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ORIGINAL ARTICLE

Temporal stability of soil water storage in three landscapes in the middle reaches of the Heihe River, northwestern China

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Abstract Temporal stability of soil moisture is important for the sustainability of compound ecosystems where different landscapes coexist and interact with each other. In this study, an arid region composed of desert, cropland and wetland in northwestern China was selected to evaluate the temporal stability of soil water storage (SWS) and identify the representative locations of the spatial mean SWSs in diverse soil layers of each landscape. Soil water storages of 0–1, 1–2 and 2–3 m soil layers were estimated from volumetric water contents measured at fixed intervals in a regular 1 × 1 km grid in an area of 100 km^2 from May 2011 to December 2012 using a neutron probe. Spearman's rank correlation and relative difference analysis both indicated the increasing temporal stability of SWS with depth in the three landscapes. Locations with the lowest standard deviation of relative differences accurately estimated the spatial mean SWSs after providing constant offsets. At the representative locations in the three layers of the desert, the cumulative probabilities for clay, silt, sand and soil organic carbon contents were <0.25, <0.25, >0.75 and between 0.5 and 0.75, respectively, and the respective values in the cropland were >0.75, between 0.5 and 0.75, between 0.25 and 0.5 and between 0.5 and 0.75. An a priori approach was then proposed to select the potential representative locations in larger areas of the desert and cropland, from which actual representative locations can be identified after long period measurement. This strategy is economic and labor saving, and can benefit upscaling studies.

Keywords Inland arid region · Soil moisture · Spatial pattern · Temporal persistence

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Introduction

In the middle reaches of the Heihe River in northwestern China, oases of different shapes and sizes coexist with widespread desert. Oases consist of cropland and wetland. These three landscapes are interrelated and interact with each other, and water resources act as the linkage to maintain the compound ecosystem (Zhao and Cheng 2002). Environmental degradation, secondary salinization and land desertification due to water shortages severely threaten the sustainability of the ecosystem (Chen et al. 2005). The spatiotemporal distribution and dynamics of soil water storage (SWS) may provide information on the exchange of soil moisture among landscapes and between groundwater and surface water. Monitoring SWS accurately is thus essential in hydrological research at different spatio-temporal scales (Entin et al. 2000), but is difficult due to high spatial or temporal variability (Hu et al. 2009; Jia and Shao 2013). Site-specific measurements with fine resolution in both space and time are time-consuming, costly and laborious. The analysis of temporal stability may be an

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alternative strategy to accurately estimate average SWS with reduced effort (Hu et al. 2012).

Vachaud et al. (1985) first proposed the concept of temporal stability. Soil water storage varies over space and time, making it challenging to monitor SWS in large areas for long periods. The pattern of spatial variability, however, is most often stable over time. If a field is surveyed repeatedly, the field-averaged SWS can remain stable over time. The phenomenon is also termed temporal persistence (Kachanoski and de Jong 1988) or rank stability (Tallon and Si 2004). Temporal stability of SWS has been observed on a large variety of scales (Pachepsky et al. 2005; Martínez-Fernández and Ceballos 2005), covering a wide range of terrains, sampling methods, land uses and climate regions (Cosh et al. 2008; Hu et al. 2011; Penna et al. 2013). A recent study using multivariate empirical mode decomposition indicated that temporal stability of SWS can be scale- and season-specific (Hu et al. 2014). The essence of using the concept of temporal stability in developing an efficient sampling strategy is to identify reliable locations that can evaluate the spatial mean SWS. Future sampling or observation can then be limited to these representative locations. Biswas (2014) reported that the temporal stability of SWS in a hummocky landscape was season-dependent, and the representative locations were depth-dependent. The concept of temporal stability has been applied to estimate mean soil moisture in an area with the measured soil moisture at the most time stable location in an adjacent or distant area (Gao et al. 2013a, b; Hu et al. 2013). Mean soil water content in profile at a point or a hillslope scale could be well estimated from soil water content at a certain depth at a point (Hu and Si 2014). The temporal stability may be of relevance for the scaling and interpolation of measurements of soil moisture, serving for the in situ ground truth locations for remotely sensed calibration and validation of soil moisture (Heathman et al. 2012).

Characterization of spatiotemporal variability of soil moisture in areas larger than 100 km^2 has proved fundamental for developing techniques for soil moisture scaling (Brocca et al. 2012). Previous studies on temporal stability of soil moisture have been conducted either in large regions but for short periods (Choi and Jacobs 2007, 2011) or for long periods but in small regions (Jia et al. 2013). Research in large regions has focused on shallow layers (Cosh et al. 2008; Brocca et al. 2012; Zucco et al. 2014). Direct measurements at depth were rare, and study for complex patterns of landscapes has received little attention. Site in grassland was identified as the most representative of soil moisture in the 0–15 cm soil at a catchment with various types of land use (Zucco et al. 2014). Previous study in large irrigated cropland was rare, and whether soil moisture of cropland was stable during the growing period under irrigation was little known. Various studies have identified representative locations, but no conclusive means of determining the definable features of such locations has been ascribed (Guber et al. 2008; Zhao et al. 2010b). Representative locations are usually determined after long periods of observation, and an a priori approach is more appealing. Multiple linear regression equations have been established to predict the best locations of temporal stability of soil moisture in an artificial revegetation desert area, China. These equations used elevation, bulk density, soil organic matter, clay content and silt content as independent variables, and mean relative difference as dependent variables (Wang et al. 2013). To get insight into the temporal stability of SWS in a compound ecosystem, we measured SWS of three landscapes in an arid region of northwestern China over 18 occasions. The specific objectives of this study were: (1) to analyze the temporal stability of SWS and identify the representative locations in different soil layers of each landscape and (2) to determine predictors of the potential representative locations in larger regions of each landscape.

Materials and methods

Study area

The study was performed in Linze County, Gansu Province, China (Fig. 1). The region has a continental arid climate with cold winters and hot summers (mean annual lowest and highest air temperature is −27 and 39.1 °C in January and August, respectively) and a mean annual air temperature of 7.6 °C. Mean annual precipitation is 120 mm, about 60 % of which falls from July to September, while only 3 % falls during winter. Mean annual potential pan evaporation is 2,360 mm, and the drying index is 15.9 (Zhao et al. 2010a). This region is characterized by desert with fixed or half-fixed sand dunes, cropland in patchily distributed oases and wetland with seasonal flooding. Zonal soil in the northern marginal oasis is an Aridisol derived from diluvial-alluvial materials. Entisols form after the long-term encroachment of drift sand from the Badain Jaran Desert and the deposition of aeolian sand. In the old oases in the central and southern parts of the study area, Siltigi-Orthic Anthrosols develop under long-term irrigation from sediment-rich water, fertilization and cultivation (Su et al. 2009). Inceptisols develop in meadow wetland in the southwestern part of the study area. The natural desert vegetation includes *Calligonum gobicum* (Bge.) A. Los., *C. mongolicum* Turcz., *Nitraria sphaerocarpa* Maxim., *Reaumuria soongorica* (Pall.) Maxim., *Haloxylon ammodendron* (C.A. Mey.) Bge., *Caragana korshinskii* Kom., *Hedysarum scoparium* Fisch. et Mey., and *Tamarix chinensis* Lour. Maize (*Zea mays* L.) for seeds is the staple crop.

