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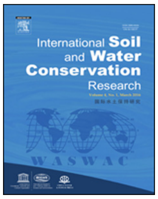

Original Research Article

Monitoring and predicting the soil water content in the deeper soil profile of Loess Plateau, China

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ABSTRACT

Estimation of soil water content (SWC) in deep soil profiles is of crucial importance for strategic management of water resource for sustainable land use in arid and semi-arid zones, as well as for soil and water conservation. Soil properties have a very important effect on SWC. This study aimed to analyze the influence of soil particle size on SWC, for the first time using soil particle size to estimate SWC in deep soil profiles. SWC was measured mainly in farmland, natural grasslands and plantations of Caragana from the surface to more than 20 m depth. The same soil samples were also tested for particle size. The results show that the soil desiccation is formed in the caragana forest in 3–18 m soil layers, but almost no formation in 18–24 m layers; water content of farmland and grassland is different in all soil profiles although they are both shallow rooted plants. Correlation analysis indicated that SWC could be well predicted by clay content and the close correlation between SWC and clay content yielded a coefficient of determination (R^2) of 0.82 and 0.72, respectively, for farmland and grassland. After multiple regression analysis, a regression model was built using SWC, clay content and sand content data, giving $R^2=0.66$. The model provided reliable estimates of SWC profile based on textural class. This can assist in estimating water depletion by vegetation, by comparing moisture of farmland and grassland soils with that of plantation forests, and in selecting sustainable land use of arid land.

Contents

1. Introduction

Soil water content (SWC) is used to calculate "the available water storage capacity, which is defined as the moisture held between field capacity (FC) and permanent wilting point (PWP)" and is

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critical for practical application which is related to agricultural, water and soil resources management (Rao, 1998; Starks, Heathman, Ahujab, & Ma, 2003). It is also a critical factor in evaluating the suitability of the given vegetation in that region. The transmissivity parameters (e.g., soil hydraulic conductivity vs. SWC relationships) used in physically-based models that make basic assumptions of soil uniformity and homogeneity, are also highly sensitive to SWC (Givia, Prasher, & Patel, 2004). However, direct measurement of SWC is usually hard, expensive and time-consuming for most researches and management applications, especially on a relatively large scale. When the researched area is relatively homogeneous in its physical soil makeup and topography, SWC is related to other physical characteristics such as particle size distribution, structure, bulk density and organic matter content (Rao, 1998). It is possible to develop empirical relationships that provide adequate estimates of SWC through numbers of sampling sites which are inexpensive and easy to access. Most methods are named pedotransfer functions (PTFs) (Bouma & Van Lanen, 1987).

Correlations between soil properties (SWC, organic carbon content, and percentage of sand, silt, clay etc.) have been studied since early in the twentieth century (Briggs & Shantz, 1912; Salter & Williams, 1965; Doorenbos & Pruitt, 1977). With the development of computer modeling and databases, more PTFs have been developed (Rawls, Gish, & Brakensiek, 1991; Wösten, Pachepsky, & Rawls, 2001). Rawls, Brakensiek, and Saxton (1982) developed PTFs using 5350 sets of soil data. Baumer (1992) developed PTFs using 18 000 soil horizon measurements from the US National Soil Pedon Characterization database to predict SWCs at FC and wilting point (WP). Wösten, Lilly, Nemes, and Le Bas (1999) proposed PTFs based on the HYPRES database that contains 5521 sets of soil data. Bruand, Perez Fernandez, and Duval (2003) formulated PTFs use particle size and bulk density to calculate gravimetric water content at 7 water potentials. Furthermore, the accuracy of PTFs in predicting the SWC has been evaluated. Givia et al. (2004) showed that the PTFs developed for soils having similar characteristics to those being studied generally perform better than others. Cornelis, Ronsyn, Van Meirvenne, and Hartmann (2001) presented that a PTF performs much better if it is used to the developed region.

However, concrete measurement of the required soil characteristics is not practicable and the present PTFs are most be developed for estimating water retention and available water content in surface soil (Schaap, Nemes, & Van Genuchten, 2004). Currently, we can only get a crude spatial distribution of soil textural composition by field survey (Starks et al., 2003). Particle-size composition could be related to FC, WP, and available water content via regression equation (Pidgeon, 2006). The relationships predicting SWC have been developed from those found in different countries, including England (Pidgeon, 2006), USA (Leij, Alves, van Genuchten, & Williams, 1996), France (Bruand et al., 2003), Rosetta (Schaap, Leij, & Van Genuchten, 2001) and other parts of Europe (Wösten et al., 1999). In China there is still little data available.

