fig. 2). The mean water content was higher in the rainy season (summer) than in dry seasons (spring and autumn) but never rose above 10%. Rain is the main source of soil moisture in this area because of the deep water tables. Because this area is characterized by low precipitation and high evapotranspiration, the soil is subjected to drought most of the time.

The mean SWC generally increased after a significant rainfall and decayed rapidly during dry periods. Relatively larger rainfalls always corresponded to higher SWCs, but this relationship was largely due to the timing of the sampling relative to the periods of rain. The higher SWCs occurred immediately after a rainfall event (e.g. 31 July and 15 August), with a lag following the rain. As seen in Fig. 2, the two most significant rainfall events occurred on 5 June (15.8 mm) and 27 June (14.4 mm), but did not give rise to the highest SWCs, which were on 18 June and 30 June, long after the rains. Rain wets the soil easily, and the water content accordingly increases quickly. The amount of water in the surface soil then decreases rapidly due to drainage to the sublayer and due to high evapotranspiration. The water content of the surface soil is to a very large extent influenced by the timing, amount and intensity of the rain. The influence of prior conditions of SWC, though, should also be considered. A wetter antecedent condition can produce greater water content when comparing rainfall events with the same amount and intensity (Pan *et al*. 2008). This phenomenon was not very evident in this study because of the low frequency of data collection.

3.2 Statistical analysis of SWC

3.2.1 Statistical parameters The variability of SWC in space and time was surveyed by calculating the temporal mean of CV of the spatial SWC, CV_k, and the spatial mean of CV of the time series of SWC, CV_i. The value of CV_k ranged from 26.57%

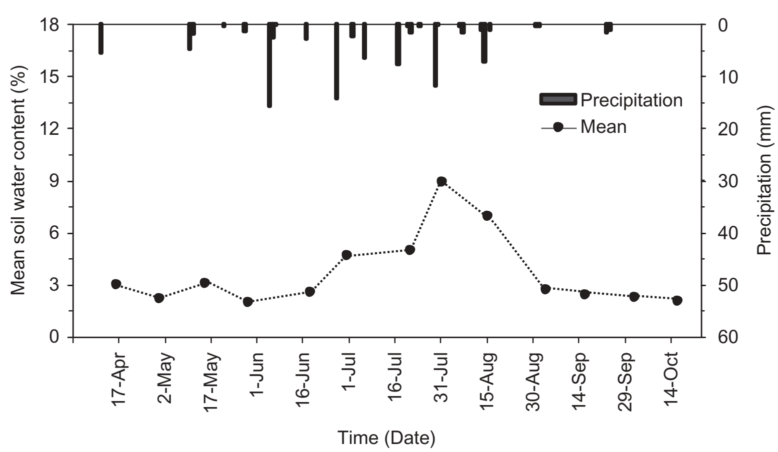

Fig. 2 Daily precipitation depth (mm) and mean soil water content (SWC, %) in the surface (0–6 cm) layer *vs* time.

Table 1 Statistical properties of the data for surface soil (0–6 cm) water content during the observation period (15 April–15 October 2012).

Date	Minimum (%)	Maximum (%)	Mean (%)	σ (%)	CV (%)	Skewness	Kurtosis	K-S test
16 Apr	1.56	8.32	3.37	1.50	44.41	1.51	1.66	0.000
30 Apr	1.16	4.84	2.15	0.82	38.31	1.44	1.63	0.000
15 May	1.41	7.73	3.06	1.40	45.65	1.48	1.61	0.000
29 May	0.83	4.99	1.94	0.93	47.87	1.44	1.63	0.000
18 Jun	1.31	6.64	2.53	1.00	39.70	1.58	2.68	0.000
30 Jun	1.62	13.95	4.63	2.47	53.38	1.40	1.78	0.000
21 Jul	1.46	19.90	4.94	2.75	55.57	2.00	5.50	0.000
31 Jul	4.33	22.16	8.90	4.60	51.70	1.38	2.08	0.027
15 Aug	1.83	30.08	6.93	4.42	63.78	1.87	4.76	0.001
3 Sep	1.58	12.90	2.71	1.35	49.96	3.75	19.99	0.000
16 Sep	0.94	6.95	2.42	1.01	41.60	1.73	3.83	0.003
2 Oct	0.77	6.84	2.28	0.93	40.83	1.75	4.11	0.002
16 Oct	0.27	4.91	2.07	0.55	26.36	1.34	5.32	0.000

σ: standard deviation; CV: coefficient of variation.

to 63.78% (Table 1), with a mean of 46.09%, indicating that SWC in this region was moderately variable. Based on the results of Hills and Reynolds (1969), CV_k should remain above 5% for any specific field. In our study, all values were larger than 25%, which may have been due to the low amount of SWC in this area. In contrast, the mean CV_i was 60.42% (ranging from 40.61% to 97.9%), which was obviously larger than the mean CV_k, suggesting that the temporal variability of SWC should receive more attention than spatial variability in studies of SWC (Brocca *et al*. 2010). Coarse spatial sampling at a high frequency may thus be a good option for modelling hydrological processes in this region.

Statistical parameters were tested for the field mean water content, $\overline{\theta_k}$, to determine if the variability of surface soil water was related to the conditions of wetness. Figure 3(a) shows increasing standard deviation (σ_k) with increasing mean water content. This result is in accordance with previous studies by Famiglietti *et al*. (1998), Western *et al*. (1998) and Li *et al*. (2013), but is contrary to the studies of Meyles *et al*. (2003) and Brocca *et al*. (2007), who stated that the relationship between σ_k and mean water content is linked to climatic conditions; in humid regions, σ_k is larger when the soil is dry, while in semi-arid regions, σ_k increases as the soil becomes wetter. Vereecken *et al*. (2007) demonstrated that the change of σ_k with soil wetness was largely determined by the ability of soil to retain water and by the associated spatial variability.

