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Soil-water storage to a depth of 5 m along a 500-km transect on the Chinese Loess Plateau

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ABSTRACT

Soil-water storage (SWS) is an important indicator of the sustainability of regional water resources and is the foundation for developing strategies of land-use management around the world, especially in areas with deficits of soil water. An investigation of the characteristics of SWS at large regional scales can provide valuable information. We measured SWS and available soil-water storage (ASWS) to a depth of 5 m along a 500-km transect across two climatic regions on the Chinese Loess Plateau (CLP). $SWS_{5\ m}$ tended to decrease from southeast to northwest and was 320 mm higher in the subhumid than the semiarid zone. $SWS_{5\ m}$ and $ASWS_{5\ m}$ were lower in the dry than the rainy season, but $SWS_{1\ m}$ and $ASWS_{1\ m}$ did not differ significantly between the two seasons except in the 0–100 cm layer. $SWS_{1\ m}$ and $ASWS_{1\ m}$ tended to increase with depth in the semiarid zone and did not change substantially with depth in the subhumid zone. $SWS_{5\ m}$ and $ASWS_{5\ m}$ varied with land use, in the orders cropland > orchard > forest in the subhumid zone and grassland > shrubland > forest in the semiarid zone. Climatic conditions and soil textures were predominant factors affecting SWS at the transect scale. $SWS_{5\ m}$ and $ASWS_{5\ m}$ in the subhumid zone were dependent on clay content, elevation, latitude and the interaction of latitude and temperature, while clay content played a dominant role in the semiarid zone. Understanding this information is helpful for assessing regional water resources, optimizing the rational use of land and modeling eco-hydrological processes on the CLP and possibly in other water-limited regions around the world.

1. Introduction

Soil-water storage (SWS), as an important indicator of water resources, is the foundation for developing governmental strategies for sustainable development in water-limited ecosystems. Available soil-water storage (ASWS) is a crucial indicator for evaluating how much soil water can be used by plants and is a vital foundation for managing vegetation selection and distribution in areas with water deficits. SWS has a strong influence on many eco-hydrological processes, such as the generation of surface and subsurface runoff (Zehe et al., 2010), flooding (Borga et al., 2007), soil erosion (Cotler and Ortega-Larrocea, 2006), solute transport (Xia and Shao, 2008), plant growth and land-atmosphere interactions (Yang, 2001).

SWS is highly spatially and temporally variable and is scale-dependent due to the complex effects of many factors, such as precipitation, terrain, land use, atmospheric evaporation, soil properties and runoff (Western et al., 2002; Western et al., 2004). Its spatial distribution has been studied using both ground-based and remotely sensed measurements focusing on small and large scales, respectively (Choi and Jacobs, 2007; Western et al., 2004). Ground-based measurements and the analysis of spatial correlations, however, are often limited by the small number of measurements. Remote sensing provides more complete data sets over large areas but cannot account for the highly heterogeneous characteristics of soil-water within remotely sensed footprints, especially for vegetated surfaces. Subsurface soil moisture, especially below 5 cm, however, cannot be measured remotely. Ground-based measurements of SWS on a relatively large scale are thus indispensable for improving the previous records.

By using ground-based measurements of SWS, attempts have been made to characterize the spatial variability of SWS in different regions of the world by investigating a variety of factors or processes believed to determine SWS (Chen et al., 2007; Cho and Choi, 2014; Gomez-Plaza et al., 2001; Zehe et al., 2010). Most of these studies, however, were conducted on small spatial scales (e.g. plots, slopes and small watersheds). At regional scales, the study of the spatial characteristics of SWS and related factors is hampered by the difficulty of sample collection and by the investments of cost and time. More information is thus needed on the regional distribution pattern of SWS for sustainable

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soil-water management and ecological restoration in water-limited ecosystems.

On the Chinese Loess Plateau (CLP), which is a typical water-limited ecosystem, soil-water is the main factor restricting plant growth and ecological environmental reconstruction (Wang et al., 2009). Currently, global warming and human activities are having profound effects on the traditional geographic-ecological processes on the CLP. The soil is becoming drier, and dried soil layers are having a negative impact on the ecology and hydrology (Chen et al., 2008; Jia et al., 2015; Li et al., 2008; Wang et al., 2010a; Wang et al., 2010b), so exploring the mechanism of SWS spatial distribution at a large scale is essential. Understanding the regime of regional soil-water accumulation in different climatic regions is thus necessary for the maintenance of regional water resources and for balancing water inputs and outputs, not only for the CLP but also for other similar semiarid areas around the world.

The objectives of this study were therefore to: (1) investigate the spatial and temporal distribution of SWS and ASWS along an extended transect, (2) compare the characteristics of SWS and ASWS in different climatic regions and (3) identify the impacts of climatic conditions, soil properties and land uses on SWS and ASWS. This information is important for evaluating and managing regional water resources and for the rational use of vegetation.

2. Materials and methods

2.1. Description of the study area

This study was conducted along a 500-km transect from southeast to northwest across the CLP (597–1567 m a.s.l.) (Fig. 1). The transect crosses the provinces of Shaanxi, Gansu and Ningxia, and has a typical

