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Statistical analysis of the temporal stability of soil moisture in three desert regions of northwestern China

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Abstract Soil moisture and its variations are key factors for understanding hydrological processes, which are characterized by a high temporal variability at different scales. The study was conducted at three field stations in the desert regions of northwestern China, where soil moisture measurements with gravimetric method were used to characterize the temporal stability of soil moisture using various statistical parameters and an index of temporal stability (ITS). The soils are a gray–brown desert soil at the Linze station, an aeolian sandy soil at the Fukang station, and a brown desert soil at the Cele station. Soil textures are accordingly sandy loam at Linze and Cele, and loamy sand at Fukang. The dynamic variation in soil moisture depends strongly on the rainfall pattern (amount and frequency) in these desert ecosystems. Soil moisture content is low and significantly different among the three desert ecosystems, with the maximum at the Linze station (6.61 ± 2.08 %), followed by the Cele (4.83 ± 0.81 %) and Fukang (3.46 ± 0.47 %) stations. The temporal pattern exhibits high variability because soil moisture is characterized by low temporal stability and a high coefficient of variation (CV). The standard deviation, CV, and ITS increase significantly with increasing soil moisture. Soil moisture displays a skewed frequency distribution that follows a logarithmic function at lower soil moisture but a log-normal distribution at higher values.

Keywords Desert ecosystems · Soil moisture · Temporal variability · Spatial patterns

Introduction

Soil moisture and its variation are key factors for understanding hydrological processes at different spatial and temporal scales (Entin et al. 2000). The variability of near-surface hydrologic and energy balances is controlled by soil moisture, which is characterized by a high temporal variability at different scales (Brocca et al. 2007; Pan and Wang 2009). Soil moisture also controls the dynamics of terrestrial ecosystems, especially in desert regions. In arid environments, the rates of transpiration, carbon assimilation, and biomass production are often limited by soil moisture during the growing season, and the nutrient cycle and organic matter budgets in the soil are also strongly affected by the dynamics of soil moisture (Porporato et al. 2002). Therefore, the temporal variations of soil moisture have received increasing attention in recent years (e.g., Starks et al. 2006; Brocca et al. 2009). It is particularly important to study the temporal variations of soil moisture in desert regions because of the importance of the processes that govern changes in soil moisture and their role in the expansion of desert ecosystem (Martinez et al. 2008).

Soil moisture is particularly complex and highly temporally and spatially variable in desert ecosystems (Western et al. 2004; Hebrard et al. 2006) as a result of the high

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uncertainty and variability of rainfall. The variability of soil moisture is influenced by a number of interacting factors, including soil properties, topography, depth of the water table, vegetation types, and seasonal and annual climate variations (e.g., Mahmood and Vivoni 2008; Noto et al. 2008). In general, the number of sampling sites used in previous studies was limited because the measurement of soil moisture over large areas and long time periods was expensive and time-consuming; thus, the selection of monitoring locations might be done randomly or based on the convenience of the researchers rather than in a statistically representative way (Martínez-Fernández and Ceballos 2005; Zhou et al. 2007). However, to estimate the average soil moisture for an inland region, Brocca et al. (2007) determined the required number of point measurements using a statistical model of wetness conditions. In other studies that did not use this kind of approach, the monitoring sites that were selected might not represent the range of mean soil moisture contents in the field. Therefore, the development of new methodologies that could optimize the number of observations without losing important information on regional variability has become increasingly important for studies of the spatial variation of soil moisture at a regional scale. To solve this problem, temporally stable locations were generally selected based on previously collected data. The application of the temporal stability concept for developing an efficient and effective sampling strategy aimed to find a reliable location that reliably represented an area's mean moisture content within a given time period and sampling frequency. The concept of temporal stability was introduced by Vachaud et al. (1985) to define the time-invariant spatial association of soil moisture with site factors. Their approach improved the understanding of soil water dynamics, because temporal stability occurred when covariances exist between various variables of interest and the deterministic factors that underlie these variables. In particular, the relative differences between individual and spatially averaged values could be used to characterize the temporal stability. Cosh et al.'s (2006) results supported the validity of using temporal stability measurements in soil moisture surveys. Brocca et al. (2009) provided a more descriptive understanding of the patterns of soil moisture using different techniques of temporal stability analysis in central Italy. The temporal stability approach was successfully applied, and the temporally stable points could accurately represent the mean soil moisture value even beyond the measurement period. In addition, this approach demonstrated that soil moisture measurements on a limited number of dates or under a limited range of soil moisture conditions could be transformed into a more complete time series using techniques such as predictive models applied to temporally stable locations.

The dynamics of soil moisture controls the soil water balance at a regional scale, and understanding the statistical aspects of the temporal variation in soil moisture is, therefore, critical for evaluating soil moisture variability at regional and inter-annual scales. Unfortunately, few investigations around the world have attempted to compare soil moisture distributions over a range of regional scales (e.g., Motovilov et al. 1999; Western et al. 1999; Anderson et al. 2001; Mahmood and Vivoni 2008), especially in desert ecosystems. Hassan and Gregory (2002) investigated the changes in soil water content over weekly and half-hourly time scales, Fuentes et al. (2003) reported that the annual temporal dynamics of soil water were similar between conventional and no-till cropping systems, and Wendroth et al. (1999) studied the patterns and covariance structures of soil water status. Soil moisture is characterized by small temporal variability for most of the year in these desert regions, followed by sudden and rapid changed in soil moisture after the rare rainfall events. Performing a statistically valid analysis of the spatiotemporal pattern of soil moisture is critical for evaluating soil moisture variability.

In China, several previous studies have been carried out to assess the annual dynamics of soil moisture under arid conditions (e.g., Liu and Zhang 2007). For example, Zhao et al. (2010) not only described the stable soil moisture patterns in a semi-arid steppe, but also identified the factors that controlled their stability. Liu and Zhang (2007) measured the temporal dynamics of soil moisture after rainfall events in southwestern China. Pan and Wang (2009) studied the main factors that controlled surface soil moisture patterns and quantified the variation in these factors for desert ecosystems in northern China. However, the temporal dynamics and variability of soil moisture in these studies focused mainly on an intra-seasonal scale and a plot scale (i.e., a short duration and small spatial scale). The significant differences in soil properties affect the temporal variation in soil moisture on regional and inter-annual scales in the desert regions of northwestern China; these factors include soil textures, nutrient and soil bulk density. Simultaneously, soil moisture is also affected by seasonal variations in vegetation and climate.

Soil moisture is particularly important in desert regions, and its seasonal changes have a significant impact on vegetation dynamics, as water availability controls plant growth and phenology (Shinoda et al. 2007; Nandintsetseg and Shinoda 2011). At a regional scale, the area from the Heihe River Basin to the Cele River Basin in northern China has an arid climate (Fig. 1, ESM only), although the environment ranges from arid to extremely arid at a local scale. Soil moisture has an equally variable pattern, with a high soil water content in some regions and a low soil moisture in others, where the establishment and survival of vegetation are difficult due to inadequate availability of moisture. Soil moisture data were available for a few isolated regions, such as Mongolia (Nandintsetseg and Shinoda 2011), but generally for only short periods. In China, little work has been done on the temporal stability of soil moisture in desert regions, and there has been little use of advanced techniques such as temporal stability analysis. To provide some of the missing data, the study obtained long-term, frequently updated measurements from three field stations in the desert region of northwestern China from 2005 to 2009. Our primary objectives are (1) to investigate the spatial and temporal patterns of soil moisture, and use the results to identify locations with temporally stable soil moisture; (2) to examine the interannual variability in soil moisture; and (3) to determine how variations in soil moisture determine the magnitude of differences at regional and inter-annual scales in the desert regions of China. To support this analysis, a water balance model is developed to examine regional soil moisture dynamics and open avenues for future process-based studies and regional scale predictions of desert ecohydrology.