An inherent characteristic of σ_k, though, is its strong dependence on $\overline{\theta_k}$, which usually restricts its application when comparing datasets with widely varying mean water contents. To overcome this difficulty, the relative variance, i.e. CV_k, can be used, which can remove the influence of the different means. The CV_k exhibited a general convex upward relationship with $\overline{\theta_k}$, with its highest value at a moderate level of wetness, as shown in Fig. 3(b). The variability of SWC is mainly regulated by the wilting point in extremely dry conditions, the

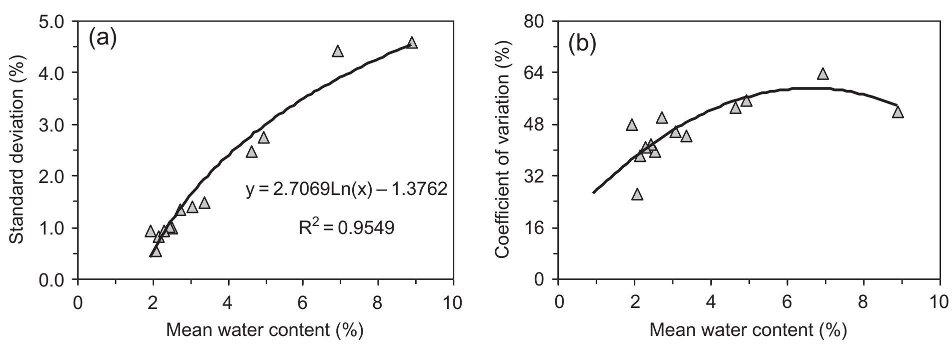

Fig. 3 Relationships between mean soil water content (SWC, %) and (a) standard deviation (%) and (b) coefficient of variation (%) in the study area.

hydraulic conductivity in mid-range conditions and the soil porosity in wet conditions (Lawrence and Hornberger 2007). In moderate conditions, small patches of quickly drying soil (generally characterized by coarse texture) may coexist with patches that remain wet (generally characterized by fine texture), leading to heterogeneous conditions of wetness (Hills and Reynolds 1969). This situation, though, is not common, as demonstrated by the above studies that indicated a universal negative relationship between CV_k and $\overline{\theta_k}$ over all conditions of wetness. However, this negative relationship may be due to the limited periods of measurement or to the low frequencies of measurement in these studies, which would limit the data to an incomplete range of soil wetness. The relatively wetter climates of their study areas could further restrict the range of SWCs.

The relationship between σ_k and $\overline{\theta_k}$ can be well described logarithmically as: $\sigma_k = 2.7069\ln(\overline{\theta_k}) - 1.3762$, which can quantify the amount of sampling needed to determine $\overline{\theta_k}$ at given confidence levels and relative errors. The sampling number as a function of $\overline{\theta_k}$ for predefined confidence levels of 95% and 90% and relative errors of 5, 10 and 15% is shown in Fig. 4. The required amount of sampling generally exhibited higher values for the 95% than for the 90% confidence level and declined slightly as the allowable relative error increased from 5% to 15%. In accordance with other studies, these results indicated that many more samples are needed in relatively drier conditions for estimating $\overline{\theta_k}$ in the study area. The maximum number of samples needed coincided with a water content of approximately 4.5%. The number of sampling points in our study (187) was sufficient to meet the requirement of a relative error of ±10% at a 95% confidence level, which had a maximum sampling number of approximately 150.

3.2.2 Variability of SWC and size of area

Estimating the variability of SWC over a wide variety of scales has significant implications for developing an effective scheme of data acquisition and monitoring. For each sampling date, the coefficient of variation of the sampling point (three measurements at each point), CV_k^{point}, was calculated as the mean of the coefficients determined for each point and was compared with CV_k of the entire area. The value of CV_k^{point} ranged from 7.34% to 27.99% and averaged 17.12%, which was considerably lower than CV_k. This comparison suggests an increasing trend of variability as the size of the investigated area increases. As displayed in Fig. 5, the coefficient of variation for the entire study area had a significant linear relationship with the coefficient at the point scale (i.e. CV_k and CV_k^{point}), and the determining coefficient was as high as 0.78, implying that the change of spatial variability at the point scale follows a trend similar to that of the entire area: when the latter is high, so is the former.

To further detect the tendency of the variability of SWC to change with the size of the study area, a series of sampling-point allocations of different sizes were re-sampled using all sampling points (n = 187) in the study area (5 km × 8 km). For convenience, the east−west and north−south spans of the re-sampling area were assigned integral multiples of 1 km to generate five re-sampling options for the west−east

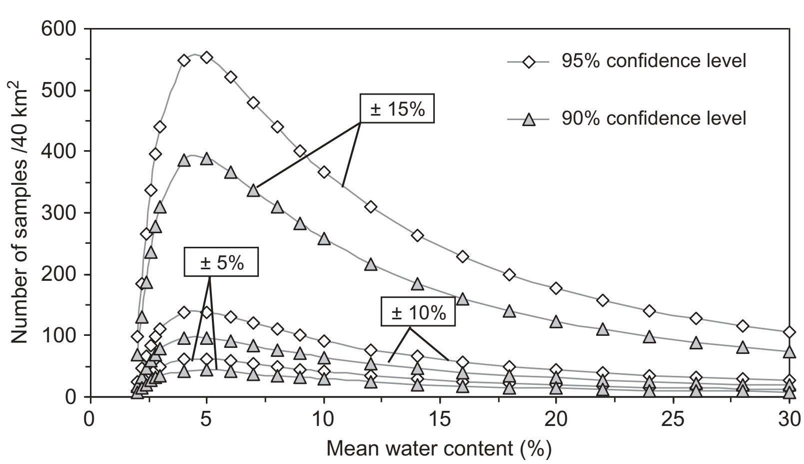

Fig. 4 Number of samples (per 40 km^2) for accurate measurement of field mean SWC (%) at 95% and 90% confidence levels and for relative errors of ±5%, ±10% and ±15% in the study area.

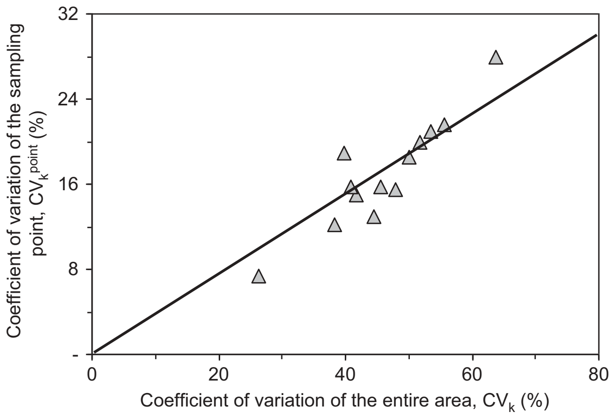

Fig. 5 Relationship between the spatial coefficients of variation computed for the entire area, CV_k (%), and the average of the coefficients computed for each sampling point, CV_k^{point} (%), in the study area.

