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Full Length Research Paper

Assessing Soil Water Storage Through Spatial Dependence in Deposited Agricultural Soils

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Spatial dependence was widely recognized in field observations and the existence was very helpful to the development of precision agriculture. On the Loess Plateau of China, the soil water contents (SWCs) at a deposited soil farmland (DF) were measured using the neutron tubes on two sampling lines during two years. The objectives of this research were to recognize their spatial dependence to predict soil water storage (SWS) and to divide the DF for future study in such kind farmland. The results showed that the mean SWCs of 0-80 cm soil depth decreased at the prior part and increased at the later part of the DF. The coefficient of variation (CV) decreased exponentially with the mean SWC on all observations. Estimated autocorrelation values began at higher value than critical criteria and gradually decreased towards negative values following the increased lag distance. The Moran's *I* and ACF both illustrate the existence of spatial correlation of neighboring points on the silting direction, and the cluster characteristics were used to predicate SWS and divide the DF. The topsoil water contents (10 cm) have a good linear relationship with its SWSs (80 cm) since the deposition characteristics of sediment. Three parts of DF should be divided in the related studies on such land. Future studies should focus on the spatial dependence of more soil variables at the DF to help the development of precision agriculture and manage soil resources.

Key words: Autocorrelation, check-dam, linear regression, soil water content.

INTRODUCTION

Spatial data including the distributions of soil water content (SWC) are related by the distance or spatial location and characterized by spatial dependency and spatial heterogeneity (Anselin, 1995). As Tobler (1979) First Law of Geography states: "Everything is related to everything else, but near things are more related than distant things". Spatial dependence exists when there is significant similarity between the values of variables and to process similar attributes at two locations. It is usually described by statistics such as spatial autocorrelation function Moran's *I* (Moran, 1950) and autocorrelation function (ACF) (Box and Jenkins, 1976). Similar with autocorrelation, Moran's *I* which is an same phenomenon are correlated. Spatial autocorrelation statistics could analyze the degree of spatial dependence in part of the whole study field and identify the autocorrelation between a single variable and its indicators of spatial association represents adjacent observations of the neighbors in a specified lag distance from itself. Although spatial autocorrelation was recognized decades ago in the statistical literature, its application had been restricted by platform limitation of spatial datasets, computation capacity, and software availability and so on (Ping et al., 2004). Hengeveld (1979) reported that the value of organism (*D. globosus*) at any location is similar to the one at neighboring place. The spatial dependence of cotton yield was explored by Ping et al. (2004) using autocorrelation statistics. The spatial autocorrelation had widely focused on spatial variables, however, there is very little report on the application of these statistics to the understanding of spatial dependence of SWC at the

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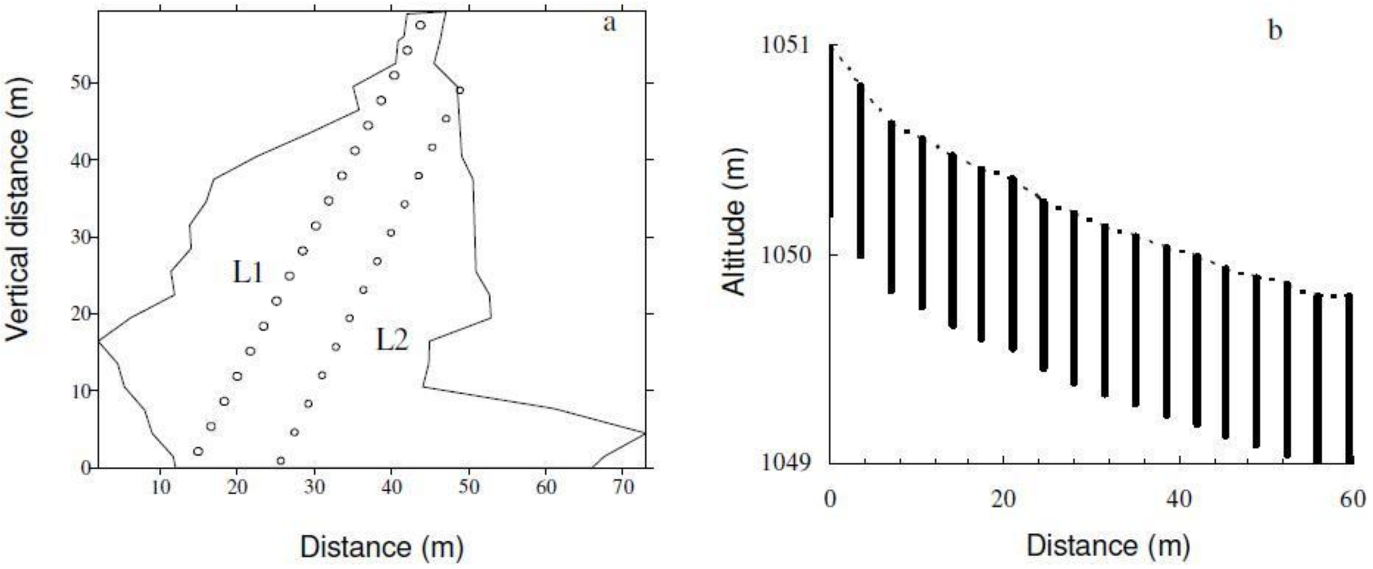