Materials and methods

Study area

The study area include sites in the desert regions of northwestern China, at three field stations of the Chinese Academy of Sciences (Fig. 1, ESM only): Linze Station (39°18′N, 100°07′E), Fukang Station (44°18′N, 87°55′E), and Cele Station (37°00′N, 80°43′E). These regions are characterized by arid to extremely arid climates. The study areas at the three stations were described in detail by Liu et al. (2010, 2011), Xu and Li (2006), and Gui et al. (2010). The soils at the study sites are a gray–brown desert soil at the Linze station, an aeolian sandy soil at the Fukang station, and a brown desert soil at the Cele station. The geomorphologic pattern is characterized by sand dunes, including fixed, semi-fixed, semi-mobile, and mobile dunes, as well as inter-dune lowlands. The vegetation is dominated by desert plants growing in groups or with a patchy distribution pattern. Desert shrubs are found on fixed and semi-fixed dunes, and include *Haloxylon ammodendron*, *Elaeagnus angustifolia*, *Tamarix ramosissima*, *Nitraria sphaerocarpa*, and *Reaumuria soongorica* (Deng et al. 2003; Su et al. 2003; Xu and Li 2006; Gui et al. 2010; Liu et al. 2010, 2011). In contrast, annual herbaceous rain-fed species appear in the inter-dune lowlands and between dunes, and include *Bassia dasyphylla*, *Halogeton arachnoideus*, *Suaeda glauca*, and *Agriophyllum squarrosum* (Liu et al. 2010, 2011). The vegetation physiognomy is generally homogeneous, with vegetation cover ranging from 5 to 7 % (Liu et al. 2011).

Measurements

Field measurements of soil moisture were conducted at the three field stations, which represent three river basins in arid northwestern China. At the Linze and Fukang stations, soil moisture measurements were carried out during the warm season (April to October), but were not measured in winter (November to March) because the soil was frozen; data were obtained at the Cele Station throughout the year. Soil moisture was measured every 10 days from 2005 to 2009, at 10-cm intervals from the soil surface to a depth of 150 cm. Values were determined gravimetrically for the samples, with five replicates. The samples were obtained from five sites (each representing a different region) at each field station, with five 20 × 20 m sample plots at each site. Soil samples were sealed in plastic containers immediately after they were collected in the field (to prevent moisture loss), the fresh weight was measured in the laboratory, and then the samples were oven-dried (DGG-9036A oven, Shanghai Linping Instrument Company Limited, Shanghai, China) at 105 °C for 24 h to determine the dry weight. The study also measured the soil's bulk density, water content at the wilting point (W_{wp}), and field capacity (W_{fc}) at each site, as well as parameters of the characteristic soil moisture retention curve every year from 2005 to 2009.

Rainfall was measured using tipping-bucket rain gauges (model TE525, metric; Texas Electronics, Dallas, TX) installed on meteorological towers at the study sites. The rainfall data were measured at a frequency of 10 Hz and recorded as 10-min averages using a CR1000 datalogger (Campbell Scientific Inc., Logan, UT). All measurement methods and instruments were the same at the three field stations.

Statistical analysis

Temporal stability analysis

Temporal stability was determined according to the method of Vachaud et al. (1985). This method, in which the degree of temporal stability in soil moisture patterns was used to predict time series for soil moisture at locations where little data were available and is often performed using continuous records from nearby locations (Pachepsky et al. 2005; Fernández-Gálvez et al. 2006). The soil water content ($\theta_{i,j,t}$) at location i in field j at time t is used to calculate the mean value (μ, $\overline{\theta}_{j,t}$), the mean relative difference (MRD, $\overline{\delta}_{i,j}$), and standard deviation (SD, σ).

$$\overline{\theta}_{j,t} = \frac{1}{n_{j,t}} \sum_{i=1}^{n_{j,t}} \theta_{i,j,t} \quad (1)$$

$$\overline{\delta}_{i,j} = \frac{1}{n_t} \sum_{i=1}^{n_t} \frac{\theta_{i,j,t} - \overline{\theta}_{j,t}}{\overline{\theta}_{j,t}} \quad (2)$$

$$\sigma(\delta)_{i,j} = \frac{1}{n_t - 1} \sum_{i=1}^{n_t} \left(\frac{\theta_{i,j,t} - \overline{\theta}_{j,t}}{\overline{\theta}_{j,t}} - \overline{\delta}_{i,j} \right) \quad (3)$$

where n represents the number of sample sites.

Following the method of Jacobs et al. (2004) and Mapfumo et al. (2004), the study computed an index of temporal stability (ITS) using a combination of MRD (δ) and its SD (σ), as follows:

$$\mathrm{ITS}_{i,j} = \sqrt{\overline{\delta}_{i,j}^2 + \sigma(\delta)_{i,j}^2} \quad (4)$$

The study evaluated the stability of the soil moisture's temporal pattern over time using Spearman's rank-correlation coefficient (r_s), which is defined as follows (Brocca et al. 2009):

$$r_s = 1 - 6 \sum_{i=1}^{N} \frac{(R_{ij} - R_{il})}{N(N^2 - 1)} \quad (5)$$

where N is the total sample size, R_{ij} is the rank of the soil moisture observation θ_{ij} for sample point i in field j, and R_{jl} is the rank of the soil moisture observation at the same location (l).

Soil moisture modeling

The water balance model was applied that was developed for arid regions to represent the characteristics of changes in soil water in the dry and rainy seasons (Nandintsetseg and Shinoda 2011), including the effects of winter soil freezing and spring snowmelt. This model was used for soil moisture observations from the soil surface to a depth of 150 cm at the three field stations using data from 2005 to 2009. The model calculated the absolute plant-available soil water content using the daily precipitation and energy balance method, with a limited number of measured soil parameters, as expressed by the following equations:

$$\begin{aligned} \frac{\mathrm{d}W(t)}{\mathrm{d}t} &= P_r(t) - ET(t) + M(t) - R(t) \\ R &= W - W_{\mathrm{fc}} \quad \text{for } W > W_{\mathrm{fc}} \\ R &= 0 \quad \text{for } W \le W_{\mathrm{fc}} \end{aligned} \quad (6)$$

where W, the plant-available soil moisture, is expressed as the actual soil moisture minus the soil water content at the wilting point (mm); t is time (days); P_r is daily rainfall (mm); and M is the water content of the snow (expressed as the snow water equivalent, mm) that accumulates when the air temperature is equal to or below 0 °C. If air temperature is above 0 °C, the accumulated snow melts. ET is the evapotranspiration (mm) and R is the sum of surface runoff and deep drainage (mm). In arid regions, the annual precipitation is less than or equal to 200 mm, and is always less than the annual evapotranspiration (Robock et al. 2000). Most of the precipitation quickly returns to the atmosphere from the upper layers of the soil via evapotranspiration, and precipitation rarely infiltrates to depths below 20 cm (Yamanaka et al. 2007). Thus, the study considered that even though the treatment of surface runoff and deep drainage in our model is simplistic, this would not lead to serious errors in the soil moisture estimation.

The evapotranspiration (ET) is obtained by the energy balance method without accounting for advection effects. The latent heat flux was obtained by

$$\lambda \mathrm{ET} = -\left(\frac{R_n - G}{(1 + \gamma \Delta T / \Delta e_a)} \right), \quad (7)$$

where λ (2.501 MJ kg^{-1}) is the latent heat of vaporization, R_n is the net radiation (Wm^{-2}), G is the soil heat flux (W m^{-2}), γ is the psychrometric constant (kPa °C^{-1}), and ΔT and Δe_a are the temperature (°C^{-1}) and vapor pressure differences at two levels above a crop canopy (1 and 2 m). The latent heat flux (λET) is divided by λ to obtain evapotranspiration (mm day^{-1}).

Data analysis

The study tested for the significant differences in temporal patterns of soil moisture using repeated-measures ANOVA to compare the main effects (region, inter-annual variation, and inter-monthly variation) and their interaction effects using version 13.0 of the SPSS software (SPSS Inc., Chicago, IL, USA). The study analyzed the differences in soil hydraulic properties and soil moisture characteristics between regions using ANOVA followed by Tukey's HSD test, and differences were considered to be significant at $P < 0.05$. The study used Spearman's rank-correlation coefficient (r_s) to estimate the magnitude of the correlation in the temporal pattern of soil moisture between sampling dates. Prior to the correlation analysis, the study tested the data for a normal distribution using the Kolmogorov–Smirnov test. By removing one or two outliers and transforming the data, the study obtained a normal distribution for each variable.

Results and analyses

Rainfall and soil property characteristics

Rainfall data for the three study regions were collected during the 5 years from 2005 to 2009. The results indicate that the annual rainfall averages 111.9 mm at Linze, 179.7 mm at Fukang, and 41.7 mm at Cele (Fig. 1). The annual rainfall varies relatively little at the Linze station, with an average coefficient of variation (CV) of 8.9 %. However, the interannual variability of annual rainfall is 32.8 % at the Fukang station and 37.1 % at the Cele station. The rainfall exhibits a strong seasonal distribution at all three sites, and is concentrated mainly from July to September (Fig. 2, ESM only), the primary growing season for the region's plant species. This period accounts for 81.2, 64.2, and 71.3 % of the annual rainfall at the Linze, Fukang, and Cele stations, respectively. Although the monthly variability in rainfall has the same seasonal tendency as the number of rainfall days at each station, the variability in rainfall appears to vary widely with rainfall day between three stations (Fig. 3, ESM only). The maximum number of days with rainfall is greatest at the Linze station (62.8 days/year), followed by the Fukang station (51 days/year) and the Cele station (13.2 days/year). Thus, Linze has more frequent rain, but a smaller rainfall during each event.