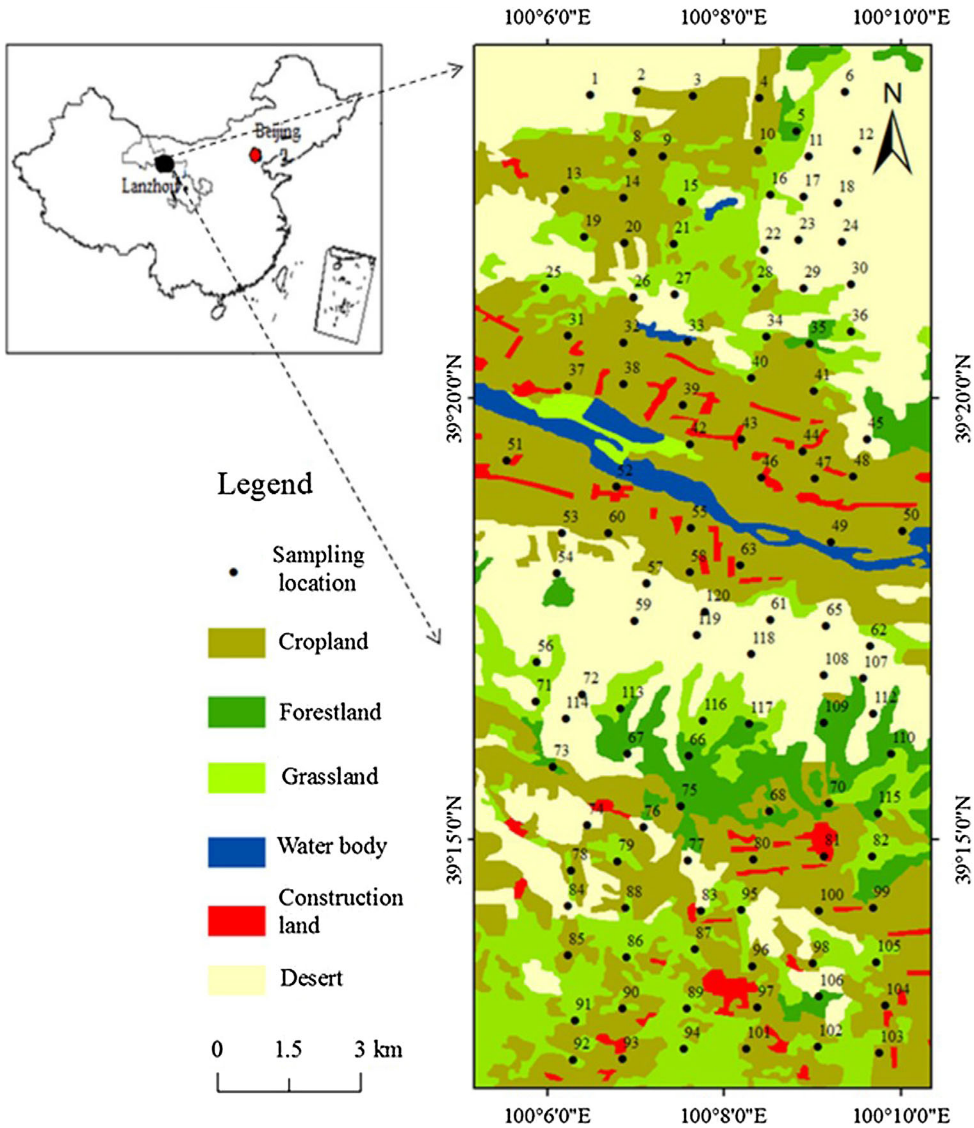

Fig. 1 The location of the study area in China and the sampling locations in the study area

Maize was sown on 9–11 April and harvested on 10–12 September in 2011 and sown on 14–16 April and harvested on 14–15 September in 2012. Agriculture relies on conventional flood irrigation sourced from groundwater (Chen et al. 2005). Maize was irrigated with 120 mm seven times (at 15–17 day intervals) during the growing period. The predominant species in wetland are Common Reed (*Phragmites australis* (Cav.) Trin. ex Steud.), Common Leymus (*Leymus secalinus* (Georgi) Tzvel.), *Achnatherum splendens* (Trin.) Nevski, *Kalidium foliatum* (Pall.) Moq. and *Nitraria tangutorum* Bobr.

This study covered a rectangular area (20 × 5 km) oriented lengthwise north–south and located at the Linze Inland River Basin Comprehensive Research Station (39°21′N, 100°07′E, 1,380 m a.s.l.), Chinese Ecosystem Research Network. The northern part of the study area includes the southern margin of the Badain Jaran Desert. The Heihe River flows across the middle of the area from east to west (Fig. 1).

Measurement of soil moisture

An array of 116 aluminum neutron-probe access tubes was installed in a 1 × 1 km grid in April 2011 (Fig. 1). Only 100 and 77 tubes were able to reach depths of 2–3 m, respectively, due to anthropogenic disturbances. Soil volumetric water contents (θ, cm^3 cm^{-3}) were measured at the 116 locations using a neutron probe and the piecewise constant rule (at 0.1- and 0.2-m intervals for the 0–1 and 1–3 m soil layers, respectively) was applied. The measurements were implemented once a month and lasted for 5 days from May to October in 2011, in December 2011 and from February to December in 2012, forming a dataset with a total of 18 occasions. The measurements in May of the 2 years were before the first irrigation after sowing, and the other 16 occasions were several days after irrigation. Soil water storage for location i at time j, $SWS_{i,j}$ (mm), in the 0–1, 1–2 and 2–3 m soil layers, was calculated from $\theta(i,j,k)$ (where k is soil depth, m) by:

$$\begin{aligned} SWS_{i,j}(0-1\,\mathrm{m}) &= [\theta(i,j,0.1)+\theta(i,j,0.2)+\cdots+\theta(i,j,1.0)]\times 100 \\ SWS_{i,j}(1-2\,\mathrm{m}) &= [\theta(i,j,1.2)+\theta(i,j,1.4)+\cdots+\theta(i,j,2.0)]\times 200 \\ SWS_{i,j}(2-3\,\mathrm{m}) &= [\theta(i,j,2.2)+\theta(i,j,2.4)+\cdots+\theta(i,j,3.0)]\times 200 \end{aligned} \tag{1}$$

To measure the mechanical composition and soil organic carbon (SOC) content, sampling was implemented using a hand auger 5 cm in diameter before the measurement period. Disturbed soil samples were collected at the same intervals described above and were sealed in air-tight bags and taken to the laboratory. The samples were air dried and divided into two subsamples. One was passed through a 2-mm mesh to analyze the mechanical composition by laser diffraction with a Mastersizer 2000 particle-size analyzer (Malvern Instruments, Malvern, England). The other subsample was passed through a 0.25-mm mesh to determine SOC content by the dichromate method (Walkley and Black 1934).

