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Spatio-temporal variability of root zone soil moisture in artificially revegetated and natural ecosystems at an arid desert area, NW China

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ABSTRACT

Soil moisture is a major component of the hydrologic cycle, being highly variable and nonlinear in space and time. Knowledge of soil moisture regime, especially at the root zone, is critical to the management of water resources and restoration of vegetation. As such, techniques that allow identifying and reducing the number of samples for soil moisture analysis are required. In this study, a spatial variability and temporal stability analysis were used to analyze the volumetric soil moisture content of root zone collected by neutron probe at 36 days during three years in Shapotou, China. The specific concern was to investigate the temporal stability of soil moisture at different depths in the soil profile, determine the effects of soil and vegetation characteristics on temporal stability, and to conduct such a study in an area larger than 1 km^2. Additionally, we aimed to determine whether temporally stable sites are invariable at different depths, and compare with temporally stable shallow layer (0–6, 0–15, 0–30 cm) sites that are previously identified by Wang et al. (2013b) in the same study area. Results showed that the mean soil profile moisture demonstrated a moderate spatial variability which decreased with increasing soil moisture content at 0–60 cm depth; however, the variability of soil moisture and CV were both low and no significant correlations were found at 0–300 cm depth. A high temporal stability existed at two deeper soil layers compared with the soil surface observed by Wang et al. (2013b). The sampling locations, representative of the dry conditions in the field, were always more temporally stable. Identified representative locations at two depths well-represented the mean soil moisture content in our study area larger than 1 km^2. Furthermore, strong correlations at two soil layers revealed that spatial patterns of sampling points were preserved for all depths and that time stability of shallow measurements was a good indicator of deep soil layer time stability. Soil texture was the primary influence factor on soil profile moisture temporal stability and the dependence of soil moisture temporal stability on soil texture was consistent among different soil depths. Knowledge of the underlying stable soil moisture distribution could provide a useful basis for precise water management in arid areas.

1. Introduction

Soil moisture is a key variable controlling hydrological and energy fluxes at different spatio-temporal scales (Brocca et al., 2009; Heathman et al., 2009), which controls the exchange of water and energy between the land surface and atmosphere through evaporation and transpiration, determines the partitioning of precipitation into runoff, infiltration, and surface storage, as well as the partitioning of incoming solar radiation and long wave radiation into outgoing long wave radiation, latent heat, ground heat, and sensible heat fluxes (Pachepsky et al., 2003; Baroni et al., 2013). Soil moisture in arid environments is also crucial in limiting seed germination rates and vegetation growth, serving as the main constraint on permanently controlling desertification (Berndtsson et al., 1996; Jia et al., 2013), and largely determines the carrying capacity for vegetation and the organization and function of ecosystems (Rodriguez-Iturbe et al., 1999). Hence the patterns of soil moisture in arid environments are very important for the conservation and restoration of vegetation. However, the amount of soil moisture is a result of interactions among a series of variables, such as topography, soil properties, vegetation, water-routing processes, depth of water table and meteorological conditions (Western et al., 1999; Gómez-Plaza et al., 2000), making it highly variable over time and space across different scales (Albertson and Montaldo, 2003; Manfreda and Rodriguez-Iturbe, 2006; Famiglietti et al., 2008; Brocca et al., 2007, 2010;

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Penna et al., 2009, 2010; Zhang and Shao, 2013). Understanding such a variability characteristic is essential for a thorough comprehension of the water-related processes.

Traditional sampling methods generally assume that spatial variability patterns of soil moisture are random. However, factors controlling soil moisture exhibit non-random patterns that may persist over time (Gao and Shao, 2012). In other words, in addition to the strong spatio-temporal variability, soil moisture also shows a somewhat strong temporal stability of spatial pattern (Mohanty and Skaggs, 2001; Martínez-Fernández and Ceballos, 2005; Brocca et al., 2009, 2010; Hu et al., 2009; Zhao et al., 2010). The concept of temporal stability was first introduced by Vachaud et al. (1985), who defined it as "the time-invariant association between spatial location and classical statistical parameters of a given soil property" and suggested the ranking stability method. It is a reflection of the temporal persistence of soil moisture within a spatial distribution pattern (Kachanoski and de Jong, 1988; Zhou et al., 2007; Schneider et al., 2008). This means that soil moisture at each single sampling location varies over time but the relative spatial organization of all soil moisture values is temporally preserved (Penna et al., 2013). The purpose of temporal stability study was to propose a method for reducing the number of field sampling sites while at the same time accurately characterizing the behavior of soil moisture in the study area over time. One of the most useful applications is the potential to identify sampling locations that could reliably represent the mean moisture content of the entire study area. The idea was introduced by Grayson and Western (1998) who demonstrated the existence of certain parts of the landscape which consistently represented mean behavior of soil moisture irrespective of the overall wetness of the whole study area. However, several processes can disrupt temporal stability. Joshi et al. (2011) indicated that soil texture and topography were two significant physical controls jointly affecting the spatio-temporal evolution and temporal stability of soil moisture at point and remotely sensed footprint scales; the research of Gómez-Plaza et al. (2000) in a semi-arid environment had shown that at the transect scale, when the factors affecting soil moisture were limited to geographic position or local topography, spatial patterns showed temporal stability, but when other factors, such as vegetation, were taken into account, the spatial patterns became time unstable. At the point scale, and in the same areas, geographic position was the main factor controlling temporal stability. Meanwhile, the actual scale of observation and number of measurements affected the temporal stability analysis of soil moisture (Gómez-Plaza et al., 2000; Brocca et al., 2009; Heathman et al., 2009), and the depth of observation is also an important aspect in the study of the temporal stability of soil moisture (Martínez-Fernández and Ceballos, 2003; Starks et al., 2006). Although many authors applied Vachaud's approach over several climatic regions, a direct comparison among the achieved results is not straightforward because of the differences in the investigated area, in the sampling scheme, in the investigation depth, and in the study period (Martínez-Fernández and Ceballos, 2003, 2005; Tallon and Si, 2003; Thierdefelder et al., 2003; Cosh et al., 2004, 2006; Grant et al., 2004; Jacobs et al., 2004; Petrone et al., 2004; Pachepsky et al., 2005; Bosch et al., 2006; Starks et al., 2006; Teuling et al., 2006; Wang et al., 2013b).

There were still some deficiencies in soil moisture temporal stability analysis. Firstly, although direct measurement is the most accurate method for estimating soil moisture, this technique is expensive, time consuming and only provides point measurements which limited the study of spatio-temporal variations in soil moisture in arid environments (Gao et al., 2013). The development of modeling techniques to estimate soil moisture availability has been an area of extensive research during the past decade (Jacobs et al., 2004; Cosh et al., 2006, 2008; Starks et al., 2006; Vivoni et al., 2008). However, retrieved soil moisture products by remote sensing have focused on near surface soil moisture and very few reports refer to the whole soil profile or the relationship between surface and profile variability (Kachanoski and de Jong, 1988; Hupet and Vanclooster, 2002; Schmugge et al., 2002; Martínez-Fernández and Ceballos, 2003, 2005; Pachepsky et al., 2005; De Lannoy et al., 2006; Starks et al., 2006; Guber et al., 2008). For most practical applications, knowledge of soil moisture must be understood for layers deeper than the thin surface layers observed using remote sensing instruments. Entire soil moisture profiles provide an enhanced characterization for hydrologic applications (Western et al., 1998) and a more integral understanding of soil moisture dynamics (Bloschl and Sivapalan, 1995). The dynamics of soil moisture at deeper layers may also significantly influence surface soil moisture variability (Jacques et al., 2001). Secondly, the observation time was short for most previous studies. For a successful application of the temporal stability concept, the selected points need to represent average moisture dynamics beyond the time period they were determined for (Martínez-Fernández and Ceballos, 2003), to capture possible changes in the spatial pattern due to seasonality and to remove the influence of short-term weather patterns, samples of soil moisture should be collected on at least 13 occasions within a minimum sampling period of one year (Martínez-Fernández and Ceballos, 2005; Schneider et al., 2008). Thirdly, the concept of temporal stability has rarely been applied to desert areas (Pan et al., 2009; Wang et al., 2013b; Zhang and Shao, 2013), where rainfall is the only soil moisture source, and where soil moisture is the most crucial factor for the restoration of vegetation. To gain a deeper insight into the temporal stability of soil moisture in arid desert areas, we measured soil moisture in eight adjacent artificial revegetation desert areas and natural vegetation areas over 36 occasions from 1990 to 1992, analyzed the potential of time-stable points to estimate average soil moisture content at the field scale. The specific objectives of the study were to: (1) investigate the distribution patterns of soil moisture at different soil layers as a basis for subsequent analysis; (2) detect variations in temporal stability in soil profiles and determine whether time-stability persists between consecutive growing seasons, and (3) understand the mechanisms controlling temporal stability of soil moisture under the combined influences of vegetation type, soil depth, and soil texture. This study is expected to contribute to our understanding of soil moisture patterns in arid desert environments, which have important implications for ground sampling design, hydrologic modeling, and sustainable vegetation restoration.