The saturated soil moisture content, field capacity, and moisture content at the wilting point differ significantly among the three stations, with the lowest values of each parameter at Linze and the highest values at Cele (Table 1). In contrast, bulk density is highest at Linze and lowest at Cele, but Cele and Fukang do not differ significantly. The total porosity is greatest for the aeolian sandy soil at Fukang, followed by the brown desert soil at Cele and the gray–brown desert soil at Linze. Moreover, the coefficient of the characteristic soil moisture curve is significantly greater at Cele (8.45) than at the other stations, which does not differ significantly (5.61 at Fukang and 4.76 at Linze). The exponent of this curve is significantly higher at Cele than at the other stations, which does not differ significantly. Soil organic matter is significantly higher at Linze (2.30 ± 0.35) than at Cele (1.83 ± 0.24) and Fukang (1.65 ± 0.27). Whereas the total and available nitrogen at Linze is significantly lower than at Fukang and Cele. There are significant differences for the available potassium and conductance among three stations ($P < 0.05$). Moreover, the available phosphorus and pH are not significantly different among three stations. Sand, silt and clay account for 63.84, 33.05 and 3.11 % of soil particle content at Linze (Fig. 4A, ESM only), whereas account for 71.22, 26.75 and 2.03 % at Cele (Fig. 4C, ESM only). Based on the USDA soil taxonomy, soil texture is basically the same type with the sandy loam at Linze and Cele. But, at Fukang, soil particle occupies 84.33, 14.00 and 1.56 % of soil particle content, respectively, and soil type is the loamy sand (Fig. 4C, ESM only; Table 1).

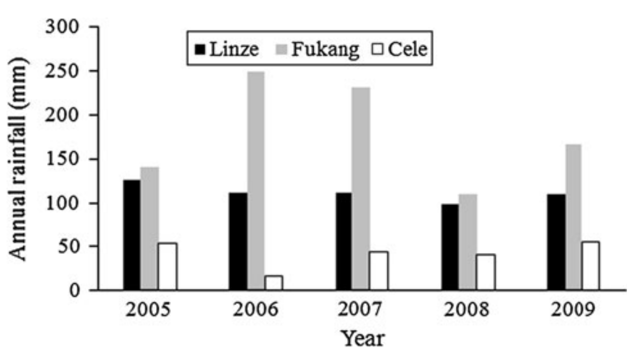


Fig. 1 The interannual variability of rainfall in three desert regions of northwestern China

Temporal stability of soil moisture

Temporal patterns of soil moisture

Although rainfall led to a sharp increase of soil water content, the temporal pattern of soil moisture differ significantly among the three field stations (Fig. 2). The variation in soil moisture is consistent with the rainfall pattern at the Linze station, with a steep rise to a maximum during the rainy season (July–September), followed by a slow decrease during the dry season until May or June of the following year (Fig. 2a). In contrast, soil moisture exhibits hardly any response to rainfall at the Fukang and Cele stations. The maximum soil moisture appeared after thawing of the soil in the spring, but thereafter, under the influence of evaporation from the soil and vegetation water demand, soil moisture decreased gradually until late in the growing season, reaching a minimum in September or October (Fig. 2b, c). Consequently, although annual rainfall is greatest at Fukang, soil moisture is lower than at the other stations.

Soil moisture is substantially higher at the Linze station (a) mean of $\mu \pm \sigma = 6.61 \pm 2.08$ % throughout the study period; Fig. 2a), followed by the Cele station (4.83 ± 0.81 %; Fig. 2c) and the Fukang station (3.46 ± 0.47 %; Fig. 2b), and exhibits clear temporal stability (Fig. 2), but these differences among the stations are significant for most parameters (Table 2). However, the temporal patterns reflect a stable pattern of soil moisture variation at Cele except when the rainfall is unusually high (Fig. 2c). The standard deviation of soil moisture shows the same trend (Table 2), but with significantly higher variability at higher soil moisture levels (Fig. 2). Soil moisture

Table 1 Soil properties in the desert regions of northwestern China

Parameter	Linze	Fukang	Cele
Soil type	Gray–brown desert soil	Aeolian sandy soil	Brown desert soil
Soil texture	Sandy loam	Loamy sand	Sandy loam
Saturated soil moisture content (%)	25.60 (3.11)c	29.40 (1.31)b	38.67 (4.55)a
Field capacity (W_{fc}, %)	8.08 (2.58)c	12.05 (1.72)b	19.86 (1.88)a
Wilting point (W_{wp}, %)	2.56 (0.78)c	3.04 (0.46)b	3.88 (1.66)a
Total porosity (%)	38.72 (2.30)c	52.94 (2.82)a	43.41 (2.29)b
Bulk density (g cm^{-3})	1.59 (0.11)a	1.52 (0.06)a	1.25 (0.07)b
Characteristic curve			
Coefficient	4.76 (1.49)b	5.61 (0.78)b	8.45 (2.75)a
Exponent	0.2294 (0.016)b	0.2278 (0.034)b	0.2957 (0.033)a
Soil nutrient			
Soil organic matter (g kg^{-1})	2.30 (0.35)a	1.65 (0.27)b	1.83 (0.24)b
Total nitrogen (g kg^{-1})	0.16 (0.02)b	0.22 (0.03) a	0.20 (0.02)a
Available nitrogen (mg kg^{-1})	10.70 (1.71)b	29.22 (12.10)a	28.76 (7.30)a
Available phosphorus (mg kg^{-1})	3.99 (0.83)a	3.32 (1.19)a	3.47 (0.65)a
Available potassium (mg kg^{-1})	118.33 (22.30)c	290.93 (69.28)a	208.11 (13.70)b
Soil pH	7.86 (0.19)a	7.96 (0.32)a	7.80 (0.09)a
Conductance (ms/cm)	1.21 (0.23)a	0.86 (0.12)b	0.69 (0.10)c

Values represent means ($n = 5$) followed by the standard deviation in parentheses

Means within a row followed by different letters differ significantly (Tukey's HSD, $P < 0.05$)

is characterized by high spatial and temporal variability. The coefficient of variation (CV) increases from 21.21 ± 7.61 % at Fukang to 36.33 ± 11.76 % at Linze, which provides an idea of the tremendous spatial heterogeneity in soil moisture in the desert regions of China.

Variations in the temporal stability of soil moisture

MRD and ITS both generally show temporal stability at the three field stations during the monitoring period (Fig. 3). The patterns of MRD and ITS are similar to the patterns for soil moisture content; i.e., variability is greatest at Linze and lowest at Fukang. However, there is considerable uncertainty in the MRD and ITS values for desert ecosystems. MRD does not differ significantly between the Linze (−1.47 ± 1.93; Fig. 3a) and Fukang (−1.49 ± 0.91; Fig. 3b) stations, and is greatest (least negative) at the Cele station (−0.42 ± 0.99; Fig. 3c). Table 2 shows that soil moisture is significantly more stable at Linze (ITS = 3.41 ± 1.15) than at Cele (ITS = 1.82 ± 0.37) or Fukang (ITS = 1.76 ± 0.73), which does not differ significantly. In general, SD, CV, and ITS increase significantly with increasing soil moisture (Table 2).

Statistical analysis of soil moisture

Table 3 presents the ANOVA results for soil moisture and ITS throughout the study period. At the regional scale, there are significant differences in the spatial and temporal patterns of soil moisture ($F_2 = 7.50$, $P < 0.05$) and in ITS ($F_2 = 14.25$, $P < 0.01$), and significant region × inter-annual interactions for both parameters ($P < 0.001$). The region × inter-monthly interaction is only significant for soil moisture ($F_{23} = 1.91$, $P < 0.05$). However, there is a significant region × inter-annual × inter-monthly interaction for both soil moisture and ITS ($P < 0.05$). Both parameters are not significantly affected by inter-annual or inter-monthly variation, or by the interaction between these periods.