Analysis of data

Spearman's rank correlation coefficient, r_s, was used to determine the correlations of location rankings between observations from different dates. It assessed the temporal persistence of SWS spatial patterns for each landscape during the measurement period. The coefficient is evaluated as:

$$r_s = 1 - \frac{6\sum_{i=1}^{n}\left(R_{i,j}-R_{i,j'}\right)^2}{n(n^2-1)} \tag{2}$$

where n is the number of observed locations for each landscape, $R_{i,j}$ is the rank of SWS measured at location i and time j and $R_{i,j'}$ is the rank of SWS measured at location i but at time j'. The value of r_s ranges from -1 to 1. A value of $r_s = 1$ corresponds to a total agreement of rank for any location and implies perfect temporal stability between dates j and j'. The closer r_s is to 1, the more stable the SWS spatial pattern (Hu et al. 2012).

The analysis of relative differences is applied for evaluating temporal stability of SWS at individual locations. According to Vachaud et al. (1985), the relative difference, $\delta_{i,j}$, between a determination of SWS at a specific location and time and the spatial mean SWS at the same time is defined as:

$$\delta_{i,j} = \frac{SWS_{i,j} - \overline{SWS_j}}{\overline{SWS_j}} \tag{3}$$

where $SWS_{i,j}$ is SWS for location i at time j and $\overline{SWS_j}$ is the spatial mean SWS at time j. The mean relative difference for each location, $\overline{\delta_i}$, and the standard deviation of the relative differences, $\sigma(\delta_i)$, over the measurement period can be calculated by:

$$\overline{\delta_i} = \frac{1}{m}\sum_{j=1}^{m}\delta_{i,j} \tag{4}$$

and

$$\sigma(\delta_i) = \sqrt{\frac{1}{m-1}\sum_{j=1}^{m}\left(\delta_{i,j}-\overline{\delta_i}\right)^2} \tag{5}$$

where m is the number of measurement occasions. Relative difference analysis identifies locations that consistently overestimate ($\overline{\delta_i} > 0$), underestimate ($\overline{\delta_i} < 0$) or approach ($\overline{\delta_i} \approx 0$) the spatial mean over time. $\sigma(\delta_i)$ characterizes the variability of $\delta_{i,j}$ at each location during the period of measurement. The location with the lowest $\sigma(\delta_i)$ is regarded as the most stable over time.

Representative location is defined as the location where measured SWS either is close to the spatial mean SWS or can obtain the spatial mean SWS after easy transformation (Vanderlinden et al. 2012). The simplest method to identify representative location is to select the location with the $\overline{|\delta_i|}$ closest to zero and low $\sigma(\delta_i)$ (Vachaud et al. 1985). Although SWS at such location mostly approximates to the spatial mean SWS, it may not be the most stable due to the inherent error of $\sigma(\delta_i)$. The most stable location will give more precise estimates because bias is potentially correctable, whereas standard deviation is not (Schneider et al. 2008). According to Grayson and Western (1998), $\overline{SWS_j}$ can be indirectly estimated by providing a constant offset of $\overline{\delta_i}$ to the SWS at the most stable location, SWS_i, which can be expressed as:

$$\overline{SWS_j} = \frac{SWS_i}{1+\overline{\delta_i}} \tag{6}$$

Results and discussion

The temporal pattern of SWS

The time series of the spatial mean SWSs and the coefficients of variation (CVs) in the 0–1, 1–2 and 2–3 m soil layers in the desert, cropland and wetland are shown in Fig. 2. The 0–1 m soil layer had the highest root activity and was susceptible to change in meteorological conditions, resulting in more dynamic SWS (Fig. 2a) (Hu et al. 2010). The spatial mean SWSs were highest in the wetland and lowest in the desert at individual depths during the measurement period (Fig. 2a). Significant differences in spatial mean SWSs were observed among the three

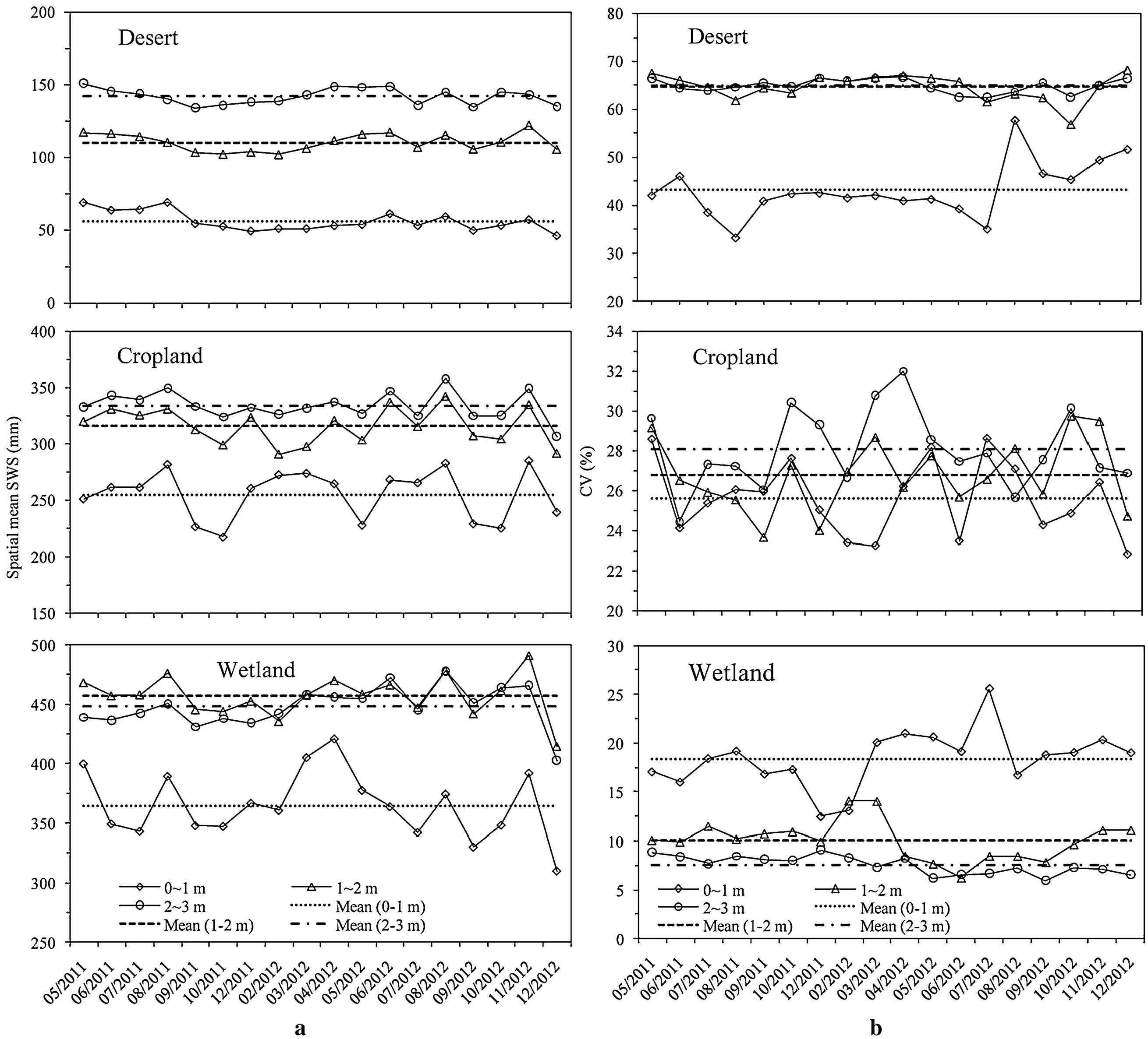

Fig. 2 Temporal series of the spatial mean soil water storage (**a**) and the coefficient of variation (CV) for SWS (**b**)

landscapes at each depth and among the three layers in the desert and cropland ($P < 0.05$).