2. Materials and methods

2.1. Experimental site description

The experiment was carried out in the desert steppe region at the Shapotou Desert Research and Experiment Station bordering the Tengger Desert. The average elevation is 1288 m above the sea level. The area has large and dense reticulate dune chains and the main dune crest migrates southeastward at a velocity of 0.3–0.6 m per year. According to meteorological records from the weather station, annual mean temperature is 10.6 °C. The lowest temperatures are observed during January, with a mean value of −6.3 °C and the highest temperatures are observed during July, with a mean value of 24.9 °C. Annual mean precipitation is 193 mm, most of which falls during the monsoon period between May and September. The annual potential evaporation is approximately 3000 mm. The growing period ranges from 150 to 180 days per year. The natural predominant plants are *Helianthemum scoparium* and *Agriophyllum squarrosum* with a cover of approximately 1–2%

(Shapotou Desert Experimental Research Station, Chinese Academy of Sciences, 1991). The soil is classified as orthic sierozem and aeolian sandy soil (Li et al., 2007).

To stabilize the shifting sand dunes, straw checker-boards (spacing $1 \times 1\,m^2$) were firstly established by inserting straw vertically into soil to a depth of 15–20 cm, so that it protruded approximately 10–15 cm above the dune surface. The straw checker-boards structures remain intact for 4–5 years. Xerophytic shrubs (e.g., *Salix gordejevvi*, *Calligonum arborescens*, *Atraphaxis bracteata*, *Caragana korshinskii, Artemisia ordosica*, and *Hedysarum scoparium*) were then planted in straw checker-board plots in 1956, 1964, and extended by the following years, along the east–west Baotou–Lanzhou railway. Over time, a revegetation restored desert ecosystem was established with rows in a northeast–southwest direction forming banded vegetation (Wang et al., 2013a). The experimental field lies in the artificially re-vegetated desert area initiated in 1956 (A1), 1964 (A2), 1973 (A3), and 1982 (A4) (37°32′N, 105°02′E) year, where a desert shrub ecosystem with a dwarf shrub and biological soil crusts (BSCs) cover on the stabilized sand dunes has been formed, the BSCs evolved from the initial cyanobacteria-dominated crusts to lichen- and moss-dominated crusts. *Artemisia ordosica*, *C. korshinskii* and *H. scoparium* are the main shrub types at A1, A2, A3, and A4, the coverage remains at around 30% and the differences are not significant for four revegetated experimental field. The crustal coverage which included cyanobacteria–lichen crusts and moss crusts increased along with the increasing sand fixed number of years. The natural vegetation areas included natural *A. ordosica* vegetation area (N1) and natural *C. korshinskii* vegetation area (N2) in Hongwei (37°27′N, 104°44′E), natural *A. ordosica* vegetation area in Yiwanquan (N3) (37°25′N, 104°37′E) where both sides face mountain, guaranteeing the sufficient water. The common members of BSCs in revegetated and natural area included cyanobacteria, algae, lichens, and mosses (Li et al., 2011). Moss crusts were green under wet conditions and were 8–20 mm thick while cyanobacteria–lichen crusts were dark brown or black with a clear surface microtopography and were 2–3.5 mm thick. The average coverage of BSCs is high with more than 80% of the revegetated areas (Jia et al., 2008) and more than 50% of natural vegetation area (Table 1). The total area of experimental field was more than $2\,km^2$. Moving sand area is chosen as control sample area (Fig. 1). The natural vegetation and BSCs composition and coverage for different study field site are shown in Table 1.

2.2. Experimental design and data collection

For soil moisture measurements, 8 polyethylene neutron probe access tubes were installed, with one tube in each area (Fig. 1). The access tubes (50 mm diameter, 2 mm thickness, and 3.2 m long) were inserted vertically into the 3.5 m soil profiles. An auger with a similar diameter was used during installation to provide an adequate fit between the tube and the soil. Neutron probe readings (the neutron counting rate (CR)) were carried out once a month during 1990 and 1992 at different depths (an increment of 20 cm from 20 cm to 300 cm) in eight different study field areas, comprising 36 measurement campaigns. During the neutron counting measurement period, gravimetrical soil water contents (u, $g\,g^{-1}$) were also evaluated for each experimental site at the corresponding depths at 6 experimental days, about 50 cm away from each neutron access tube to establish calibrations of the neutron probe. This was made under the assumption that the variability of soil water content in a distance of 50 cm to the access tube was negligible due to similar topography and microhabitat. These measurements covered different soil water conditions, ranging from very dry before the rainy season in December, 1991 to very wet after the rainy season in July, 1992. At each site, 50 cm away from the access tube, a 300 cm deep pit was excavated to take the undisturbed soil samples at the corresponding depths to obtain the dry soil bulk density (BD, $g\,cm^{-3}$) and transform u to corresponding volumetric soil water contents (θ, $cm^3\,cm^{-3}$). The determination of neutron probe calibration equation and calculation of soil moisture content referred to the method of Hu et al. (2009), the most complete calibration procedure with each site having its own linear calibration equation were employed. The relative errors were all about $0.04\,cm^3\,cm^{-3}$ at eight experimental

Table 1
Vegetation and biological soil crusts (BSCs) characteristics in the study field site.

Code	A1	A2	A3	A4	N1	N2	N3	N4
Vegetation	*A. ordosica* and *C. korshinskii*, community[a]	*A. ordosica*,*C. korshinskii* and *H. scoparium*, community[b]	*C. korshinskii*, community[c]	*C. korshinskii*, *H. scoparium* and *A. ordosica*, community[d]	*A. ordosica*, community[e]	*C. korshinskii*, community[f]	*A. ordosica*, community[g]	Moving sand[h]
Cover (%)	30	33	25	30	70	85	70	<1
Cyanobacteria–lichen crusts cover (%)[i]	39	31.2	11.8	6.9	36.5	43.5	39.4	0
Moss cover (%)[i]	56.54	57.46	54.02	49.82	19.1	14.6	12.1	0
Crustal cover (%)[i]	95.54	88.66	65.1	56.72	55.6	58.1	51.5	0

A1, artificially re-vegetated desert area initiated in 1956; A2, artificially re-vegetated desert area initiated in 1964; A3, artificially re-vegetated desert area initiated in 1973; A4, artificially re-vegetated desert area initiated in 1982; N1, natural *A. ordosica* vegetation area in Hongwei; N2,natural *C. korshinskii* vegetation area in Hongwei; N3, natural *A. ordosica* vegetation area in Yiwanquan; N4, moving sand.

[a] *Artemsia ordosica*, *Caragana korshinskii*, *Bassia dasyphylla*, *Echinops gmelinii*, *Salsola ruthenica*, *Eragrostis poaeoides*, and *Corispermum hyssopifolium*.

[b] *Artemisia ordosica*, *Hedysarum scoparium*, *Caragana korshinskii*, *Eragrostis poaeoides*, *Agriophyllum squarrosum*, *Bassia dasyphylla*, *Aristida adscensionis*, and *Echinops gmelinii*.

[c] *Caragana korshinskii*, *Artemsia ordosica*, *Bassia dasyphylla*, *Eragrostis poaeoides*, *Chloris virgata*, *Setaria viridis*, *Echinops gmelinii*, *Salsola ruthenica*, and *Agriophyllum squarrosum*.

[d] *Artemsia ordosica*, *Caragana korshinskii*, *Hedysarum scoparium*, *Eragrostis poaeoides*, *Bassia dasyphylla*, *Corispermum hyssopifolium*, and *Aristida adscensionis*.

[e] *Artemsia ordosica*, *Caragana korshinskii*, *Stipa glareosa*, *Carex capilliformis*, *Lespedeza durica*, *Cleistogenes squarrosa*, *Aristida adscensionis*, *Stipa bungeana*, and *Oxytropi spsammocharis*.