Soil desiccation (SD) is a particular hydrological phenomenon in semiarid area of the Loess Plateau in China, which is induced by the excessive depletion of deep soil water and long-term insufficient rainfall supply (Chen, Shao, & Li, 2008). It was found firstly by Li (1983) in 1960s in semiarid area of Shaanxi and Gansu provinces and often took place below the depth of soil which was affected by rainfall infiltration about 3 m (Yang & Shao, 2000; Fan, Shao, & Wang, 2006; Li et al., 2007). However, it was paid limited attention to until 1980s, when it was found in artificial forestland with a depth from 0.4 m to more than 10 m (Yang & Yu, 1992; Mu, Xu, Wang, Wen, & Du, 2003, Wang, Shao, Wang, & Jia, 2005). In the present study we investigated the SWC of farmland, grassland and artificial vegetation. One specific objective of the study was first measurement of the SWC after rainy season of the soil and parent material from the surface to 24 m depth. And then discussion of the variations recorded due to the vegetation excessive depletion of deep soil water, evaluate the relationship between SWC and soil particle size and to develop a statistically supported PTF for predicting SWC from soil particle size data. The PTF should help us in sustainable land-use planning and soil and water conservation planning.

2. Materials and methods

2.1. Study area description

The study was carried out in the catchment of the Suide County Shaanxi Province, the semiarid area of the Loess Plateau of China (Fig. 1). The latitude is N37° 31′ 16″ with longitude is E110° 17′ 05″. Suide County occupies an area of approximately 1878 km^2. The climate is semi-arid with a yearly-averaged temperature of 9.7 °C, a yearly-averaged precipitation of 439 mm of which more than 70% falls from May to Sep. called wet season (Table 1). SWC was recharged in the wet season. The average annual potential evaporation is nearly 1900 mm. The landform is typical loess hilly landscape with an elevation ranging from 608 m to 1287 m. The soil is calcareous silt loam (Calcic Cambisols) with the parent material is loess. The field capacity is 15.8%, and the permanent wilting point is 4%. The present natural forest species are *Pyrus betulaefolia*, *Zizyphus sativa*, *Artemisia gmelini*, *A. grandii*, *Stipa bungeana*, *Heteropappus altaicus* and *Lespediza dahurica*. The re-grown forest species are *Robinia pseudoacacia L, Pinus tabulaeformis*, *Platycladus orientalis, Ulmus pumila* and *Caragana microphylla Lam*. They were planted in late 1970s. Introduced turf is *Alfalfa*.

2.2. Sampling site

The sampling sites were within a limited area with similar topographic characteristics and altitude. The land use of three sites was farmland, grassland and caragana located on middle slope positions on east-facing slopes. The farmland crops are mainly annual crops (millet) and cash crops (castor oil plant, *Ricinus communis*). The castor oil plant was planted in 2007. The grassland

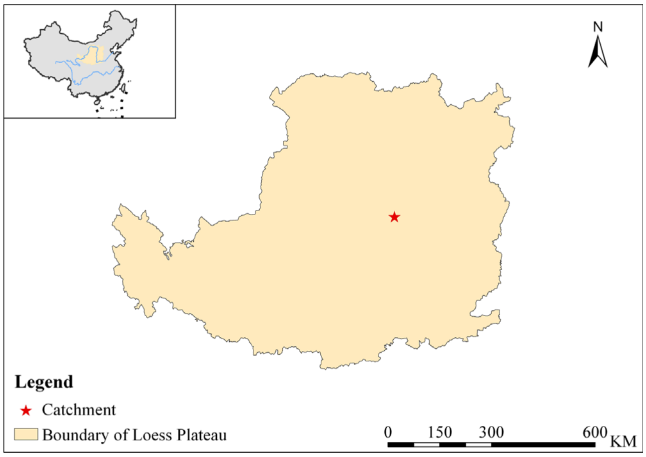

Fig. 1. The location of study catchment.

Table 1
Precipitation (mm) of Suide County, Shaanxi (1981–2010).

Annual	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
243	0	0	3	7	16	33	61	63	44	12	4	0

Table 2
Site characteristics of a soil water content study in the Suide Catchment on the Loess Plateau.