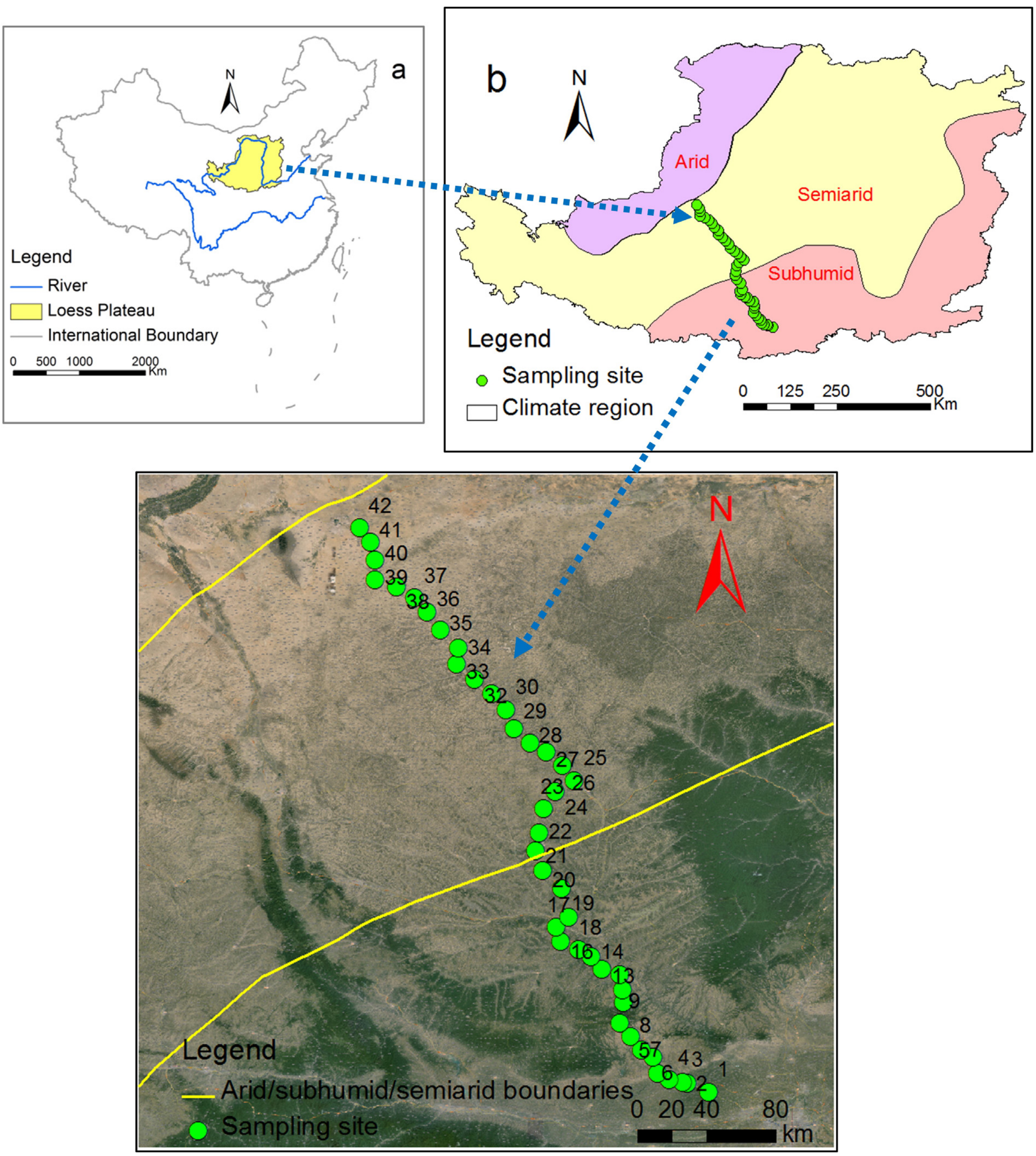

Fig. 1. Location of the Loess Plateau in China (a) and the sampling sites (n = 42) along the transect (b and c).

continental monsoon climate. Annual precipitation ranges from 260 mm in the northwest to 590 mm in the southeast and falls mainly during June to September (55–78%). Annual pan evaporation ranges from 1400 to 2000 mm. The mean annual temperatures are 8.7 °C in the northwest and 13.1 °C in the southeast, and the annual solar radiation ranges from 5.02×10^9 to 6.7×10^9 J/m^2 (Wang et al., 2012).

The study area is classified as subhumid and semiarid zones from the southeast to the northwest (Fig. 1b). The soil is generally sandier in the northwest and contains more clay in the southeast. The predominant types of land use in this region are cropland, orchard, forest, shrubland and native grassland.

2.2. Sampling sites and measurement

Soil samples were collected along the transect at 42 sites, with ~10 km between adjacent sites to guarantee that the sampling represented the soil water of each climatic zone. We selected sampling sites in flat areas where apple trees and other crops were planted at the beginning of the transect. Elevation increased along the transect. We generally chose up-slope sampling points to reduce the possible effect of topography. The vegetation zones were distributed in the sequence forest, forest-steppe, typical steppe and desert-steppe from the subhumid to the semiarid zone, and we selected the dominant species at each sampling site to reflect the SWS status of the corresponding vegetation zone.

We used a GPS receiver (5 m precision) to locate the sampling sites and for recording the longitude, latitude and altitude at each site. Of the 42 sites, 20 and 22 were in the subhumid and semiarid zones, respectively. The vegetation types along the transect from southeast to northwest are crops, apple trees, locust (*Robinia pseudoacacia* L.), bunge needlegrass (*Stipa bungeana* Trin.), korshinsk peashrub (*Caragana korshinskii* Kom.), sea buckthorn (*Hippophae rhamnoides* L.) and alfalfa (*Medicago sativa* L.).

An aluminum neutron-probe access tube was installed at each site to measure volumetric soil-water content (SWC, θ) at 10-cm intervals from 0 to 100 cm in depth and at 20-cm intervals from 100 to 500 cm in depth. SWC at each depth was calculated from the slow-neutron count rates using the calibration curve provided by Wang et al. (2015):

$$\theta = 62.233CR + 0.9459 \left(R^2 = 0.9239, P<0.001\right) \quad (1)$$

SWC was measured five times from 2015 to 2016, three times in the rainy season (June, July and August in 2015) and two times in the dry season (November 2015 and March 2016). We obtained a total of 5250 SWC data-points and collected 1050 disturbed soil samples, which were air-dried and sieved through a 1-mm mesh for determining soil-particle composition by laser diffraction using a Mastersizer 2000 (Malvern Instruments, Malvern, England).

