Research papers

Spatial-temporal variability of soil water content in a cropland-shelterbelt-desert site in an arid inland river basin of Northwest China

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ARTICLE INFO

Article history:

Received 17 March 2016

Received in revised form 30 June 2016

Accepted 4 July 2016

Available online 5 July 2016

This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Renato Morbidelli, Associate Editor

Keywords:

Soil water content

Spatial variance

Temporal stability

Sampling frequency

Land use pattern

Oasis-desert ecotone

ABSTRACT

Knowledge of the spatial-temporal variability of soil water content (SWC) is critical for understanding a range of hydrological processes. In this study, the spatial variance and temporal stability of SWC were investigated in a cropland-shelterbelt-desert site at the oasis-desert ecotone in the middle of the Heihe River Basin, China. The SWC was measured on 65 occasions to a depth of 2.8 m at 45 locations during two growing seasons from 2012 to 2013. The standard deviation of the SWC versus the mean SWC exhibited a convex upward relationship in the shelterbelt with the greatest spatial variation at the SWC of around 22.0%, whereas a linearly increasing relationship was observed for the cropland, desert, and land use pattern. The standard deviation of the relative difference was positively linearly correlated with the SWC ($p < 0.05$) for the land use pattern, whereas such a relationship was not found in the three land use types. The spatial pattern of the SWC was more time stable for the land use pattern, followed by desert, shelterbelt, and cropland. The spatial pattern of SWC changed dramatically among different soil layers. The locations representing the mean SWC varied with the depth, and no location could represent the whole soil profile due to different soil texture, root distribution and irrigation management. The representative locations of each soil layer could be used to estimate the mean SWC well. The statistics of temporal stability of the SWC could be presented equally well with a low frequency of observation (30-day interval) as with a high frequency (5-day interval). Sampling frequency had little effect on the selection of the representative locations of the field mean SWC. This study provides useful information for designing the optimal strategy for sampling SWC at the oasis-desert ecotone in the arid inland river basin.

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1. Introduction

Soil water is vital to the knowledge of a series of hydrological processes, including infiltration, runoff, and evapotranspiration, at different temporal and spatial scales (Heathman et al., 2009; Corradini, 2014). It is an integrative state variable affected by climate, soil property, land cover, and topography (Famiglietti et al., 1998; Huang et al., 2016). However, the temporal variation in the spatial pattern of soil water content (SWC) might not change with time, as that if a location is the driest at a given time, it would remain the driest at other times. Vachaud et al. (1985) defined this time-invariant association between spatial location and classical statistical parametric values as temporal stability. The analysis of

the temporal stability of SWC in the arid area is important for understanding the eco-hydrological process and maintaining the sustainable development of ecosystems.

The temporal stability of SWC has been validated in different regions worldwide, from arid to humid regions (Brocca et al., 2007; Hu et al., 2009; Zhang and Shao, 2013). It was studied at different scales from field to catchment (Martinez-Fernandez and Ceballos, 2005; Brocca et al., 2007; She et al., 2015) with the smallest spatial unit from the order of less than 1 hm² (Brocca et al., 2007) to larger than 1000 km² (Martinez-Fernandez and Ceballos, 2005). Temporal stability of SWC was studied in various land use types including farmland, grassland, forestland, shrub land, and wetland (Jacobs et al., 2004; Martinez-Fernandez and Ceballos, 2005; Cosh et al., 2006; Gao et al., 2013; Liu and Shao, 2014; Li and Shao, 2015). The studied depth of temporal stability of SWC was from 5 cm (Cosh et al., 2006) to 21 m (Wang et al., 2015c) and the studied period was from several days (Jacobs et al.,

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2004) to nearly ten years (Liu and Shao, 2014). The monitoring frequency of SWC was from several minutes (Guber et al., 2008) to one month (Liu and Shao, 2014). Despite various issues were involved in the study of temporal stability of SWC, it is not well known how the monitoring frequency affects the statistics of temporal stability of SWC, and whether it affects the determination of representative locations to estimate the mean soil water content in the field.

The factors controlling the temporal stability of SWC are complex. Soil texture could significantly affect the temporal stability due to the different water holding capacities. Better temporal stable features were observed in fields with sandy loam soil than those containing silty loam soil (Mohanty and Skaggs, 2001). Land use types would result in different temporal stability of SWC due to different water uptake patterns by roots (Liu and Shao, 2014). Vegetation tended to reduce temporal stability and increase spatial variability of SWC, and plant phenology influenced the change in the inter-seasonal patterns of temporal stability (Wang et al., 2015b). The soil water condition also had an important effect on the temporal stability of SWC (de Souza et al., 2011). Therefore, temporal stability of SWC could be related to the period of sampling schemes (e.g., growing versus non-growing season and high versus low soil water conditions). Management practice, such as mulching (de Souza et al., 2011) and grazing intensities (Schneider et al., 2008), was an additional important factor for characterizing the field variability of SWC. On a large scale, the temporal stability of SWC was the result of the interplay among climate, soil properties, and survey protocols (Hu et al., 2010a; Zhu et al., 2014). In the shallow groundwater area, the fluctuant water table had a significant influence on the variations of SWC (Leung et al., 2011; Corcobado et al., 2013). However, the effects of groundwater on temporal stability of SWC need further investigation.