Interannual variability of soil moisture

To assess the interannual variability of soil moisture in the desert regions of northwestern China, the study performed the comparison based on the soil moisture content and ITS. The interannual variability of soil moisture is higher at the Linze station than at the Fukang and Cele stations (Fig. 4a). Soil moisture at the Linze station increased from 4.6 % in 2005 to 9.9 % in 2009, with an average SD of 1.99. However, soil moisture varied little among the years at the Fukang and Cele stations, with maximum values of 4.0 % in 2005 at Fukang and 5.2 % in 2007 at Cele and SD values of 0.32 and 0.27, respectively (Fig. 4a). ITS showed a similar trend at the Linze station, ranging from 3.3 to 4.2, with an SD of 0.65; however, ITS decreased greatly in 2009. The small changes in ITS at Fukang and Cele reveal considerable temporal stability of soil moisture at these stations (Fig. 4b).

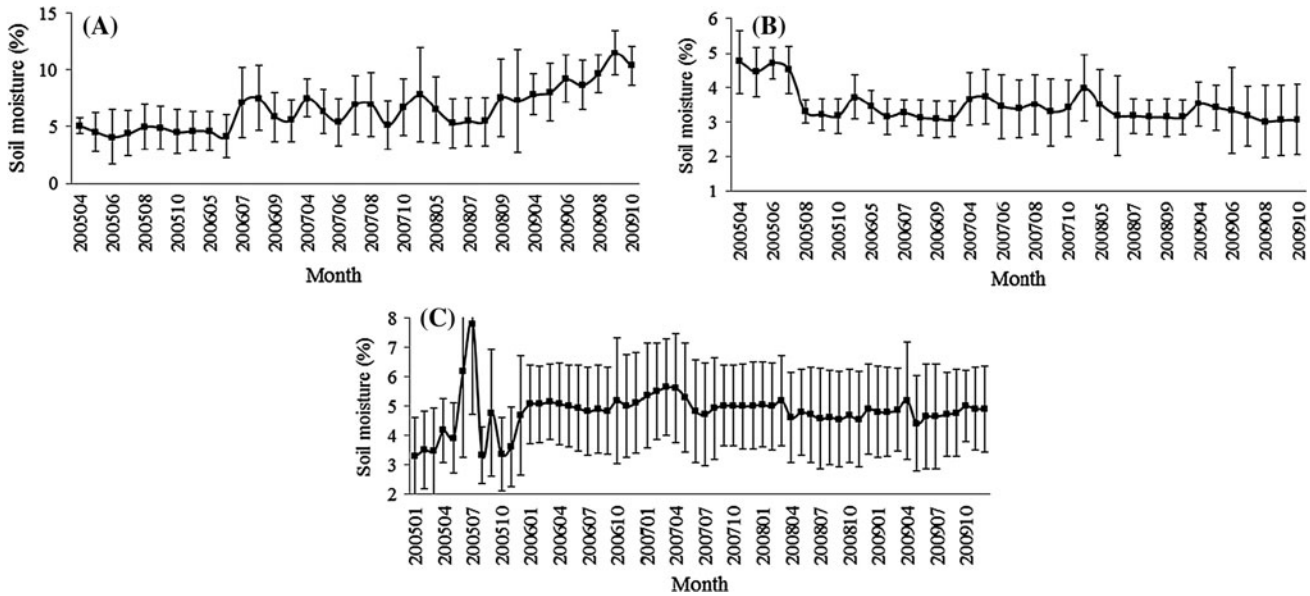


Fig. 2 Temporal variation of soil moisture in three desert regions of northwestern China: **a** Linze, **b** Fukang, and **c** Cele. *Values* represent means and standard deviations

Table 2 Soil moisture characteristics in the desert regions of northwestern China

	Linze	Fukang	Cele
Soil moisture (%)	6.61 (2.08)a	3.46 (0.47)c	4.83 (0.81)b
MRD (%)	−1.47 (1.93)b	−1.49 (0.91)b	−0.42 (0.99)a
SD (%)	2.26 (0.73)a	0.73 (0.25)c	1.59 (0.35)b
CV (%)	36.33 (11.76)a	21.21 (7.61)b	33.13 (5.23)a
ITS (%)	3.41 (1.15)a	1.76 (0.73)b	1.82 (0.37)b

Values represent means, with the standard deviation in parentheses

Means within a row followed by different letters differ significantly (Tukey's HSD, $P < 0.05$)

MRD Mean relative difference, *SD* standard deviation, *CV* coefficient of variation, *ITS* index of temporal stability

Frequency distribution for soil moisture

Soil moisture frequency distributions reveal clear differences among the stations, particularly clear differences between the Linze and Fukang stations (Fig. 5). Soil moisture displays a skewed frequency distribution that is close to a logarithmic function at Fukang (Fig. 5b). However, the histogram resembles a normal distribution at the Linze and Cele stations (Fig. 5a, c), and the probability density functions resemble logistic and Gaussian functions, respectively. The frequency distribution at Linze exhibits a much lower degree of skewness ($\delta = 1.28$; Fig. 5a) than that at Cele ($\delta = 6.95$; Fig. 5c). The Linze station has a higher mean (μ) and SD ($\sigma = 2.33$; Fig. 5a) for soil moisture than at Fukang ($\sigma = 0.49$; Fig. 5b) and Cele ($\sigma = 1.17$; Fig. 5c), as well as a lower skewness. This indicates that vegetation at the Linze station experiences a broader range of soil moisture conditions, which tend to be wetter on average than at the other stations. The results reveal that the greatest frequency at Linze was a soil moisture of 5–7 %, with a frequency of 39.6 %. However, the maximum value of the frequency distribution is 62.9 % at the Fukang station, which occurs in the 3.0–3.5 % moisture class (Fig. 5c). At the Cele station (Fig. 5c), the maximum frequency is 42 %, which occurs in the 4–5 % moisture class.

To better understand the change processes responsible for the temporal patterns of soil moisture, the study examined the relationship between soil moisture variability and the soil moisture content using the CV. The CV could be expressed as an exponential function of the moisture content (θ): $\mathrm{CV} = A\ \exp[B\theta]$ (Table 4). The regression equation is statistically significant and has a high coefficient of determination ($R^2 > 0.7$) at all three stations. The R^2 value is higher at the Linze station than at the Fukang and Cele stations. The parameters A and B indicate the relative variability (the proportionality effect) and the dependence of the variability on mean moisture conditions (the degree of nonlinearity), respectively. The value of A ranges from 37.6 at the Cele station to 74.29 at the Linze station. The parameters of B are all negative, with values of −0.11, −0.21, and 0.03 at the Linze, Fukang, and Cele stations. These results suggest that the CV decreases with increasing soil moisture. Therefore, soil moisture has the greatest variability in a dry environment and a relatively rapid decrease in variability with increasing moisture

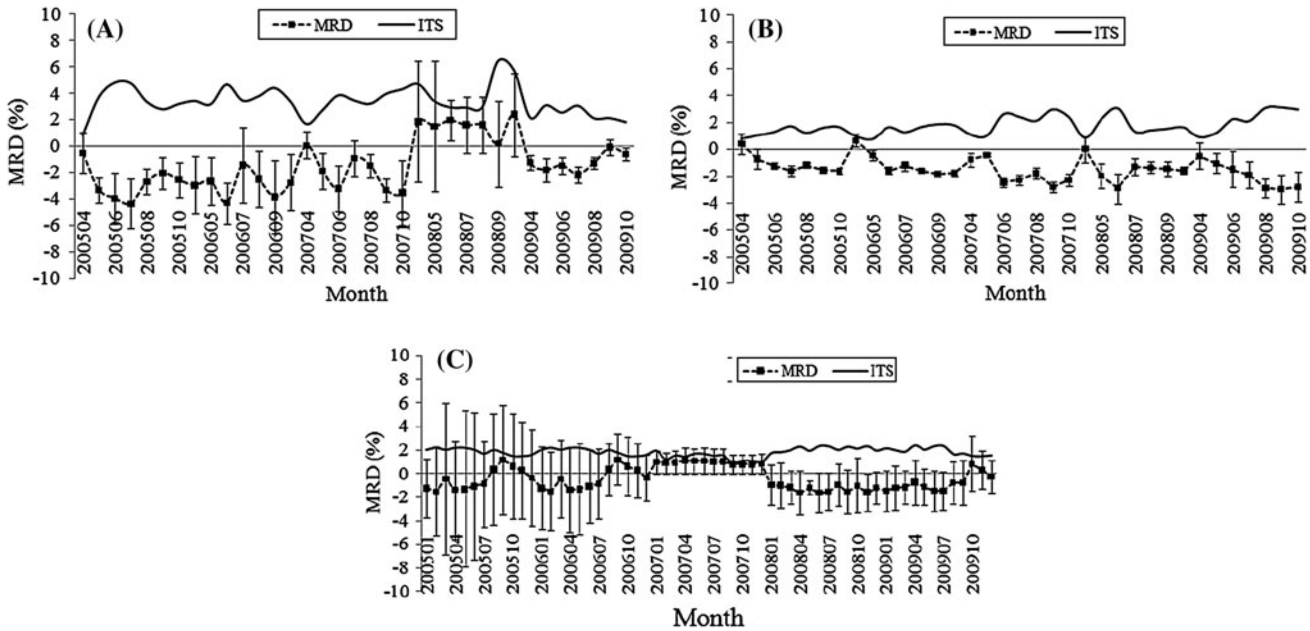


Fig. 3 Temporal variability of the mean relative difference (MRD) and the index of temporal stability (ITS) in three desert regions of northwestern China: **a** Linze, **b** Fukang, and **c** Cele. *Values* represent means and standard deviations