We also evaluated the impact of climatic factors on the soil-water regime across the 42 sites by collecting data for annual precipitation and annual temperature (51 years from 1951 to 2001) for each site from a nearby meteorological station, which may indicate the overall climatic conditions of the sites to some extent. Measuring the climatic factors (e.g. precipitation, temperature and antecedent precipitation) for each site is a large practical challenge.

The measured and/or collected environmental factors (e.g. soil-particle composition, longitude, latitude, altitude, annual precipitation and annual temperature) are more stable than SWC, especially for one-time measurements, so we used the mean SWC (which was measured three times in the rainy season and two times in the dry season) at each site to represent the overall soil-water condition within a year. Only the mean SWC for each layer at each site was subsequently used to calculate SWS and ASWS. We then (1) evaluated the variations of SWS and ASWS among the soil layers and sampling sites by calculating the coefficients of variation (CVs) and (2) assessed the relationships between SWS and ASWS and the measured variables by conducting a correlation analysis.

2.3. Calculation of soil-water storage

We calculated SWS using Eq. (2). The calculation of ASWS requires information for SWC at the wilting point, SWC_{wp} (= volumetric SWC at −1.5 MPa) (Grassini et al., 2010), which was calculated by using a robust pedotransfer function that has been described in detail by Wang et al. (2013b). We then calculated ASWS using Eq. (3).

$$SWS_h = \theta \cdot \Delta h \cdot 10 \quad (2)$$

$$ASWS_h = \left(\theta - SWC_{wp}\right) \cdot \Delta h \cdot 10 \quad (3)$$

where SWS_h is the soil-water storage (mm) in soil layer h (10 cm for the 0–100 cm layer and 20 cm for the 100–500 cm layer), θ is the volumetric SWC in soil layer h and 10 is a unit conversion factor (mm cm^{-1}). We regarded ASWS as 0 when SWC was less than SWC_{wp}. The vertical distribution of soil water down to 500 cm in the profile was evaluated by calculating SWS and ASWS for each 100 cm layer ($SWS_{1\ m}$ and $ASWS_{1\ m}$) and for the entire 0–500 cm profile ($SWS_{5\ m}$ and $ASWS_{5\ m}$). The calculations are:

$$SWS_{1\ m} = \sum_{h=10}^{100} SWS_h \quad (4)$$

$$ASWS_{1\ m} = \sum_{h=10}^{100} ASWS_h \quad (5)$$

$$SWS_{5\ m} = \sum_{h=10}^{500} SWS_h \quad (6)$$

$$ASWS_{5\ m} = \sum_{h=10}^{500} ASWS_h \quad (7)$$

2.4. Statistical analysis

Primary statistical analyses, such as the determinations of means, standard errors (SE) and coefficients of variation (CV) of the measured SWS, were conducted with Microsoft Excel (version 2007). Multiple comparisons using the least significance difference (LSD) test (based on the homogeneity of variance) to identify significant differences among SWS (or ASWS) were conducted with SPSS (version 16.0). Pearson correlation analysis was used to determine the strength of possible relationships between SWS (or ASWS) and soil-particle composition and other measured variables were also carried out in SPSS (version 16.0).

We further explored the relative contribution of different factors to the patterns of SWS (or ASWS) by conducting a forward selection, stepwise multiple linear regression analysis (SMLR) in SPSS (version 16.0) by using all measured soil and environmental factors (including their possible combinations) as independent variables and SWS (or ASWS) as dependent variables. We also used SMLR to detect and then exclude any potential multicollinearity by evaluating the tolerance and variance inflation factor of the predictor variables. Independent variables are generally considered to be multi-collinear when the tolerance is <0.1 or the variance inflation factor is >10 (Wang et al., 2012). The regression models of SWS (or ASWS) were consequently developed with fewer but significant factors and their possible combinations. The accuracy of the regression models developed by SMLR was evaluated using the coefficient of determination. The locations of the sampling sites were mapped using GIS software (ESRI® ArcMap™ 9.2). The diagrams were made using SigmaPlot 12.5.

3. Results and discussion

3.1. Basic soil properties and site conditions on the transect

Table 1 presents the basic soil properties and site conditions on the transect. The mean SWC along the transect in the measured periods was 14.8%, with a low CV of 7%. The soil was composed of 13.5, 71.3 and 15.3% sand, silt and clay, respectively. The sand content was most variable (CV = 70%), followed by clay (CV = 23%) and silt (CV = 10%) contents.

The vertical distribution of soil-particle composition differed within the 0–500 cm profiles in the two climatic zones, with less sand and more clay and silt in the subhumid than the semiarid zone (Fig. 2). Soil-particle composition in the subhumid zone consisted of sand, silt and clay contents of approximately 6.3, 75.2 and 18.5%, respectively. In the semiarid zone, however, sand content tended to decrease and clay and silt contents tended to increase with soil depth. The CVs in the 0–500 cm profiles indicated a more variable soil-particle composition in the semiarid than the subhumid zone, with CVs of 47.9–61.1% for sand, 9.2–17.6% for silt and 19.1–34.3% for clay in the semiarid zone and of 29.3–45.3% for sand, 1.9–3.4% for silt and 9.8–12.7% for clay in the subhumid zone, implying that soil texture was more heterogeneous in the semiarid zone.

3.2. Characteristics of SWS in the 0–500 cm soil profiles on the transect

Mean $SWS_{1\ m}$ differed among the sites, with several peaks, such as the sites at 72.5, 295.3 and 434.6 km (Fig. 3). $SWS_{1\ m}$ generally tended to decrease with increasing elevation along the transect, perhaps because less rain falls at higher elevations. Mean $SWS_{1\ m}$ was higher in the subhumid than the semiarid zone, in accordance with annual precipitation. $ASWS_{1\ m}$, however, did not have a similar trend along the transect.