Land Type	Slope position	Gradient	Elevation (m)	Vegetation cover (%)	Sampling date
Agriculture	Mid-slope	35°	1013	–	10/31/2007
Grassland	Slope shoulder	36°	1021	55	11/14/2007
Forest	Mid-slope	32°	980	80	11/10/2007

had been grazed until it was prohibited in 2002. The grass species is mainly *Artemisia gmelini, Heteropappus altaicus* and *Lespediza dahurica*. Caragana plantations were first established in 1985. Table 2 summarizes the main characteristics of the sampling sites.

2.3. SWC testing and soil particle size analysis

Soil samples were obtained in late October or early November with a petrol-driven percussion drilling (percussion drilling sets, Eijkelkamp) to measure profile SWCs and physical properties in every 10 cm layers to a depth of 25 m in farmland, 20 m in grassland and 24 m in caragana forest. The machine is 1.0 m long and 0.08 m in diameter with the stem extended to 30 m. At the time of this soil survey, according to the study of Wang, Liu, and Wang (2007), the wet season had passed and the soil water recharge got a maximum level.

Stable SWC was obtained by oven-dry method of 105 °C, which is expressed as a gravimetric percentage in g 100 g^{-1}.

Composite soil samples of about 0.5 kg were collected from these sampling locations. The samples were air-dried and filtered by a 2 mm sieve. The fraction less than 2 mm was to analyze particle-size distribution by sodium pyrophosphate as dispersing agent. The sieve method for the sand fractions (0.05–2 mm) and the pipette method are to measure silt (2–50 μm) and clay (< 2 μm), on the basis of the USDA texture classification scheme. The particle-size distribution was measured at 1 m spacing for all vegetation types, and at smaller intervals where the SSWC showed marked variation. We have taken the $CaCO_3$ out by hydrochloric acid.

3. Results

3.1. The SWC characteristic of soil profile

Gravimetric water content profiles in cropland, grassland and caragana with same aspect and slope are shown in Fig. 2. The SWC of cropland and grassland were similar but bigger than that of caragana in soil profile. The SWC in farmland and grassland showed diverse changes and the average SWC was 11.78%, whereas SWC of the caragana forest exhibited only very small changes in the 3–18 m soil layers which the average SWC was 4.91% little more than the temporary wilting point. However, the average SWC of the caragana in 18–24 m soil layers was 10.55%. This indicated that (1) the SD was formed in the caragana forest in 3–18 m soil layers, but there was almost no formation in 18–24 m layers and (2) water content of farmland and grassland is different in all soil profiles although they are both shallow rooted plants.

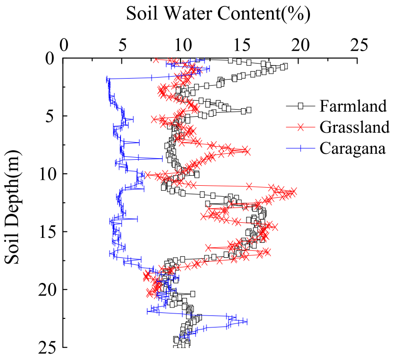

Fig. 2. Soil water content vs. depth for different vegetations.

3.2. The relationship between SWC and clay content in soil profile

SWC is a significant factor responding to soil physical properties and water vegetation interactions. It is needed to consider why SWC showed critical difference between farmland and grassland, and sever SD was formed in caragana under same climate conditions and terrain. To find the cause of these SWC changes in farmland and grassland, we analyzed the relationship between SWC and particle size composition. Experimental data from our study showed that the SWC of farmland and grassland changed synchronously with clay content and there was a manifest difference of clay content between farmland and grassland; the SWC for caragana forest below 18 m depth showed same changes with clay content (Fig. 3), which denoted that clay content difference has a significant effect on the value of SWC. Since clay content played a significant role in soil water-holding characteristics, its variation can be used as an indicator for change of SWC.

Correlation analysis indicated that SWC could be well predicted by clay content as shown in Table 3. The close correlation between SWC and clay content yielded a coefficient of determination (R^2) of 0.82 and 0.72 respectively for farmland and grassland when the SWC and particle size values were analyzed (n=38 in farmland, 29 in grassland).

The SWC below 3 m is used to analyse the relationship between clay content and SWC. SWC of farmland and grassland increased with clay content. Linear relationship exists between SWC and clay content (Fig. 4).

