Factors controlling the spatial variability of surface soil moisture within revegetated-stabilized desert ecosystems of the Tengger Desert, Northern China

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Abstract:
The spatial structure of surface soil moisture was investigated at a grid scale with 10 × 10 m intervals on a plot of 4500 m² in a re-vegetated desert area in Shapotou, the Tengger Desert. The site topography varies from dune crest to dune hollow, and again to dune crest. Volumetric soil moisture contents were measured 21 times over 6 months in 2006 by using Delta-T Theta-Probes in the 0–6 cm surface soil layer before and after rainfall. At the same time, soil texture, relative elevation, and plant coverage were measured, to examine (i) the spatial variability of surface soil moisture; (ii) the main factors controlling the spatial variability patterns; and (iii) how the importance of these factors varies with the seasonal variations in soil moisture content. The results indicated that the normal distribution of surface soil moisture was more obvious in wet conditions than in dry conditions; the spatial variability of surface soil moisture was inherent and decreased with increased soil moisture content; and precipitation increased the spatial dependence of surface soil moisture. The relative elevation of the landscape, the shrub coverage of the community, and the soil texture were the main factors influencing surface soil moisture variability, while the effect of soil texture strengthened gradually following the heavy precipitation events. The correlation between the spatial variability of surface soil moisture and the environmental factors, such as, the dry and wet conditions, the landscape coverage and the relative elevation suggests that increasing stability of the soil moisture resulted in a significant increase of soil moisture. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS surface soil moisture; coefficient of variation; relative elevation; shrub coverage; herbage coverage; soil particle size

Received 31 March 2008; Accepted 21 January 2009

INTRODUCTION
Soil moisture is a key state variable for understanding numerous hydrological processes involved in a broad variety of natural processes (e.g. geomorphic, climatic, ecological) that act at different spatio-temporal scales (Entin et al., 2000), and is arguably the most important state variable that controls near-surface hydrologic and energy balance variability (Western et al., 2003). Soil moisture limits the number and size of perennial plant species in arid environments (Nash et al., 1991), and is therefore the main constraint for vegetation development, thus governing the potential to halt desert encroachment (Berndtsson and Chen, 1994). Charney et al. (1977) studied the effect of soil moisture on desertification processes using general circulation models, pointed out that soil moisture data is useful in understanding the ecosystem of arid and semiarid areas. In arid desert ecosystems precipitation is highly variable throughout the year and occurs in infrequent and discrete events (Noy-Meir, 1973). Thus soil moisture exhibits a high degree of spatial and temporal variability.

Understanding the results of a statistical analysis (e.g. coefficient of variation and mean calculations) on spatio-temporal soil moisture data is critical for evaluating soil moisture variability. The relationship between the coefficient of variation of soil moisture and its mean value is an important issue in determining the number of sampling points to estimate the mean soil moisture content within a specified limit of error (Bell et al., 1980; Owe et al., 1982), and vice versa. Charpentier and Groffman (1992) used such a relationship in estimating the variability of soil moisture with the remotely sensed mean soil moisture value, moreover in determining the accuracy and precision of remote sensing in different soil moisture conditions. Contrarily, there is no systemic relationship between spatial variability of soil moisture and its mean value (Hawley et al., 1983; Charpentier and Groffman, 1992), while Owe et al. (1982) found the highest spatial variability of soil moisture in the midrange of mean soil moisture values. Understanding the variability characteristic of soil moisture is crucial for soil parameterization in atmospheric and hydrological models, but it
is controlled by many factors, such as weather, soil texture, vegetation and topography (Buttafuoco et al., 2005). Reynolds (1970) characterized the variability in small plots using gravimetric surveys and attributed variability to two sources: static properties (e.g. soil type) and dynamic influences (e.g. precipitation). Seyfried (1998) identified vegetation, soil type and elevation (a surrogate for climate) as effective sources of soil moisture variability at different scales in the Reynolds Creek Experimental Watershed (RCEW) in Idaho. Western et al. (1999) found that the combination of indices linked to the lateral water redistribution and those linked to evapotranspiration, generally can predict the majority of the organized component of the soil moisture spatial variability in wet and dry condition for the Tarrawarra catchment in Australia. Entin et al. (2000) noted that the spatial variability of soil moisture is expected to be influenced by a small-scale component dominated by soil type, topography and vegetation and a large-scale component due to atmospheric quantities such as precipitation and evapotranspiration. Famiglietti et al. (2008) evaluated the spatial distribution characteristic of each factor and successfully related factors to the spatial variability of soil moisture. In addition, the importance of these factors can vary with the study area or seasonal variations in the soil moisture content (Famiglietti et al., 1998).