Figure 1. The sampling outline on the silting (a) and vertical direction (b), L1 = line 1 and L2 = line 2.

deposited soil farmland (DF). As the importance of DF on soil conservation and great contribution to crop yield, more attentions should be paid to this kind artificial farmland or similar lands (Mekuria et al., 2009; Zhao et al., 2010). At the DF, the reorganization of SWC's spatial dependence was helpful to the development of precision agriculture which relies on the existence of soil variability. For example, the knowledge of SWC's spatial dependence was beneficial to know the soil water infiltration capability and the appropriate amount of irrigation at the DF. This knowledge was also helpful to find a point to interpolate the time series of SWC if a few data are unavailable from the nearby locations. In addition, the criterion of dividing the DF was optional, such as two plots in the field campaign of Wang et al. (2008), three plots in the studies of Wang et al. (1999) and Zhang et al. (2007). A scientific proof to divide the DF for future study is also necessary. The main objectives of this research were (1) To evaluate the spatial dependence of SWC at the DF which was artificial structure; (2) To predicate soil water storage (SWS) using spatial dependence if it existed, and (3) To provide a scientific basis to divide DF for the future study on such kind artificial farmlands.

STUDY SITE AND DATA SET

Experimental set up

The experiment was carried out at a DF in Liudaogou catchment. The description of the study area could be found from paper of Zhao et al. (2010). Due to the DF was formed in the gully which was narrow and long, only the direction which following the water flows (silting) was considered in this study. As shown in Figure 1a, 18 and 14 observation points were set up at the DF separately on two lines (18 was on line 1 and 14 was on line 2, two lines spaced 10 m, each point spaced 4 m) (Figure 1b). Soil samples were collected every 10 cm depth in all observation points from surface to 80 cm depth, resulted total of 256 samples. Those samples were offered for particle size distribution (PSD) analysis using Mastersizer 2000 (Malvern Instruments, Malvern, England). After the sampling, the neutron tubes of 1 m long were carefully installed to the sampled holes. Figure 2b shows the installation on the vertical direction on line 1 (the same way on line 2). The soil water content was measured from June 17, 2008 to October 1, 2009 with an interval of about 20 days. The data in 2009 was used to compare the prediction results on time scale. The calibration procedure of the SWC at this DF can be found from the paper of Zhao et al. (2010).

Methods of analysis

Classical method was used in this study to characterize the variability of SWC at the DF. The descriptive statistics such as the mean, variance, and coefficient of variation (CV) were calculated using SPSS16.0 software and normality was assessed using the one-sample Kolmogorov-Smirnov (KS) test (SPSS, 2007). CV can be used to qualitatively ascertain the magnitude of the spatial variability as low when CV ≤ 10%, moderate if 10% < CV < 100%, and high when CV ≥ 100% (Nielsen and Bouma, 1985). Moran's *I* is calculated similar to Pearson statistics, a measure of the classical correlation coefficient. The Moran's *I* range from -1 to +1. A higher positive Moran's *I* indicate the high spatial autocorrelation, which implies that values in neighboring positions tend to cluster together. A low negative Moran's *I* is an indication that high and low values are interspersed. When Moran's *I* is near to zero, there is no spatial autocorrelation of the variables. The result means the data are randomly distributed in the field (Ping et al., 2004).