The values of $SWS_{1\ m}$ in the subhumid zone ranged from 99 mm to 284 mm, and the mean $SWS_{1\ m}$ fluctuated from 177 to 192 mm (Table 3). The values of $SWS_{1\ m}$ in the semiarid zone ranged from 54 mm to 316 mm and varied widely among all layers, and mean $SWS_{1\ m}$ increased from 101 to 142 mm with increasing soil depth. Mean $ASWS_{1\ m}$ was similar in the two climatic zones, and the CVs were higher for $ASWS_{1\ m}$ than $SWS_{1\ m}$, indicating that ASWS was more variable at the large scale.

$SWS_{5\ m}$ tended to decrease from the subhumid to the semiarid zone, consistent with the climatic factors. Precipitation was higher and evaporation was lower in the subhumid than the semiarid zone, producing conditions of higher soil-water in the subhumid zone. Jia et al. (2015) also reported that factors associated with soil and climate dominated the soil-water conditions along a south-north transect across the CLP. The distribution of SWS at large scales is due to many factors, such as geographical features, climatic conditions, patterns of soil type, solar radiation and the distribution of vegetation (Cho and Choi, 2014; Li, 2000). In our study, SWS peaked at various sites along the transect, indicating its high spatial variation. The high value of SWS at two sites in the semiarid zone may be attributed to the soil properties and geomorphological landscape (Gao and Shao, 2012; Jia et al., 2013); in particular, the sites were at the end of the transect in an irrigated area of the Yellow River, so large amounts of infiltration likely contributed to the high soil-water storage. We also compared $SWS_{1\ m}$ and $ASWS_{1\ m}$ in the rainy and dry seasons, and found no significant differences below 100 cm. $SWS_{5\ m}$ and $ASWS_{5\ m}$ in the deep soil layers (100–500 cm) was lower in the dry than the rainy season, implying that

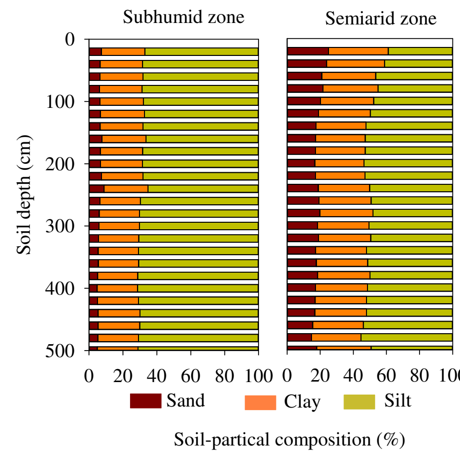

Fig. 2. Vertical distribution of soil-particle composition in the subhumid and semiarid zones.

Table 1
Basic soil properties and elevation along the 500-km transect.

Variable	*n*	Min	Max	Mean	CV (%)
SWC (%)	5250	2.6	32.5	14.8	7
Sand (%)	1050	3.5	43.7	13.5	70
Clay (%)	1050	7.4	21.1	15.3	23
Silt (%)	1050	44.0	78.9	71.3	10
Elevation (m)	42	510	1567	1187	24
AP (mm)	42	260	590	454	27
AT (°C)	42	8.7	13.1	10.3	16

Note: *n*, number of samples; CV, coefficient of variation; SWC, soil-water content; AP, annual precipitation; AT, annual temperature.

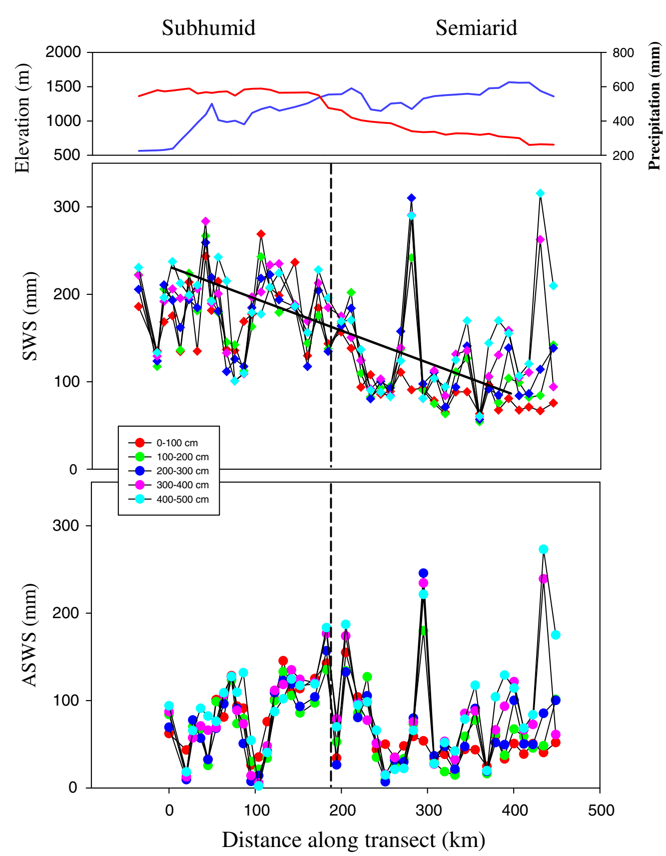

Fig. 3. Characteristics of soil-water storage (SWS) and available soil-water storage (ASWS) in each 100-cm layer along the transect. The top panel indicates the site elevation (blue line) and precipitation (red line) along the transect. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

SWS was relatively stable during the measured period. $SWS_{1\ m}$ and $ASWS_{1\ m}$ tended to fluctuate considerably in the 0–100 cm layer, indicating that the shallow soil layers were highly influenced by environmental factors (e.g. precipitation, infiltration and evaporation).