Considering the importance of soil moisture and its complicated spatial distribution characteristic in arid and semi-arid areas, the spatial variability of surface soil moisture was studied in Shapotou area, where precipitation is the predominant source of freshwater. Groundwater is a potential source but it is found below 80 m and is not a viable source to maintain a natural vegetative cover for a large area. Dew and condensation are restrained by the biological soil crust developed in sand surface (Wang et al., 2004).

To stabilize the shifting sand dunes, a major problem in the Shapatou region of China, straw checkerboards were installed and artificially sand-binding vegetations were planted in 1956. Shrubs consisted predominantly of Caragana korshinskii, Hedysarum scoparium, and Artemisia ordosica. The development of dwarf shrub and microbiotic soil crust on the stabilized sand dunes is hypothesized to have changed the surface soil attributes and soil moisture content (Wang et al., 2007a). To further investigate this hypothesis, this paper has three main objectives: (i) to define the spatial variability of surface soil moisture (0–6 cm) in an artificially re-vegetated desert area in Shapotou, (ii) to indicated the main factors controlling surface soil moisture patterns in this semiarid environment, and (iii) to quantify the variation of these factors with seasonal changes in the soil moisture content.

STUDY AREA

The experiment was carried out in the desert steppe region at the Shapotou Desert Experimental Research Station bordering the Tengger Desert at 37°32’N and 105°02’E. The average elevation is 1288 m above the sea level. According to meteorological records between 1955 and 2005 from the weather station, annual mean temperature is 10.6°C. Low temperatures are observed during the month of January, with a mean value of −6.3°C and high temperatures are observed during the month of July, with a mean value of 24.9°C. Annual mean precipitation is 193 mm, most of which is received during the monsoon period between May and September (Figure 1). The annual potential evaporation is approximately 3000 mm. The growing period ranges from 150 to 180 days per year. The natural predominant plants are Hedysarum scoparium and Agriophyllum squarrosum with a cover of approximately 1–2% (Shapotou Desert Experimental Research Station, Chinese Academy of Sciences, 1991). The soil is classified as orthic sierozem and Aeolian sandy soil (Li et al., 2007). The experimental field lies in the artificially re-vegetated desert area initiated in 1956 (refer to Wang et al. (2006) for details regarding mobile sand stabilization) (Figure 2).

**EXPERIMENTAL DESIGN AND DATA COLLECTION**

The study site consisted of a 4500 m² experimental plot, with a length of 90 m (oriented west–east) and a width of 50 m (oriented south–north), the landscape comprises of leeward, hollow and windward from west to east (Figure 2). Survey stakes were set along a 10 m × 10 m grid throughout the site, resulting in a total of 60 locations for soil moisture content measurements.

Volumetric soil moisture contents were measured from 0–6 cm using portable FDR probes (Delta-T Devices Ltd., Burwell, UK). Data were collected during a total of 21 measurement periods between May and September in 2006, measured prior to, during, and following rainfall events (Table I), and the measurements were intensified
to a day for each rainfall event. A field-specific volumetric calibration method that compares impedance probe measurements with soil moisture measurements (Cosh et al., 2005) was used to calibrate the probes. Accuracy of the general calibration curve is ±0.03 cm$^3$ cm$^{-3}$ for measurements taken in mineral soils. In total, 1260 water content measurements were made during the experiment.

To count the number of herb species and to measure the coverage of the plant community, 60 quadrats 1 × 1 m$^2$, and 60 quadrats 10 × 10 m$^2$ were marked using survey stakes inside the experimental plot. Measurements were made in late September 2006. The herb and shrub coverages were computed as percentage of the area.

Surface soil samples (0–6 cm) were collected within a 1-m radius of the survey stakes for each quadrat. Four soil samples were collected at each surveyed location and then mixed completely creating a composite sample. Soil samples were analysed for particle size distribution using a MS-S light scattering apparatus (Malvern Instruments Ltd, Malvern, UK) by Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences.

Elevation data were measured at each sampling location using GPS (global positioning system) and geometry gradiometer. Elevation ranged from 1284 to 1292 m (Figure 2). Rainfall was measured by a siphon rain gauge with an observational error less than ±0.2 mm for rainfall events less than 10 mm, and less than ±0.02 mm for rainfall events greater than 10 mm. The measurements were made using a weather station (MILOS 520, Vaisala, Finland) at the Shapotou Desert Experimental Research Station, located approximately 100 m away from the study site.