span and eight options for the south–north span. The random combination of these two sets of options thus yielded 40 potential re-sampling methods. Some of these methods, though, were the same within the study area, so a final total of 24 types of re-sampling areas were obtained (see Table 2). The variability of SWC for an area was first computed by averaging the CV_k values of all possible re-sampling scenarios with the same area for each sampling date, and the resulting data were then averaged over the observation period. The averaged spatial CV_k clearly increased with the size of area and could be well parameterized as a power function of the size (Fig. 6(a)). The factors influencing the variability were scale dependent. As the size increases, the causes of variation, such as vegetation, topographical parameters and parental material, may become increasingly complex and heterogeneous, leading to greater variability. The fractal power parameter of the function was 0.0838, nearly half the value obtained by Brocca *et al.* (2012), who discussed the changes of spatial CV_k with sizes of between 1 m^2 and 250 km^2. The different increases of spatial CV_k with size may be attributed to the characteristics of the different regions or to the different methods used to obtain the results. The conclusions of Brocca *et al.* (2012) were mainly derived from the information reported in previously published studies. The spatial CV_k of the different sizes was determined for different times, so the final results are not likely to be very accurate due to the changes in spatial CV_k over time.

We also discovered that the spatial CV_k had a convex upward pattern with the field mean water content independent of the point scale or the other size scales, confirming that the relationships between the two statistical parameters were characterized by similar behaviours at different scales. The variability of the spatial CV_k over time, however, differed at different scales. As seen in Fig. 6(b), the coefficient of variability of the CV_k over time significantly decreased with increasing size. This relationship may be due to the dependence on scale of the factors influencing the variability of surface water content. How they change over time is also dependent on scale.

3.3 Geostatistical analysis of SWC

The coefficients of skewness and kurtosis, together with the non-parametric K-S test of the observations (Table 1), indicated that the SWCs for all dates were not normally distributed, so we logarithmically transformed the data. The transformed data for all dates passed the K-S test at the 0.05 significance level and consequently could be used for geostatistical analyses. The semivariograms of the SWCs were optimally fitted by exponential models; the structural parameters are given in Table 3. All models were

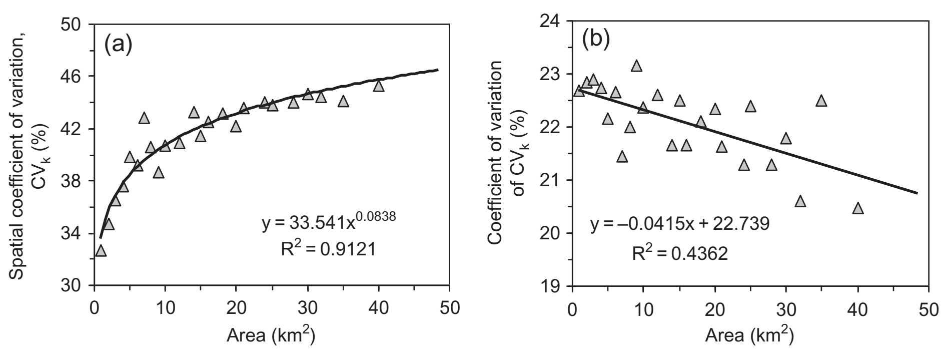

Fig. 6 Relationship between the size of the study area (km^2) and (a) the coefficient of variation of SWC (%) and (b) the coefficient of variation of CV_k (%).

Table 2 Details of the re-sampling areas and sampling methods.

Re-sampling area (km^2)	Sampling method	Re-sampling area (km^2)	Sampling method
1	1 × 1*	15	3 × 5; 5 × 3
2	1 × 2; 2 × 1	16	2 × 8; 4 × 4
3	1 × 3; 3 × 1	18	3 × 6
4	1 × 4; 4 × 1; 2 × 2	20	4 × 5; 5 × 4
5	1 × 5; 5 × 1	21	3 × 7
6	1 × 6; 2 × 3; 3 × 2	24	3 × 8; 4 × 6
7	1 × 7	25	5 × 5
8	1 × 8; 2 × 4; 4 × 2	28	4 × 7
9	3 × 3	30	5 × 6
10	2 × 5; 5 × 2	32	4 × 8
12	2 × 6; 3 × 4; 4 × 3	35	5 × 7
14	2 × 7	40	5 × 8

* The digit before the multiplication sign represents the west–east sampling distance (km), and the digit after it represents the south–north sampling distance (km).

satisfactory, with R^2 varying from 0.572 to 0.917, suggesting that the theoretical models well represented the space structure feature of the surface SWC in the study area.

The nugget effect, C_0, representing the variation at zero distance, ranged from 0.007 to 0.0648, perhaps due to an undetected sampling error, a finer-scale variability or an inherent random heterogeneity. The sill values, $C_0 + C$, representing the total variation, ranged from 0.105 to 0.375. The differences in C_0 and $C_0 + C$ over time markedly influenced the degree of soil-water heterogeneity under different water conditions. Both C_0 and $C_0 + C$ had convex upward relationships with the field mean water content, $\overline{\theta_k}$ (Fig. 7(a), (b)). Soil water after a significant rainfall can move easily on the soil surface, so the distribution of SWC is relatively uniform over the study area. However, irregular upward evapotranspiration and downward infiltration during periods of drying become increasingly significant forces for the distribution of soil water, increasing its spatial heterogeneity. When the SWC falls below the level at which C_0 or $C_0 + C$ is maximal, evapotranspiration is then water limited, and the distribution pattern is mainly controlled by the wilting coefficient. The wilting coefficient is distributed quite uniformly across the study area and thus leads to a reduction in spatial heterogeneity. Pan *et al*. (2007) and Gao *et al*. (2011) also demonstrated that the spatial heterogeneity of SWC peaked in moderate conditions of wetness and then decreased independent of further soil drying or wetting. The degree of spatial heterogeneity of SWC is determined by the percentage of total variation explained by the systemic variation, i.e. $C/(C_0 + C)$. This ratio varied with soil wetness, with values ranging between 0.731 and 0.933 (Fig. 7(d)), indicating that SWC was strongly to moderately spatially dependent. A strong spatial dependence is generally caused by intrinsic factors such as soil parental material and topographical parameters.