The correlations between $SWS_{5\ m}$ and elevation, annual precipitation, annual temperature, longitude, latitude and soil-particle compositions for the entire transect were statistically significant (Table 2, $P < 0.05$), indicating that climatic factors and soil properties affected $SWS_{5\ m}$ status. Within each climatic zone, however, $SWS_{5\ m}$ was not significantly correlated with annual precipitation or annual temperature, implying that climatic factors in the same climatic zone had a weak impact on deep soil-water storage. $SWS_{5\ m}$ was significantly correlated with clay content ($P < 0.05$) in the subhumid zone, and was correlated negatively with sand content ($P < 0.05$) and positively with clay content ($P < 0.01$) in the semiarid zone, which may partly be attributed to the amount of variation of the soil-particle compositions in the two climatic zones (Fig. 2). In contrast, $ASWS_{5\ m}$ was only significantly correlated with clay content in the semiarid zone ($P < 0.05$) and with climatic (annual temperature) and topographical factors (elevation, longitude and altitude) in the subhumid zone ($P < 0.05$).

3.3. Factors affecting soil-water storage along the transect

3.3.1. Climatic zone

Mean $SWS_{5\ m}$ differed significantly between the subhumid and semiarid zones, with values of 920 and 598 mm, respectively. $ASWS_{5\ m}$, however, did not differ significantly between the two climatic zones, with values of 415 and 355 mm, respectively. SWC_{wp} was higher in the subhumid than the semiarid zone, so $ASWS_{5\ m}$ did not differ significantly between the two climatic zones, which may be attributed to the integrated effects of soil properties, climatic and vegetation conditions. The horizontal distribution of $SWS_{5\ m}$ in the subhumid zone, however, varied less (CV = 19%), implying that the storage of soil-water was more complex in the semiarid than in the subhumid zone, likely due to the different soil properties, heterogeneous topography, diversity of vegetation and intensity of the meteorological conditions in the semiarid zone.

The mean CVs of $SWS_{1\ m}$ and $ASWS_{1\ m}$ were lower in the subhumid than the semiarid zone, with values of 21 and 40% for SWS and 53 and 73% for ASWS, respectively, indicating that $SWS_{1\ m}$ and $ASWS_{1\ m}$ were highly variable in the semiarid zone.

$SWS_{1\ m}$ differed significantly in all five layers between the subhumid and semiarid zones. The distribution of $ASWS_{1\ m}$, however, only differed significantly between the subhumid and semiarid zones in the 0–100 cm layer (Fig. 4). $ASWS_{1\ m}$ did not differ significantly among the layers in the subhumid zone but differed significantly between the 0–100, and 400–500 cm layers in the semiarid zone, with values of 53 and 93 mm, respectively. Both $SWS_{1\ m}$ and $ASWS_{1\ m}$ tended to increase with soil depth in the semiarid zone, and fluctuated among the layers in the subhumid zone.

$ASWS_{1\ m}$ first decreased and then increased with soil depth in the subhumid zone, perhaps due to the integrated effect of rainfall and vegetation. Plants always absorb shallow soil water (which can be recharged by precipitation) to support their physiological activities. Precipitation cannot infiltrate quickly, so ASWS was lower in the deep soil layers where deep plant roots can take up water, consistent with the results reported by Zhang et al. (2016). $ASWS_{1\ m}$ was lower in the surface than the deeper layers in the semiarid zone, perhaps due to the uptake of water by shallow plant roots that are common in the region. Low precipitation and intensive evaporation can also decrease SWC in surface soil layers (Jian et al., 2015). Wang et al. (2012) reported that SWC across the CLP was controlled by the combined influence of plant characteristics (plant type and age), topographical and geographical features (latitude, longitude and altitude), soil properties (soil texture and infiltrability), climatic conditions and eco-hydrology (evaporation zone and soil-water ecological zone).

Table 3
Statistical summary of soil-water storage (SWS) and available soil-water storage (ASWS) in different soil layers along the 0–500 cm profile in the two climatic zones.

Climatic zone	Soil layer (cm)	SWS (mm)				ASWS (mm)			
		Min	Max	Mean	CV	Min	Max	Mean	CV
Subhumid	0–100	122	269	187	19	13	181	83	48
	100–200	100	267	179	21	5	160	75	52
	200–300	105	259	177	21	4	153	73	58
	300–400	100	284	185	22	0	178	81	56
	400–500	99	284	192	22	0	175	88	50
	0–500	550	1337	920	19	52	804	415	47
Semiarid	0–100	62	192	101	32	17	216	53	61
	100–200	54	228	109	39	8	211	60	75
	200–300	57	310	116	43	6	236	67	79
	300–400	55	291	131	43	12	258	82	76
	400–500	60	316	142	42	12	283	93	74
	0–500	238	1224	598	33	88	1163	355	65

Note: CV, coefficient of variation.

Mean SWS_h was lower in the semiarid than the subhumid zone in all soil layers (Fig. 5a). Mean $ASWS_h$ fluctuated in the two zones with increasing soil depth but was lower in both zones in the shallow soil layers and was higher in the deep layers. Precipitation was low in the semiarid zone, but the loss of soil water by plant uptake in the deep layers was also low, and intensive evaporation can only affect shallow soil-water status. The profiles of the CVs for $ASWS_h$ were similar in the two climatic zones, which fluctuated with increasing depth to 300 cm and then tended to decrease to 500 cm; the CVs of both SWS_h and $ASWS_h$, however, were higher in the semiarid than the subhumid zone, consistent with the profile distribution of the soil particles.