### DATA ANALYSIS METHODS
The methodologies used to assess the soil moisture spatial variability include:

1. Statistical analysis, aimed at defining the statistical distribution characteristics of the sampled soil moisture and to depicting its variability through corresponding statistical parameters;
2. Geostatistical analysis, using experimental variograms to represent the variance as a function of distance between measurement points;
3. Regression analysis, considering the influence of every factor to be included in a model and eliminating those factors that do not contribute new information to the model (Draper and Smith, 1981), at a significance level of less than 0.05 for including the factor in the model, and a significance level greater than 0.1 for excluding the factor.

### RESULTS

**Precipitation**

Precipitation data collected during the 2006 experimental period and average monthly precipitation data collected between 1955 and 2005 are provided in Figure 1. Annual precipitation was approximately 130 mm during the experimental period. Due to monsoonal effects, and based on 50 years of mean monthly precipitation data, approximately 80% of annual precipitation falls between May and September. For 2006 data, 40% of the annual total precipitation occurred in July. Based on the long-term monthly average rainfall, May and September in the experimental year 2006 corresponded with a normal season, while July and August in 2006 corresponded with a wet and dry season, respectively (Figure 1).

**Statistical parameters and variability characteristics of surface soil moisture**

A statistical summary of soil moisture data collected during the experimental period is provided in Table I. The minimum soil moisture content was 1.22% (collected on 12 August), and the maximum soil moisture content

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**Table I. Summary of surface soil moisture statistics during the experiment period (Std., Standard Deviation; CV, coefficient of variation)**

<table>
<thead>
<tr>
<th>Date</th>
<th>Mean (%)</th>
<th>Std.</th>
<th>CV (%)</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>9-May</td>
<td>13.74</td>
<td>4.23</td>
<td>30.81</td>
<td>−0.23</td>
<td>−1.09</td>
</tr>
<tr>
<td>10-May</td>
<td>6.65</td>
<td>2.25</td>
<td>33.83</td>
<td>−0.15</td>
<td>−0.80</td>
</tr>
<tr>
<td>21-Jul</td>
<td>15.29</td>
<td>2.99</td>
<td>19.53</td>
<td>−0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>22-Jul</td>
<td>13.80</td>
<td>3.25</td>
<td>23.56</td>
<td>0.24</td>
<td>0.04</td>
</tr>
<tr>
<td>23-Jul</td>
<td>11.16</td>
<td>3.67</td>
<td>32.92</td>
<td>0.09</td>
<td>−0.07</td>
</tr>
<tr>
<td>24-Jul</td>
<td>6.79</td>
<td>2.40</td>
<td>35.29</td>
<td>0.42</td>
<td>−0.48</td>
</tr>
<tr>
<td>26-Jul</td>
<td>3.57</td>
<td>1.87</td>
<td>52.53</td>
<td>0.85</td>
<td>−0.15</td>
</tr>
<tr>
<td>31-Jul</td>
<td>14.53</td>
<td>3.10</td>
<td>21.36</td>
<td>0.22</td>
<td>0.50</td>
</tr>
<tr>
<td>1-Aug</td>
<td>7.44</td>
<td>2.42</td>
<td>32.48</td>
<td>−0.01</td>
<td>−0.78</td>
</tr>
<tr>
<td>3-Aug</td>
<td>4.50</td>
<td>1.70</td>
<td>37.83</td>
<td>0.40</td>
<td>−0.73</td>
</tr>
<tr>
<td>8-Aug</td>
<td>2.75</td>
<td>0.65</td>
<td>23.67</td>
<td>0.13</td>
<td>−0.32</td>
</tr>
<tr>
<td>12-Aug</td>
<td>1.22</td>
<td>0.30</td>
<td>24.31</td>
<td>0.27</td>
<td>0.82</td>
</tr>
<tr>
<td>14-Aug</td>
<td>12.30</td>
<td>2.74</td>
<td>22.29</td>
<td>−0.38</td>
<td>−0.66</td>
</tr>
<tr>
<td>15-Aug</td>
<td>8.90</td>
<td>2.76</td>
<td>31.04</td>
<td>0.17</td>
<td>−0.21</td>
</tr>
<tr>
<td>16-Aug</td>
<td>5.88</td>
<td>1.95</td>
<td>33.22</td>
<td>0.20</td>
<td>−1.08</td>
</tr>
<tr>
<td>4-Sep</td>
<td>15.15</td>
<td>3.04</td>
<td>20.05</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>5-Sep</td>
<td>14.30</td>
<td>3.26</td>
<td>22.78</td>
<td>0.28</td>
<td>0.17</td>
</tr>
<tr>
<td>6-Sep</td>
<td>10.15</td>
<td>3.00</td>
<td>29.59</td>
<td>0.15</td>
<td>−0.51</td>
</tr>
<tr>
<td>8-Sep</td>
<td>6.36</td>
<td>2.36</td>
<td>37.18</td>
<td>0.82</td>
<td>0.27</td>
</tr>
<tr>
<td>14-Sep</td>
<td>3.11</td>
<td>1.34</td>
<td>43.19</td>
<td>1.26</td>
<td>1.33</td>
</tr>
<tr>
<td>22-Sep</td>
<td>1.82</td>
<td>0.46</td>
<td>25.01</td>
<td>0.31</td>
<td>2.18</td>
</tr>
</tbody>
</table>
was 15.29% (collected on 21 July). The mean surface soil moisture content responded predictably to rainfall (Figure 3), increasing after storm events and decreasing thereafter. Larger rainfall corresponded to higher surface soil moisture contents.