The combinations of land use or vegetation type had substantial effects on the variations of soil water, especially in arid and semi-arid regions (She et al., 2014; Shen et al., 2014). In the oasis-desert ecotone of the arid inland river basin such as the Heihe River Basin in China, irrigation and groundwater support both natural and agricultural ecosystems. Various land use types (i.e., cropland, woodland, desert and grassland) are distributed patchily and interspersed with each other, resulting in many representative land use patterns such as cropland-shelterbelt, shelterbelt-desert, and cropland-shelterbelt-desert. Previous studies about the spatial-temporal variability of SWC in the arid inland river basin usually focused on a single land use type such as steppe (Pan et al., 2015), desert (Zhang and Shao, 2013), wetland (Li and Shao, 2015), and agricultural field (Li and Shao, 2015). The spatial-temporal variability of SWC in the representative land use pattern requires extensive analysis. Did a temporal stability pattern of SWC exist in the land use pattern with different land uses involved? How did the irrigation management and groundwater influence the spatial-temporal variability of SWC? Did the sampling frequency affect the statistics of temporal stability of SWC? Understanding these issues is essential for ecosystem management and water resources distribution in the arid inland river basin.

In this study, a cropland-shelterbelt-desert field site with shallow groundwater table in the Heihe River Basin was selected. The SWC was measured at 45 locations to the depth of 280 cm with 65 occasions during the two growing seasons from 2012 to 2013. The objectives of this study were to (1) evaluate the spatial-temporal variability of SWC at various soil layers of a single land use type and the land use pattern, (2) investigate the factors influencing the spatial-temporal variability of SWC, and (3) identify the effect of sampling frequency on the statistics of temporal stability of SWC. This study was important to demonstrate the variation of SWC in sites with constructed land use subjected to the combined

effects of irrigation and groundwater, and provide useful information for designing the optimal strategy for sampling SWC.

2. Materials and methods

2.1. Site description

The study area was located in a desert-oasis ecotone in the middle of the Heihe River Basin, Linze County, Gansu province, China (39°21' N, 100°07' E, altitude 1374 m) (Fig. 1). The area has a continental arid temperate climate with an average annual precipitation of 116.8 mm and an average annual potential evaporation of 2390 mm. The average annual temperature is 7.6 °C with the highest temperature of 39.1 °C in July and the lowest of −27.3 °C in January. The main soil textures are sandy loam and sandy soil according to the U.S. Soil Taxonomy, and the main soil type is greyish-brown desert soil according to Chinese Soil Classification (Su et al., 2007). The main land use types are cropland, woodland, grassland, wetland, artificial land, and desert (Fig. 1c). The main plant species in the desert-oasis ecotone are maize, poplar shelterbelt trees, shrub sand-fixation plants, and other desert species, including *Populus gansuensis*, *Populus bolleana*, *Calligonum mongolicum*, *Hedysarum scoparium*, *Tamarix chinensis*, *Nitraria sphaerocarpa*, *Reaumuria soongorica*, *Bassia dasyphylla*, *Halogeton arachnoideus*, *Suaeda glauca*, *Agriophyllum squarrosum*, and *Eragrostis pilosa*.

The experiment was conducted in a flat site with a typical cropland-shelterbelt-desert land use pattern at the edge of a new oasis over two consecutive growing seasons (2012–2013) (Fig. 2a). A narrow shelterbelt was bounded on the south by cropland and on the north by desert. The cropland was farmed with maize (*Zea mays*) from March to September. The shelterbelt was established in 1982 with Gansu Poplar (*P. gansuensis*). The desert was planted with Korshinsk peashrub (*Caragana korshinskii*).

2.2. Field measurement

Three transects with 6-m intervals were laid out along the cropland-shelterbelt-desert site. Fifteen Trime-TDR access tubes (4-cm diameter, polycarbonate) with depths of 3 m and 4-m intervals were installed along each transect to measure volumetric SWC (Fig. 2b). The Trime-TDR access tube was capped at the bottom with a water-tight seal, and a removable cap was placed on top to prevent water entering the tube. A rubber gasket was sheathed the tube at the soil/tube interface to protect water infiltration along the tube. There were four, five, and six Trime-TDR tubes in the cropland, shelterbelt, and desert of each transect, respectively. The volumetric SWC was measured by TDR (TRIME-TDR-PICO-IPH-T3, Imko, Germany) at 20-cm intervals to a depth of 280 cm periodically (every 5 days) from 19 April to 27 September in 2012 and 19 April to 21 September in 2013. Additional measurements were performed before and after irrigation and rainfall events. There were 65 occasions of measurements during the two growing seasons. The two complete seasonal cycles of measurements were sufficient to determine the spatial-temporal variability of SWC (Martinez-Fernandez and Ceballos, 2005). The measured volumetric SWC was calibrated in field with the gravimetric method under both low and high soil water conditions. In total, 43 locations were used for analysis due to two damaged Trime-TDR access tubes. SWC mentioned in the following text referred to the volumetric SWC, and it was represented as a percentage.