The clay content and SWC data of farmland and grassland provide the regression models in Eqs. (1) and (2) which incorporate the logarithmic relationships between clay content and the SWC

$$m_f = 14.24 \ln c_f - 27.553,\ n = 38,\ R^2 = 0.66 \tag{1}$$

$$m_g = 11.342 \ln c_g - 19.852,\ n = 29,\ R^2 = 0.61 \tag{2}$$

where m_f is farmland SWC (%); c_f is farmland clay content (%); m_g is grassland SWC (%); and c_g is grassland clay content (%). Combining the farmland to grassland data gives the regression model

$$m = 12.074 \ln c - 21.749,\ n = 67,\ R^2 = 0.63 \tag{3}$$

where m is SWC (%) and c is clay content (%).

The SWC of the farmland and grassland calculated from Eq. (3) shows good consistency between observed and predicted values of farmland and grassland (Fig. 5).

3.3. The influence of soil particle size on SWC

The correlation between the soil particle size (sand, silt, and clay content) and SWC was analyzed using the multiple regression method. Table 4 shows that there is a good correlation between them. Below a depth of 3 m, the R^2 values increase from 67.3% (clay content only) to 73.3% (sand content included) for farmland, and from 63.6% to 69.7% for grassland.

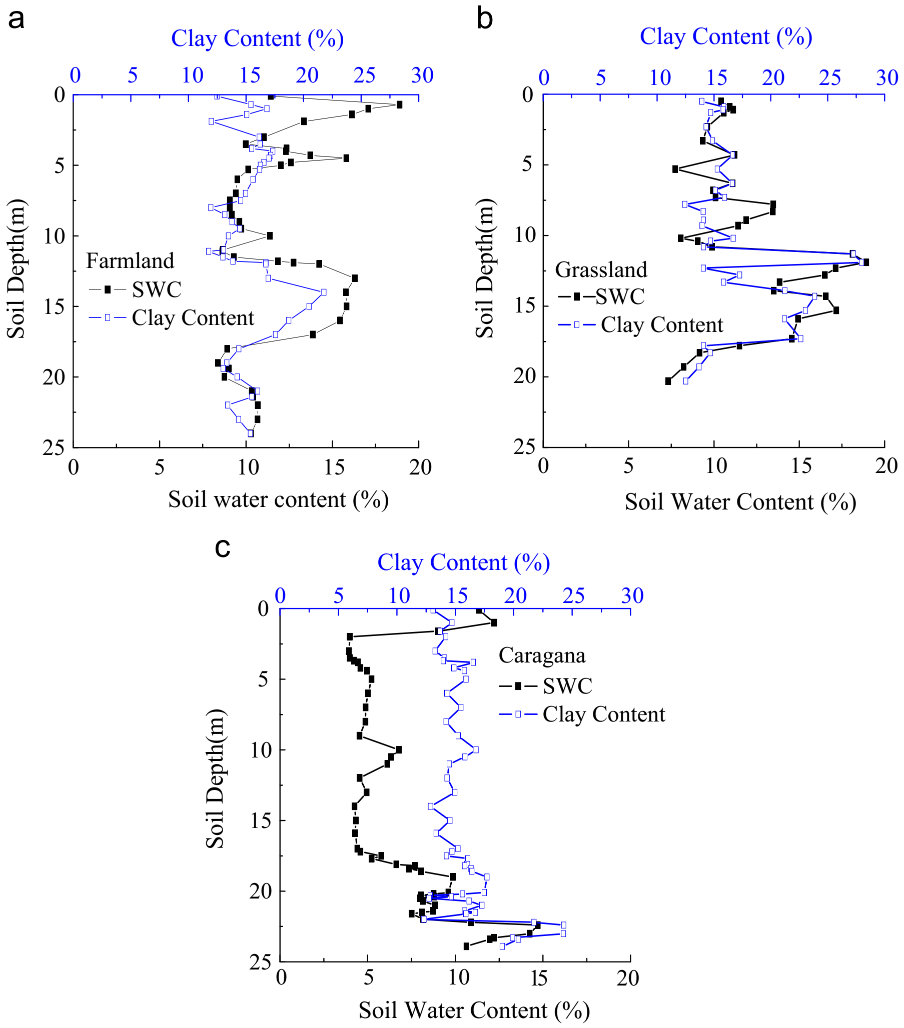

Fig. 3. Soil water content and clay content of different vegetation along soil profiles.