In the Shapotou area of the Tengger Desert, sand dunes stabilized by barriers of straw checkerboard and revegetation enhanced the recovery of topsoil on dune systems and accordingly improved the water holding capacity and moisture content of topsoil (Wang et al., 2007a). The temporal variability characteristics of surface soil moisture indicate that precipitation is the main source of surface soil moisture in this area (Figure 3), dew and condensation are secondary inputs typical for desert areas. However, the annual amount of dew is about 3–4 mm and, thus, this component has no significant effect on shrubs and semi-shrubs, except for indirect long-term water balance changes due to crust development from bacterial, cryptogam, and ephemeral plant growth in the sand surface (Wang et al., 2004). The biological soil crust cover has a significant negative influence on the infiltration of precipitation of less than 10 mm (Wang et al., 2007b).

The surface soil moisture content within the experiment field varied between upper and lower limits of 18% and 0.09%, respectively. The variance highlights a general increasing trend with increasing mean soil moisture contents (Figure 3). The coefficient of variation, a ratio of the standard deviation and mean, suggests the relative variability of soil moisture content. Jacobs et al. (2004) pointed out that the relationship between soil moisture variability and mean become more evident when standard deviation is scaled by mean, and this scaling relationship can be seen in Figure 4. Given the measurement error (±0.03 cm$^3$ cm$^{-3}$) using the impedance probe, soil moisture values under 0.03 cm$^3$/cm$^3$ should be eliminated. As shown in Figure 4, relative variability decreased with increasing soil moisture contents except for extremely dry conditions (soil moisture content less than 0.03 cm$^3$ cm$^{-3}$). This result is consistent with previous experimental campaigns in different regions (Jacobs et al., 2004; Famiglietti et al., 2008), where the coefficient of variation is always higher than 20%. But it is opposite to the results for depths of 0–15 and 0–30 cm in the same area and the values of coefficient of variation in the present study are obviously higher those of the deeper layers (Pan et al., 2008).

To test the frequency distribution characteristics of surface soil moisture and to link the distribution to a particular soil moisture condition (drying or wetting), skewness and kurtosis were both determined (Figure 5) and compared with mean soil moisture content. Both show an increase in positive values with a decrease in mean soil moisture contents; however, significant scatter exists (correlation coefficient $r = -0.36$ and $-0.27$, respectively; $\alpha = 0.05$). Such relationships suggest dry conditions, and skewness and kurtosis values clustered around zero suggest wet conditions. Similar to the research results for soil moisture at depths of 0–15 and 0–30 cm at the same plot, surface soil moisture was normally distributed at the grid-scale (Pan et al., 2008) and the present experiment further indicates that the normal distribution characteristics are more obvious in wet conditions than in dry conditions.