Soil samples at a distance of 40 cm from each TDR tube were obtained with 20 cm depth intervals from the soil surface to 280 cm depth using a soil auger with a diameter of 5 cm. These samples were analyzed in the laboratory for the soil mechanical

Fig. 1. The location of the study site in the middle of the Heihe River Basin, China.

composition (Mastersizer 2000, Malvern Instruments, England), and chemical properties including the pH (1:2.5 soil:water), soil organic matter (SOM) (Walkley-Black method) (Walkley and Black, 1934), total carbon (TC), and total nitrogen (TN) (Vario EL III, Elementar, German). Furthermore, a stabilized soil profile (300-cm depth $\times$ 200-cm length $\times$ 80-cm width) was dug to a depth of 300 cm in each land use type. Undisturbed soil samples were taken from the soil profile in every 20 cm depth with three replications using standard pre-weighed 100 ml Kopecki rings (a core sampling device). The soil samples were collected to measure the bulk density (BD, gravimetric method), soil water retention curve (Hitachi-CR21G, Hitachi, Japan), and saturated hydraulic conductivity (K_s , constant head method). The soil profile was divided into five layers (0–20 cm, 20–120 cm, 120–160 cm, 160–240 cm, and 240–280 cm) according to the measured soil properties. Please refer to the detailed soil properties in Table 1 of Shen et al. (2014).

The cropland was irrigated by conventional flood irrigation once every 7–14 days with the irrigation amount of approximately 100 mm (0.1 m³ per one m²). The irrigation water was from the Heihe River sourced from the snowmelt in the Qilian Mountain, and therefore the chemical properties of the irrigation water on SWC variation could be ignored. The shelterbelt was irrigated on 20 June in 2012 and 19 May in 2013 with the irrigation amount of approximately 250 mm (Fig. 3a). Precipitation (mm), air temperature (°C), relative humidity (%), solar radiation (w/m²), wind speed (m/s), and atmospheric pressure (hpa) were measured by an AG1000 automatic weather station (Onset Computer Corporation, Pocasset, MA, USA) with approximately 300 m distance from the site. The meteorological data were recorded every 5 min with a CR1000 data logger (Campbell Scientific Inc., Logan, UT), and then stored as 30-min mean data. Precipitation and wind data were stored every 10 min. The daily reference evapotranspiration was estimated using the FAO 56 Penman-Monteith equation (Allen et al., 1998). The variations of precipitation and reference evapotranspiration are presented in Fig. 3a and b, respectively.

One groundwater level monitoring well was established in each land use type along the middle transect (Fig. 2b). The water table

was automatically recorded every 20 min by the water level logger (Hobo U20-001-04, Onset Computer Corporation, USA). The resolution of the water table depth measurements was 0.14 cm with an uncertainty of ± 0.3 cm. The fluctuation in water table depth during the study period is shown in Fig. 3c. The variation of water table was closely related to the local groundwater movement and the irrigation events.

2.3. Statistical analysis

The standard deviation of SWC ($\sigma(\theta_j)$) at time j was used to assess the spatial variability of SWC. $\sigma(\theta_j)$ was formulated as:

$$\sigma(\theta_j) = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (\theta_{ij} - \bar{\theta}_j)^2} \quad (1)$$

and

$$\bar{\theta}_j = \frac{1}{n} \sum_{i=1}^n \theta_{ij} \quad (2)$$

where θ_{ij} was the SWC at location i and on time j , $\bar{\theta}_j$ was the average SWC at time j , and n was the number of measurement locations in the site ($n = 43$ in this study).

Spearman rank correlation was one of the correlation analysis methods, and it could explain the temporal stability of SWC in the field with numerous sampling locations (Vachaud et al., 1985). The Spearman nonparametric test was widely used to evaluate the temporal persistence of the spatial pattern of SWC (Martinez-Fernandez and Ceballos, 2005; Schneider et al., 2008). The Spearman's rank correlation coefficient (r_s) was calculated as follows (Vachaud et al., 1985):

$$r_s = 1 - \frac{6 \sum_{i=1}^n (R_{ij} - R_{ij'})^2}{n(n^2 - 1)} \quad (3)$$

where R_{ij} was the rank of SWC measured at location i and on time j , $R_{ij'}$ was the rank of SWC measured at the same location i on time j' . The locations were ranked in order from dry to moist and assigned a

Fig. 2. View of cropland-shelterbelt-desert site and schematic locations for monitoring soil water content and water table.

number. The value of r_s ranged from -1 to 1 , and greater r_s implied stronger temporal stability between different time j and j' .

The relative difference (δ_{ij}) at location i and on time j was introduced to assess the temporal stability, and δ_{ij} was expressed as:

$$\delta_{ij} = \frac{\theta_{ij} - \bar{\theta}_j}{\bar{\theta}_j} \quad (4)$$

The mean relative difference ($\bar{\delta}_i$) and the standard deviation of relative difference ($\sigma(\delta_i)$) for each location were used to determine the representative location of the field mean SWC and the most temporally stable location:

$$\bar{\delta}_i = \frac{1}{m} \sum_{j=1}^m \delta_{ij} \quad (5)$$

$$\sigma(\delta_i) = \sqrt{\frac{1}{m-1} \sum_{j=1}^m (\delta_{ij} - \bar{\delta}_i)^2} \quad (6)$$

where m was the number of measurements for each location ($m = 65$ in this study).