3.3.2. Land use

$SWS_{5\ m}$ and $ASWS_{5\ m}$ generally differed among the land uses within each climatic zone or along the transect ($P < 0.05$) (Fig. 6). $SWS_{5\ m}$ and $ASWS_{5\ m}$ in the subhumid zone were similar between the orchard and cropland, which were higher than those of the forest. $SWS_{5\ m}$ and $ASWS_{5\ m}$ in the semiarid zone were higher in the grassland and shrubland than the forest.

$SWS_{1\ m}$ and $ASWS_{1\ m}$ in the subhumid zone tended to increase with depth for cropland but fluctuated in the orchards and first decreased and then increased in the forests. In contrast, $SWS_{1\ m}$ and $ASWS_{1\ m}$ in the semiarid zone tended to increase with depth for the grassland and shrubland and to decrease in the forests (data not shown).

Land use has a large effect on the soil-water cycle in the soil-plant-atmosphere system, because water resources can be used differently

Table 2
Pearson correlation coefficients between soil-water storage (SWS) and available soil-water storage (ASWS) and measured environmental factors in the 0–500 cm profile.

Item	Climatic zone	Elevation	Annual precipitation	Annual temperature	Longitude	Latitude	Clay	Silt	Sand
$SWS_{5\ m}$	Transect	−0.442**	0.657**	0.368*	0.522**	−0.609**	0.836**	0.394**	−0.613**
	Subhumid	0.206	0.126	−0.119	−0.147	0.027	0.436*	−0.305	−0.164
	Semiarid	−0.14	0.227	0.339	0.197	−0.27	0.844**	0.197	−0.405*
$ASWS_{5\ m}$	Transect	0.151	0.127	−0.115	−0.075	0.065	0.392*	−0.005	−0.143
	Subhumid	0.631**	−0.089	−0.518*	−0.587**	0.508*	−0.012	−0.383	0.272
	Semiarid	0.107	−0.176	0.137	−0.257	0.336	0.492*	−0.172	−0.030

Note: *, correlation is significant at $P < 0.05$ (two-tailed); **, correlation is significant at $P < 0.01$ (two-tailed).

Table 4
Pearson correlation coefficients between soil-water storage ($SWS_{1\ m}$) and available soil-water storage ($ASWS_{1\ m}$) and soil-particle composition in the two climatic zones.

	Soil layer (cm)	Subhumid			Semiarid		
		Clay	Silt	Sand	Clay	Silt	Sand
$SWS_{1\ m}$	0–100	0.472*	−0.126	−0.334	0.937**	0.549**	−0.671**
	100–200	0.705**	−0.398	−0.386	0.830**	0.449*	−0.606**
	200–300	0.426	−0.091	−0.229	0.869**	0.282	−0.476
	300–400	−0.206	−0.133	−0.120	0.850**	0.035	−0.312
	400–500	0.355	−0.076	−0.292	0.850**	0.240	−0.276
$ASWS_{1\ m}$	0–100	0.164	−0.422	0.101	0.807**	0.299	−0.429*
	100–200	0.212	−0.534*	0.172	0.730**	0.312	−0.469*
	200–300	−0.019	−0.270	0.215	0.769**	0.137	−0.325
	300–400	−0.125	−0.236	0.310	0.802**	−0.072	−0.200
	400–500	0.127	−0.148	−0.007	0.823**	−0.334	−0.173

Note: *, correlation is significant at $P < 0.05$ (two-tailed); **, correlation is significant at $P < 0.01$ (two-tailed).

between the surface and deep layers (Fu et al., 2003; Yang et al., 2012). Different land uses produce different patterns of vegetation, root systems and leaf canopies that affect evapotranspiration rates, soil-water patterns and microclimates. $SWS_{5\ m}$ differed significantly between cropland and forest in the subhumid zone but did not differ significantly among the land uses in the semiarid zone, indicating that land use, in some cases, had no significant impacts on $SWS_{5\ m}$ in the two climatic zones (Fig. 6). Land use is generally a dominant factor of soil-water storage at watershed scales (Yang et al., 2012; Wang et al., 2012; Wang et al., 2013a), but our study implied that large-scale sampling schemes may simultaneously magnify the influence of climate and mask the effect of land use.

$ASWS_{5\ m}$ differed significantly among the land uses along the transect. Jia et al. (2015) reported that the properties of the vegetation had little impact on soil-water conditions at a large regional scale. In contrast, other studies have reported an apparent relationship between land use and soil moisture at plot and catchment scales (Fu et al., 2003; Wang et al., 2013a; Yang et al., 2012). $ASWS_{5\ m}$ in our study differed significantly between forest and the other land uses, with a lower value in both climatic zones, indicating that water consumption and evapotranspiration were higher for forest than the other vegetation and that canopy interception was larger for forest than the other vegetation, as previously reported (Jian et al., 2015; Chen et al., 2007), in accordance with previous results by Wang et al. (2015) that grassland would be an optimal land use for restoring the fragile environment on the CLP.

$ASWS_{1\ m}$ varied with depth for the different types of vegetation. The $ASWS_{1\ m}$ of forest in the subhumid zone initially decreased and then increased with depth, which may have been due to the effect of root distribution associated with afforestation projects (e.g. the Grain for Green project implemented in 1999). Similarly, the $ASWS_{1\ m}$ in the grassland and shrubland in the semiarid zone generally increased with depth, which may also have been due to their shallow root systems, which would be a crucial factor in determining SWC in the root zone (Cheng et al., 2009; Wang et al., 2015). Plants act as a pathway along which water is transferred from the soil around roots to the atmosphere in soil-plant-atmosphere systems, which is a primary mechanism for the loss of soil-water.