The time series of spatial CVs for SWS exhibited distinctive characteristics among different landscapes at each depth and among different soil layers in each landscape (Fig. 2b). For the desert, SWSs were more spatially variable in the deeper layers than in the 0–1 m soil layer, but the spatial patterns in deeper layers were more stable over time (Fig. 2b). Low precipitation, high evaporation and the water uptake by roots were likely responsible for the lower spatial variability, and the seasonal changes of these factors may account for the higher temporal variability of SWS in the 0–1 m soil layer in the desert. For the cropland, the relatively low spatial variability in SWS in the 0–1 m layer was due to the uniform cultivation, tillage and irrigation practices (Fig. 2b). The temporal mean CVs were 25.6, 26.8 and 28.0 % in the 0–1, 1–2 and 2–3 m soil layers, respectively. These values were slightly larger than that (21 %) of water content in the 0–15 cm cropland soil of two catchments covering areas of 178 and 242 km^2 (Brocca et al. 2012). The CVs of the spatial CVs over time were 7.3, 6.7 and 7.0 % in the 0–1, 1–2 and 2–3 m soil layers, respectively. The moderate spatial variability of SWS in the cropland changed uniformly and weakly over time. For the wetland, the spatial variability in SWS decreased with increasing depth. The spatial variability in SWS changed moderately over time with temporal CVs of 16.1, 20.3 and 12.3 % in the 0–1, 1–2 and 2–3 m soil

Table 1 Pearson correlation coefficients between the spatial mean soil water storage and the standard deviation of soil water storage over space during the period of measurement

Depth range (m)	Desert	Cropland	Wetland
0–1	0.52*	0.74**	0.52*
1–2	0.82**	0.60**	−0.05
2–3	0.85**	0.21	0.04

*, ** The correlation is significant at the 0.05 and 0.01 levels, respectively

layers. Soil water storage in the 1–2 m soil layer was less stable over time owing to the influence of seasonal fluctuations of groundwater. The different magnitudes of spatial variability in SWS among landscapes were due to differences in the capacity of the soils to retain water, which is determined by soil texture, SOC content, bulk density, hydraulic conductivity and the coverage and diversity of vegetation.

Positive correlations between the spatial mean SWS and the standard deviation of SWS over space indicated higher spatial variability in relatively wetter soils of the desert and cropland (Table 1). This result is consistent with the report by Brocca et al. (2012). The correlation increased with depth in the desert (Table 1). Severe evaporation and water uptake by shrubs and annual herbs weakened the spatial heterogeneity of soil moisture in the 0–1 m layer in the desert. In deeper layers, the conditions of soil moisture dominantly controlled the spatial variability in SWS. Similar findings have been reported in different soils (Hupet and Vanclooster 2002; Gao and Shao 2012). The trend of higher spatial variability in SWS in wetter soils declined with increasing depth in the cropland (Table 1). Flooding irrigation dramatically affected soil moisture in the 0–1 m soil layer in the cropland and served as the key controller of SWS during the growing period. The spatial variability in SWS was also high at wet locations in the 0–1 m layer in wetland. A shallow level of groundwater saturated the soils in the lower layers (soil volumetric water contents ranged from 30 to 60 %), and soil water could easily move elsewhere, resulting in a relatively homogeneous spatial pattern of SWS in the lower layers in the wetland.

Temporal stability of SWS

Temporal persistence of SWS spatial patterns

Due to the space limitation, only r_s for the 0–1 and 2–3 m soil layers in the desert are presented (Table 2). For the desert, strong atmospheric demands dominate water fluxes and allow the SWS spatial patterns to persist, although the capacity of the soil to hold water is reduced by the coarse texture, loose structure and low SOC content (Schneider et al. 2008). High r_s between the 18 occasions indicated the temporal persistence of SWS spatial patterns in soil profiles of the desert, cropland and wetland. The mean r_s increased with depth for the three landscapes. Increases in the temporal persistence of spatial patterns of soil moisture with depth have been extensively reported (Kamgar et al. 1993; Gao and Shao 2012; Penna et al. 2013). This result can be attributed to a lack of water uptake by roots, the relatively stable pattern of pedogenetically derived variations, the much more pronounced dynamics of soil structure and the ability of the soil to retain water in deeper layers (Korsunskaya et al. 1995; Cassel et al. 2000). The time that water took to percolate from surface to deeper layers also decreased the temporal variation in soil moisture in deeper layer than in the topsoil (Penna et al. 2013).

The mean r_s decreased by varying degrees at individual depths for different landscapes when the time interval between observing dates increased (Fig. 3). The mean r_s for the 0–1 m soil layer decreased by 0.08 and 0.18 for the desert and by 0.03 and 0.12 for the cropland when time lags increased from 3 months to 6 and 12 months, respectively (Fig. 3). Schneider et al. (2008) and Penna et al. (2013) also observed declines in the temporal persistence of soil moisture with increasing time lags between samplings. Changes in air temperature, precipitation, surface coverage, species composition and the rooting structure of vegetation all affect evapotranspiration, thus impacting SWS in the 0–1 m soil layer (Gómez-Plaza et al. 2000; Zhao et al. 2010b). The decreases in mean r_s with increasing time lags could be ignored in deeper layers in the desert and cropland (Fig. 3). The decrease in mean r_s at individual depths of wetland soil was relatively larger within the same time intervals (Fig. 3). Relatively stronger temporal variability in SWS of the wetland with increasing time lags may be due to fluctuations of the shallow groundwater by the pumping for irrigation in the growing period of maize and the freeze–thaw cycles in winter and spring. However, r_s was significant at all depths of the three landscapes ($P < 0.01$ or 0.05). The spatial patterns of SWS in soil profiles of the three landscapes were generally persistent with lower frequencies of observation. The temporal persistence of soil moisture spatial patterns can thus be revealed equally well by low-frequency observation as it can by high-frequency observation (Guber et al. 2008).