Locations with $\bar{\delta}_i$ near zero and low $\sigma(\delta_i)$ were usually selected as representative locations to evaluate the field mean SWC (Vachaud et al., 1985). To make a tradeoff between $\bar{\delta}_i$ and $\sigma(\delta_i)$, Jacobs et al. (2004) introduced an index of temporal stability (ITS), which was calculated by:

$$ITS = \sqrt{\bar{\delta}_i^2 + \sigma(\delta_i)^2} \quad (7)$$

In this case, the location with the lowest ITS was identified as the representative location.

The SWC of the representative location obtained from the ITS was used to predict the field mean SWC. The coefficient of determination (R^2) and the root mean square error (RMSE) were used to evaluate the strength of the statistical relationship between the measured and predicted field mean SWC. R^2 and RMSE were defined as

$$R^2 = 1 - \frac{\sum_{j=1}^m (y_j - \hat{y}_j)^2}{\sum_{j=1}^m (y_j - \bar{y})^2} \quad (8)$$

$$RMSE = \sqrt{\frac{1}{m} \sum_{j=1}^m (y_j - \hat{y}_j)^2} \quad (9)$$

where $\hat{y}_j$ and y_j was the predicted and observed SWC on time j , respectively; $\bar{y}$ was the mean observed value.

3. Result

3.1. Spatial variability versus mean soil water content

The time series of the SWC at different soil layers for the whole land use pattern are presented in Fig. 4 with box and whisker plots. The box and whisker plots presented the minimum, maximum, median, lower quartile, upper quartile and the mean of the observed SWC for one observed event. The trends of the mean SWC variations in the upper four soil layers were the same, which were different from those in the deepest soil layer due to the effects of irrigation, precipitation, and groundwater. At the upper four soil layers, the SWC decreased and then fluctuated with the irrigation events and with the maximum value of around 18.0% after the flood irrigation in the shelterbelt. At the deepest soil layer (240–280 cm), the time series of mean SWC varied more dramatically than the upper four soil layers due to the influence of groundwater. The water table depth was nearly 2.8 m after the flood irrigation in the shelterbelt, and it always fluctuated with the irrigation events in the cropland, with the value around 3.2 m (Fig. 3c). The mean SWC in the 240–280 cm layer was 22.0%, which slightly exceeded the field capacity (i.e., 20.4%).

Fig. 5 showed the distribution of SWC of different locations (43 locations in this text) at different soil layers during the two growing seasons with the box and whisker plots. The maximum value of SWC was largest in the shelterbelt compared with cropland and desert. At the first three soil layers, the spatial patterns were nearly the same (Fig. 5a–c). At the depth of 160–240 cm, the spatial pattern changed, and the SWC fluctuated more strongly compared with the above three soil layers because of the integrated effect of groundwater and irrigation (Fig. 5d). The SWC at the depth of 240–280 cm was characterized by a lower spatial variability among different locations, which indicated that the 43 locations had the same pattern of SWC at this depth (Fig. 5e).

Fig. 6 shows $\sigma(\theta_j)$ versus the SWC at each land use type and the cropland-shelterbelt-desert land use pattern. The $\sigma(\theta_j)$ at the cropland was the lowest among the three land use type with a mean value of 1.7% followed by the shelterbelt (2.0%) and desert (2.6%).

Table 1Statistical summary of the Spearman' rank correlation coefficient (r_s) in different soil layers during the two growing seasons (2012–2013).

Land use	Soil layer (cm)	Mean	Standard deviation	Maximum	Minimum	Coefficient of variation
Cropland-shelterbelt-desert	0–20	0.801/0.601 ^a	0.112/0.253	0.988/0.975	0.305/–0.218	14%/42%
	20–120	0.817/0.800	0.153/0.153	0.997/0.992	0.309/0.222	19%/19%
	120–160	0.921/0.845	0.050/0.147	0.997/0.996	0.757/0.226	5%/17%
	160–240	0.778/0.877	0.303/0.110	0.994/0.993	0.001/0.396	39%/13%
	240–280	0.532/0.815	0.577/0.218	0.999/0.999	–0.757/0.005	108%/27%
Cropland	0–20	0.607/0.489	0.297/0.250	0.982/0.982	–0.555/–0.473	49%/51%
	20–120	0.679/0.605	0.419/0.319	1.000/1.000	–0.569/–0.296	62%/53%
	120–160	0.636/0.619	0.317/0.285	0.991/0.998	–0.218/–0.209	50%/46%
	160–240	0.726/0.731	0.236/0.178	0.998/1.000	0.036/0.036	33%/24%
	240–280	0.579/0.576	0.418/0.354	1.000/1.000	–0.764/–0.620	72%/62%
Shelterbelt	0–20	0.668/0.594	0.233/0.228	0.986/0.989	0.043/–0.239	35%/38%
	20–120	0.680/0.717	0.299/0.225	1.000/0.994	–0.059/0.165	44%/31%
	120–160	0.674/0.561	0.233/0.278	0.996/0.996	0.007/–0.204	35%/49%
	160–240	0.796/0.808	0.206/0.261	1.000/0.996	–0.071/–0.356	26%/32%
	240–280	0.615/0.801	0.517/0.278	1.000/1.000	–0.604/–0.750	84%/35%
Desert	0–20	0.290/0.205	0.328/0.410	0.971/0.953	–0.529/–0.701	113%/200%
	20–120	0.853/0.802	0.195/0.110	0.998/1.000	0.234/0.245	23%/14%
	120–160	0.838/0.777	0.131/0.125	0.993/0.992	0.400/0.232	16%/16%
	160–240	0.797/0.962	0.389/0.026	1.000/1.000	–0.243/0.836	49%/3%
	240–280	0.784/0.961	0.427/0.029	1.000/1.000	–0.301/0.828	54%/3%