The function Moran's *I* is calculated according to the method reported by Cliff and Ord (1981):

$$I = \frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \qquad (1)$$

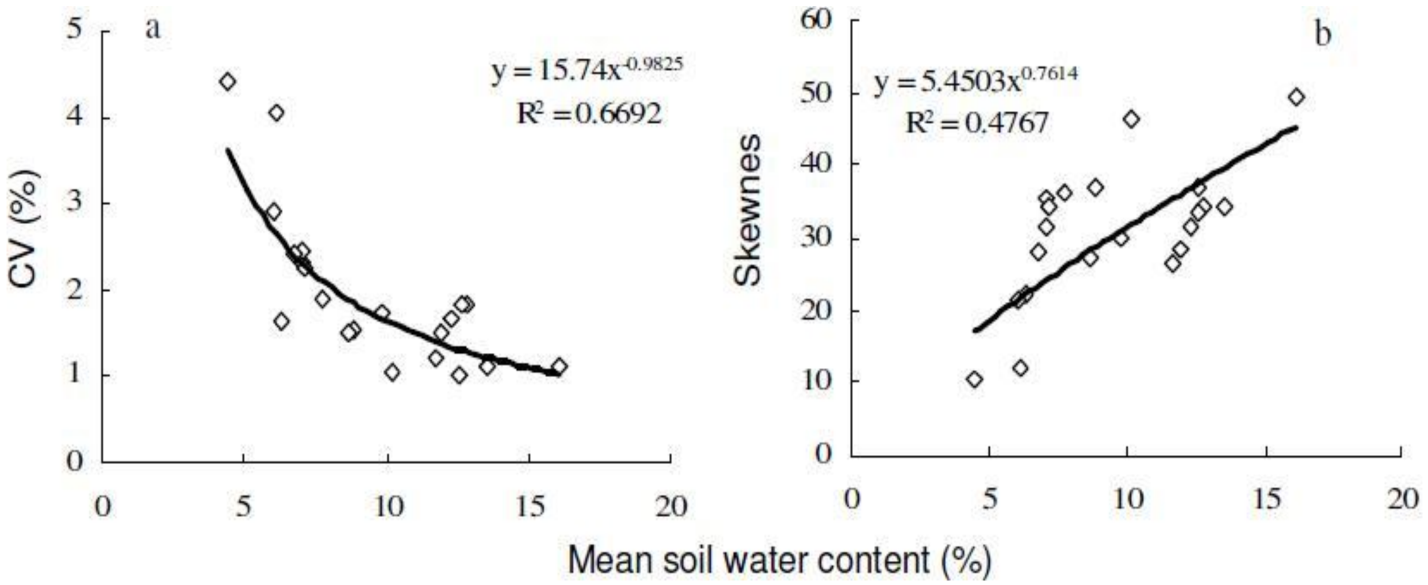

Figure 2. The relationship between CV and mean soil water content (a), skewness and mean soil water content (b).

where n equals the number of observations; w_{ij} is the weight between locations i and j; x_i and x_j are the values at locations i and j; $\bar{x}$ is the average over all locations of the variable:

The ACF measures the linear predictability of the series at location t, say, x_t, using only the values x_s. We can show easily that $-1 \leq \rho(S,T) \leq 1$ using the Cauchy–Schwarz inequality. If we can predict x_t perfectly from x_s through a linear relationship, $x_t = \beta_0 + \beta_1 x_s$, then the correlation will be 1 when $\beta_1 > 0$, and -1 when $\beta_1 < 0$. Hence, we have a rough measure of the ability to forecast the series at location t from the value at location s. Consequently, ACF was used to determine whether the experimental data was generated from a random process. It was also important to decide whether a non-linear or time series model was more appropriate model than a simple constant plus error model for the data. Randomness is one of the key assumptions in determining if a univariate statistical process is in control. If the assumptions of constant location and scale, randomness, and fixed distribution are reasonable, then the univariate process can be modeled as:

$$Y_i = A_0 + E_i \tag{2}$$

where E_i is an error term. If the randomness assumption is not valid, then a different model needs to be used. This will typically be either a time series model or a non-linear model (with time as the independent variable). The sample covariance function was then:

$$\rho(h) = Cov[Z(x), Z(x+h)] / \{D[Z(x)]D[Z(x+h)]\} \tag{3}$$

where $\rho(h)$ is autocorrelation coefficient, Cov is the covariance for any two values of Z at a distance h apart, Var is the variance for any two values of Z at a distance h apart, h is the lag distance, $\rho(h)$ is the sample correlogram, and $Z(x)$ and $Z(x+h)$ are the measured SWCs at points x and $x+h$, respectively. The significance of the autocorrelation coefficient $\rho(h)$ is often assessed by the critical values of t, which can be written as follows (Hu et al., 2009):