Temporal stability of SWS at individual locations

Figures 4, 5, 6 present the ranked $\overline{\delta_i} \pm \sigma(\delta_i)$ of SWS in the three soil layers in each landscape. The wetland had the lowest and the desert had the highest ranges of $\overline{\delta_i}$ in the

Table 2 Spearman's rank correlation coefficients, r_s, between the soil water storage measurements over the 18 occasions in the 0–1 m (A) and 2–3 m (B) soil layers in the desert

	1[a]	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1_A	1.00	0.88	0.80	0.74	0.64	0.64	0.63	0.69	0.65	0.62	0.66	0.59	0.64	0.59	0.54	0.45	0.43	0.47
2_A		1.00	0.89	0.82	0.79	0.78	0.82	0.85	0.84	0.84	0.78	0.67	0.70	0.66	0.67	0.43	0.38	0.54
3_A			1.00	0.92	0.88	0.86	0.86	0.90	0.85	0.87	0.86	0.66	0.72	0.68	0.70	0.49	0.52	0.60
4_A				1.00	0.93	0.92	0.91	0.93	0.92	0.92	0.90	0.71	0.76	0.67	0.71	0.59	0.53	0.64
5_A					1.00	0.97	0.95	0.94	0.96	0.94	0.87	0.72	0.71	0.66	0.71	0.51	0.49	0.65
6_A						1.00	0.99	0.96	0.98	0.97	0.89	0.72	0.73	0.69	0.75	0.53	0.54	0.68
7_A							1.00	0.97	0.98	0.96	0.91	0.74	0.76	0.67	0.71	0.48	0.55	0.62
8_A								1.00	0.95	0.94	0.90	0.74	0.74	0.70	0.70	0.51	0.54	0.61
9_A									1.00	0.96	0.92	0.78	0.76	0.72	0.71	0.49	0.55	0.65
10_A										1.00	0.94	0.70	0.76	0.71	0.71	0.54	0.59	0.66
11_A											1.00	0.75	0.79	0.74	0.73	0.59	0.59	0.68
12_A												1.00	0.76	0.71	0.68	0.47	0.41	0.57
13_A													1.00	0.80	0.80	0.70	0.67	0.69
14_A														1.00	0.75	0.63	0.64	0.72
15_A															1.00	0.67	0.57	0.72
16_A																1.00	0.76	0.75
17_A																	1.00	0.78
18_A																		1.00
1_B	1.00	0.99	0.99	0.97	0.99	0.98	0.97	0.97	0.97	0.96	0.97	0.97	0.95	0.93	0.93	0.92	0.94	0.95
2_B		1.00	1.00	0.97	0.99	0.99	0.97	0.97	0.97	0.96	0.97	0.97	0.96	0.94	0.95	0.93	0.96	0.94
3_B			1.00	0.98	0.99	0.99	0.96	0.95	0.95	0.94	0.96	0.97	0.97	0.95	0.95	0.93	0.96	0.93
4_B				1.00	0.99	0.98	0.96	0.95	0.95	0.95	0.94	0.95	0.95	0.92	0.92	0.91	0.93	0.92
5_B					1.00	0.99	0.97	0.97	0.96	0.96	0.97	0.98	0.97	0.95	0.96	0.94	0.95	0.94
6_B						1.00	0.98	0.98	0.98	0.97	0.97	0.97	0.96	0.94	0.95	0.92	0.93	0.96
7_B							1.00	0.98	0.98	0.98	0.96	0.95	0.94	0.90	0.93	0.89	0.92	0.96
8_B								1.00	1.00	0.99	0.98	0.94	0.93	0.88	0.91	0.87	0.89	0.97
9_B									1.00	0.99	0.97	0.94	0.92	0.87	0.90	0.86	0.88	0.97
10_B										1.00	0.98	0.95	0.91	0.87	0.90	0.85	0.89	0.98
11_B											1.00	0.97	0.94	0.91	0.93	0.90	0.92	0.96
12_B												1.00	0.98	0.97	0.98	0.93	0.96	0.94
13_B													1.00	0.97	0.97	0.97	0.98	0.92
14_B														1.00	0.96	0.95	0.97	0.90
15_B															1.00	0.94	0.96	0.89
16_B																1.00	0.97	0.86
17_B																	1.00	0.90
18_B																		1.00

[a] Ascending numbers refer to the soil water storage measurements from May 2011 to December 2012 in sequence

three soil layers, and the 0–1 m soil layer had the lowest range of $\overline{\delta_i}$ for the three landscapes (Figs. 4, 5, 6). The $\sigma(\delta_i)$ increased with the increasing $\overline{\delta_i}$ in soil profiles of the desert and wetland (Figs. 4, 6). Positive correlations between these two variables indicated that the temporal stability of SWS declined at wetter locations for the desert and wetland (Table 3). Negative correlations between $\overline{\delta_i}$ and $\sigma(\delta_i)$ in the cropland indicates that wetter locations were likely to be more stable over time (Table 3). High temporal stabilities of soil moisture in dry soils have been reported by different studies (Martínez-Fernández and Ceballos 2003; Jacobs et al. 2004; Cosh et al. 2008). In contrast, Guber et al. (2008) found no dependence of temporal stability on the average water content at a particular location. Differences in land use, soil properties and hydrological factors may account for the conflicting findings of these studies. Using the location with $|\overline{\delta_i}|$ closest to zero to represent the spatial mean SWS may thus be inappropriate due to the high $\sigma(\delta_i)$.