**Spatial variability characteristics of surface soil moisture**

To further explore the spatial variability of soil moisture, geostatistical analysis (Table II) shows the parameters of semivariograms for soil moisture collected between May and September 2006. Data were fitted to spherical and exponential models. Nugget semivariance ($C_0$) is the variance at zero distance, which is caused by measurement error and small scale variability. The spatial heterogeneity of surface soil moisture contents under different moisture conditions differs markedly due to the difference in nugget $C_0$. The ratio of nugget semivariance to sill was used to define different classes of spatial dependence for surface soil moisture (after López-Granados et al., 2002). For this research, if the ratio was $\leq$25%, the surface soil moisture was considered to be...
at the 0–6 cm soil layer, which are very different from deeper soil layers, where ranges reached about 200 m (Pan et al., 2008). The values of range decrease with increasing surface soil moisture content (the correlation coefficient \( r = -0.862 \) at the 0-01 level), thus, the spatial dependence of surface soil moisture is higher as moisture content increases. The determination coefficient, \( R^2 \), denotes the fitting reliability to a certain degree. All the models refer to a higher determination coefficient, so they can generally reflect the spatial distribution characteristics of surface soil moisture. RSS or residual sums of squares provides an exact measure of how well the model fits the variogram data, the lower the RSS, the better the model fits. Furthermore, the fractal dimension, D, also reflects the spatial heterogeneity; the larger the D value, the higher the spatial heterogeneity. Part of the semivariograms are shown in Figure 6 indicate the variability of various parameters at different soil moisture conditions.

Environmental controls on surface soil moisture variability

In this section we explore the relative role of topography, vegetation and soil in controlling the variability of surface soil moisture content in the area. Terrain indices aim to represent the key hydrological processes controlling the spatial distribution of soil moisture in a simplified but realistic way (Western et al., 1999). They can be grouped into primary terrain attributes, such as slope, aspect, curvature, specific contributing area and compound attributes that are combinations of primary attributes (Moore et al., 1991), such as the steady state wetness index of Beven and Kirkby (1979), which have been widely applied in hydrology. Slope angle influences infiltration, drainage and runoff, steeper slopes are likely to be drier than flat areas (Famiglietti et al., 1998). At our field site, the slope angle of the west-facing hillslope is steeper than the east-facing hillslope, and the hollow is a flat area (Figure 2). Therefore, the spatial distribution characteristics of surface soil moisture should be higher in the hollow area than the east-facing hillslope, which should be higher than the west-facing hillslope, as shown in Figure 7.

Aspect influences solar irradiance and thus evapotranspiration and surface soil moisture content. The results showed that the east-facing hillslope in the western part of the experiment field was somewhat wetter than the west-facing slope. Although more solar irradiation

Table II. Geostatistics analysis of surface soil moisture contents on selected measurement dates (\( R^2 \), the determination coefficient; RSS, the residual sums of squares; D, the fractal dimension)

<table>
<thead>
<tr>
<th>Date</th>
<th>Geostatistics</th>
<th>Model</th>
<th>Nugget ( C_0 )</th>
<th>Sill ( C_0 + C )</th>
<th>Range ( A_0 ) (m)</th>
<th>( C_0/C_0 + C )</th>
<th>( R^2 )</th>
<th>RSS</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-May</td>
<td>Exponential</td>
<td>0.72</td>
<td>5.28</td>
<td>8.5(25-5)</td>
<td>0.136</td>
<td>0.509</td>
<td>0.718</td>
<td>1.932</td>
<td></td>
</tr>
<tr>
<td>21-Jul</td>
<td>Spherical</td>
<td>0.08</td>
<td>8.93</td>
<td>18-4</td>
<td>0.009</td>
<td>0.483</td>
<td>1.96</td>
<td>1.962</td>
<td></td>
</tr>
<tr>
<td>26-Jul</td>
<td>Exponential</td>
<td>0.5</td>
<td>3.7</td>
<td>7.6 (22-8)</td>
<td>0.135</td>
<td>0.578</td>
<td>0.202</td>
<td>1.944</td>
<td></td>
</tr>
<tr>
<td>15-Aug</td>
<td>Exponential</td>
<td>1.00</td>
<td>7.99</td>
<td>8 (24)</td>
<td>0.125</td>
<td>0.415</td>
<td>2.21</td>
<td>1.947</td>
<td></td>
</tr>
<tr>
<td>5-Sep</td>
<td>Exponential</td>
<td>1.00</td>
<td>10.79</td>
<td>6 (18)</td>
<td>0.093</td>
<td>0.404</td>
<td>1.94</td>
<td>1.971</td>
<td></td>
</tr>
<tr>
<td>22-Sep</td>
<td>Exponential</td>
<td>0.03</td>
<td>0.22</td>
<td>8.5 (25-5)</td>
<td>0.118</td>
<td>0.353</td>
<td>2.6 × 10^{-3}</td>
<td>1.946</td>
<td></td>
</tr>
</tbody>
</table>
strikes the east-facing hillslope, because of the influence of the perennial north-west monsoon, the atmospheric convection accelerates the evapotranspiration of surface soil moisture on the east windward slope. However, most measurements were made after precipitation, so the effect of solar irradiance decreases, and the redistribution effect of surface soil moisture is most distinct. Considering the topography of the experimental area and the lack of convexity and concavity of the landscape, the effects of curvature and specific contributing area were neglected.