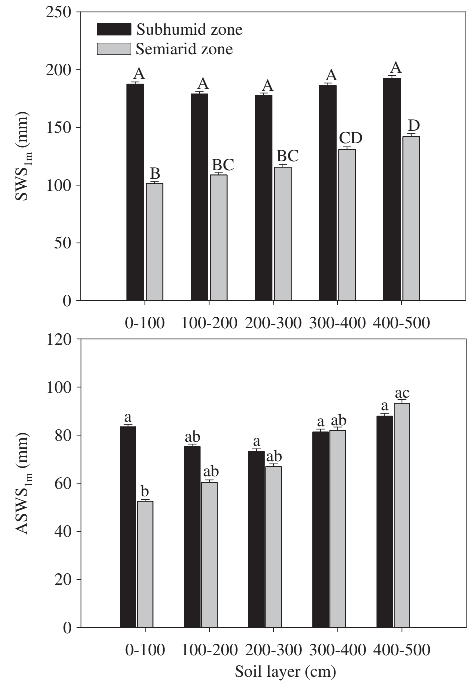

Fig. 4. Distribution of mean and standard error of soil-water storage (SWS) and available soil-water storage (ASWS) in each 100-cm layer in the two climatic zones. Different upper- and lowercase letters indicate significant differences among the five layers at $P < 0.05$.

3.3.3. Soil-particle composition

The correlation coefficients between both $SWS_{1\ m}$ and $ASWS_{1\ m}$ and clay content in the semiarid zone were statistically significant ($P < 0.01$) in all soil layers, but the coefficients between $SWS_{1\ m}$ and sand and silt contents were significant only for the 0–200 cm layers (Table 4). $SWS_{1\ m}$ and $ASWS_{1\ m}$ in the subhumid zone, however, were generally not significantly correlated with soil-particle composition, except that $SWS_{1\ m}$ was significantly correlated with clay content in the 0–200 cm layer. $SWS_{5\ m}$ was expected to be correlated positively with clay and silt contents and negatively with sand content, consistent with the distribution of $SWS_{1\ m}$ in the five layers in the semiarid zone (Fig. 4). $ASWS_{1\ m}$, however, was not significantly correlated with soil-particle composition in the subhumid zone, except for silt content in the 100–200 cm layer (Table 4), indicating that soil properties played a more important role in determining SWS in the semiarid zone. A favorable soil-particle composition can effectively improve soil structure, water-holding capacity and infiltration and thereby influence SWS (Zhao et al., 2010). In contrast to previous studies, SWS was erratically distributed in the subhumid zone. For example, Wang et al. (2013b) reported that soil texture within 0–21 m profiles was highly correlated with SWC for various land uses. The status of soil-water in the subhumid zone may thus be due to a complex interaction among climatic conditions, soil properties, type and age of vegetation, topographical characteristics and human management.

Table 5
Multiple linear regression between soil-water storage (SWS) and available soil-water storage (ASWS) and measured factors in the 0–500 cm soil profile.

	Climatic zone	Regression equation	R^2	P
$SWS_{5\ m}$	Transect	SWS = 0.97 × Clay + 0.22 × Elevation − 0.18 × (AT × Latitude)	0.799	<0.001
	Subhumid	SWS = 0.72 × Clay + 0.98 × Elevation − 0.73 × Latitude − 0.63 × (AT × Latitude)	0.793	<0.001
	Semiarid	SWS = 0.83 × Clay + 0.37 × (AP × Elevation)	0.781	<0.001
$ASWS_{5\ m}$	Transect	ASWS = 1.11 × Clay − 0.29 × AT + 0.69 × Latitude + 0.28 × (AP × Elevation)	0.600	<0.001
	Subhumid	ASWS = −0.71 × Elevation − 0.57 × (AT × Latitude) + 0.39 × Clay	0.724	<0.001
	Semiarid	ASWS = 1.01 × Clay + 0.54 × Latitude − 0.38 × (AP × Longitude)	0.840	<0.001

Note: AP, annual precipitation; AT, annual temperature.

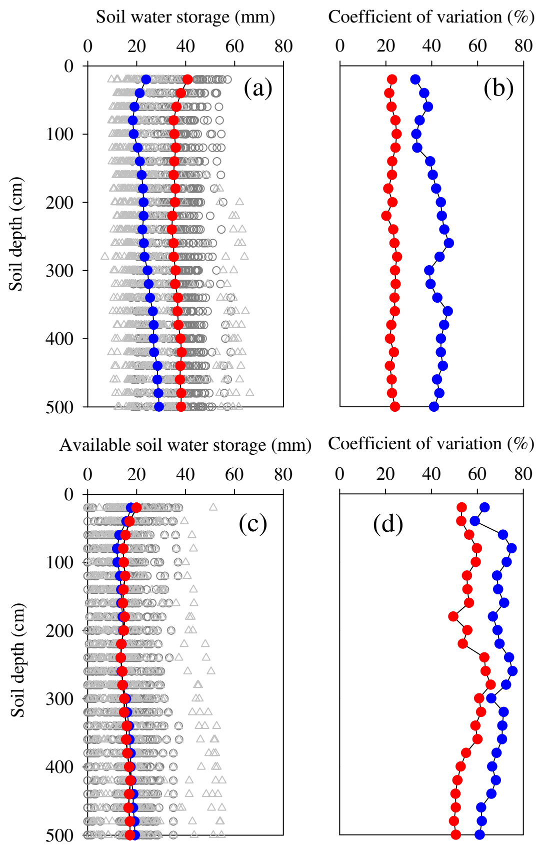

Fig. 5. Vertical distribution of soil-water storage (SWS) and available soil-water storage (ASWS) in the 0–500 cm soil profile in the two climatic zones: mean (a and c) and coefficient of variation (CV) (b and d) of SWS and ASWS, respectively. The gray circles and triangles represent the SWS and ASWS at the sampling sites in the subhumid and semiarid zones, respectively. The red and blue dots represent SWS and ASWS in the subhumid and semiarid zones, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The regression equations for $SWS_{5\ m}$ and $ASWS_{5\ m}$ on the transect, and in both the subhumid and semiarid zones ($R^2 > 0.60$, $P < 0.001$), generally contained soil (e.g. clay content), topography (e.g. elevation) and climatic factors (e.g. annual precipitation and annual temperature) (Table 5), further indicating that the soil-water regime was the combined result of a series of biotic and abiotic processes.