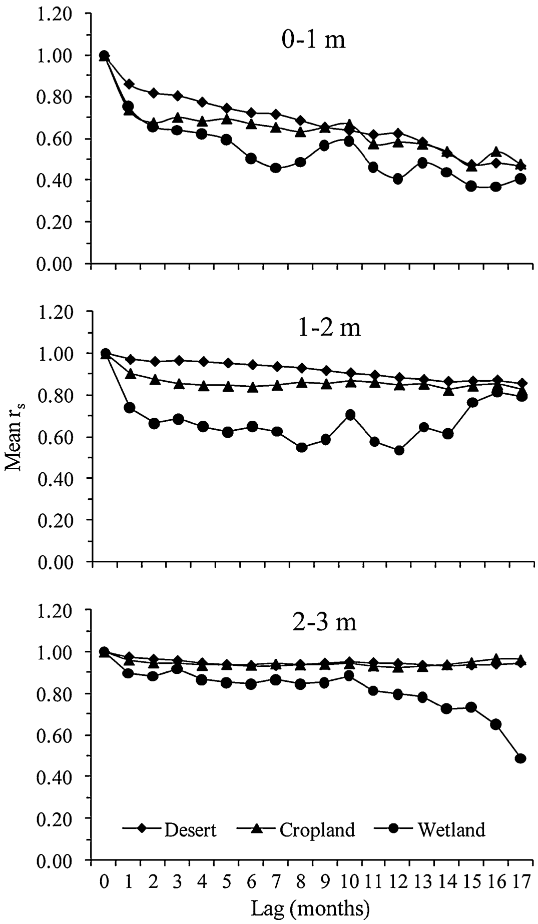

Fig. 3 Time dependence of the mean Spearman's rank correlation coefficients

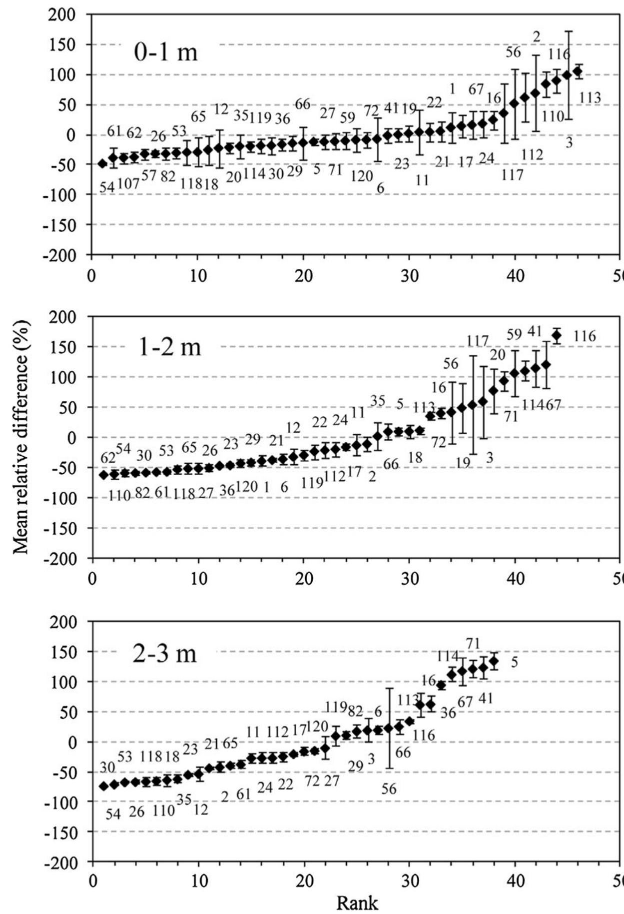

Fig. 4 Ranked mean relative differences of soil water storage in the desert. Values *above* or *below* the *bars* are the location numbers. Standard *error bars* correspond to ±1 standard deviation of the relative differences

The lowest temporal stability of SWS in the 1–2 m wetland soil can be due to the influence of the freeze–thaw cycles and the seasonal fluctuations of the groundwater. A shallow water table has been reported to cause considerable temporal variability in relative water content (Guber et al. 2008).

Representative locations

Table 4 lists the statistics for comparing the spatial mean SWS with SWS of the location with the $\overline{|\delta_i|}$ nearest to zero and with SWS of the most stable location by providing a constant offset of $\overline{\delta_i}$. Locations 54, 62 and 30 were the driest and the most stable in the 0–1, 1–2 and 2–3 m soil layers in the desert, respectively (Fig. 4). Soil water storages at the most stable locations in the cropland were slightly higher than the spatial means (Fig. 5; Table 4). The most stable locations in the wetland were relatively drier (Fig. 6; Table 4). After applying the constant offset of $\overline{\delta_i}$, the most stable location estimated the spatial mean SWS at individual depth of each landscape well through a higher coefficient of determination and a lower mean bias error and root mean square error (Table 4). The most stable locations after offset could accurately estimate the average SWSs at individual depths in the three landscapes. This result coincides with previous report (Starks et al. 2006). No single location could represent the three layers simultaneously in any of the landscapes, which was consistent with previous studies (Heathman et al. 2009; Martinez et al. 2013).

Factors influencing the temporal stability of SWS

The sensors used, temporal frequency of measurement, topography of study area and site-specific soil properties have been shown to affect the temporal stability of soil moisture (Vanderlinden et al. 2012). The representative locations were generally found with average topographic characteristics (Thierfelder et al. 2003; Brocca et al. 2009; Sur et al. 2013). Even though representative locations in this study were in the central position of each landscape,

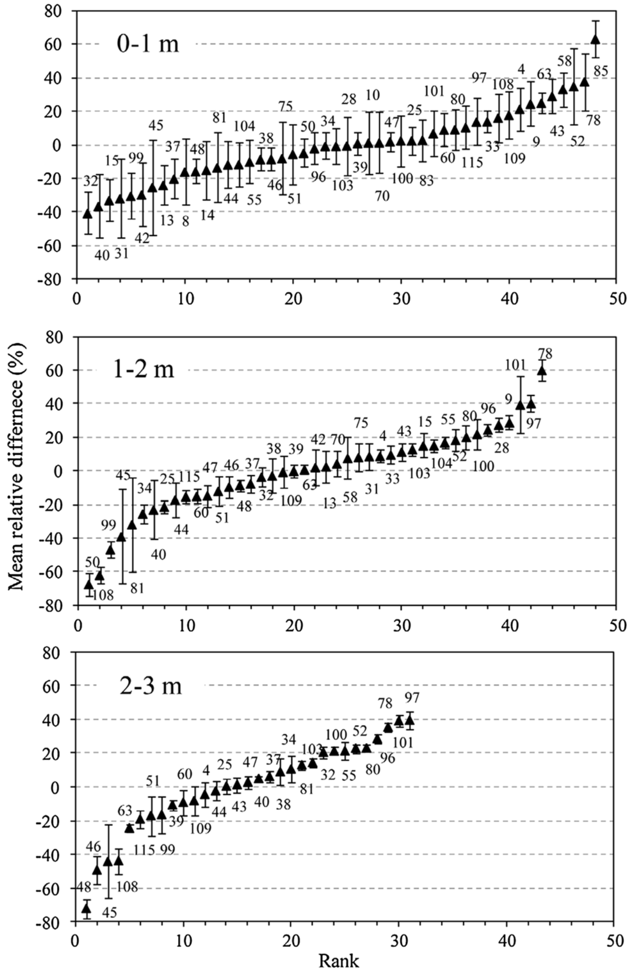

Fig. 5 Ranked mean relative differences of soil water storage in the cropland. Values *above* or *below* the *bars* are the location numbers. Standard *error bars* correspond to ±1 standard deviation of the relative differences

the study area was flat and the effect of topography on SWS spatial patterns could be excluded (Teuling et al. 2006).

The determination of SWS temporal stability might be affected by the type of soil-moisture sensor used. Landscapes are interrelated in the study area and soil textural layers differed both vertically and horizontally (Li and Shao 2013). The neutron probes measured average soil water content integrated over a "sphere of influence", which minimized the influence of variability in soil texture on the temporal stability of SWS (Kirda and Reichardt 1992). The careful calibration of instruments and the identification of representative locations as those with the lowest $\sigma(\delta_i)$ avoided some potential artificial errors (Reichardt et al. 1997; Hu et al. 2009).

Measurement frequency and total time span of observations are components of the temporal scale for defining temporal stability (Vanderlinden et al. 2012). Martínez-Fernández and Ceballos (2005) and Hu et al. (2012) found 1 year of measurements was required to identify the representative locations of soil moisture. Brocca et al. (2010) found that the representative locations were correctly