Table 3 ANOVA results for soil moisture and the index of temporal stability (ITS) in the desert regions of northwestern China

Factor	*df*	*F* statistic	
		Soil moisture	ITS
Region	2	7.50*	14.25**
Inter-annual	4	0.77	0.45
Inter-monthly	11	0.29	1.85
Region × inter-annual	8	17.63***	3.61***
Region × inter-monthly	23	1.91*	1.37
Inter-annual × inter-monthly	44	1.05	0.41
Region × inter-annual × inter-monthly	48	1.66*	1.78**

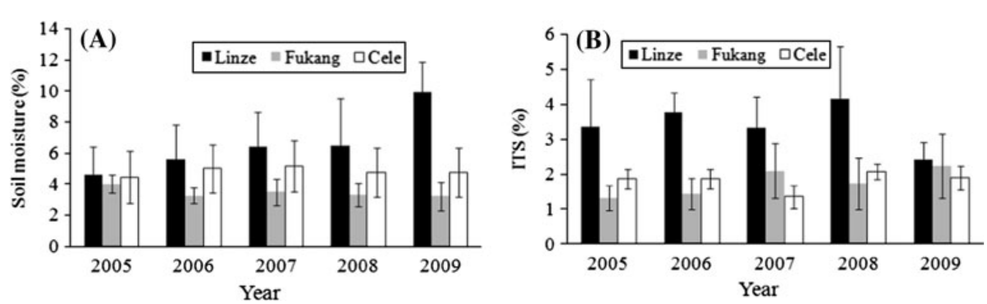
* $P < 0.05$ ** $P < 0.01$ *** $P < 0.001$

content at Linze. In contrast, the Fukang station has lower variability because of the drier conditions and shows a limited decrease with increasing soil moisture. The Cele station is intermediate between the two.

Correlation analysis for soil moisture

The study analyzed the stability of the temporal pattern and the inherent relationship between interannual variations using Spearman's rank-correlation coefficient (r_s). At Linze, there was at least one significant positive correlation for soil moisture for all years except 2006, which suggests that variations of soil moisture interacted between years. At Fukang, most years except 2007 showed significant

Fig. 4 The interannual variability of **a** soil moisture content and **b** the index of temporal stability (ITS) in three desert regions of northwestern China



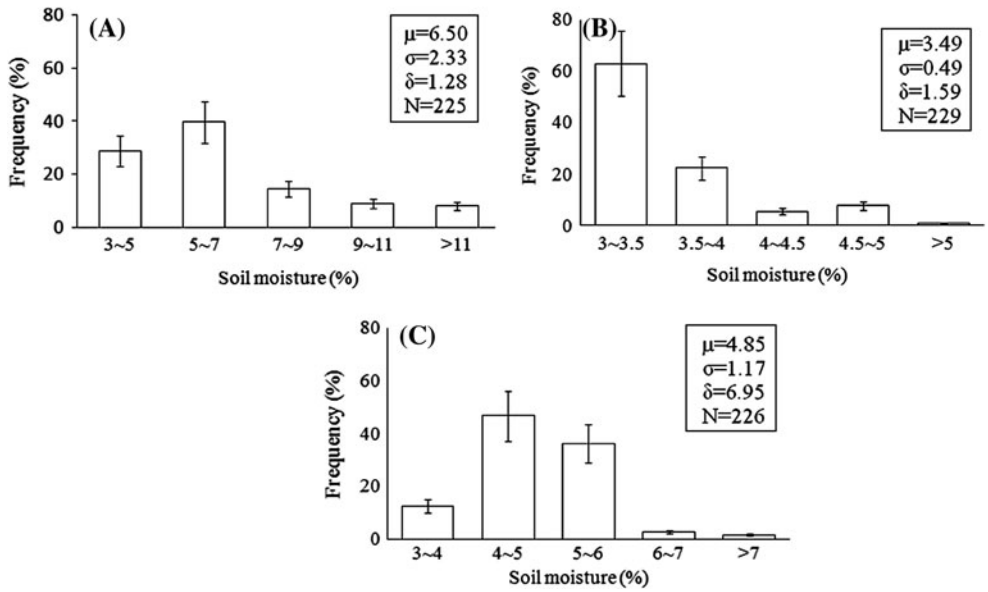


Fig. 5 Frequency distributions for soil moisture content in three desert regions of northwestern China: **a** Linze, **b** Fukang, and **c** Cele. For each distribution, the mean (μ), standard deviation (σ), skewness (δ), and number of sampling points (N) are shown

correlations with other years, which suggests stable temporal patterns because the values of r_s were high and significant in most cases. At Cele, there were significant correlations from 2006 to 2009 (Table 5). Therefore, variations of soil moisture appear to be closely interrelated among the years at each station, despite strong differences in rainfall, although the patterns of correlation differ among the stations.

Soil moisture estimation

The study expressed the variation in soil water content by means of multiple linear regression against the meteorological variables. The resulting model performs well, explaining the 58.8–87.4 % of the variation in soil water content (Table 6). The study carried out a regression analysis for the relationship between the measured and estimated values and found strong linear correlations, with a y-intercept ranging from 0.32 to 0.87 % and a slope ranging from 0.71 to 0.94 (Fig. 6). The model simulates the measured soil moisture variations reasonably well in the desert regions of northwestern China; the correlation coefficients between the measured and estimated values of soil moisture are 0.94 for the Linze station, 0.92 for the Fukang station, and 0.88 for the Cele station.

Table 4 Regression parameters for the relationship between the coefficient of variation (CV) and soil moisture (θ), where CV $= A \exp[B\theta]$

	Parameters		
	A	B	R^2
Linze	74.29	−0.11	0.903
Fukang	41.43	−0.21	0.702
Cele	37.60	−0.03	0.798

Discussion and conclusions

Soil moisture and its variability appear to vary widely in different region and climate zone, so the results of existing studies are not always in agreement (Reichle et al. 2004; Hebrard et al. 2006). In the semi-arid region, soil moisture increases significantly with increasing soil depth; the heavier rains and higher moisture contents are often associated with lower spatial variability in the Loess Plateau of China (Qiu et al. 2001). However, soil moisture content is low, but exhibited high variability depending strongly on the rainfall pattern in desert ecosystems. For example, the variability of soil moisture using the ERS Scatterometer data is particularly high at the temporally and spatially scale in the Ukraine (Wagner et al. 1999). In contrast to arid region, soil moisture was highly variable on daily, monthly, and yearly time scales from the extreme arid region of the Atacama where the dew is not a significant source of moisture in the soil or under stones (McKay et al. 2003).