^a Statistics in the 2012 growing season/statistics in the 2013 growing season. **Fig. 3.** Temporal variations of (a) precipitation and irrigation, (b) reference evapotranspiration (ET_0), and (c) water table depth over the two growing seasons (2012–2013).

In the cropland and desert, $\sigma(\theta_j)$ increased with increasing SWC (Fig. 6a and c). In the shelterbelt, a convex upward relationship was found where $\sigma(\theta_j)$ increased until the SWC reached approximately 22.0% and then decreased beyond that (Fig. 6b). At the depth of 240–280 cm, $\sigma(\theta_j)$ was always low and did not show a clear trend with the SWC (Fig. 6) due to the groundwater effect, where the SWC was greater than field capacity. At the land use pattern scale, the mean value of $\sigma(\theta_j)$ was 3.4%, and the relationship between $\sigma(\theta_j)$ and SWC showed a similar pattern with cropland and desert (Fig. 6d).

3.2. Temporal stability of soil water content patterns at field scale

The temporal stability of the spatial patterns of field SWC were evaluated by r_s between different observation times during the two growing seasons (2012–2013) in three typical land use types and the whole land use pattern (Table 1). The r_s matrix of different observation times in different soil layers is not shown here for the sake of brevity. The mean r_s of different soil layers was significant ($p < 0.05$) in each land use type except for the surface and bottom soil layers (0–20 cm and 240–280 cm) in the cropland,

Fig. 4. Time series of the soil water content in different soil layers during two growing seasons (2012–2013) at the cropland-shelterbelt-desert site. Vertical bars represent $\pm$ standard deviation of the soil water content. The whiskers and box lines indicate the minimum, 25th, 50th, 75th percentile, and the maximum, respectively. The multiplication sign indicates the mean value.

and the surface soil layer in the desert. Whereas, the mean r_s was significant in all soil layers over the whole land use pattern ($p < 0.01$) and shelterbelt ($p < 0.05$). The spatial pattern of the SWC was more time stable for the land use pattern followed by desert, shelterbelt, and cropland.

The mean r_s corresponding to different time lags in different soil layers is presented in Fig. 7. The time lags were the monitoring intervals of SWC, and one time lag was 5 days. The mean r_s decreased slightly with increasing time lags up to approximately 24 time lags. The spatial pattern of SWC could persist for a long time. As the mean r_s presented in Table 1, the variations in mean r_s in different land use types were different, where it was most stable in the cropland-shelterbelt-desert land use pattern, followed by desert with the 0–20 cm soil layer excepted. In the cropland and shelterbelt, the variations in mean r_s with increasing time lags had similar patterns except for the last soil layer (240–280 cm).

3.3. Temporal stability of soil water content at point scale

Fig. 8 presents $\bar{\delta}_i$, $\sigma(\delta_i)$, and ITS for each location in different soil layers. The results showed that the largest range of $\bar{\delta}_i$ appeared at the depths of 0–20 cm, 120–160 cm, and 160–240 cm, followed by 20–120 cm, and 240–280 cm. The range of $\sigma(\delta_i)$ varied greatly at different layers, with the largest value was at 120–160 cm layer ranging from 0.09 to 0.56, followed by 0.20–0.56 at 0–20 cm layer, 0.10–0.43 at 160–240 cm layer, 0.08–0.29 at 20–120 cm layer, and 0.02–0.13 at 240–280 cm layer. The surface soil had the largest value of ITS ranging from 0.20 (location 2–7) to 1.17 (location 1–1) followed by the 120–160 cm layer from 0.13 (location 1–8) to 1.09 (location 1–1), the 20–120 cm layer from 0.17 (location 3–6) to 0.58 (location 2–1), and the 160–240 cm layer from 0.13 (location 3–15) to 1.01 (location 3–12). The deepest soil layer (240–280 cm) had the minimum value of ITS, ranging from 0.02 (location

Fig. 5. The variability of soil water content among different locations during two growing seasons (2012–2013). The whiskers and box lines indicate the minimum, 25th, 50th, 75th percentile, and the maximum, respectively. The multiplication sign indicates the mean value.

2–5) to 0.30 (location 3–12). The locations with the minimum values of ITS were considered as the most representative location, which could be used to estimate the average field value on long time scales. However, the selected representative location changed with the depth, and no location could represent soil water content of the whole soil profile.