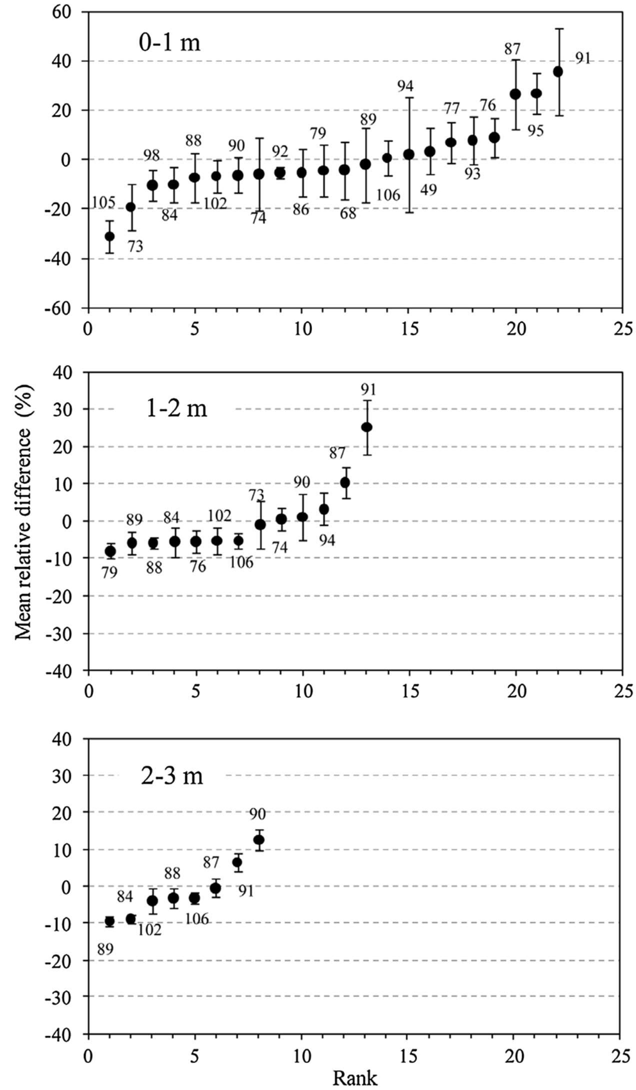

Fig. 6 Ranked mean relative differences of soil water storage in the wetland. Values *above* or *below* the *bars* are the location numbers. Standard *error bars* correspond to ±1 standard deviation of the relative differences

Table 3 Pearson correlation coefficients between the mean relative difference and the standard deviation of the relative differences of soil water storage in the study area

Depth range (m)	Desert	Cropland	Wetland
0–1	0.60**	−0.24	0.39
1–2	0.59**	−0.22	0.73**
2–3	0.39*	−0.52**	0.54

*, ** The correlation is significant at the 0.05 and 0.01 levels, respectively

Table 4 Comparison between the spatial mean soil water storage and soil water storages at the most stable locations and at the locations with the mean relative differences nearest to zero

Landscape	Depth range (m)	Location number	$R^{2,a}$	MBE (mm)	RMSE (mm)
Desert	0–1	54 (23)[b]	0.90 (0.68)	0.026 (0.28)	2.33 (6.26)
	1–2	62 (35)	0.87 (0.15)	−0.024 (2.54)	2.16 (25.4)
	2–3	30 (27)	0.92 (0.02)	−0.06 (−14.5)	2.02 (28.6)
Cropland	0–1	47 (28)	0.72 (0.50)	−0.056 (0.71)	12.8 (45.2)
	1–2	63 (39)	0.74 (0.62)	−0.26 (−0.59)	8.11 (11.8)
	2–3	40 (25)	0.90 (0.39)	0.066 (1.31)	4.60 (14.7)
Wetland	0–1	92 (106)	0.91 (0.44)	−0.078 (1.91)	8.59 (25.3)
	1–2	88 (74)	0.82 (0.46)	−0.10 (2.33)	7.32 (14.1)
	2–3	89 (87)	0.78 (0.64)	0.035 (−3.85)	5.18 (11.7)

MBE mean bias error, *RMSE* root mean square error

[a] R^2 is the coefficient of determination

[b] Statistics out of the brackets are for the most stable locations. Statistics in the brackets are for the locations with the mean relative differences nearest to zero

determined after 12 sampling occasions. A total of 18 occasions of measurement in this study met the requirements of temporal frequency. Representative locations were identified as those with the lowest $\sigma(\delta_i)$. Researchers proposed, however, that $\sigma(\delta_i)$ might shift over a longer time series (Martínez-Fernández and Ceballos 2003; Schneider et al. 2008). Longer-term observations are essential for verifying the feasibility of this method to determine the representative locations.

Soil particle-size distribution and SOC content strongly affect the existence and extent of temporal stability of soil moisture (Hu et al. 2010; Joshi et al. 2011). Temporally stable locations were identified with higher clay content on mountainous hillslopes in Northeast Asia (Sur et al. 2013). The effects of SOC, clay, silt and sand contents on the temporal stability of SWS differed among landscapes. $\sigma(\delta_i)$ were positively correlated with SOC, clay and silt contents and were negatively correlated with sand content in the desert and wetland (Table 5). Soil water storage is much more persistent over time in coarse-textured soils for the desert and wetland. Mohanty and Skaggs (2001) also found better stability in sandy loam soil than in silt loam soil. In the desert, evapotranspiration generally exceeds rainfall, and soil profiles are dry and will rarely or never change to a wet state. Vertical fluxes of evapotranspiration dominate, and the spatial pattern of soil moisture is influenced by soil properties and local terrain (Gómez-Plaza et al. 2000; Zhao et al. 2010b). Rainfall wets the surface soil uniformly and is evapotranspired soon before any significant lateral redistribution occurs (Grayson et al. 1997).

In the desert, the sand contents at the representative locations were 96.8, 96.6 and 92.4 % in the 0–1, 1–2 and 2–3 m soil layers, respectively, being much higher than the spatial means of 81.7, 70.9 and 67.4 %. The clay contents of 1.28, 0.91 and 3.15 % at the representative locations were remarkably lower than the spatial means of 6.55, 14.7 and 4.65 % in the 0–1, 1–2 and 2–3 m soil layers, respectively. Soil organic carbon contents at the representative locations of the desert were 0.94, 0.89 and 0.64 g kg^{-1} in the 0–1, 1–2 and 2–3 m soil layers, respectively, being lower than the spatial means of 1.02, 1.05 and 1.11 g kg^{-1}. Water-holding capacity is reduced by low SOC and clay contents, high sand content and poor structure, but strong atmospheric demands in terms of evapotranspiration dominate water fluxes and surpass the impacts of soil properties (Schneider et al. 2008). For the wetland, the clay contents at the representative locations were 21.8, 27.8 and 33.6 % in the 0–1, 1–2 and 2–3 m soil layers, respectively, being lower than the spatial means of 30.0, 30.2 and 35.9 %. The sand contents at the representative locations were 36.4, 23.7 and 16.0 % in the 0–1, 1–2 and 2–3 m soil layers, respectively. The spatial mean sand contents were 24.6, 28.4 and 19.5 % in the respective layers. Soil organic carbon contents at the representative locations were 3.72 and 2.15 g kg^{-1} in the 0–1 and 2–3 m soil layers, respectively, being lower than the spatial means of 5.01 and 2.56 g kg^{-1}. Soil organic carbon content of 4.37 g kg^{-1} at the representative location for the 1–2 m

Table 5 Pearson correlation coefficients between the standard deviation of relative differences of soil water storage and soil properties

Landscape	Depth range (m)	Clay content (%)	Silt content (%)	Sand content (%)	SOC[a] content (g kg^{-1})
Desert	0–1	0.47**	0.58**	−0.53**	0.42**
	1–2	0.27	0.42**	−0.36**	0.44**
	2–3	0.28	0.29	−0.30**	0.25**
Cropland	0–1	−0.24	−0.23	0.24	−0.18
	1–2	−0.28	−0.24	0.27	−0.14
	2–3	−0.37**	−0.33	0.36*	−0.27
Wetland	0–1	0.47*	0.38	−0.43*	0.21
	1–2	0.35	0.40	−0.65*	0.58
	2–3	0.65	0.65	−0.73	0.38