The distribution of soil moisture is an important issue in studies of hydrological cycles at a regional scale, and strongly influences the interactions among vegetation, the underlying soil, and the atmosphere (e.g., Bhuttle et al. 2000; Rodrı́guez-Iturbe 2000). Soil moisture depends on

Table 5 Spearman's rank-correlation coefficient (r_s) for soil moisture content between years for the desert regions of northwestern China

	2005			2006		2007	2008	2009
(a) Linze station								
2005	1.000							
2006	0.321			1.000				
2007	0.500*			0.357		1.000		
2008	0.685*			0.018		0.162	1.000	
2009	0.321			0.214		0.596*	0.577*	1.000
(b) Fukang station								
2005	1.000							
2006	0.821*			1.000				
2007	0.429			0.714		1.000		
2008	0.857*			0.964**		0.786*	1.000	
2009	0.750*			0.857*		0.571*	0.893**	1.000
(c) Cele station								
2005	1.000							
2006	−0.448	1.000						
2007	−0.371	0.608*	1.000					
2008	−0.462	0.601*	0.524*		1.000			
2009	−0.417	0.536*	0.046		0.224	1.000		

* $P < 0.05$; ** $P < 0.01$

the soil texture, total rainfall, and the rates of water removal through evapotranspiration and deep drainage (Mahmood and Vivoni 2008). Generally, soil heterogeneity affects soil moisture through variations in soil texture, soil water-holding capacity, and pore-scale hydraulic properties (Jacobs et al. 2004). Soil pore radius has a significant effect on soil water movement at low water content, and the smaller porosity with the lower sand and the higher silt and clay for the gray–brown desert soil at the Linze station would restrain evapotranspiration and reduce the loss of soil moisture compared with the larger porosity soils for the aeolian sandy soil at the Fukang station and the brown desert soil at the Cele station. Soil texture has been shown to be one of the most important factors that affected the variation of soil moisture in the desert regions of northwestern China. Simultaneously, soil bulk density is greater at the Linze station, which has smaller soil particles that would also retain moisture better due to surface tension effects, and this would help to maintain a good soil moisture status. The significant differences in soil organic matter inevitably affect the temporal variation in soil moisture in the desert regions of northwestern China. With the increase of organic matter, water content gradually increases. Therefore, soil moisture is substantially higher with the higher organic matter at the Linze station, followed by the Cele station and the Fukang station. The lower nitrogen and potassium content maintain the higher soil moisture, whereas the phosphorus content is converse in the desert regions of northwestern China. These factors might explain why soil moisture is greatest at the Linze station despite a higher annual precipitation at Fukang. For example, Comegna and Basile (1994) also found that soil homogeneity decreases the differences in soil moisture among locations. Nevertheless, soil moisture is also affected by seasonal variations in vegetation and climate (e.g., Rodrı́guez-Iturbe and Porporato 2004; Noto et al. 2008). The Fukang station has the highest vegetation cover, which increases plant water requirements compared with the other stations. The lower soil moisture at the Fukang station may have resulted from a larger leaf area of shrubs, which would increase rainfall interception, and the thicker layer of hydrophobic litter would have reduced water infiltration (Zhao et al. 2007).

The temporal stability of soil moisture is likely to be controlled in complex ways because the controlling factors are interdependent and, therefore, produce integrated effects (Famiglietti et al. 1998). This makes it difficult to isolate the influence of any single factor. Soil moisture under wet conditions (mean volumetric moisture contents >20 %) is previously reported to be more stable than that under dry conditions (<10 %) or moist conditions (10–20 %) in a semi-arid steppe in Inner Mongolia (Zhao et al. 2010), which suggests that the temporal stability is higher for wetter soils in this region (Zhou et al. 2007). Soil moisture is lowest in the top layer and has the largest fluctuation, and gradually increases and then decreases with increasing depth in the soil (Fig. 7), and there is a turning point about variations of soil moisture in each field station. The maximum soil moisture at Linze is 7.44 % at a depth of 120 cm versus values of 6.76 % at 130 cm at Cele and 3.99 % at 110 cm at Fukang (Fig. 7). However, the present results indicate that the variation in the index of

Table 6 Regression equations for soil water content and the significant meteorological variables

	df	Regression equation	R	F statistic
Linze	5.34	$y = -1.257 - 0.131\ \mathrm{T} - 0.064\ \mathrm{RH} + 0.183\ \mathrm{u} + 0.909\ \mathrm{P} + 2.397\ \mathrm{WTD}$	0.617	3.574**
Fukang	5.34	$y = -1.324 - 0.01\ \mathrm{T} - 0.006\ \mathrm{RH} + 0.182\ \mathrm{u} + 0.208\ \mathrm{P} + 0.602\ \mathrm{WTD}$	0.588	1.813*
Cele	5.34	$y = 2.973 + 0.024\ \mathrm{T} + 0.006\ \mathrm{RH} + 0.204\ \mathrm{u} + 0.561\ \mathrm{P} + 0.05\ \mathrm{WTD}$	0.874	3.87***

T air temperature, *RH* relative humidity, *u* wind speed, *P* precipitation, *WTD* water depth

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

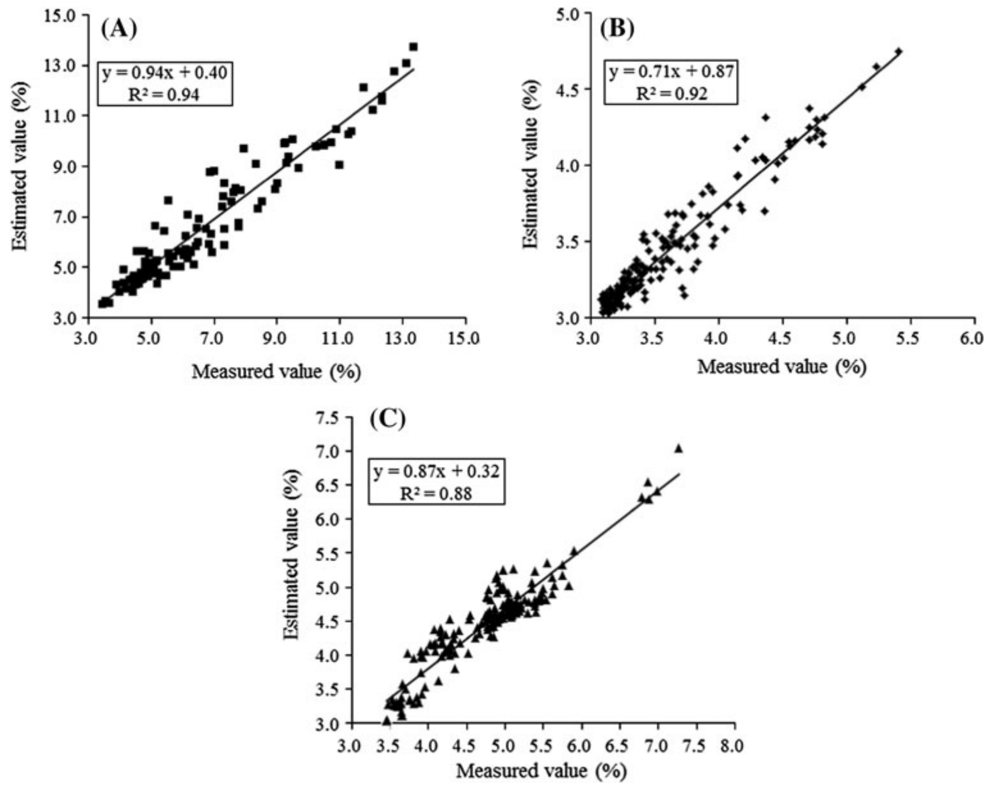


Fig. 6 Regression for the estimated value of soil moisture as a function of the measured value using the water balance model for three desert regions of northwestern China: **a** Linze, **b** Fukang, and **c** Cele

temporal stability (ITS) as a function of soil moisture followed a power function (Fig. 8), and the exponents in this function increase from −2.51 at Fukang to −0.84 at Cele and −0.56 at Linze (Fig. 8). The temporal stability, therefore, decreases significantly with increasing soil moisture in these arid regions, which suggests that the patterns of soil moisture under dry conditions ($\theta < 10$ %) would be more stable than those under wet conditions ($\theta > 20$ %). This result is consistent with those of Jacobs et al. (2004) and Martínez-Fernández and Ceballos (2005), who found that soil moisture at drier locations is less variable than at wetter locations in semiarid environments. In contrast, the variability of soil moisture in humid climates is greater at drier sites (Meyles et al. 2003; Western et al. 2004; Brocca et al. 2007).

Several consequences of the temporal stability in soil moisture patterns have recently increased interest in this parameter (Gómez-Plaza et al. 2000). The present study analyzes differences in the temporal patterns of soil moisture among three sites and compared the main effects to reveal differences in these patterns. Soil moisture and ITS both show a significant three-way interaction (region × inter-annual × inter-monthly; Table 3). This suggests that the differences in the soil moisture patterns are simultaneously affected by differences in all three main effects. Several researchers have suggested a need for longer observation periods to identify representative locations where soil water sensors should be installed. For example, Lin (2006) found that the degree of temporal stability in soil moisture patterns varied spatially and between seasons in complex terrain with heterogeneous soils and landforms. The observations in the present study appeared to provide sufficient resolution to choose suitable stations, but the duration for which the stability is calculated may be specific to the locations and spatial scales used in our study, and should not be generalized to other sites. Nonetheless, on the basis of the present results, the Fukang and Cele stations show relatively small variations in ITS and, therefore, appear to be suitable stations for monitoring soil moisture trends in arid northwestern China.