[f] *Caragana korshinskii*, *Artemsia ordosica*, *Stipa glareosa*, *Carex capilliformis*, *Lespedeza durica*, *Cleistogenes squarrosa*, *Aristida adscensionis*, *Stipa bungeana*, and *Oxytropisp sammocharis*.

[g] *Artemsia ordosica*, *Caragana korshinskii*, *Stipa glareosa*, *Carex capilliformis*, *Lespedeza durica*, *Cleistogenes squarrosa*, *Aristida adscensionis*, *Stipa bungeana*, and *Oxytropisp sammocharis*.

[h] *Hedysarum scoparium* and *Agriophyllum squarrosum*.

[i] The BSCs cover data in A1, A2, A3, and A4 were quoted from Li et al. (2011) and Liu et al. (2013); the others were acquired by field survey.

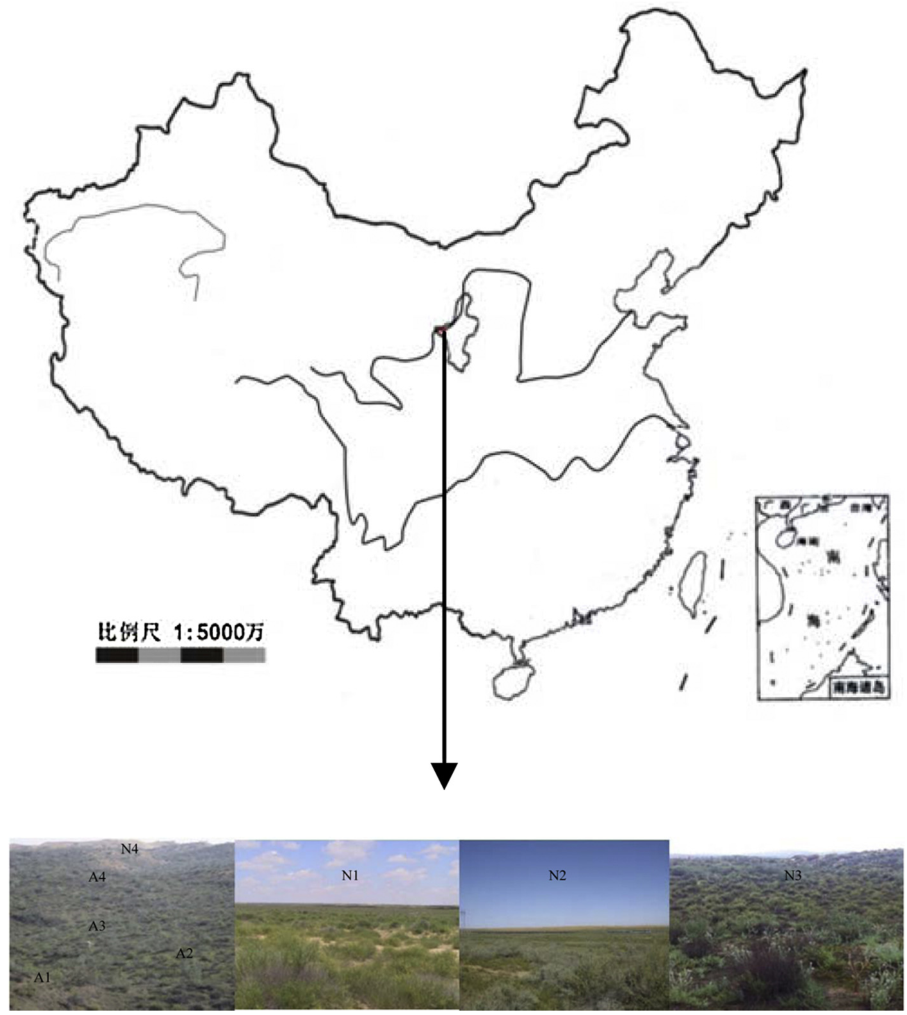

Fig. 1. Location and landscape pictures of the study area and experimental field site.
A1, artificially re-vegetated desert area initiated in 1956; A2, artificially re-vegetated desert area initiated in 1964; A3, artificially re-vegetated desert area initiated in 1973; A4, artificially re-vegetated desert area initiated in 1982; N1, natural *A. ordosica* vegetation area in Hongwei; N2, natural *C. korshinskii* vegetation area in Hongwei; N3, natural *A. ordosica* vegetation area in Yiwanquan; N4, moving sand.

sites. All the neutron probes were installed at flat terrain and similar microhabitats eliminating the influences of topography and microhabitat.

The spatial variability and temporal stability of near surface soil moisture (0–30 cm) had been studied by Pan et al. (2008), Pan and Wang (2009) and Wang et al. (2013b). Moreover, according to the research of Zhang (2006) at the same area, 0–60 cm soil layer is the main distribution range of thick roots, and the fine roots distribute widely at 0–300 cm depth for *A. squarrosum* and *C. korshinskii*. Based on the above consideration, soil moisture data of 0–60 cm and 0–300 cm depths were analyzed in this paper.

Groundwater is too deep (>80 m) to support vegetation growth and precipitation is usually the only source of fresh water in Shapotou area. The properties of upper soil layer probably had a greater influence on soil moisture content, by controlling rainwater infiltration and evaporation, than that of deeper soil layers (Gao and Shao, 2012). Therefore, soil samples at the depth of 0–5 cm profile were collected for subsequent analysis. Soil particle size distribution was analyzed using MS-S lighter scattering apparatus (Malvern Instruments Ltd., Malvern, UK). Soil organic matter was determined by the $K_2Cr_2O_7$ method.

For estimating the coverage of the plant community, 10 quadrats of $1 \times 1\,m^2$, and 10 quadrats of $10 \times 10\,m^2$ were marked using survey stakes inside each study field area. Measurements were made in late September of each year. The herb and shrub coverage were computed as the percentage of the area.

Rainfall amount was measured by a siphon rain gauge with an observational error less than ± 0.02 mm for rainfall events less than 10 mm, and less than ± 0.2 mm for rainfall events greater than 10 mm.

2.3. Method of analysis

2.3.1. Descriptive statistics

The K–S test was used for descriptive statistics and adherence to normal distribution analysis using the statistic software SPSS 13.0. In order to characterize the degree of variability, the coefficient of variation (CV) values were analyzed as suggested by Nielsen and Bouma, (1985). CV can quantitatively ascertain the magnitude of the spatial variability as weak when CV < 10%, moderate if 10% < CV < 100% and strong when CV > 100%.

2.3.2. Temporal stability analysis

Temporal stability was evaluated using the relative difference between individual measurements of soil moisture at location i at time j and the areal mean soil moisture at the same time ($\overline{\theta_j}$). The relative difference ($\delta_{i,j}$) can be expressed as

$$\delta_{i,j} = \theta_{i,j} - \overline{\theta_j} \tag{1}$$

where $\overline{\theta_j} = (1/N)\sum_{i=1}^{N}\theta_{i,j}$ and N is the number of sensor locations.

A temporal mean of the relative difference ($\overline{\delta_i}$) and its standard deviation ($\varsigma(\overline{\delta_i})$) for each location were used to determine the most temporally stable sites according to:

$$\overline{\delta_i} = \frac{1}{m}\sum_{j=1}^{m}\delta_{i,j} \tag{2}$$

$$\varsigma(\overline{\delta_i}) = \sqrt{\sum_{j=1}^{m}\frac{(\delta_{i,j} - \overline{\delta_i})^2}{m-1}} \tag{3}$$

where m is the number of measurements derived from a single location. When temporal mean values are plotted from the smallest to largest, one can determine whether a sensor location underestimates or overestimates the field average soil moisture which has a zero mean relative difference. The lower values of standard deviation of a sensor location indicates a greater tendency of that location being temporally stable.

The nonparametric Spearman's test was also applied to evaluate the temporal stability of different observations. The Spearman's rank correlation coefficient is expressed as

$$r_s = 1 - \frac{6\sum_{i=1}^{N}(R_{ij\_}R_{ij'})^2}{n(n^2-1)} \tag{4}$$

where R_{ij} is the rank of $\theta_{i,j}$ at location i and time j and $R_{ij'}$ is the rank of the same variable at the same location, but at a different time j'. A Spearman's rank correlation value closer to 1 indicates the strong tendency of temporal stability between different days.