The range value, A, also changed significantly with mean SWC (Fig. 7(c)). These changes were likely due to the control of the distribution of soil moisture by different hydrological processes under different conditions of wetness. The sampling conducted immediately following a heavy rainfall event (e.g. 31 July and 15 August) presented relatively high range values (7185 and 8646 m) (Table 3). These results agree with the findings of Grayson *et al*. (1997) and Brocca *et al*. (2007) that SWC under wet conditions can exhibit much better distributions of spatial continuity. The high range under wet

Table 3 Parameters of the semivariogram models for the surface soil (0–6 cm) water content during the observation period. The semivariograms were optimally fitted by exponential models.

Date	Nugget, C_0 (%^{2})	Sill, $C + C_0$ (%^{2})	$C/(C_0 + C)$	Range, A (m)	R^2
16 Apr	0.036	0.137	0.734	1503	0.572
30 Apr	0.007	0.105	0.933	1359	0.622
15 May	0.019	0.146	0.869	1485	0.653
29 May	0.013	0.165	0.919	1476	0.660
18 Jun	0.008	0.116	0.932	2085	0.785
30 Jun	0.065	0.241	0.731	4368	0.818
21 Jul	0.025	0.220	0.891	1269	0.755
31 Jul	0.037	0.174	0.790	8646	0.917
15 Aug	0.059	0.375	0.843	7185	0.846
3 Sep	0.010	0.122	0.919	2874	0.694
16 Sep	0.021	0.151	0.858	6057	0.857
2 Oct	0.023	0.140	0.839	6234	0.848
16 Oct	0.026	0.108	0.760	9342	0.824

R^2: coefficient of determination.

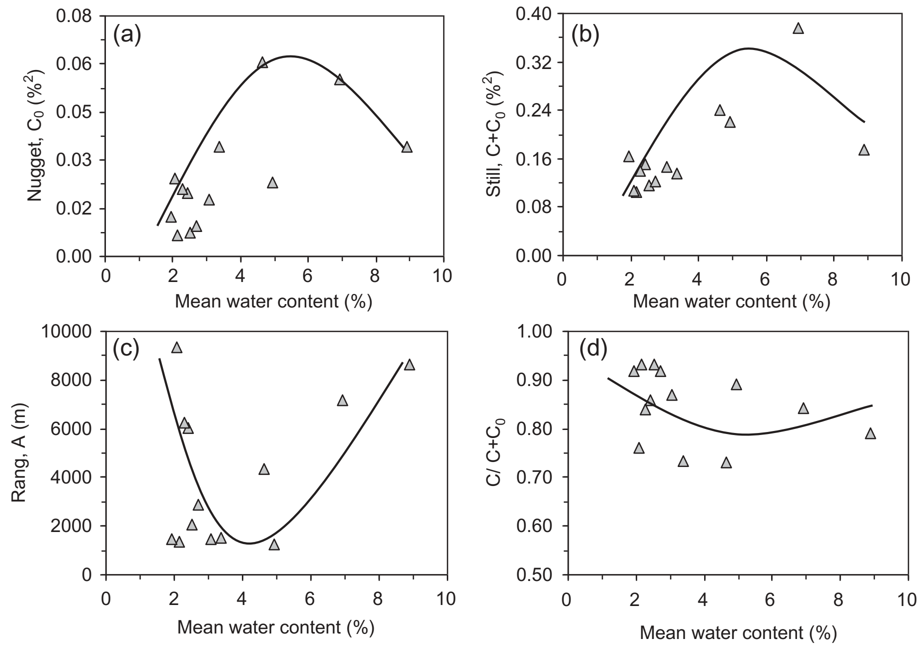

Fig. 7 Relationship between mean SWC (%) and (a) the geostatistical parameters nugget, C_0 (%^{2}), (b) sill, $C + C_0$ (%^{2}), (c) range, A (m) and (d) $C/(C + C_0)$ in the study area.

conditions may be attributed to spatially uncorrelated sampling errors and can play a relatively more significant role in these wet conditions (Brocca *et al.* 2012). As the soil dried, even with sporadic light rain during the drying period, the surface SWC tended to be much more independent and was characterized by a stochastic pattern of water content (Fig. 7(c)). For example, on 30 June, three days after the last large rainfall event (14.4 mm on 27 June), the range decreased to 4368 m. On 18 June, 13 days after the last heavy rainfall (15.8 mm on 5 June, but with light intervening rain), the range was only 2085 m (Table 3). When the soil dries enough for the wilting point to control the distribution of water content, however, the range can again increase. As displayed in Table 3, the range increased from 2874 to 9342 m between 3 September and 16 October.

3.4 Factors regulating the spatial pattern of SWC

Correlation analysis was conducted for all dates to evaluate the possible relationships between SWC and potentially associated properties (relative elevation, soil properties and vegetation). The coefficients are presented in Table 4 and Table 5 is the correlation matrix of these associated properties. Significant correlations were observed between some of these properties.

3.4.1 Relative elevation Relative elevation is an important topographical property that always varies jointly with some other soil and topographical properties (e.g. the specific contributing area, clay content, etc.), which can significantly regulate the pattern of surface soil water by its effect on the lateral redistribution of soil water (e.g. infiltration and runoff). Relative elevation was negatively correlated with surface SWC in this study (Fig. 8), in agreement with other studies (Qiu *et al.* 2001, Hébrard *et al.* 2006) that highlighted a declining trend of SWC with increasing relative elevation. The magnitude of the negative correlation generally increased with an increase in mean water content (Fig. 8). According to Pan *et al.* (2008), rain can increase the relative significance of elevation on the spatial pattern of surface SWC, because elevation becomes the dominant factor governing the redistribution of soil water immediately after a rainfall event. The effect of relative elevation, though, can quickly be replaced by strong evapotranspiration soon after a rainfall event. The degree of association between SWC and relative elevation in drier conditions when redistribution is minor or absent may thus decrease (Grayson *et al.* 1997). However, relative elevation also correlated strongly with soil and vegetation properties (Table 5), so the increasingly weaker correlations as soil dries are also likely to be the consequence of the joint contributions of soil and vegetation properties.

Table 4 Pearson's correlation coefficients between surface soil (0–6 cm) water content and topographical, soil and vegetation properties during the observation period. * and ** indicate that the correlation is statistically significant at probability levels of 5% and 1%, respectively.