Soil moisture is lower at the Fukang station than at the Linze and Cele stations (Fig. 2), and as a result, the probability density functions resemble skewed and log-normal distributions, respectively (Fig. 5). This indicates that a normal distribution is more likely to occur under wet conditions than under dry conditions, which agrees with the results of Buttafuoco et al. (2005) and Pan et al. (2008). Soil moisture displays a log-normal distribution that resembles a Gaussian function at the Cele station (Fig. 5c), which agree with the results of Vivoni et al. (2008). In previous research, the distribution of soil moisture evolves from negatively skewed under very wet conditions to normal at moderate moisture contents, and then to positively skewed under dry conditions (Famiglietti et al. 1998). The average value of soil moisture, combined with other parameters such as its standard deviation and

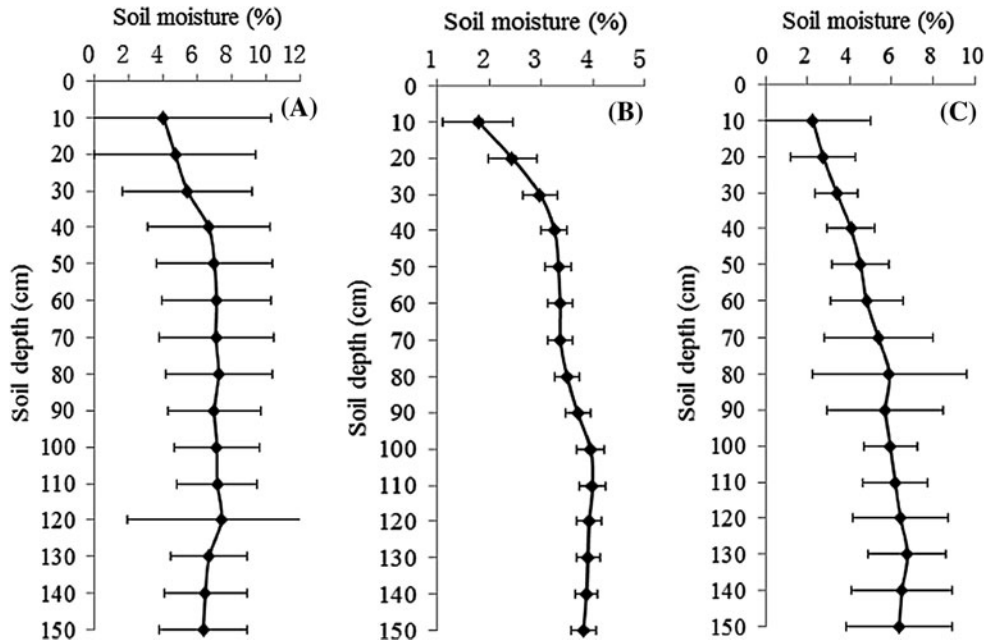


Fig. 7 Variation of soil moisture content with soil depth in three desert regions of northwestern China: **a** Linze, **b** Fukang, and **c** Cele. *Values* represent means and standard deviations for 10-day intervals from 2005 to 2009

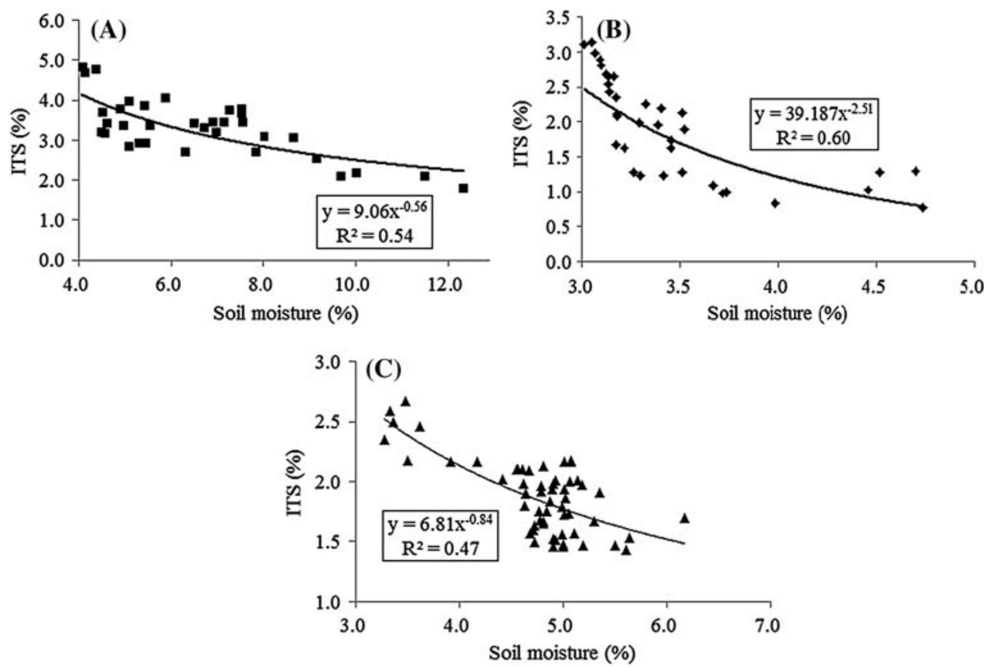


Fig. 8 Relationship between soil moisture content and the index of temporal stability (ITS) in three desert regions of northwestern China: **a** Linze, **b** Fukang, and **c** Cele

frequency distribution, provides a clear picture of the temporal variability of soil moisture during a given time period, but fails to fully capture the temporal variability of soil moisture. Conversely, time series data provide both an increased understanding of the temporal variations in soil moisture and comparisons of drying and wetting trends among sites (Zhou et al. 2007; Zhao et al. 2010). The present results show that the coefficients of variation obtained during this research are all higher than 20 %, probably because of the low soil moisture contents in our study area, and that the magnitude of the variation in soil moisture increases with increasing mean soil moisture (μ); this relationship could be expressed using a simple exponential function (Table 4), which is consistent with the previous research carried out in regions with arid or semi-arid climates (Williams et al. 2003; Western et al. 2004). Other researchers (e.g., Jacobs et al. 2004; Famiglietti et al. 2008) have also suggested using the same form of equation.

In general, the model estimates the regional and inter-annual variations in the measured soil moisture reasonably well ($R^2 \geq 0.88$, $P < 0.05$), suggesting that this model provides an appropriate basic method for predicting soil moisture in the desert regions of northwestern China. The advantage of this model is that it permits simple calculations based on daily data that can be observed operationally over long periods. Although the present study only examined data from three sites, our results suggest that the approach shows promise for larger-scale studies. Future research should investigate inter-annual variations of soil moisture using the water balance model in the arid and semi-arid regions of northwestern China.

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References

Anderson J, Refsgaard JC, Jensen KH (2001) Distributed hydrological modeling of the Senegal River Basin-model construction and validation. J Hydrol 247:200–214

Bhuttle JM, Creed IF, Pomeroy JW (2000) Advances in Canadian forest hydrology, 1995–1998. Hydrol Process 14:1551–1578

Brocca L, Morbidelli R, Melone F, Moramarco T (2007) Soil moisture spatial variability in experimental areas of central Italy. J Hydrol 333:356–373

Brocca L, Melone F, Moramarco T, Morbidelli R (2009) Soil moisture temporal stability over experimental areas in Central Italy. Geoderma 148:364–374

Buttafuoco G, Castrignano A, Busoni E, Dimase AC (2005) Studying the spatial structure evolution of soil water content using multivariate geostatistics. J Hydrol 311:202–218

Comegna V, Basile A (1994) Temporal stability of spatial patterns of soil water storage in a cultivated Vesuvian soil. Geoderma 62:299–310

Cosh MH, Jackson TJ, Starks P, Heathman G (2006) Temporal stability of surface soil moisture in the Little Washita River watershed and its applications in satellite soil moisture product validation. J Hydrol 323:168–177

Deng X, Li XM, Zhang XM, Ye WH, Foezki A, Runge M (2003) Studies on gas exchange of *Tamarix ramosissima* Lbd. Acta Ecol Sin 23:180–187 (in Chinese with English summary)

Entin JK, Robock A, Vinnikov KY, Hollinger SE, Liu S, Namkhai A (2000) Temporal and spatial scales of observed soil moisture variations in the extratropics. J Geophys Res 105:11865–11877

Famiglietti JS, Rudnicki JW, Rodell M (1998) Variability in surface moisture content along a hillslope transect: Rattlesnake Hill, Texas. J Hydrol 210:259–281

Famiglietti JS, Ryu D, Berg AA, Rodell M, Jackson TJ (2008) Field observations of soil moisture variability across scales. Water Resour Res 44:W01423

Fernández-Gálvez J, Simmonds LP, Barahona E (2006) Estimating detailed soil water profile records from point measurements. Eur J Soil Sci 57:708–718