The root mean square error (RMSE) was determined to further assess offset estimates at the representative sensor sites and the most time-stable sites in each field. It was calculated as:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(S_i - O_i)^2}{N}} \tag{5}$$

where N is the number of days with measured and estimated soil moisture, O and S are the observed and estimated data, respectively. The closer the RMSE value is to zero, the less error in the offset estimate.

Another index to characterize temporal stability is the mean absolute bias error (MABE) as suggested by Hu et al. (2009).

3. Results and discussions

3.1. Precipitation

Precipitation data collected in observational years and the average monthly precipitation data collected between 1955 and 2012 are provided in Supplementary Fig. 1. Due to monsoonal effects, approximately 86% of annual precipitation falls between May and September during 1955–2012. Annual precipitation was approximately 215, 121, and 181 mm in 1990, 1991, and 1992, respectively, which accounted for 128%, 72%, and 107% of annual mean precipitation between 1955 and 2012. According to the annual mean rainfall amount of 1955–2012, 1990 can be regarded as a wet year, while 1991 a typical dry year, and 1992 a normal year. Therefore, the experimental period provided a contrast in soil moisture conditions. The precipitation characteristics were similar at the eight experimental fields.

3.2. Description statistics of soil moisture content

The eight measurement points showed low soil moisture contents at 0–60 cm and 0–300 cm depths over the entire measurement period (Table 2). The highest mean soil moisture content was 2.93 $cm^3\,cm^{-3}$ observed at N3. The lowest soil moisture content (1 $cm^3\,cm^{-3}$), was observed at A1 for 0–60 cm soil layer. The highest and lowest mean soil moisture content were 3.05 (N4) and 1.11 $cm^3\,cm^{-3}$ (A2) at 0–300 cm soil layer. Soil moisture contents at artificial revegetation area were lower compared with the natural vegetation area. The former landscape at the artificial revegetation area is characterized by large and dense reticulate barchans chains of sand dunes, the groundwater is more than 60 m to support large areas of the native vegetation cover (Li et al., 2007). The terrain is flat at natural vegetation area, while it is surrounded by hillsides and abundant water gather here from hill. The main shrubs used for artificial revegetation are *A. ordosica* and *C. Korshinskii* in the study area, they are adaptive to limited rain-fed conditions and consumes relatively less water. Other studies also reported that a serious water deficit existed in this area (Duan et al., 2004; Xiao et al., 2004; Wang et al., 2008). Furthermore, as an important type of surface cover that occur at sand surface after the stabilization of sand dunes through

Table 2
Summary statistics of soil moisture and other soil parameters which were measured at 0–5 cm depth.

Code	BD ($g\,cm^{-3}$)	Sand (%)	Silt (%)	Clay (%)	SOM (%)	0–60 cm SWC ($cm^3\,cm^{-3}$)	0–300 cm SWC ($cm^3\,cm^{-3}$)
A1	1.40	66.96	29.62	3.42	0.574	1	1.16
A2	1.52	76.45	20.68	2.87	0.386	1.15	1.11
A3	1.51	72.06	24.86	3.08	0.296	1.65	1.27
A4	1.52	88.92	9.58	1.50	0.164	1.71	1.43
N1	1.33	72.51	23.28	4.21	0.666	1.5	1.74
N2	1.33	68.39	27.30	4.31	0.657	1.89	1.74
N3	1.31	80.29	15.51	4.20	0.741	2.93	2.55
N4	1.60	99.72	0.11	0.17	0.045	2.72	3.05
Mean	1.44	78.16	18.88	2.97	0.44	1.86	1.76
Standard deviation	0.11	11.2	9.96	1.47	0.26	0.92	0.7
CV (%)	7.7	14.33	52.8	49.41	58.27	52.08	39.74
Distribution	N	N	N	N	N	N	N

BD, bulk density; SOM, soil organic matter; SWC, soil water content; N: normal distribution.

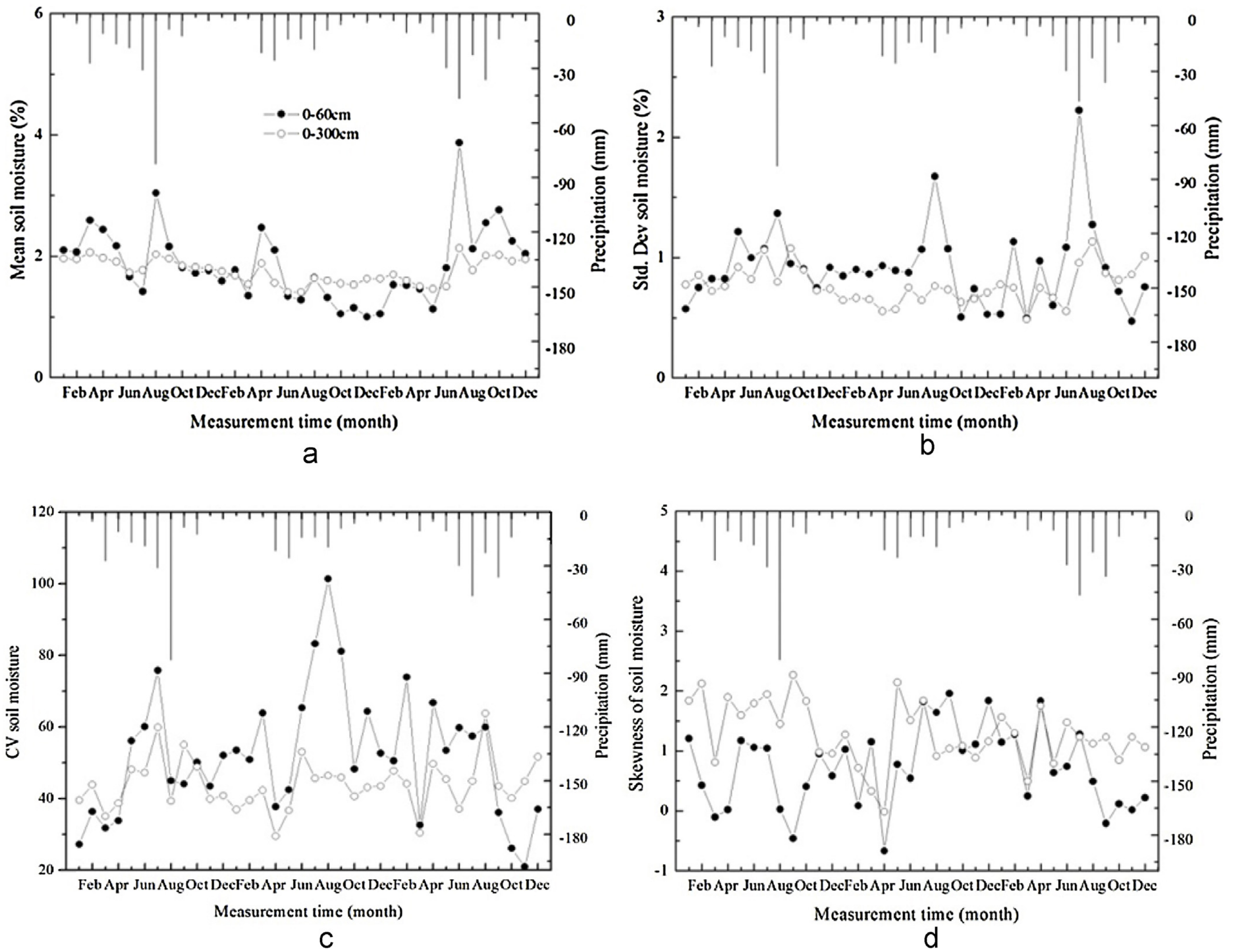

Fig. 2. The time series of precipitation and the mean (a), standard deviation (b), the coefficient of variation (CV) (c), and skewness (d) of volumetric soil moisture at 0–60 cm and 0–300 cm depths.

revegetation, biological soil crusts (BSCs) play a vital hydrological role in determining soil moisture and vegetation changes in sandy desert areas. BSCs altered the initial soil water balance by influencing rainwater infiltration, soil evaporation and dew water entrapment, such as improved soil moisture availability at shallow soil layer, and reduced the amount of rainwater that reaches into deeper soil (0.4–3 m), with at least 80% of annual rainfall being intercepted by BSCs and prevented from infiltration to deeper soil (Li et al., 2010). Considering 0.6–3 m layer is the main distribution zone for roots of planted shrubs (Shapotou Desert Experimental Research Station, Chinese Academy of Sciences, 1991), the negative influence of BSCs on deeper soil water gave rise to a low level of deeper soil water, supporting a limited shrubs coverage.