	16 Apr	30 Apr	15 May	29 May	18 Jun	30 Jun	21 Jul	31 Jul	15 Aug	3 Sep	16 Sep	2 Oct	16 Oct
Relative elevation	−0.351**	−0.358**	−0.353**	−0.346**	−0.399**	−0.432**	−0.253**	−0.522**	−0.430**	−0.262**	−0.409**	−0.389**	−0.298**
BD	−0.635**	−0.661**	−0.664**	−0.641**	−0.651**	−0.689**	−0.596**	−0.720**	−0.624**	−0.532**	−0.609**	−0.591**	−0.556**
Gravel	−0.207**	−0.227**	−0.215**	−0.220**	−0.217**	−0.231**	−0.156**	−0.259**	−0.213**	−0.126**	−0.165**	−0.165**	−0.149**
Sand	−0.556**	−0.550**	−0.562**	−0.534**	−0.608**	−0.621**	−0.466**	−0.580**	−0.542**	−0.474**	−0.551**	−0.546**	−0.513**
Silt	0.536**	0.540**	0.547**	0.524**	0.597**	0.608**	0.452**	0.584**	0.530**	0.446**	0.539**	0.526**	0.501**
Clay	0.559**	0.546**	0.561**	0.530**	0.603**	0.616**	0.467**	0.573**	0.540**	0.485**	0.548**	0.549**	0.512**
SOC	0.420**	0.432**	0.423**	0.420**	0.483**	0.468**	0.383**	0.421**	0.418**	0.420**	0.471**	0.484**	0.482**
K_S	−0.189**	−0.178**	−0.193**	−0.193**	−0.146*	−0.186**	−0.191**	−0.197**	−0.189**	−0.130	−0.140	−0.138	−0.176*
Species richness	−0.256**	−0.268**	−0.269**	−0.260**	−0.224**	−0.240**	−0.150*	−0.321**	−0.236**	−0.125	−0.201**	−0.188**	−0.128
Shrub coverage	−0.109	−0.107	−0.123	−0.116	−0.086	−0.071	−0.139	0.037	−0.061	−0.158*	−0.057	−0.086	−0.108
Herb coverage	−0.049	−0.045	−0.025	−0.046	−0.059	−0.032	−0.003	0.084	0.156*	−0.094	−0.075	−0.098	−0.088

BD: bulk density; SOC: soil organic carbon concentration; K_S: soil saturated hydraulic conductivity.

3.4.2 Soil properties Soil BD, soil texture, gravel content, SOC concentration and K_S have been considered as the main soil properties regulating the distribution of SWC. Table 4 shows remarkable correlations between water content and most of the soil properties. These correlations confirm the importance of the spatial heterogeneity of soil properties to the variability of SWC.

In our study, BD and soil texture were the most crucial properties regulating the distribution of surface SWC. The SWC was highly inversely correlated with BD and sand content but was positively correlated with silt and clay contents for all dates (Table 4). The BD strongly reflects soil structure and the distribution of large pores and thus plays a major role in soil saturation and hydraulic conductivity. Soil texture can influence hydraulic properties and the ability of soil to retain water and can hence have a particularly significant effect on the distribution pattern of SWC. These results are supported by other studies (Zhao *et al*. 2010, Gao and Shao 2012), which also found strong correlations between SWC and soil texture and BD. Increased SOC content generally leads to a better-aggregated soil structure and a lower BD, and therefore encourages an enhanced capacity of soil to retain water, which can considerably reduce the loss of water (mainly by evapotranspiration and deep percolation).

Compared with the soil properties mentioned above, gravel content and K_S had much weaker effects on the distribution of SWC. The relationship between K_S and SWC did not even reach a significant level on some drier days (Table 4). Variations in stone content and K_S in this area may thus at best have a much lower influence on the distribution of SWC. Correlations with soil texture were largely unaffected by soil wetness, which were nearly constant over the complete range of soil wetness (Fig. 8). This result agrees with that of Gómez-Plaza *et al*. (2001), who found that the role of soil texture in the distribution of SWC did not vary with seasonal variations of soil wetness condition. The strong correlation with SWC thus suggests that soil texture is important in both wet and dry conditions. In contrast, the correlations between SWC and other soil properties (BD, gravel content, K_S and SOC concentration) were affected by soil wetness. The correlations with BD, gravel content and K_S were stronger in wet conditions, and the correlation with SOC concentration was stronger in dry conditions. These results suggest that the relative significance of these soil properties in regulating the distribution of SWC

Table 5 Pearson's correlation coefficients among topographical, soil and vegetation properties. * and ** indicate that the correlation is statistically significant at probability levels of 5% and 1%, respectively.

	Relative elevation	BD	Gravel	Sand	Silt	Clay	SOC	K_S	Species richness	Shrub coverage	Herb coverage
Relative elevation	1.000	0.375**	0.386**	0.469**	−0.471**	−0.456**	−0.267**	−0.116	0.397**	−0.336**	−0.201**
BD		1.000	0.409**	0.659**	−0.671**	−0.634**	−0.413**	0.146*	0.307**	−0.058	−0.004
Gravel			1.000	0.448**	−0.458**	−0.429**	−0.196**	0.145*	0.402**	−0.230**	−0.176*
Sand				1.000	−0.984**	−0.990**	−0.679**	0.176*	0.336**	−0.234**	−0.004
Silt					1.000	0.949**	0.677**	−0.167*	−0.329**	0.229**	0.017
Clay						1.000	0.665**	−0.179*	−0.333**	0.232**	−0.006
SOC							1.000	−0.158*	−0.115	0.022	−0.108
K_S								1.000	0.211**	0.023	0.078
Species richness									1.000	−0.140	−0.092
Shrub coverage										1.000	0.325**
Herb coverage											1.000

BD: bulk density; SOC: soil organic carbon concentration; K_S: soil saturated hydraulic conductivity.