Table 3
Correlation between soil water content and particle size distribution at soil depth > 3 m in the Suide Catchment of the Loess Plateau.

Land type	Sand	Silt	Clay	n
Agricultural	−0.303	0.022	0.820**	38
Grassland	−0.685**	0.444*	0.722*	29

* Correlation is significant at $p \leq 0.05$ (2-tailed).
** Correlation is significant at $p \leq 0.01$ (2-tailed).

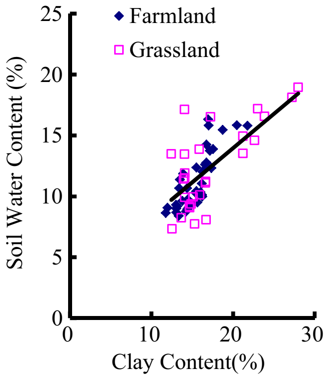

Fig. 4. Relationship between soil water content and clay content in farmland and grassland.

A multiple regression analysis using the combined farmland and grassland data was then carried out to further refine Eq. (3), giving

$$m = 3.953 + 0.596c - 0.08s,\ n = 67,\ R^2 = 0.66 \quad (4)$$

where m is SWC (%); c is clay content (%); and s is sand content (%).

To validate the predictor, model efficiency (ME) was selected to assess the capacity of the predictor in SWC calculations

$$ME = 1 - \frac{\sum (Q_o - Q_p)^2}{\sum (Q_o - Q_m)^2} \quad (5)$$

where Q_o is the observed value; Q_p is the predicted value; and Q_m is the mean predicted value. The ME is 0.64 and 0.63 respectively for farmland and grassland.

4. Discussion and conclusions

Although previous researchers have developed many PTFs for predicting soil hydraulic conductivity and soil water retention curves, it is suggested that these are not adequate for determining the moisture available in deep soil layers for sustainable planting, especially in arid land.

SD may lead to formation of a dried soil layer in the soil profile at a specified depth. Mu, Chen, and Guo (1992) and Li (1983,1985) pointed out that in farmland and grassland, this given depth is

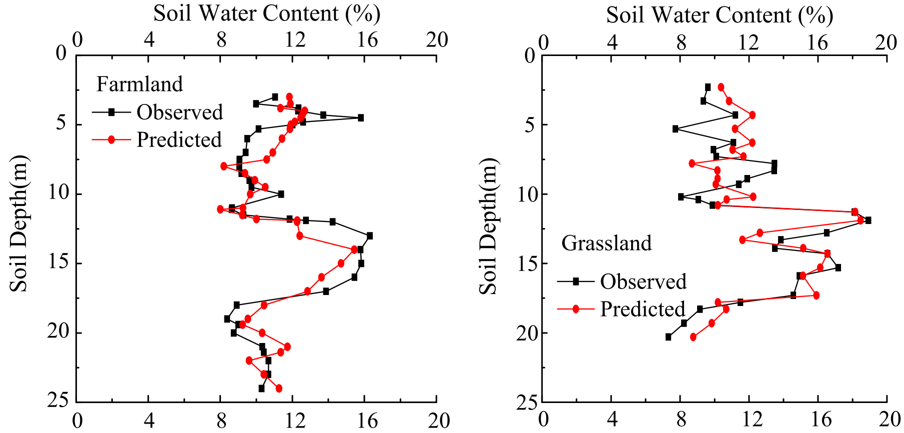

Fig. 5. Comparison of observed and predicted soil water content.

Table 4
Regression analysis between soil water content and soil particle size distribution in the Suide Catchment of the Loess Plateau.

Land type	Particle size	Soil depth	R^2
Agricultural	Clay Sand, clay	> 3 m	0.67 0.73
Grassland	Clay Sand, clay	> 3 m	0.64 0.7

below 3 m. The SWC of top 3 m layer varies due to the influence of rainfall, evaporation and differences in vegetation cover (Mu, Chen, & Zhao, 1990; Mu et al., 1992; Chen et al., 2008). From three years' investigation data of Wang et al. (2007) in this area, we found little variation in the SWC at depth below 3 m. The PTFs outlined in the present study aim to predict SWC available for plants at greater depth, based on our finding, there are no inter-annual moisture changes in soils below 3 m depth. The main conclusion from this research is that there is a good correlation between clay content and SWC. A logarithmic increasing trend was found to exist between clay content and SWC below 3 m soil depth, similar to that reported by Li, Han, and Wang (1985) in the Loess Plateau. Clay content has a significant impact on SWC. The larger the clay content is, the stickier the soil texture is which leads to greater specific surface area, absorbent capacity and holding capacity. In short, the clay content influences the soil moisture mainly through regulating the soil texture, structure, size of the gap and matric potential. SD is induced by excessive depletion of deep soil water at 3–18 m depth