The distributions of $\bar{\delta}_i$, $\sigma(\delta_i)$, and ITS compared with r_s in different soil layers are showed in Table 2 to evaluate the spatial correlation between different soil layers. The result presented that the r_s was significant ($p < 0.01$) between the depths of 0–20 cm, 20–120 cm, and 120–160 cm, with the value ranging from 0.775 to 0.847, 0.498 to 0.801, and 0.510 to 0.767 for $\bar{\delta}_i$, $\sigma(\delta_i)$, and ITS, respectively. The results indicated that the spatial pattern of the SWC was correlated between the upper three soil layers. However, the relationship between the 160–240 cm layer and other soil layers was not significant. The correlation coefficient for $\bar{\delta}_i$ at the depth of 240–280 cm was negatively significant with the depths

of 0–20 cm, 20–120 cm, and 120–160 cm ($p < 0.05$), and positively significant with the depth of 160–240 cm ($p < 0.05$). The r_s for $\sigma(\delta_i)$ and ITS at the depth of 240–280 cm was only positively significant with those at the depths of 20–120 cm and 120–160 cm. The spatial pattern was not always persistent with depth, especially at the depth of 160–240 cm with the high variability in SWC.

Fig. 9 shows the SWC of representative locations versus that of the land use pattern at different soil depths for the entire data series. The linear fitting between every two of them was significant ($p < 0.01$). These results indicated that the temporally stable locations could predict the mean SWC of the land use pattern. The RMSE at the 240–280 cm layer was lowest with the value of 0.5% followed by the 120–160 cm (0.8%) and 20–120 cm layers (1.1%), whereas the RMSE was the largest at the depths of 0–20 cm and 160–240 cm with values of 1.2% and 1.3%, respectively. The R^2 ranged from 0.97 at the 240–280 cm depth to 0.51 at the 160–240 cm depth. The SWC obtained from the representative locations slightly

Fig. 6. Relationship between the standard deviation of soil water content and mean soil water content in (a) cropland, (b) shelterbelt, (c) desert, and (d) the cropland-shelterbelt-desert site.

overestimated the value of the land use pattern in the upper four layers, whereas the agreement was good at the depth of 240–280 cm (Fig. 9).

The SWC was positively correlated with $\sigma(\delta_i)$ ($p < 0.05$) in the land use pattern (Fig. 10). This correlation indicated that $\sigma(\delta_i)$ tended to be higher at the wetter locations, therefore the locations with high soil water condition were always temporally more variable than the locations with low soil water condition. However, the above relationship was not obvious in the single land use type (data not shown).

3.4. Effects of sampling frequency on the statistics of temporal stability

The effects of the sampling frequency on the statistics of temporal stability characteristics were evaluated by $\bar{\delta}_i$ and ITS. Data collected at intervals of 5, 10, 15, and 30 days were used. The $\bar{\delta}_i$ and ITS at each location were ranked in different soil layers, and then the distributions of $\bar{\delta}_i$ and ITS were compared with r_s at the four measurement intervals in Table 3, respectively. The high r_s indicated that the relationships were all significant ($p < 0.01$), with a value ranging between 0.979 and 1.000 for $\bar{\delta}_i$, and between 0.958 and 0.999 for ITS. The results indicated that the distribution of the locations almost did not change with the sampling frequency, and the spatial pattern was nearly same among the four measurement intervals in the same soil layer.

The locations represented the field mean SWC selected by $\bar{\delta}_i$ did not change at the four measurement intervals in different soil layers except at 15 and 30 days intervals at the depths of 20–120 cm, 120–160 cm, and 160–240 cm. However, the representative locations selected by the last two measurement intervals (15 and 30 days) were still near the same as those selected by the first two measurement intervals (5 and 10 days). The result implied

that the locations selected by $\bar{\delta}_i$ at different sampling frequency could well represent the field mean SWC with the same location. Similar result was found in the selection of the representative locations by ITS (data not shown). The result showed that the statistics of temporal stability of SWC was almost equal between the low and high frequency of monitoring. Sampling frequency had little effect on the selection of the representative locations of the field mean SWC. However, if one want to obtain the time series of SWC, it is reasonable to have higher sampling frequency of SWC.

4. Discussion

4.1. Spatial variability of soil water content

The standard deviation over space ($\sigma(\theta_j)$) increased with increasing SWC in the cropland, desert, and land use pattern (Fig. 6a, c and d), while a convex upward trend was found in the shelterbelt and the maximum $\sigma(\theta_j)$ was found at the SWC of approximately 22.0% which was close to the field capacity of the 240–280 cm layer (20.4%) (Fig. 6b). The convex upward relationship indicated that when SWC was in the transition state or in the dry-wet cycle, the spatial pattern of SWC was unstable and more sampling locations were needed to obtain the field mean SWC in this state. Furthermore, greatest variation of SWC occurred under medium porosity and soil water condition. The maximum $\sigma(\theta_j)$ changed with the land use, and the maximum $\sigma(\theta_j)$ in the cropland and shelterbelt was 6.3% and 5.5%, respectively, which were lower than that in the desert (11.0%). The soil properties influenced the spatial variance of SWC. As presented by Famiglietti et al. (2008), there were boundaries at the wilting point and porosity, with normally exhibiting minimum variances, which caused a minimum spatial variability at the boundaries. Furthermore, there was a threshold in the shelterbelt with the value of approximately

Fig. 7. Mean Spearman's rank correlation coefficient (r_s) corresponding to different time lags in cropland, shelterbelt, desert, and the cropland-shelterbelt-desert site during two growing seasons (2012–2013). Time lag was the monitoring interval of soil water content, and one time lag was 5 days.