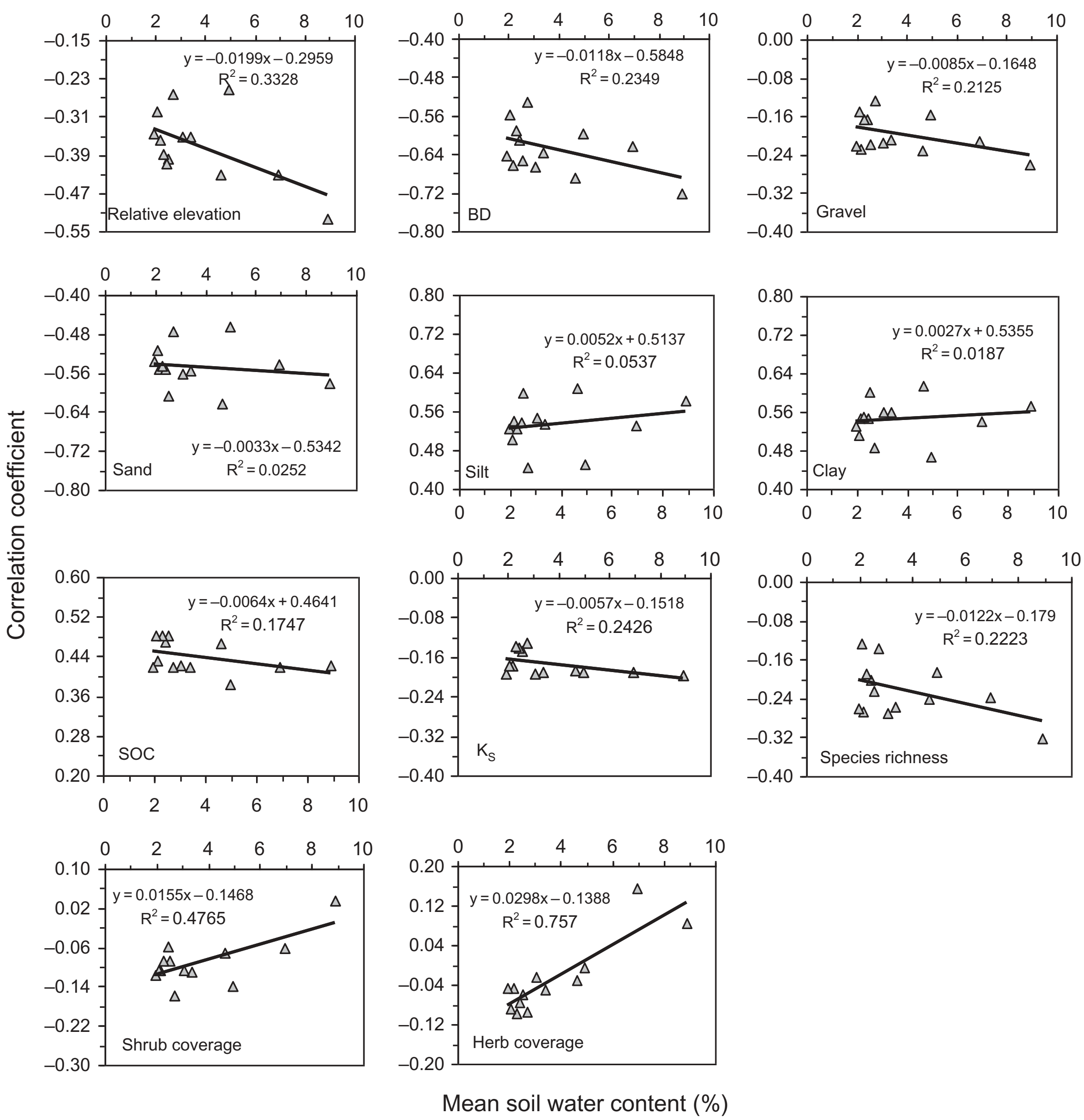

Fig. 8 Correlation coefficients between SWC and relative elevation, soil properties (gravel, sand, silt, clay and SOC content, BD and K_S) and vegetation (shrub coverage, herb coverage and species richness) plotted against mean SWC (%).

may vary with wetness. The BD can be reasonably expected to influence the distribution of SWC immediately after a significant rainfall via its relationship with soil porosity and hydraulic conductivity. Moreover, the presence of gravel on the soil surface can further promote to some degree the percolation of soil water to lower layers (Williams *et al*. 2003). As soil dries, evaporation and plant transpiration gradually become the dominant hydraulic processes, and SOC and clay content may then become more important in the distribution of SWC because of their higher capacities to retain water.

3.4.3 Vegetation properties Vegetation regulates the pattern of SWC mainly by intercepting rain, shading the soil surface, extracting soil water for transpiration, increasing the infiltration of soil water and reducing soil temperatures. Also, plant litter and root residues accumulate on the soil surface and thereby prolong the periods of increased levels of soil water. Species composition affects interspecific competition for the limited water resources and may thus play a significant role in the evaporation and storage of SWC.

Surprisingly, we found no obvious dependence of SWC on the coverages of shrubs and herbs (low correlation coefficients, as shown in Table 4), except on a few days. Other studies have indicated that the dynamics of SWC should be strongly influenced by variations in vegetation coverage (Reynolds 1970, Hawley *et al*. 1983, Bhark and Small 2003). The relatively weak dependence of SWC on vegetation coverage in the present study might be ascribed to the very limited amount of data collected (one time in mid-August). The correlations based on these limited data cannot represent the entire season. As shown in Table 4, SWC was significantly correlated with herb coverage on 15 August, near the date when vegetation data were collected. On the other hand, SWC was significantly and negatively correlated with species richness (Table 4). The presence of more species will increase the intensity of interspecific competition for the scarce water and will consequently accelerate the loss of soil water.

The correlation coefficients for the vegetation properties displayed a clearly linear function for field mean water content (Fig. 8), likely due to the differential regulation of soil-water distribution by vegetation at different stages of growth. The effect of transpiration was illustrated by the negative correlation between SWC and shrub coverage under dry conditions. In contrast, shrub coverage was positively correlated with soil water under wet conditions, perhaps caused by the interception of rainfalls. This would happen, but is not likely if just a small rainfall event occurs, because the high temperature and absence of wind would enable rapid evaporation and prevent the rain from reaching the soil surface (Bhark and Small 2003). The herbs in this region are mainly annuals, such as *B. dasyphyll*a, *H. arachnoideus* and *S. ruthenica*, which prefer locations with high water contents. Herb coverage was thus positively correlated with field mean water content (Fig. 8). Interspecific competition also increases with higher SWC, as shown by the strong correlation between species richness and SWC (Fig. 8).

3.5 Stepwise linear regression analysis

The distribution of SWC was not regulated by a single factor but was governed in more complicated and comprehensive ways because many of the controlling factors were interdependent. Stepwise linear regression analysis was performed to find the factors that could best predict the dynamics of SWC. To investigate how combinations of factors changed with the seasonal variations of soil wetness, we separated the measurement campaigns into three groups based on the conditions of wetness: wet ($\overline{\theta_k} > 5\%$), medium ($\overline{\theta_k} = 3$–$5\%$) and dry ($\overline{\theta_k} < 3\%$).