The time series in the mean soil moisture content over space in two soil layers (Fig. 2a) showed a broader range at 0–60 cm depth than 0–300 cm depth indicating that the temporal changes were mainly observed at shallow soil layer (0–60 cm). Deeper layers typically have somewhat less variability in soil moisture than shallower layers. After rainfall events, the mean soil moisture increased and the response was more sensitive at 0–60 cm than at 0–300 cm, and soil at upper layers had a quicker drying than deeper soil layers. During the study period, the spatial mean soil moisture content of 0–60 cm layer varied by 52.1% ranging from 1% to 3.87%, with a time-averaged value of 1.86%. For 0–300 cm soil layer, the mean soil moisture content had relatively little temporal changes, and a variance of 43.96% was observed. The time-averaged mean soil moisture content was 1.76% ranging from 1.41% to 2.13%. Although the mean soil moisture content over time decreased from 1.86% to 1.76% with increasing soil depth, no significant differences were found between the two soil layers based on a paired-sample t-test. This agreed with the finding of Wang et al. (2013b) who observed no significant differences for soil moisture content between soil depths of 0–15 and 0–30 cm within the same experimental field. However, soil moisture content of 0–6 cm was significantly higher than that of the deeper layer. Soil moisture content was a function of rainfall, infiltration, upward water movement, and water uptake by plant roots. The dependence of soil moisture on soil depth may be related to precipitation, surface evaporation, root water uptake, etc.

The temporal changes in standard deviations and CV of soil moisture content over space (SDs and CVs) (Fig. 2b and c) showed that soil moisture content of shallow soil layers had greater SDs and CVs, being significantly different ($p < 0.05$) by a paired-sample t-test. This indicated that the spatial variability of mean soil moisture content tended to be temporally more stable for deeper soil layers. The maximum SD of soil moisture was 2.22% and 1.13% at 0–60 cm and 0–300 cm, respectively. The differences for the maximum SD were likely caused by continuous rainfall events in

June and July of 1992. The maximum SD occurred during wet period (Fig. 2b). The time-averaged SDs values of soil moisture for two soil layers were 0.92% and 0.77% in experimental field. The SDs of soil moisture tended to decrease with increasing soil depth which was consistent with Choi and Jacobs (2007), their research indicated further that the maximum SD of soil moisture did not occur at the surface, but at 5 cm depth.

The CV, a ratio of SD to mean, suggests the relative variability of soil moisture. Jacobs et al. (2004) pointed out that the relationship between soil moisture variability and mean become more evident when SD is scaled by mean. The mean soil moisture at 0–60 cm and 0–300 cm demonstrated a moderate spatial variability, with a CV of 52.08% and 39.74%, respectively (Table 2). The spatial variability of soil moisture was greater at 0–60 cm depth than at 0–300 cm. Furthermore, the relative variability highlights a general decreasing trend with increasing mean soil moisture (Fig. 2c), however, the variance of CV lags behind the soil moisture. Schneider et al. (2003) showed that an increase in soil moisture often lags behind precipitation that was received days to weeks earlier.

The largest skewness occurred at 0–300 cm layer in September of 1990 (Fig. 2d). An average soil moisture skewness of 0.73 and 1.29 was observed at 0–60 and 0–300 cm depths, respectively. The kurtosis showed similar variation trend with skewness. For all measurement campaigns, a normal distribution could describe the results (Table 2).

Fig. 3a showed the relationship between the mean soil moisture and SDs by soil depth. While considerable scatter exists, the relationship between the mean soil moisture and SDs of soil moisture at 0–60 cm depth showed an increasing trend and then decreased with increasing soil moisture. Overall, soil moisture variability showed the highest values at moderate moisture conditions (1.5–2.25%) and lower values for drier and wetter conditions. The soil moisture contents at 0–300 cm depth were lower ranging from 1.41 to 2.13%, positive relationships were evident for mean soil moisture and SDs. Our positive relationships are consistent with our previous study (Pan and Wang, 2009), positive relationships were found between surface mean soil moisture and SDs at same area. This is corroborated by many other studies (Hills and Reynolds, 1969; Henninger et al., 1976; Bell et al., 1980; Robinson and Dean, 1993; Famigliettiet al., 1998; Martínez-Fernández and Ceballos, 2003). These studies postulated that variability peaked under wet soil moisture conditions, because soil heterogeneity would be maximized after rainfall events (Famiglietti et al., 1998). Contradictory relationships may also be

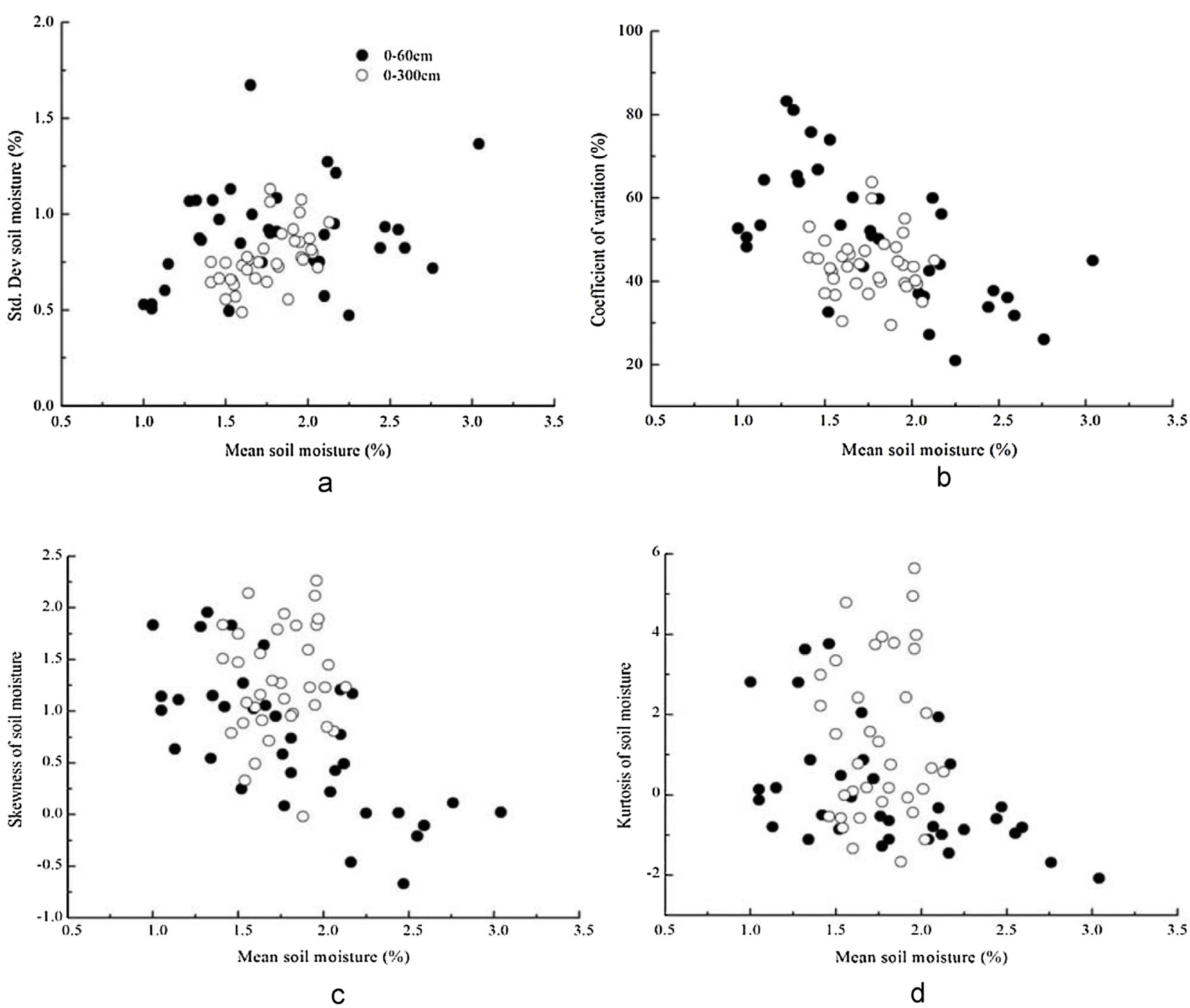

Fig. 3. Relationships between volumetric soil moisture and statistical parameters. (a) Standard deviations, (b) coefficients of variation, (c) skewness, and (d) kurtosis.

found by combined physical effects of soil texture, hysteresis effects, vegetation, topography, and sampling scale (Famiglietti et al., 1998; Hupet and Vanclooster, 2002; Choi and Jacobs, 2007). Penna et al. (2009) reported that variability was greatest in soil moisture ranging 23–29%. When soil moisture was below this range, mean values and SDs were positively correlated, when soil moisture was above this range, SDs of soil moisture decreased with increasing soil moisture.