We analysed the effects of elevation, vegetation cover and soil texture on the redistribution of surface soil moisture. Except for herb coverage, other factors showed significant correlation with surface soil moisture (Table III). Negative correlation was found between elevation and soil moisture content, although the correlation coefficient increased with larger precipitation events ($R^2 = -0.6$ at the 95% significance level) (Figure 8a). The correlation between shrub coverage and surface soil moisture was positive and it was enhanced by precipitation, the temporal variability was consistent with elevation (Figure 8b), which was in contrast with the results at depths 0–15 and 0–30 cm, where the herbage coverage was found to be significantly correlated with the spatial pattern of soil moisture rather than with shrub coverage (Pan et al., 2008). The relationship between soil texture and surface soil moisture was explored by means of particle size analysis. A positive correlation existed between soil moisture content, clay and silt content; while a negative correlation was found between the sand content. The particle size–soil moisture content correlation coefficients were highest after large precipitation (Figure 8c), on the contrary, in deeper soil layers, the effect of soil texture was evident after a relative dry period (Pan et al., 2008).

The spatial distribution of shrub cover and sand content in the experimental field are shown in Figure 9, indicating the influence of shrub coverage and soil texture on surface soil moisture spatial distribution in different soil moisture states (compared with Figure 7.)

**Table III.** Correlation coefficient obtained using Pearson’s parametric regression analysis between surface soil moisture content and measured factors. The soil moisture data are temporally averaged at each measurement point for each moisture status.

<table>
<thead>
<tr>
<th>Moisture status</th>
<th>Dry</th>
<th>Medium</th>
<th>Wet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation</td>
<td>-0.444**</td>
<td>-0.522**</td>
<td>-0.452**</td>
</tr>
<tr>
<td>Shrub</td>
<td>0.283*</td>
<td>0.39*</td>
<td>0.359**</td>
</tr>
<tr>
<td>Herb</td>
<td>0.218NS</td>
<td>0.165NS</td>
<td>-0.077NS</td>
</tr>
<tr>
<td>Sand</td>
<td>-0.211NS</td>
<td>-0.411**</td>
<td>-0.589**</td>
</tr>
<tr>
<td>Silt</td>
<td>0.209NS</td>
<td>0.409**</td>
<td>0.587**</td>
</tr>
<tr>
<td>Clay</td>
<td>0.232NS</td>
<td>0.426**</td>
<td>0.597**</td>
</tr>
</tbody>
</table>

* $P < 0.05$; ** $P < 0.01$; NS: not significant;
A factor complicating the study of soil moisture spatial variability is that variations at a given scale may change with the mean wetness of the field site (Famiglietti et al., 2008). To determine the main factors influencing the spatial distribution of surface soil moisture and to quantify how the importance of these factors vary with the seasonal variations in soil moisture contents, a system developed by Gomez-Plaza et al. (2001) was used that classifies soil moisture as wet, medium or dry. Wet status is defined when the spatially averaged soil moisture content is greater than 0.1 cm$^3$ cm$^{-3}$, medium status refers to values between 0.05 and 0.1 cm$^3$ cm$^{-3}$, and dry status refers to average soil moisture values less than 0.05 cm$^3$ cm$^{-3}$. For all measurements (Table I), nine were considered wet, six were considered medium and six were considered dry. The surface soil moisture content for each status was the mean value of each specified measurement corresponding to the wet, medium and dry status.

To determine the influence of each measured environmental factor on surface soil moisture distribution patterns in different moisture states, a parametric correlation analysis was done between the surface soil moisture content at every measured point and the measured factors influencing the soil moisture status (Table III), namely elevation, shrub coverage and soil particle size distribution. The analysis was done for each soil moisture status separately. The importance of these factors, however, varies with the seasonal variations in soil moisture.
Figure 9. The spatial distribution characteristics of shrub cover (%) (a) and sand content (%) (b) in the experiment field.

status. For the results in this study, the surface soil moisture content decreased with increasing relative elevation (Figure 10).