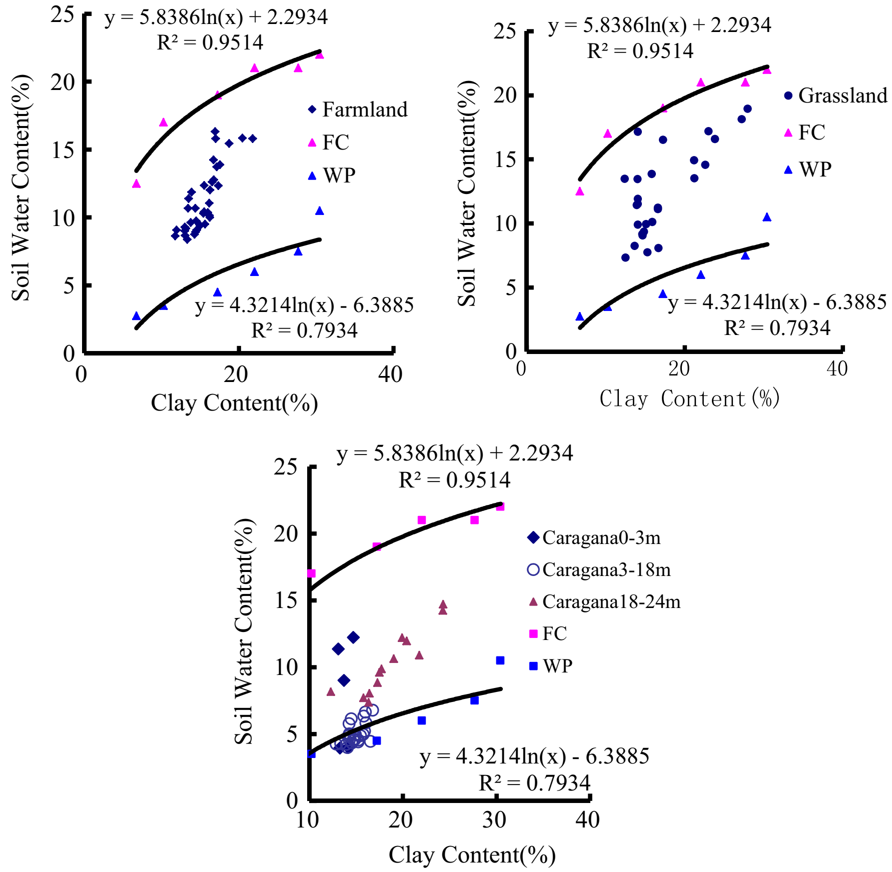

Fig. 6. Relationship between soil water content and clay content.

by planted caragana forest which has a well correlation with climate drought and loess properties.

The FC and PWP criteria for measuring the amount of water that is supplied to the plant from the soil are very important for partitioning the valid and invalid water (Li et al., 1985) who stated that FC and PWP have a good linear correlation with clay content in sandy loam and light loam in which the physical clay content (<0.01 mm) is below 27% as shown in Fig. 6. The data of FC and PWP of Fig. 6 were from the literature of Li et al. in 1985. In the present work, we investigated moisture content between PWP and FC and found the relationships between SWC and clay content for farmland and grassland to be similar to those data reported by Li et al. (1985).

Fig. 6 also shows that with similar clay content, the SWC of caragana forest in 3–18 m soil layers is less than that at 18–24 m, which suggests that the excessive depletion of soil water in deep layers by artificial vegetation in the 3–18 m soil layers, causing soil desiccation and the correlation between moisture and clay content is unaffected by vegetation.

Multiple regression analysis indicates that SWC is correlated to clay and sand content and R^2 values are found to increase when sand content is incorporated into the analysis. The correlation between SWC and clay content is positive, while negative between SWC and sand content. The PTFs represented by the sand and clay content of soil can be used in predicting the SWC.

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