Table 6 shows that the factors regulating the distribution of SWC varied with wetness, although BD was the most dominant factor in all three conditions. Under wet conditions, relative elevation and clay content were also important factors influencing the pattern of SWC. Under dry conditions, clay content and shrub coverage became more important through the ability to retain water and to transpire, respectively. Stone content and K_S also reached significant levels, but played minor roles in the variability of SWC compared to other soil properties. These results have led us to the conclusion that the major factors controlling the dynamics of SWC changed from combinations of topographical and soil properties under wet conditions to combinations of soil and vegetation properties under dry conditions.

4 CONCLUSIONS

This study surveyed the variability of surface soil (0–6 cm) water content in space and time, and identified the factors influencing the distribution of SWC

Table 6 Stepwise linear regression of surface soil (0–6 cm) water content with selected properties under different wetness conditions.

Wetness	Property	Standardized coefficient	t	P	Adjusted R^2
Wet	BD	**−0.476**	**−7.949**	**0.000**	0.664
	Relative elevation	**−0.327**	**−5.999**	**0.000**	
	Clay content	**0.299**	**4.711**	**0.000**	
	Shrub coverage	−0.180	−3.740	0.000	
	Gravel content	0.181	3.436	0.001	
	K_S	−0.103	−2.208	0.029	
Medium	BD	**−0.484**	**−7.450**	**0.000**	0.605
	Clay content	**0.324**	**4.709**	**0.000**	
	Shrub coverage	**−0.243**	**−4.656**	**0.000**	
	Relative elevation	−0.201	−3.407	0.001	
	Gravel content	0.182	3.196	0.002	
	K_S	−0.108	−2.130	0.035	
Dry	BD	**−0.453**	**−6.889**	**0.000**	0.595
	Clay content	**0.348**	**5.037**	**0.000**	
	Shrub coverage	**−0.251**	**−4.743**	**0.000**	
	Relative elevation	−0.222	−3.817	0.000	
	Gravel content	0.159	2.769	0.006	

BD: bulk density; K_S: soil saturated hydraulic conductivity; t: Student's t; P: significance level; R^2: coefficient of determination. The values in bold font represent the three most important factors influencing the pattern of SWC.

in a 40-km^2 area of the Gobi Desert. The spatial variability of SWC increased during drying after a wet period, peaked at specific SWCs and then decreased during further drying. The minimum amount of sampling needed coincided with a water content of approximately 4.5%. A re-sampling method further indicated that the spatial variability of SWC increased with the expansion of area and could be well parameterized as a power function of the size of the sampling area. Geostatistical analysis indicated that SWC exhibited a variable spatial dependence with time. It had a stronger spatial pattern of organization following significant rainfalls and in extremely dry conditions but had a stochastic pattern under moderate conditions of wetness. Correlation analysis implied that the dynamics of SWC in this area were linked to relative elevation, soil properties and vegetation. However, the dominant factors influencing the dynamics of SWC largely depended on the average state of SWC. Stepwise regression analysis further indicated that SWC was strongly associated with topographical and soil properties (BD, relative elevation and clay content) under wet conditions, but soil and vegetation properties (BD, clay content and shrub coverage) controlled the variability of SWC under dry conditions. This study is applicable to the description of soil-water distribution in arid regions, which may have important implications for sampling design, hydrological modelling, environmental protection and sustainability of land use.

Funding This work was supported by grants from the Major Programme of the National Natural Science Foundation of China (no. 91025018).

REFERENCES

Ampofo, E.A., 2006. Soil moisture dynamics in coastal savanna soils in the tropics under different soil management practices. *Hydrological Sciences Journal*, 51 (6), 1194–1202. doi:10.1623/hysj.51.6.1194

Berndtsson, R. *et al.*, 1996. Soil water and temperature patterns in an arid desert dune sand. *Journal of Hydrology*, 185, 221–240. doi:10.1016/0022-1694(95)02987-7

Bhark, E.W. and Small, E.E., 2003. Association between plant canopies and the spatial patterns of infiltration in shrubland and grassland of the Chihuahuan Desert, New Mexico. *Ecosystems*, 6, 185–196. doi:10.1007/s10021-002-0210-9

Brocca, L., *et al.*, 2007. Soil moisture spatial variability in experimental areas of central Italy. *Journal of Hydrology*, 333, 356–373. doi:10.1016/j.jhydrol.2006.09.004

Brocca, L., *et al.*, 2010. Spatial-temporal variability of soil moisture and its estimation across scales. *Water Resources Research*, 46, W02516. doi:10.1029/2009WR008016

Brocca, L., *et al.*, 2012. Catchment scale soil moisture spatial-temporal variability. *Journal of Hydrology*, 422–423, 63–75. doi:10.1016/j.jhydrol.2011.12.039

Charpentier, M.A. and Groffman, P.M., 1992. Soil moisture variability within remote sensing pixels. *Journal of Geophysical Research*, 97, 18987–18995. doi:10.1029/92JD00882

David, M., 1977. *Geostatistical ore reserve estimation*. Amsterdam, The Netherlands: Elsevier.

Famiglietti, J.S., Rudnicki, J.W., and Rodell, M., 1998. Variability in surface moisture content along a hillslope transect: Rattlesnake Hill, Texas. *Journal of Hydrology*, 210, 259–281. doi:10.1016/S0022-1694(98)00187-5

Gao, X.D., *et al.*, 2011. Soil moisture variability along transects over a well-developed gully in the Loess Plateau, China. *Journal of Hydrology*, 87, 357–367.

Gao, L. and Shao, M., 2012. Temporal stability of shallow soil water content for three adjacent transects on a hillslope. *Agricultural Water Management*, 110, 41–54. doi:10.1016/j.agwat.2012.03.012

Gómez-Plaza, A., *et al.*, 2001. Factors regulating spatial distribution of soil water content in small semiarid catchments. *Journal of Hydrology*, 253, 211–226. doi:10.1016/S0022-1694(01)00483-8

Grayson, R.B., *et al.*, 1997. Preferred states in spatial soil moisture patterns: Local and nonlocal controls. *Water Resources Research*, 33, 2897–2908. doi:10.1029/97WR02174

Hawley, M.E., Jackson, T.J., and McCuen, R.H., 1983. Surface soil moisture variation on small agricultural watersheds. *Journal of Hydrology*, 62, 179–200. doi:10.1016/0022-1694(83)90102-6

Hébrard, O., *et al.*, 2006. Spatio-temporal distribution of soil surface moisture in a heterogeneously farmed Mediterranean catchment. *Journal of Hydrology*, 329, 110–121. doi:10.1016/j.jhydrol.2006.02.012

Hills, R.C. and Reynolds, S.G., 1969. Illustrations of soil moisture variability in selected areas and plots of different sizes. *Journal of Hydrology*, 8, 27–47. doi:10.1016/0022-1694(69)90029-8

Hu, W., *et al.*, 2008. Soil water content temporal-spatial variability of the surface layer of a Loess Plateau hillside in China. *Scientia Agricola*, 65, 277.