Shrub coverage is also a significant influencing factor in surface soil moisture variability. The results showed that surface soil moisture content increased with increased shrub coverage (Figure 10). This relationship is stronger in wetter conditions than in drier conditions (Table III).

The correlation between soil particle size and surface soil moisture shows an obvious seasonal variation (Figure 10, Table III). The sand content explains approximately 35% of spatial variability in wet status, although the correlation decreases with medium and dry status. There is a similar correlation trend for silt and clay content.

**Regression analysis**

The spatial variability of surface soil moisture cannot be explained satisfactorily by a single factor, because the characteristics are influenced by several interacting factors. To consider the combined influence of these three factors, a linear regression analysis was performed (Table IV). It can be observed in Table IV that relative elevation is the most significant factor during dry conditions, and that the other factors do not further explain surface soil moisture distribution, which is consistent with the results at depths of 0–15 and 0–30 cm (Pan et al., 2008). In wet and medium states, relative elevation and clay content combine to influence the surface soil moisture variability. The influence of clay content becomes more significant when the soil becomes wetter. Thus, the dominant influence on surface soil moisture variability changes from a combination of soil properties and topography in wetter conditions, to local topography as the surface soil dries following heavy rain events.

**DISCUSSION**

The spatial variability characteristics of surface soil moisture

The variation of surface soil moisture increases with increasing mean soil moisture content (Figure 3). Thus, measurement error is relatively more important for dry conditions, which is consistent with previous research carried out in arid and semi-arid climates (Gomez-Plaza et al., 2001; Fernandez and Ceballos., 2003; Williams et al., 2003; Western et al., 2004a). Contrary results were obtained in humid and semi-humid climates (Meyles et al., 2003; Western et al., 2004b). In temperate regions, variance peaked at intermediate moisture contents, indicating that the magnitude of variance in soil moisture was controlled by the wilting point at low mean soil moisture contents, the soil conductivity at intermediate soil moisture contents, and the porosity at high soil moisture contents (Lawrence and Hornberger, 2007). Brocca et al. (2007) provided a peer review of soil moisture spatial variability studies, suggesting that the relationship between mean and variance indicated that the spatial variability of soil moisture in humid climates was greater for drier soil moisture patterns, whereas in semi-arid environments, the spatial variability increases as soil becomes wetter. Pan et al. (2008) analyzed the relationship between variance and mean soil moisture during a soil dry-down experiment using soil moisture dry-down equations and pointed out that, when mean soil moisture is greater than a particular threshold, variance increases with decreasing mean soil moisture. If mean soil moisture is lower than this threshold, variance decreases with decreasing mean soil moisture. The threshold depends on soil texture and is located between field capacity and wilting point. Different results are likely to be obtained for different climate conditions and different study areas in different experiments.
Considering the difference of mean soil moisture contents collected during this study, it is more correct to analyse the spatial variability of soil moisture, using the coefficient of variation, which removes the influence of different mean values. Relative variability decreases with increasing soil moisture content (Figure 4), which is consistent with the findings of earlier studies (Bell et al., 1980; Owe et al., 1982; Charpentier and Groffman, 1992). Hills and Reynolds (1969) shown clearly from their results that one cannot expect a CV of less than 5% in typical field situations. The CV values obtained during this research were higher than 20% because of the lower soil moisture content. The relationship between mean soil moisture content and the CV can be represented as

\[ CV = \frac{\beta}{D^2} = 5336 \exp\left(-0.0598\beta\right), \]

yielding \( R^2 = 0.84 \). Other researchers (Bell et al., 1980; Owe et al., 1982; Jacobs et al., 2004; Famiglietti et al., 2008) also suggested an expression using the same form of the equation. Furthermore, the results of the geostatistical analysis also indicated that precipitation increased the spatial fragmentation degree of surface soil moisture, enhancing the spatial dependence between points. Biological soil crusts are abundant at this experiment field. With its characteristic surface morphology, most precipitation is deposited within the surface crust layer, increasing saturation levels and weakening the spatial variability of surface soil moisture (Figure 4).