The CV values pointed out that the relationship between soil moisture variability and mean become more evident when SD is scaled by mean. The relationships between CV and mean soil moisture for different depths are shown in Fig. 3b. The CV decreased as the mean soil moisture increased at 0–60 cm depth. This is consistent with the previous soil moisture result of Pan and Wang (2009) at the same study area. Moreover, Bell et al. (1980), Owe et al. (1982), Charpentier and Groffman, (1992), and Famiglietti et al. (1999) also had given the same result. However, Jacobs et al. (2004) characterized the negative relationship between the surface mean soil moisture content and CV using an exponential fit for four fields of the SMEX02. Their results indicated that higher moisture contents were associated with lower CV. Timm et al. (2006) and Chicota et al. (2006) found similar results after evaluating soil moisture variations. The variability of soil moisture and CV were both less and no significant correlations were found at 0–300 cm depth.

To test the frequency distribution characteristics of soil moisture and to link the distribution to a particular soil moisture condition (drying or wetting), skewness and kurtosis were both determined and compared with mean soil moisture (Fig. 3c and d). Both showed an increase in positive values with a decrease in mean soil moisture and the skewness and kurtosis values clustered around zero at 0–60 cm depth. Similar to the results for soil moisture at depths of 0–6, 0–15 and 0–30 cm at the same study area (Pan et al., 2008; Pan and Wang, 2009), soil moisture of 0–60 cm depth was normally distributed according to the normal test formula of skewness and kurtosis at the field-scale and the normal distribution characteristics are more obvious in wet conditions than in dry conditions. The skewness and kurtosis values of soil moisture were above zero under most conditions and had no significant correlation with soil moisture at 0–300 cm depth, however, a normal distribution was found according to the calculation results.

3.3. Temporal stability analysis of soil moisture

Fig. 4 shows the time stability results by depth. These graphs indicate that a given location systematically either represents the mean soil moisture content of the study area or gives an under- or over-estimate of the mean soil moisture content regardless of observation time. Negative mean relative differences (MRDs) indicate that corresponding sites have drier spatial patterns compared to the field mean soil moisture while positive MRDs indicate that corresponding sites have wetter spatial patterns. The span of MRD is similar on these sites for two depths. The mean values were 1.17 and 1.1 at soil depths of 0–60 and 0–300 cm, respectively, which were higher than that reported by Wang et al. (2013b) whose experiment was conducted in a smaller area at similar field. Therefore, it is tempting to conclude that the range of

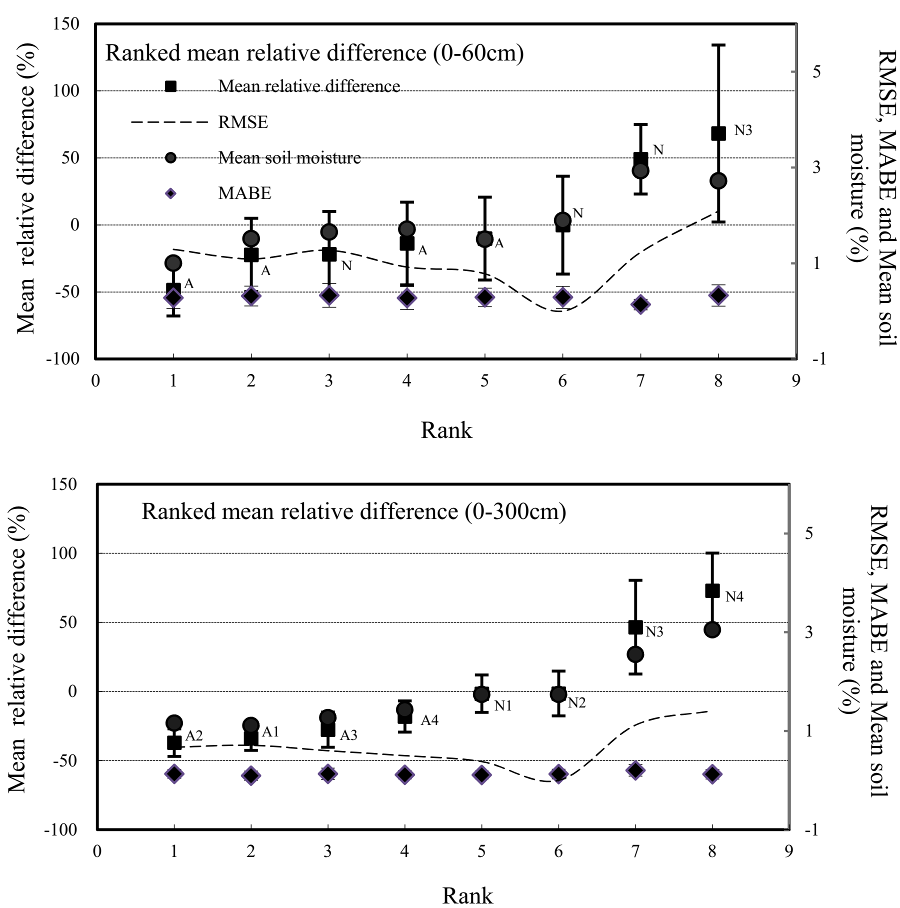

Fig. 4. Ranked mean relative differences (MRDs) with standard deviation error bars (SDRDs), root mean square error (RMSE), mean absolute bias error (MABE) and mean soil moisture content at 0–60 cm and 0–300 cm depths.

MRD increases with scale because of an expected increase in variation of soils, topography, and vegetation. However, the result has not been supported by other researches, for example, Cosh et al. (2004) observed MRDs below 40% in a 100 km^2 watershed. The values were similar to the results in a small watershed within the larger Liudaogou watershed in China where the ranges of MRD was greater than 100% for all soil depths.

The standard deviation of the mean relative difference (SDRD), and RMSE values are also indicators as to which sites capture the best field mean soil moisture. The best locations have a mean relative difference and RMSE close to zero. For this study, SDRD varied greatly in space for two depths and the ranges were 19.19–65.99% and 9.95–27.17% for 0–60 cm and 0–300 cm depths, respectively. The mean value of SDRDs slightly increased from the first half to the second half of the ranked data for two measurement depths, and this variability was more obvious at 0–300 cm depth. There was a positive linear relationship between SDRDs and MRDs (R^2 = 0.52 for 0–60 cm and R^2 = 0.83 for 0–300 cm). This is consistent with Jacobs et al. (2004), who observed low SDRDs for MRDs < 0 and high SDRDs for MRDs > 0. The SDRDs were lower compared with the research of Wang et al. (2013b) within shorter observation period. This result answered the question from Schneider et al. (2008) “whether more accurate time-stable locations with lower SDRD can be obtained when time series longer than two years”. The study of Martínez-Fernández and Ceballos (2003) also found that the quality of time-stable points shifted throughout the three years of their study. The average values of SDRD and RMSE decreased from 0.34 and 1.08 at 0–60 cm to 0.17 and 0.67 at 0–300 cm depth. Decreasing SDRD and RMSE with soil depth indicated that soil moisture tended to be more stable in deeper soil layers. Similar results were also observed in an agricultural field (Guber et al., 2008), a forest ecosystem (Lin, 2006) and a semi-arid hillslope (Gao and Shao, 2012). Combined with previous studies, the increasing temporal stability with depth in current study may have two explanations. First, the dependence of soil moisture on climatic, biologic, and hydrologic factors decrease with an increas in soil depth. Pedogenetically derived variations at deeper layers thus maintain a relatively stable pattern over time (Kamgar et al., 1993). Second, as suggested by Korsunskaya et al. (1995), soil structure and its ability to retain water are more variable in shallow soil layers. Furthermore, the calibration method of neutron probe is conducive