*, ** The correlation is significant at the 0.05 and 0.01 levels, respectively

[a] SOC is the abbreviation of soil organic carbon

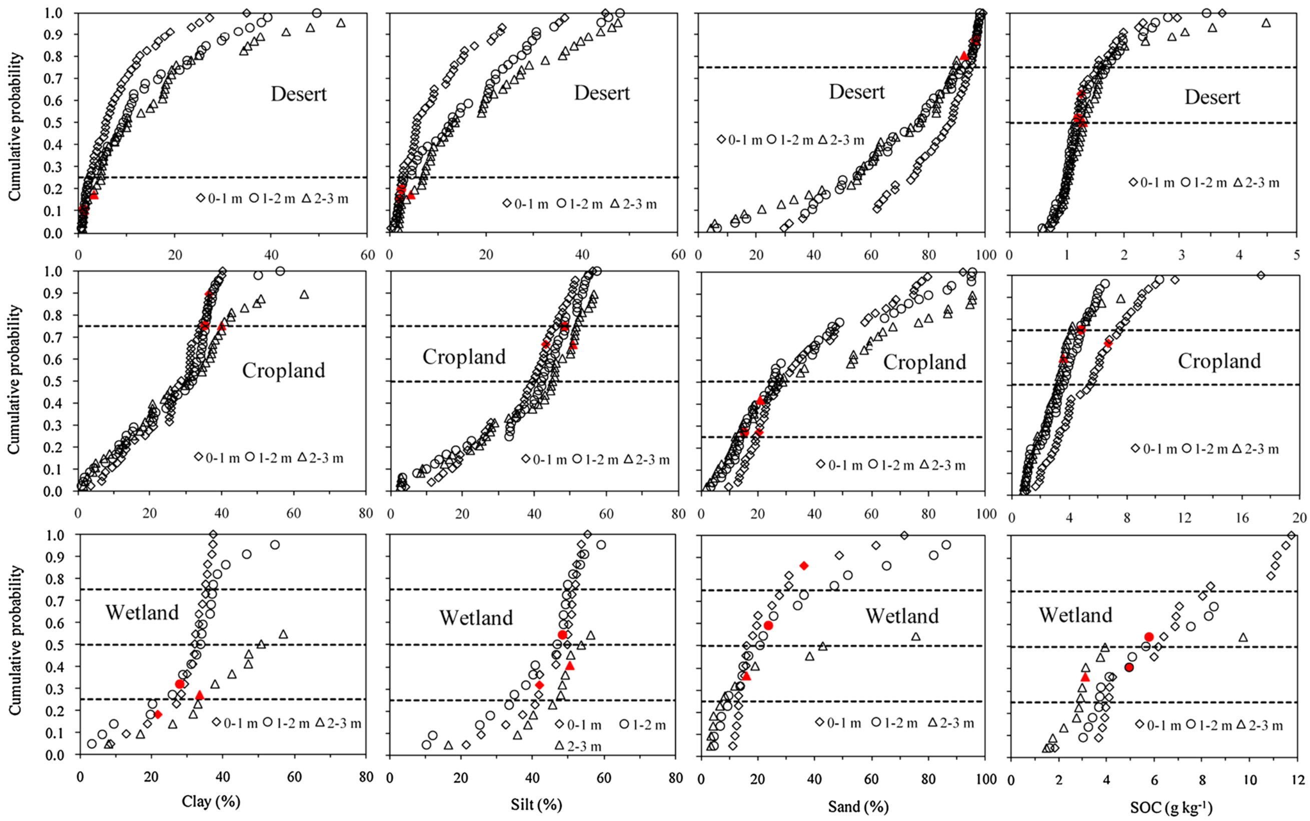

Fig. 7 The cumulative probability distributions of the clay, silt, sand and SOC contents in the study area. Representative locations are highlighted in *red* color

wetland soil was higher than the spatial mean of 3.63 g kg^{-1}. The clay and SOC contents at the representative locations were generally lower than the associated spatial means in the desert and wetland. This result agrees with the finding that sites with the highest SOC contents and high clay fractions were not the most stable sites in a semi-arid grassland of China (Schneider et al. 2008).

In the cropland, $\sigma(\delta_i)$ was negatively correlated with SOC, clay and silt contents and positively correlated with sand content (Table 5), indicating that soils of cropland rich in SOC and fine particles are likely to be more stable. The clay contents at the representative locations were 36.5, 34.3 and 28.4 % in the 0–1, 1–2 and 2–3 m soil layers, respectively, being higher than the spatial means of 26.4, 26.3 and 26.1 %. The sand contents of 20.3, 15.2 and 20.8 % at the representative locations were much lower than the spatial means of 37.2, 36.2 and 36.7 % in the 0–1, 1–2 and 2–3 m soil layers, respectively. This result coincides with the international literature. Jacobs et al. (2004) found that the most stable location was with moderate to moderately high clay content than the field average. Gao et al. (2011) reported that locations with stable soil water contents had higher clay contents than the field averages in sloping Jujube orchards. Soil organic carbon contents at the representative locations in the cropland were 5.06, 3.77 and 2.72 g kg^{-1} in the 0–1, 1–2 and 2–3 m soil layers, respectively, being higher than the spatial means of 4.24, 2.69 and 2.29 g kg^{-1}.

The cumulative probability function represented the distribution patterns of the clay, silt, sand, and SOC contents in diverse soil layers in the three landscapes (Fig. 7). At the representative locations in the desert, the cumulative probabilities of clay and silt contents were lower than 0.25, the sand contents were larger than 0.75, and SOC contents ranged from 0.5 to 0.75. At the representative locations in the cropland, probabilities of the clay contents were larger than 0.75, silt and SOC contents were between 0.5 and 0.75, whereas sand contents were between 0.25 and 0.5. The probabilities for the above soil properties were inconsistent among the representative locations in wetland. Particle-size distribution and SOC content are the most essential and easily obtained properties in a soil survey. Their probabilities at the representative locations in a small area will lead to the identification of potential representative locations in a larger region with similar soil properties. Further measurements will be limited to only these locations, from which the actual representative location can be determined. This strategy can save labor and costs, and may benefit upscaling studies on soil moisture.

Conclusions

In this study, the temporal stabilities of soil water storage were evaluated in diverse soil layers of desert, cropland and wetland in an arid region of northwestern China over 18 occasions of measurement. The temporal changes in SWS differed among landscapes. Significant differences in spatial mean SWS existed both among the three soil layers in the desert and cropland, and among the three landscapes at a specific depth. The spatial means and the spatial variability of SWS increased, but the temporal variability of SWS decreased, with depth in the desert and cropland. In the wetland, both the spatial and temporal variability of SWS decreased with depth. Spearman's rank correlations and the relative difference analysis confirmed the temporal stability of SWS. The high temporal persistence in the deeper layers indicated the feasibility of observation at low frequency.

Wetter locations were less temporally stable in the desert and wetland, but were more stable in the cropland. No single location could represent the spatial mean SWSs of the three layers simultaneously in each landscape. The representative locations were those with the lowest standard deviation of relative differences at each depth in the three landscapes. Temporal stability of SWS decreased in the desert and wetland, but increased in the cropland, with increasing SOC, clay and silt contents. The cumulative probability distributions of SOC, clay, silt and sand contents may provide an a priori approach to identify representative locations more efficiently in larger areas of the desert and cropland.

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