22.0%. Pan and Peters-Lidard (2008) indicated that the variance decreased with SWC when it exceeded the threshold, and the variance increased with SWC if it was less than the threshold. In contrast, no evidence of a threshold effect was found in the cropland, desert or cropland-shelterbelt-desert land use pattern.

The above difference among the land use types might be because the range of observed SWC did not cover the whole range of wetness conditions and prevented revelation of this relationship (Brocca et al., 2010). In the shelterbelt, the SWC ranged from 5.0% to 30.0%, whereas that in the cropland and desert was less than 18.0% in the upper four layers (Fig. 6b). This might be the reason why previous studies about this relationship were contradictory (Famiglietti et al., 1998, 2008; Hupet and Vanclooster, 2002; Brocca et al., 2007, 2010; Zhang and Shao, 2013). A stochastic analysis of the unsaturated Brooks-Corey flow in heterogeneous soils used by Vereecken et al. (2007) also proved that the standard deviation of SWC peaked between 17.0% and 23.0% for all textural

classes except “sand”. The SWC in the shelterbelt at the maximum $\sigma(\theta_j)$ with the value of approximately 22.0% was in the range of the theoretical values (17.0–23.0%). A similar threshold was also found in other studies, such as the field observations across scales from 2.5 m to 50 km during the SGP97, SGP99, SMEX02, and SMEX03 campaigns in Oklahoma and Iowa in the central United States, where the threshold was approximately 20.0% (Famiglietti et al., 2008).

The maximum $\sigma(\theta_j)$ in the desert was higher than that in the cropland and shelterbelt. Vegetation tended to reduce $\sigma(\theta_j)$ (Wang et al., 2015a). The irrigation in the cropland and shelterbelt also weakened the spatial heterogeneity and decreased the spatial variance. As expected, the heterogeneity of land use increased the spatial variability, with the mean $\sigma(\theta_j)$ at the land use pattern of 3.4%, nearly twice as large as the cropland (1.7%). Similar results were also found in central Italy, within a catchment characterized by different land uses, where the mean $\sigma(\theta_j)$ increased from the

Fig. 8. Ranked mean relative difference of soil water content and the index of temporal stability (ITS) at each location in different soil layers. Vertical bars represent $\pm$ standard deviation of the relative difference.

Table 2
Matrix of Spearman's rank correlation coefficients between different soil layers.

Statistics	Soil layer (cm)	20–120	120–160	160–240	240–280
MRD	0–20	0.800**	0.847**	0.107	–0.562**
	20–120		0.775**	0.275	–0.384*
	120–160			–0.048	–0.640**
	160–240				0.336*
STD	0–20	0.611**	0.498**	–0.190	0.006
	20–120		0.801**	–0.002	0.307*
	120–160			–0.079	0.360*
	160–240				–0.032
ITS	0–20	0.553**	0.510**	–0.111	0.273
	20–120		0.767**	–0.229	0.330*
	120–160			–0.203	0.470*
	160–240				–0.040

MRD is mean relative difference.

STD is standard deviation of relative difference.

ITS is index time stability.

** Indicates correlation is significant at the 0.01 level (two-tailed).

* Indicates correlation is significant at the 0.05 level (two-tailed).

range of 2.7–4.0% at the field scale to 4.7% at the catchment scale (Zucco et al., 2014). In addition to the effect of land use, the relative mean soil water status and soil hydraulic properties exhibited different behaviors in $\sigma(\theta_j)$, and the pore size distribution of soils controlled the maximum value of $\sigma(\theta_j)$ (Vereecken et al., 2007).

4.2. Temporal variability of soil water content

The range in mean and standard deviation of the relative difference of SWC ($\bar{\delta}_i$ and $\sigma(\delta_i)$) could represent the spatial variability and temporal stability. The ranges of $\bar{\delta}_i$ at the five soil layers (0–20 cm, 20–120 cm, 120–160 cm, 160–240 cm, and 240–280 cm) could be ranked in the ascending order of 0.45, 0.29, 0.50, 0.50, and 0.07 in the cropland, 1.08, 0.52, 0.60, 0.98, and 0.11 in the shelterbelt, 0.76, 0.84, 0.79, 1.54, and 0.32 in the desert, and 1.62, 0.98, 1.59, 1.57, and 0.38 in the land use pattern (Fig. 8). The SWC at the 240–280 cm depth, being closer to the field capacity and characterized by a lower variability range, was more stable than the other soil layers due to the influence of the groundwater at all land use

Fig. 9. Comparison of measured mean soil water content versus the value at the representative location in the cropland-shelterbelt-desert site.