Fuentes JP, Flury M, Huggins DR, Bezdicek DF (2003) Soil water and nitrogen dynamics in dryland cropping systems of Washington State, USA. Soil Till Res 71:33–47

Gómez-Plaza A, Alvarez-Rogel J, Albaladejo J, Castillo VM (2000) Spatial patterns and temporal stability of soil moisture across a range of scales in a semi-arid environment. Hydrol Process 14:1261–1277

Gui DG, Lei JQ, Zeng FJ, Runge M, Mu GJ, Yang FX, Zhu JT (2010) Ordination as a tool to characterize soil particle size distribution, applied to an elevation gradient at the north slope of the Middle Kunlun Mountains. Geoderma 158:352–358

Hassan MM, Gregory PJ (2002) Dynamics of water movement on Chalkland. J Hydrol 257:27–41

Hebrard O, Voltz M, Andrieux P, Moussa R (2006) Spatio-temporal distribution of soil surface moisture in a heterogeneously farmed Mediterranean catchment. J Hydrol 329:110–121

Jacobs JM, Mohanty BP, Hsu EC, Miller D (2004) SMEX02: field scale variability, time stability and similarity of soil moisture. Remote Sens Environ 92:436–446

Lin H (2006) Temporal stability of soil moisture spatial pattern and subsurface preferential flow pathways in the Shale Hills catchment. Vadose Zone J 5:317–340

Liu GC, Zhang JH (2007) Spatial and temporal dynamics of soil moisture after rainfall events along a slope in Regosols of southwest China. Hydrol Process 21:2778–2784

Liu B, Zhao WZ, Chang XX, Li SB, Zhang ZH, Du MW (2010) Water requirements and stability of oasis ecosystem in arid region, China. Environ Earth Sci 59:1235–1244

Liu B, Zhao WZ, Jin BW (2011) The response of sap flow in desert shrubs to environmental variables in an arid region of China. Ecohydrology 4:448–457

Mahmood TH, Vivoni ER (2008) Evaluation of distributed soil moisture simulations through field observations during the North American monsoon in Redondo Creek, New Mexico. Ecohydrology 1:271–287

Mapfumo E, Chanasyk DS, Willms WD (2004) Simulating daily soil water under foothills fescue grazing with the soil and water assessment tool model (Alberta, Canada). Hydrol Process 18:2787–2800

Martinez C, Hancock GR, Kalma JD, Wells T (2008) Spatio-temporal distribution of near-surface and root zone soil moisture at the catchment scale. Hydrol Process 22:2699–2714

Martínez-Fernández J, Ceballos A (2005) Mean soil moisture estimation using temporal stability analysis. J Hydrol 312(1–4):28–38

McKay CP, Friedmann EI, Gómez-Silva B, Cáceres-Villanueva L, Andersen DT, Landheim R (2003) Temperature and moisture conditions for life in the extreme arid region of the Atacama desert: four years of observations including the El Niño of 1997–1998. Astrobiology 3(2):393–406

Meyles E, Williams A, Ternan L, Dowd J (2003) Runoff generation in relation to soil moisture patterns in a small Dartmoor catchment, Southwest England. Hydrol Process 17:251–264

Motovilov YJ, Gottschalk L, Engeland K, Rodhe A (1999) Validation of a distributed hydrologic model against spatial observations. Agric For Meteorol 98–99:257–277

Nandintsetseg B, Shinoda M (2011) Seasonal change of soil moisture in Mongolia: its climatology and modeling. Int J Climatol 31:1143–1152

Noto LV, Ivanov VY, Bras RL, Vivoni ER (2008) Effects of initialization on response of a fully-distributed hydrologic model. J Hydrol 352:107–125

Pachepsky YA, Guber AK, Jacques D (2005) Temporal persistence in vertical distributions of soil moisture contents. Soil Sci Soc Am J 69:347–352

Pan YX, Wang XP (2009) Factors controlling the spatial variability of surface soil moisture within revegetated-stabilized desert ecosystems of the Tengger Desert, Northern China. Hydrol Process 23:1591–1601

Pan YX, Wang XP, Jia RL, Chen YW, He MZ (2008) Spatial variability of surface soil moisture content in a re-vegetated desert area in Shapotou, Northern China. J Arid Environ 72:1675–1683

Porporato A, D′Odorico P, Laio F, Ridolfi L, Rodriguez-Iturbe I (2002) Ecohydrology of water-controlled ecosystems. Adv Water Res 25:1335–1348

Qiu Y, Fu BJ, Wang J, Chen LD (2001) Spatial variability of soil moisture content and its relation to environmental indices in a semi-arid gully catchment of the Loess Plateau, China. J Arid Environ 49:723–750

Reichle RH, Koster RD, Dong JR, Berg AA (2004) Global soil moisture from satellite observations, land surface models, and ground data: implications for data assimilation. J Hydrometeor 5:430–442

Robock A, Vinnikov KY, Srinivasan G, Entin JK, Hollinger SE, Speranskaya NA, Liu S, Namkhai A (2000) The global soil moisture data bank. Bull Am Meteorol Soc 81:1281–1299

Rodrίguez-Iturbe I (2000) Ecohydrology: a hydrologic perspective on climate-soil- vegetation dynamics. Water Resour Res 36(1):3–9

Rodrίguez-Iturbe I, Porporato A (2004) Ecohydrology of water-controlled ecosystems: soil moisture and plant dynamics. Cambridge Press, Cambridge, p 422

Shinoda M, Ito S, Nachinshonhor GU, Erdenetsetseg D (2007) Notes and correspondence: phenology of Mongolian grasslands and moisture conditions. J Meteorol Soc Jpn 85:359–367

Starks P, Heathman G, Jackson TJ, Cosh MH (2006) Temporal stability of soil moisture profile. J Hydrol 324:400–411

Su PX, Zhao AF, Zhang LX, Du MW, Chen HS (2003) Characteristic in photosynthesis, transpiration and water use efficiency of *Haloxylon ammodendron* and *Calligonum mongolicum* of desert species. Acta Bot Boreal-Occident Sin 23:11–17

Vachaud G, Passerat de Silans A, Balabanis P, Vauclin M (1985) Temporal stability of spatially measured soil water probability density function. Soil Sci Soc Am J 49:822–828

Vivoni ER, Rinehart AJ, Méndez-Barroso LA, Aragón CA, Bisht G, Cardenas MB, Engle E, Forman BA, Frisbee MD, Gutiérrez-Jurado HA, Hong SH, Mahmood TH, Tai KW, Wyckoff RL (2008) Vegetation controls on soil moisture distribution in the Valles Caldera, New Mexico, during the North American monsoon. Ecohydrology 1:225–238

Wagner W, Lemoine G, Rott H (1999) A method for estimating soil moisture from ERS Scatterometer and soil data. Remote Sens Envion 70:191–207

Wendroth O, Pohla W, Koszinski S, Rogasik H, Ritsema CJ, Nielsen DR (1999) Spatio-temporal patterns and covariance structures of soil water status in two northeast-German field sites. J Hydrol 215:38–58

Western AW, Grayson RB, Green TR (1999) The Tarrawarra Project: high resolution spatial measurement, modelling and analysis of hydrological response. Hydrol Process 13:633–652

Western AW, Zhou SL, Grayson RB, McMahon TA, Bloschl G, Wilson DJ (2004) Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes. J Hydrol 286:113–134

Williams AG, Ternan JL, Fitzjohn C, de Alba S, Perez GA (2003) Soil moisture variability and land use in a seasonally arid environment. Hydrol Process 17:225–235

Xu H, Li Y (2006) Water-use strategy of three central Asian desert shrubs and their responses to rain pulse events. Plant Soil 285:5–17

Yamanaka T, Kaihotsu I, Oyunbaatar D, Ganbold T (2007) Summertime soil hydrological cycle and surface energy balance on the Mongolian steppe. J Arid Environ 69:65–79

Zhao Y, Peth S, Krümmelbein J, Horn R, Wang ZY, Steffens M, Hoffmann C, Peng XH (2007) Spatial variability of soil properties affected by grazing intensity in Inner Mongolia grassland. Ecol Model 205:241–254

Zhao Y, Peth S, Wang XY, Lin H, Horn R (2010) Controls of surface soil moisture spatial patterns and their temporal stability in a semi-arid steppe. Hydrol Process 24:2507–2519

Zhou X, Lin H, Zhu Q (2007) Temporal stability of soil moisture spatial variability at two scales and its implication for optimal field monitoring. Hydrol Earth Syst Sci Discuss 4:1185–1214