The spatial distribution of soil moisture is an important issue in the hydrological cycle. The statistical characteristics of skewness and kurtosis indicate that a normal distribution is more suitable in wet conditions than in dry conditions. Our results are consistent with others (Hill and Reynolds, 1969; Nielsen et al., 1973; Hawley et al., 1983; Vachaud et al., 1985; Francis et al., 1986; Munoz-Pardo et al., 1990; Nyberg, 1996; Anctil et al., 2002; Buttafuoco et al., 2005; Pan et al., 2008). However, Charpentier and Groffman (1992) indicated that daily distributions observed in their study had low probability of representing normal distributions. Loague (1992) noted that only the soil moisture sampled along linear transects was normally distributed, but not when sampling over a grid of points. In an intensive soil moisture campaign carried out in 1997 for the Southern Great Plains hydrology experiment (SGP97), Famiglietti et al. (1999) analysed more than 11 000 impedance probe measurements of soil moisture, they concluded that the distribution of soil moisture evolved from either negatively skewed or non-normal under very wet conditions, to normal in the midrange of moisture content, to either positively skewed or non-normal under dry conditions, Their results indicated that soil moisture content does not follow a normal distribution in areas characterized by significant relief. In these cases, the connected structure between the samples could lead to lateral redistribution of soil moisture (Western et al., 1998a).

The influence factors of surface soil moisture spatial distribution

Surface soil moisture content decreases with increasing relative elevation (Figure 10). This result corroborates those obtained by other authors, who found that soil moisture content is inversely proportional to relative
elation (Moore et al., 1988; Robinson and Dean, 1993; Nyberg, 1996; Pan et al., 2008). Because the topography at this site is characterized as being from crest to crest (Figure 2), higher elevation points have steeper slope angle, lower elevation points have shallow slope angles. Relative elevation, or slope location thus affects the distribution of surface soil moisture by influencing infiltration and runoff, with higher elevations (steeper slope angle) becoming drier than lower elevations (flat area) owing to the lower infiltration and higher surface runoff after rainfall.

Vegetation influences soil moisture variability by altering the throughfall imposed by the canopy, shading the land surface, the non-uniform rate of soil evaporation, generating turbulence and enhancing evapotranspiration rates, affecting soil hydraulic conductivity through root activity, and adding organic matter to the soil surface layer. However, the degree of its effect differs from vegetation type (Famiglietti et al., 1998). Shrub vegetation increased the surface soil moisture contents through stem flow and shading effect immediately after rainfall ceased (Figure 8, Table III), which is consistent with the study of Hawley et al. (1983). It was surprising that the relationship between herbage coverage and surface soil moisture was insignificant, regardless of the particular moisture status (Table III). The main herbage at the experimental site is Eragrostis poaeoides and Bassia dasyphylla, covering about 27%, with a root zone below 15 cm, so that root water extraction does not affect the surface soil moisture. On the contrary, at depths less than 15 cm, the root water extraction effect of herbage plants was obvious (Pan et al., 2008).

The effect of soil texture varies with the soil moisture states (Table III). The marked variations reflect a different control on surface soil moisture variability at different soil moisture states. The negative relationship between sand content and surface soil moisture content is due to the higher infiltration rates of sand, which induces more vertical fluxes and rapid drying out of the surface soil. Contrarily, silt and clay have favourable moisture storage capacity, preventing deep percolation of surface soil moisture, yielding a positive relationship with surface soil moisture content. The relationship was more significant in wet condition. Our results are in accordance with Hawley et al. (1983), who demonstrated that differences in soil water content due to soil texture increase as the soil becomes wetter.

CONCLUSIONS

The experiment characterized the variability in surface soil moisture and identified the main influencing factors in a 50 year artificially re-vegetated desert area. The results indicate that the normal distribution pattern of surface soil moisture was more significant in wetter conditions than in drier conditions. The spatial variability of surface soil moisture was inherent and decreased with increasing soil moisture content. The results of geostatistical analyses indicate that precipitation decreased the spatial variability of surface soil moisture. The factors influencing the spatial variability of surface soil moisture were relative elevation, shrub coverage and soil texture. Regression analysis indicated that the most important factor influencing variability was relative elevation in dry states, and that the effect of soil texture becomes more significant as soil moisture content increased after rainfall. The low mean soil moisture values and, consequently, the high coefficients of variation are quite different from that reported in previous studies on surface soil moisture variability. Therefore, the present study will be useful for characterizing soil moisture variability for a wider climatic range, due to the fact that the soil moisture data sampled in an arid climate is difficult, and in this climate very few studies on soil moisture spatial variability exist (Gomez-Plaza et al., 2001).

ACKNOWLEDGEMENTS

The authors are grateful to Professor Michael H. Young and Dr Jeremy Koonce of Desert Research Institute for their careful reading and correcting of the manuscript, and to anonymous reviewers for their valuable comments to improve the manuscript. The research project on which this paper is based was funded by the National Natural Science Foundation of China (40871051).

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