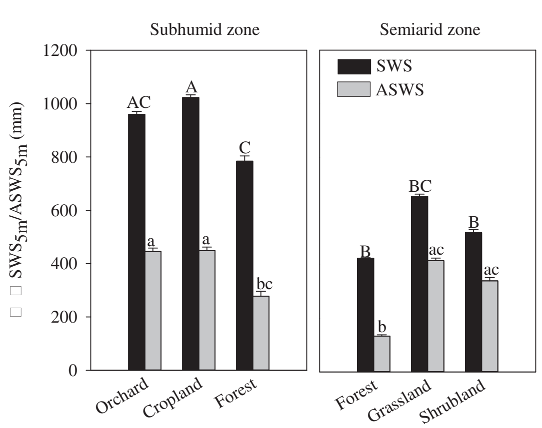

Fig. 6. Soil-water storage (SWS) and available soil-water storage (ASWS) of the land uses in the two climatic zones. Different upper- and lowercase letters indicate significant differences of $SWS_{5\ m}$ and $ASWS_{5\ m}$ in the two climatic zones at $P < 0.05$.

3.4. Implications of understanding SWS along a transect

Soil-water storage represents the ability of soil to supply water (representing a buffer against low precipitation for a period of time) and is an important indicator of the sustainability of regional water resources around the world, especially in areas with soil-water deficits. SWS depends on the soil-water balance and the water cycle in an ecosystem. When inputs of soil-water such as precipitation or irrigation increase and outputs such as evaporation or drainage decrease, a surplus of water will be stored, and a decrease in inputs and increase in outputs will lead to soil-water deficits. SWS is thus dependent on climate change and water management.

The implementation of the Grain for Green project by the Chinese government in 1999 has dramatically changed the landscape, doubling the coverage of vegetation in the last 16 years. Some researchers have realized that the continued expansion of revegetation would cause more harm than good to communities and environments, because the current coverage of vegetation has reached a level that suits the climatic conditions and water availability (Chen et al., 2015). Large-scale restoration with non-native vegetation has a high demand for water, which would decrease the storage of soil-water and lead to the formation of dried soil layers. Dried soil layers would hinder and disrupt the water cycle in the soil-plant-atmosphere system, which in turn would have a negative impact on the development of the vegetation (Li et al., 2008; Shangguan, 2007), and different changes in vegetation would lead to different patterns in flows, which would affect the soil-water status (Brown et al., 2005). Information on the spatial distribution of SWS at a large scale is thus necessary for balancing the soil-water status controlled by climatic factors. Understanding the factors affecting the balance of SWS at a local scale is also important for the sustainability of vegetation, because the local pattern of SWS may determine the ability of individual plants to obtain enough water to survive.

The heterogeneity of SWS is dependent on many factors and their interactions, which can be classified into three main categories: (1) the spatiotemporal heterogeneity of the physical and chemical properties of soil, which may lead to related mechanisms and processes that differ at different scales (Viglizzo et al., 2004); (2) the spatiotemporal variability of the land use and the supply of soil water and (3) climatic conditions, topographical elements and underground water levels (Zhu and Shao, 2008). Notably, these large-scale factors (e.g. climatic conditions) strongly influence the variability of SWS, which is stronger in arid and semiarid areas than in more humid regions where the groundwater level is a dominant factor.

Our results (Section 3.3) support a strong influence of climatic conditions and soil textures on SWS at the scale of a long transect (500 km). Soil-particle composition also played an important role in determining SWS in the semiarid zone. $SWS_{5\ m}$ and $ASWS_{5\ m}$ indicated a higher water consumption and evapotranspiration in forested land in both climatic zones, which should be incorporated into strategies of land use, as previously reported (Chen et al., 2007; Yang et al., 2012).

Selecting suitable types of vegetation and appropriately managing a system of land use based on regional SWS would be a good model for the long-term profitability and sustainable management of the CLP. These measures should take into account the spatial patterns of SWS and those of the factors that affect SWS. This study has explored the spatial pattern of SWS along a transect crossing two climatic zones and may be helpful for the control of SWS, the regional management of land use and governmental policy decisions. Further study is needed to verify the effect of climate and other factors on SWS, which is important for evaluating regional SWS at a large scale. The results of such studies could be used to predict regional water resources and to optimize land-use management and the rational distribution of vegetation, both on the CLP and in other regions around the world.

4. Conclusions

We investigated the spatial patterns of SWS to a depth of 5 m along a 500 km transect on the CLP. $SWS_{5\ m}$ tended to decrease from southeast to northwest and was approximately 320 mm higher in the subhumid than the semiarid zone. $SWS_{1\ m}$ and $ASWS_{1\ m}$ did not differ significantly between the rainy and dry seasons, except in the 0–100 cm layer. SWS and ASWS in the 0–500 cm soil profiles were more variable in the semiarid than the subhumid zone. $SWS_{1\ m}$ and $ASWS_{1\ m}$ increased with soil depth in the semiarid zone and fluctuated slightly in the profile in the subhumid zone. $SWS_{5\ m}$ and $ASWS_{5\ m}$ differed significantly among the land uses along the transect. $SWS_{5\ m}$ and $ASWS_{5\ m}$ were influenced by many factors but mostly by soil texture in the semiarid zone and by soil, elevation and latitude in the subhumid zone. Climatic conditions, topographies and soil properties played dominant roles in determining the status of $SWS_{5\ m}$ and $ASWS_{5\ m}$ at the large scale of the transect.

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