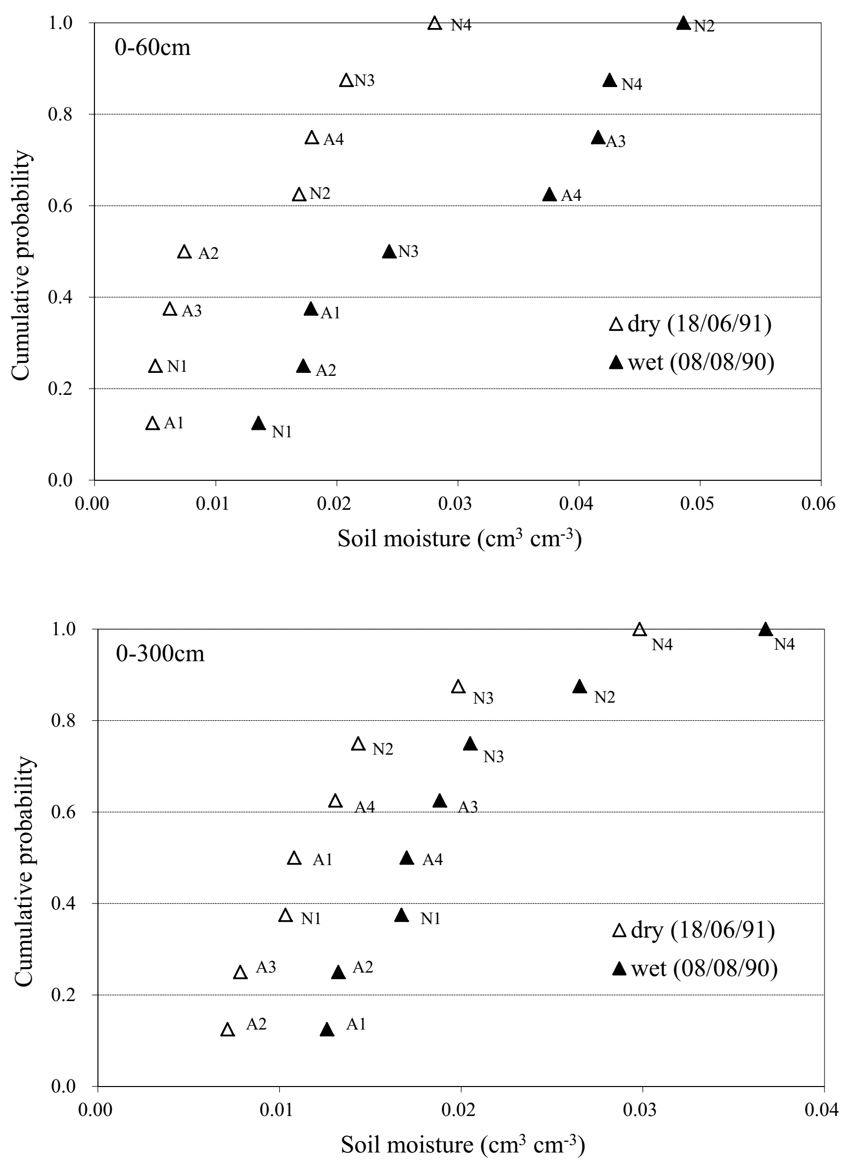

Fig. 5. Cumulative probability analysis for 0–60 cm and 0–300 cm volumetric soil moisture in experiment field.

to the maintenance of soil moisture temporal stability. According to Hu et al. (2009), the spatial variability and temporal stability of soil moisture obtained by this calibration method were not influenced by land use. This may be the reason that a higher soil moisture temporal stability maintained for our eight experimental sites of different vegetation type.

The variability of MABE was little with sampling locations. MABE ranged 13.6–32.8% and 9.4–20.2% at 0–60 cm and 0–300 cm depths, respectively. Pearson correlation coefficients (from −0.11 to 0.23) showed that the correlation of MABE and MRD was not significant for two soil depths ($p > 0.05$). SDRD was positively correlated ($R^2 = 0.61$) with MABE at the significance level of $p < 0.01$ for 0–300 cm depth. However, the value of correlation coefficient was only 0.15 and $p > 0.05$ for 0–60 cm depth. The results imply that these two indices behave with the same characteristics in terms of describing temporal stability at some situations especially at 0–300 cm depth. However, when we are aiming to choose the “representative site” to directly give an estimation of the average soil moisture content for a given area, the minimum of SDRD should be considered (Brocca et al., 2009). Note that although the SDRD for the drier areas was generally lower, the drier areas did not necessarily produce the best mean soil moisture according to MRD.

In Fig. 4, the ranked MRDs for 0–60 cm sampling locations indicate that site N2 is the most temporally stable site by having the little SDRD (STDEV = ±0.37) and its soil moisture content close to the field average moisture content (mean offset = 0.03 $cm^3\,cm^{-3}$ or 0.2% MRD). The plot results of 0–300 cm sites also show that site N2 was the most temporally stable one (STDEV = ±0.16). It is important to note that the sites maintained the similar ranking (*X*-axis) among depths in Fig. 4. This indicates a vertical transferability for the temporal stability results at different depths. In a word, the natural *C. korshinskii* vegetation area in Hongwei can be regarded as the representative site of mean soil moisture contents at 0–60 cm and 0–300 cm depths for entire experiment field. Sites A1, A2, A3, A4, and N1 exhibited very stable underestimates of the field mean value, while sites N3 and N4 yielded identical stable overestimates of the field mean at two depths in study periods. According to the previous measurements on soil surface physical and chemical parameters, sites A1, A2, A3, A4, and N1 had the similar characteristics for the shallow surface layer (0–5 cm). Hupet and Vanclooster, (2002) found that dry periods had poor stability characteristics for depths from 0 to 125 cm. However, the research of Martínez-Fernández and Ceballos (2003) in sandy soils found that dry sites had lower SDRDs than wetter sites at all soil depths (i.e., 0–100 cm). Furthermore, Mohanty and Skaggs, (2001) and Jacobs et al. (2004) confirmed this finding for surface soil moisture measurements. In our study, while the drier sites had lowest SDRDs at two depths, the MRDs were closer to zero at wetter sites. Based on this finding, recommended time stable sampling sites may include wetter sites when soil moisture of 0–60 and 0–300 cm depths are to be estimated. Some other researchers also found that the ranking of locations could be similar for different depths (Cassel et al., 2000; Tallon and Si, 2003, b; Hu et al., 2010a,b). However, most of the statistically stable locations were different at different soil depths (Guber et al., 2008; Vanderlinden et al., 2012). Finding a single location to represent the mean soil moisture content for several depths of large areas can reduce costs while maintaining a high accuracy of prediction.

The cumulative frequency plots allow one to determine if a given location maintains its rank across the experimental periods, while also allowing identification of sites that can represent the field average (cumulative frequency = 0.5) or some other values such as standard deviation from the mean. The plot data are comprised of two extreme conditions of wet and dry periods during our three years of observations. Overall, differences in ranking between sites were dependent on the soil moisture, particularly between wet and dry conditions (Fig. 5). Thus, in order to obtain a valid and representative temporal mean data set for all sites, it is necessary that measurements include a range of soil moisture conditions from wet to dry. Otherwise, the analysis could be considerably biased. Qualitative assessments of measurement site rankings from these plots indicate that in the 0–60 cm depth, no site maintained their rankings between study periods. Sites N1 and N4 maintained their rankings in 0–300 cm depth. Generally, the position fluctuation is not distinct. Kamgar et al. (1993) found that temporal persistence of soil moisture depended on the sampling depth. Surface sampling points did not show temporal persistence, whereas soil moisture down to 2.85 m depth revealed time-stable patterns.

Observation of MRD and cumulative frequency function reveal that at times site rankings vary at different soil moisture condition and different depths, thus Spearman’s rank correlation analysis was used to quantify the persistence of site rankings within study sites. The values of r_s among the different occasions when the soil moisture contents at the locations were measured, which is shown in Supplementary Fig. 2. All the Spearman’s correlation coefficients were significant ($p < 0.05$), and the majority of them were high, indicating strong temporal stability at positions with coefficients close to 1 at two depths. Similar results using this methodology to study soil moisture temporal stability were also observed by Vachaud et al. (1985) and Brocca et al. (2009). It is worth to highlight that our results involve a dense dataset comprising 36 measurement campaigns with a total of 576 observations at the two studied depths during three years beyond 1 km^2 area. The r_s values ranged 0.839–1 at 0–60 cm depth, and the corresponding value was 0.875–1 at 0–300 cm depth. Mean r_s values were 0.978 and 0.98 at 0–60 and 0–300 cm depths, respectively, which were higher than the mean value reported by Tallon and Si, (2003), Gao and Shao, (2012) and Wang et al. (2013b). Overall, our results indicate that there are persistent patterns in field moisture conditions, suggesting that there exists a ranking among soil profile moisture measurement locations in experimental field. The ANOVA results for r_s among different soil depths showed that there were no significant differences ($p > 0.05$) between the two measurement depths.