Fig. 10. Relationship between standard deviation of the relative difference and mean soil water content at each location in the cropland-shelterbelt-desert site.

types. In the shelterbelt, the ranges in the 0–20 cm and 160–240 cm soil layer were higher than those in other layers, which could be a result of the precipitation effect on the surface soil layer and the integrative effect of groundwater and irrigation on the fourth soil layer (160–240 cm). In the desert, the fourth soil layer also had largest range than other soil layers due to the influence of groundwater. The periodical irrigation in the cropland produced the smallest range compared with the other land use types. However, different land uses and irrigation management resulted in the large variability in the SWC at the land use pattern compared with the three land use types.

The selected locations with minimum values of ITS to represent the mean SWC varied with the depth (Fig. 8), and the representative locations of each soil layer could be used to estimate the mean SWC well (Fig. 9). The vertical variation of soil profile varied greatly among different locations due to different soil textures, root distributions and field managements. Therefore, the water flow along the vertical profile had great spatial variability and the spatial pattern of SWC changed dramatically among different soil layers. The location representing the mean SWC in one soil layer could not

Table 3

Matrix of Spearman's rank correlation coefficients between different monitoring frequencies at different soil layers.

Soil layer (cm)	Frequency (day)	10	15	30
0–20	5	0.998**/0.989**	0.998**/0.988**	0.993**/0.958**
	10		0.996**/0.984**	0.994**/0.969**
	15			0.994**/0.977**
20–120	5	0.998**/0.995**	0.990**/0.969**	0.996**/0.972**
	10		0.986**/0.973**	0.996**/0.985**
	15			0.993**/0.964**
120–160	5	1.000**/0.999**	1.000**/0.995**	0.998**/0.988**
	10		0.999**/0.996**	0.998**/0.990**
	15			0.997**/0.995**
160–240	5	0.999**/0.992**	0.999**/0.989**	0.990**/0.982**
	10		0.998**/0.986**	0.991**/0.986**
	15			0.990**/0.992**
240–280	5	0.997**/0.994**	0.987**/0.989**	0.982**/0.985**
	10		0.983**/0.985**	0.979**/0.986**
	15			0.995**/0.992**

Spearman's rank correlation coefficients of MRD/Spearman's rank correlation coefficients of ITS.

** Indicates correlation is significant at the 0.01 level (two-tailed).

represent the value in other soil layers. This statistical finding was important for providing insight in determining measurement locations and field scale strategy for sampling SWC, as well as providing data sets for hydrologic modeling. However, it was not

reasonable to model the SWC using one location for the whole soil profile as no location could represent the whole soil profile.

There was no clear relationship between $\sigma(\delta_i)$ and mean SWC in the three different land uses due to the soil homogeneity and flat topography under a single land use type. Similar results were reported for a 6 hm² cropland in Maryland, U.S.A. (Guber et al., 2008), and a 1.4 hm² semi-arid steppe with different grazing management schemes in Inner Mongolia, China (Schneider et al., 2008). Nevertheless, the relationship between the $\sigma(\delta_i)$ and mean SWC in the land use pattern was positively significant ($p < 0.05$) (Fig. 10). The result implied that the locations with low soil water condition were always temporally more stable than the locations with high soil water condition. The result was consistent with the studies in arid and semiarid areas by Martinez-Fernandez and Ceballos (2003) and Zhang and Shao (2013), who attributed the notable relationship to the predominance of the inability of sandy fraction to retain water, where the SWC values at the locations with sandy soil would never be high. However, as presented by Hu et al. (2010b) that the relationship was index-specific, if the mean absolute bias error (MABE) index was used, the sites with high soil water condition were more stable. In this study, the soil properties were homogeneous, and the locations with low soil water condition were distributed in the desert, whereas the locations with high soil water condition were in the cropland. The cropland was irrigated periodically, and the SWC always varied from dry to wet conditions. Therefore, the variance in the cropland was larger compared with that in the desert. The irrigation management rather than other factors produced less time-stable SWC patterns.

5. Conclusion

In this study, the spatial variance and temporal stability of SWC were investigated in a cropland-shelterbelt-desert site at the oasis-desert ecotone in the middle of the Heihe River Basin, China. The standard deviation of the SWC over space increased with SWC in the cropland, desert and land use pattern. In contrast, a convex upward relationship was found in the shelterbelt, and the SWC corresponding to the maximum standard deviation was approximately 22.0%. The standard deviation of the relative difference was positively linearly correlated with SWC ($p < 0.05$) in the land use pattern, whereas this relationship was not found in the three land use types. The stable locations varied at different soil layers as well as for the driest or wettest locations obtained from the ranked mean relative difference, and no location could represent the soil water content of the whole soil profile. The representative locations of each soil layer could estimate the mean SWC well. High-frequency data observation (5-day interval) did not provide advantages for obtaining the statistics of the temporal stability of SWC over low-frequency data observation (30-day interval). In the oasis-desert ecotone, the SWC in the land use pattern was even more temporally stable than that in the single land use type, and the land use pattern exhibited great time stability characteristics and captured the field mean behavior of SWC variation.

Acknowledgements

This research was financially supported by the National Natural Science Foundation of China (91425301 and 91025018), the joint project funded by China Postdoctoral Science Foundation and Chinese Academy Sciences (2015LH0038), and the Youth Innovation Promotion Association CAS. We would like to thank the Linze Inland River Basin Research Station Experimental for field experiment support. We thank the reviewers for their constructive comments which improve the quality of this manuscript.

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