Hu, W., *et al.*, 2010. Watershed scale temporal stability of soil water content. *Geoderma*, 158, 181–198. doi:10.1016/j.geoderma.2010.04.030

International GEWEX Project Office, 1995. Global Soil Wetness Project, 47 pp.

Jia, Y.H. and Shao, M.A., 2013. Temporal stability of soil water storage under four types of revegetation on the northern Loess Plateau of China. *Agricultural Water Management*, 117, 33–42. doi:10.1016/j.agwat.2012.10.013

Klute, A. and Dirksen, C., 1986. Hydraulic conductivity of saturated soils. *In*: A. Klute, ed. Methods of Soil Analysis. Madison, WI: ASA and SSSA, 694–700.

Lawrence, J.E. and Hornberger, G.M., 2007. Soil moisture variability across climate zones. *Geophysical Research Letters*, 34, L20402. doi:10.1029/2007GL031382

Li, H.D., *et al.*, 2013. Spatio-temporal variability of soil moisture and its effect on vegetation in a desertified aeolian riparian ecotone on the Tibetan Plateau, China. *Journal of Hydrology*, 479, 215–225. doi:10.1016/j.jhydrol.2012.12.002

Lu, H. and Shi, J.C., 2012. Reconstruction and analysis of temporal and spatial variations in surface soil moisture in China using remote sensing. *Chinese Science Bulletin*, 57, 2824–2834. doi:10.1007/s11434-012-5011-8

Meyles, E., *et al.*, 2003. Runoff generation in relation to soil moisture patterns in a small Dartmoor catchment, Southwest England. *Hydrological Processes*, 17, 251–264. doi:10.1002/hyp.1122

Nelson, D.W., and Sommers, L.E., 1982. Total carbon, organic carbon and organic matter. *In*: A.L. Page, R.H. Miller, and D.R. Keeney, eds. *Methods of soil analysis, Part 2, Chemical and Microbiological Properties*. Madison, WI: ASA and SSSA, 534–580.

Owe, M., Jones, E.B., and Schmugge, T.J., 1982. Soil moisture variation patterns observed in Hand County, South Dakota. *Journal of the American Water Resources Association*, 18, 949–954. doi:10.1111/j.1752-1688.1982.tb00100.x

Pan, Y.X., *et al.*, 2007. Variability characteristic of surface soil moisture content in sand areas covered by different vegetation types. *Journal of Soil and Water Conservation*, 21, 106–109. (in Chinese with English abstract).

Pan, Y.X., *et al.*, 2008. Spatial variability of surface soil moisture content in a re-vegetated desert area in Shapotou, Northern China. *Journal of Arid Environments*, 72, 1675–1683. doi:10.1016/j.jaridenv.2008.03.010

Pan, Y.X. and Wang, X.P., 2009. Factors controlling the spatial variability of surface soil moisture within revegetated-stabilized desert ecosystems of the Tengger Desert, Northern China. *Hydrological Processes*, 23, 1591–1601. doi:10.1002/hyp.7287

Penna, D., *et al.*, 2009. Hillslope scale soil moisture variability in a steep alpine terrain. *Journal of Hydrology*, 364, 311–327. doi:10.1016/j.jhydrol.2008.11.009

Qiu, Y., *et al.*, 2001. Spatial variability of soil moisture content and its relation to environmental indices in a semi-arid gully catchment of the Loess Plateau, China. *Journal of Arid Environments*, 49, 723–750. doi:10.1006/jare.2001.0828

Reynolds, S.G., 1970. The gravimetric method of soil moisture determination Part III An examination of factors influencing soil moisture variability. *Journal of Hydrology*, 11, 288–300. doi:10.1016/0022-1694(70)90068-5

Takagi, K. and Lin, H.S., 2012. Changing controls of soil moisture spatial organization in the Shale Hills Catchment. *Geoderma*, 173–174, 289–302. doi:10.1016/j.geoderma.2011.11.003

Vereecken, H., *et al.*, 2007. Explaining soil moisture variability as a function of mean soil moisture: A stochastic unsaturated flow perspective. *Geophysical Research Letters*, 34, L22402. doi:10.1029/2007GL031813

Wang, Y.Q., *et al.*, 2012. Regional spatial pattern of deep soil water content and its influencing factors. *Hydrological Sciences Journal*, 57 (2), 265–281. doi:10.1080/02626667.2011.644243

Western, A.W., *et al.*, 1999. Observed spatial organization of soil moisture and its relation to terrain indices. *Water Resources Research*, 35, 797–810. doi:10.1029/1998WR900065

Western, A.W., Blöschl, G., and Grayson, R.B., 1998. Geostatistical characterisation of soil moisture patterns in the Tarrawarra catchment. *Journal of Hydrology*, 205, 20–37. doi:10.1016/S0022-1694(97)00142-X

Williams, A.G., *et al.*, 2003. Soil moisture variability and land use in a seasonally arid environment. *Hydrological Processes*, 17, 225–235. doi:10.1002/hyp.1120

Yu, S.W., *et al.*, 2012. Determination of water sources of Gobi plants by D and ^{18}O state isotopes in middle reaches of the Heihe River. *Journal of Desert Research*, 32, 717–723. (in Chinese).

Zhang, J.G., *et al.*, 2011. Spatial variability and patterns of surface soil moisture in a field plot of karst area in southwest China. *Plant, Soil and Environment*, 57, 409–417.

Zhao, Y., *et al.*, 2010. Controls of surface soil moisture spatial patterns and their temporal stability in a semi-arid steppe. *Hydrological Processes*, 24, 2507–2519.

Zhao, Y., *et al.*, 2011. Factors controlling the spatial patterns of soil moisture in a grazed semi-arid steppe investigated by multivariate geostatistics. *Ecohydrology*, 4, 36–48. doi:10.1002/eco.121

Zhu, Y.J. and Shao, M.A., 2008. Variability and pattern of surface moisture on a small-scale hillslope in Liudaogou catchment on the northern Loess Plateau of China. *Geoderma*, 147, 185–191. doi:10.1016/j.geoderma.2008.08.012