SDRD and MABE for two soil depths are presented in Supplementary Fig. 3 to explore the relationship between temporal stability and soil depth. The location average SDRDs at 0–60 cm and 0–300 cm soil depths were 33.6% and 16.7%, respectively. Paired-samples *t*-test showed that significant ($p < 0.05$) differences could be found between two depths. The mean MABE values were 27.8% and 12.9% at two depths, respectively, and significant ($p < 0.05$) differences were found for two depths. The temporal stability of soil moisture content in 0–300 cm was significantly stronger than in 0–60 cm depth ($p < 0.05$). This agrees with the results obtained from Spearman’s rank correlation coefficients (Supplementary Fig. 2). According to Wang et al. (2013b), the temporal stability of soil moisture content at deeper soil layers was greater than those at surface layer. The concepts of r_s, SDRD and MABE are different. Spearman’s rank correlation coefficient is used to describe the similarity of the spatial pattern of soil moisture content distribution for the whole area at different times, while SDRD and MABE are used to characterize the degree of temporal invariability for a certain location (Hu et al., 2010a). The relationship between temporal stability and soil depth was not indicated consistently by SDRD and r_s due to the different focuses of these two indices, as reported by Hu et al. (2010a).

In order to determine the accuracy of representative site to forecast mean soil moisture, the mean soil moisture content during the experimental period was compared with the representative

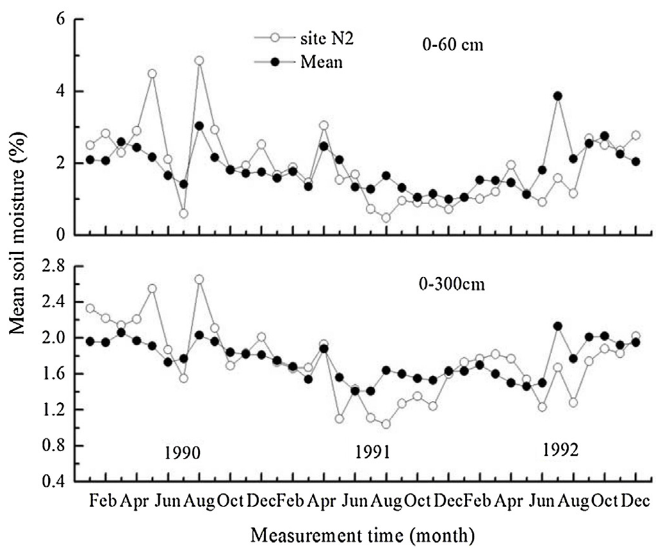

Fig. 6. Comparison between the average soil moisture contents and moisture contents at positions with temporal stability on the sampling dates.

sites calculated by MRDs (Fig. 6). Although some points did not exactly match the mean value, the differences were minimal. The technique proposed by Vachaud et al. (1985) produced satisfactory results and identified the position in the field that best represented the mean moisture content during the investigation period, thus allowing reduction of the number of samples required to analyze soil moisture behavior with high accuracy and reduced sampling efforts (Vachaud et al., 1985; Brocca et al., 2009). The analysis on the effective errors committed using only the "representative" location for the field-mean soil moisture estimation was also carried out. The correlations between the values measured at the "representative" locations and the corresponding mean values computed for the whole area were all significant ($p < 0.05$) at 0–60 cm and 0–300 cm depths for the percent volumetric soil moisture.

3.4. The relationships between soil moisture and some summary soil parameters

Soil moisture dynamics are affected by complex interactions among several factors. Understanding the relative importance of these factors is still an important challenge in the study of water fluxes and solute transport in unsaturated media (Baroni et al., 2013). All sites are flat and with comparable exposition, topographic effects on field scale persistence, thus, can be excluded in our study area. In order to determine the main influencing factors on soil moisture variability, the spatial variability of the soil moisture was compared with the spatial variability of the soil and vegetation properties. Table 3 presents the correlation between MRDs and bulk density, organic matter content, sand, silt and clay contents, and vegetation coverage. In contrast to Jacobs et al. (2004) and Wang et al. (2013b), the quality of time-stable points can only partly be explained by soil characteristics. At two depths, sand and silt contents could explain the time-stable characteristics of the sampling points, as indicated by the high R^2 values (Table 3). We could identify soil depth without varying the impact on temporal stability under different soil moisture conditions. The measurement points in this study locate in relatively level topography. Similarity of topographic and vegetative conditions at the study sites minimized these factors affecting temporal stability.

Table 3
Coefficient of determination (R^2) between soil and vegetation characteristics and mean relative difference (MRD) of soil moisture at different soil depths.

Depth (cm)	BD (g cm^{-3})	SOM (%)	Clay (%)	Silt (%)	Sand (%)	Vegetation coverage (%)
0–60	0.011	0.033	0.13	0.569*	0.516*	0.002
0–300	0.001	0.018	0.118	0.519*	0.471*	0.002

BD, bulk density; SOM, soil organic matter.
* Significant at 0.05 probability level.

A major concern during the past years has been the identification of factors controlling spatial and temporal soil moisture variability (Grayson et al., 1997; Western et al., 1999; Entin et al., 2000) and the quantification of this variability at different scales (Seyfried, 1998; Skøien et al., 2003). Famiglietti et al. (1998) showed that these factors not only changed with scale, but that their influences also depended on the initial soil moisture condition. Some studies investigated an alternative approach by attempting to find representative locations using other properties that affect soil moisture content, such as those of topography, soil, and vegetation (Tallon and Si, 2003; Schneider et al., 2008). Such properties were either themselves relatively time persistent, thus requiring fewer or even only one measurement, and/or visually observable. This priori approach toward identifying locations of temporal stability would be of greater practical value (Grayson and Western, 1998; Gómez-Plaza et al., 2000; Zhao et al., 2010). No conclusive results, however, have been obtained for identifying representative locations based on related variables. Furthermore, the findings of some studies were conflicting. Vachaud et al. (1985) pointed to the role of soil particle size in explaining the first reported observation of soil moisture temporal stability. Tomer and Anderson (1995) found that 51–77% of spatial variability in soil moisture content could be explained by a combination of elevation, slope, and curvature in a sandy hill slope. Pires da Silva et al. (2001) found that clay content, C content, and tillage method influenced soil water storage patterns. On the other hand, Tallon and Si (2003) found poor relationships between temporal stability locations and soil and topographic properties.

4. Conclusions

This study focused on the analysis of soil profile moisture temporal stability collected at eight points of different vegetation area in a desert area. Trends in the spatial distributions and temporal dynamics of soil profile moisture at 0–60 cm and 0–300 cm were obtained through a 3-year monitoring. In general, results indicated that soil profile moisture at the artificial revegetation area was lower compared with the natural vegetation area, and the normal distribution characteristics were more obvious in wet conditions than in dry conditions. The mean soil profile moisture content demonstrated a moderate spatial variability and the variability decreased with increasing soil moisture content at 0–60 cm depth; however, the variability of soil moisture and CV were both lower and no significant correlations were found at 0–300 cm depth. As expected, a high temporal stability was observed within the study area, and the characteristics of the stabilities were more obvious at deep soil profiles. Values of SDRD and MABE at 0–300 cm profile were significantly lower than at 0–60 cm profile. The changes of overall spatial patterns (based on Spearman correlation coefficients) were not consistent with the temporal stability of the individual locations (based on SDRD). The sampling locations that were representative of the dry conditions in the field were always more temporally stable. Based on the values of MRD and SDRD, one time-stable site was determined to be representative of the mean soil moisture in our study area larger than 1 km^2, which were further verified by the high value of R^2 between the mean soil moisture content and the representative location soil moisture content. Furthermore, strong correlations at two soil layers revealed that the ranking stability approach could provide information about sampling locations potentially acting as good indicators of soil moisture at other depths. In this study, soil texture was primarily responsible for the temporal patterns in soil moisture and the dependence of soil moisture temporal stability on soil texture did not have difference among different soil depths.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2015.04.019.

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