$$t = \rho[(n-2)/(1-\rho^2)]^{1/2} \tag{4}$$

RESULTS AND DISCUSSION

Classical analysis of soil water content

Tables 1 and 2 provide the dates, antecedent rainfall, number of sample points, mean, variance, CV, and number of truncated samples for each of the data set mainly in year 2008 used in the analysis. At the DF, the driest soil water pattern is found on August 4th and the wettest soil water condition is found on September 29th after a rainfall of 74.8 mm. The driest soil condition existing in in the rainfall season reflected the strong evaporation effect in this area. Thus may increase the risk of soil salinization at DF. Figure 2a shows that the CV decrease exponentially with mean SWC on line 1 ($P<0.01$). This result was the same with Hu et al. (2008) who observed topsoil water content in a small catchment. The decreased relationship could be explained by that the heterogeneity of soils in the field resulted in different range of water capacity. Once the water content increased, the differences between soil types decreased. The exponentially positive relationship between mean water content and skewness values can be seen from Figure 2b. That means SWCs at the DF tend to be normal when the water contents are increased. The distributions of mean SWCs on two lines in some random days along the silting direction are shown in Figure 3. From Figure 3a, the mean SWC decreases from the silting source to 20 m far and increase towards the end of

Table 1. Summary of 21 soil water patterns on line 1 at the deposited soil farmland.

Date	Antecedent rainfall[a] (mm)	Run	Samples	Mean (%v/v)	Variance (%v/v)	Coefficient of variation	Skewness	Number truncated	Moran I
17 Jun	84.9	1	71	12.61	42.03	76.9	1.01	73	0.282
28 Jun	0	2	72	9.83	6.49	30.0	1.72	72	0.197
22 Jul	0	3	72	6.32	3.55	22.2	1.63	72	0.180
29 Jul	0	4	144	6.15	2.07	12.0	4.06	0	0.176
4 Aug	0	5	144	4.45	1.56	10.4	4.40	0	0.173
8 Aug	20.4	6	144	6.04	6.64	21.5	2.92	0	0.204
9 Aug	1.5	7	144	7.06	18.13	35.5	2.33	0	0.155
10 Aug	0	8	144	7.18	16.71	34.1	2.25	0	0.189
11 Aug	0	9	144	7.06	14.27	31.5	2.45	0	0.169
12 Aug	4.8	10	144	6.83	11.35	28.1	2.41	0	0.191
19 Aug	22.1	11	144	7.78	18.84	36.2	1.90	0	0.179
27 Aug	29.5	12	144	8.91	19.86	37.1	1.54	0	0.145
10 Sep	55.9	13	144	10.21	30.88	46.3	1.05	0	0.183
20 Sep	3.1	14	144	8.65	10.83	27.4	1.49	0	0.183
29 Sep	74.8	15	144	16.15	35.28	49.5	1.10	0	0.221
9 Oct	6.3	16	144	13.58	16.89	34.3	1.10	0	0.264
23 Oct	8	17	144	12.81	17.04	34.4	1.82	0	0.247
25 Oct	0	18	144	12.66	16.30	33.6	1.83	0	0.281
27 Oct	0	19	144	12.30	14.28	31.5	1.66	0	0.255
31 Oct	0	20	144	11.99	11.67	28.5	1.51	0	0.260
4 Nov	0	21	144	11.72	10.17	26.6	1.22	0	0.278

[a] in ten days.

Table 2. Summary of 8 soil water patterns on line 2 at the deposited soil farmland.

Date	Antecedent rainfall (10days, mm)	Run	Samples	Mean (%v/v)	Variance (%v/v)	Coefficient of variation (%)	Skewness	Number truncated	Moran I
23 Oct	8	1	154	12.77	25.25	39.35	1.71	0	0.327
25 Oct	0	2	154	12.41	24.21	39.64	1.43	0	0.325
27 Oct	0	3	154	12.28	20.77	37.11	1.49	0	0.334
31 Oct	0	4	140	12.51	20.41	36.11	1.30	14	0.345
4 Nov	0	5	133	12.52	19.57	35.32	1.33	21	0.317
4 Mar[a]	2.6	6	140	12.53	20.64	36.25	1.23	14	0.327
14 Mar[a]	9.8	7	140	12.92	27.74	40.77	2.09	14	0.324
25 Mar[a]	0	8	140	11.96	16.76	34.23	1.37	14	0.308

[a] in year 09.

DF. The relatively high SWC on the silting source was due to the location is the place where the soil erosion happening. It is clear that the soil erosion is induced by runoff at DF. Nearer the eroded location, higher water was found. The increased trend of the mean SWC on line 2 can be observed from Figure 3b that is similar with the later part of Figure 3a. As fine particles well correspond to high water content, the increased trend of water content reflected the particle-size deposition characteristics at DF. In the soil erosion and transport processes of particles, fine materials always travel farther than the coarse particles. As a consequence, fines particles accumulated on the later part of DF reflecting by the high water content.

Spatial dependence recognition

The values of Moran's *I* for SWS on line 1 and 2 can be seen from Tables 1 and 2. They range from 0.145 to 0.282

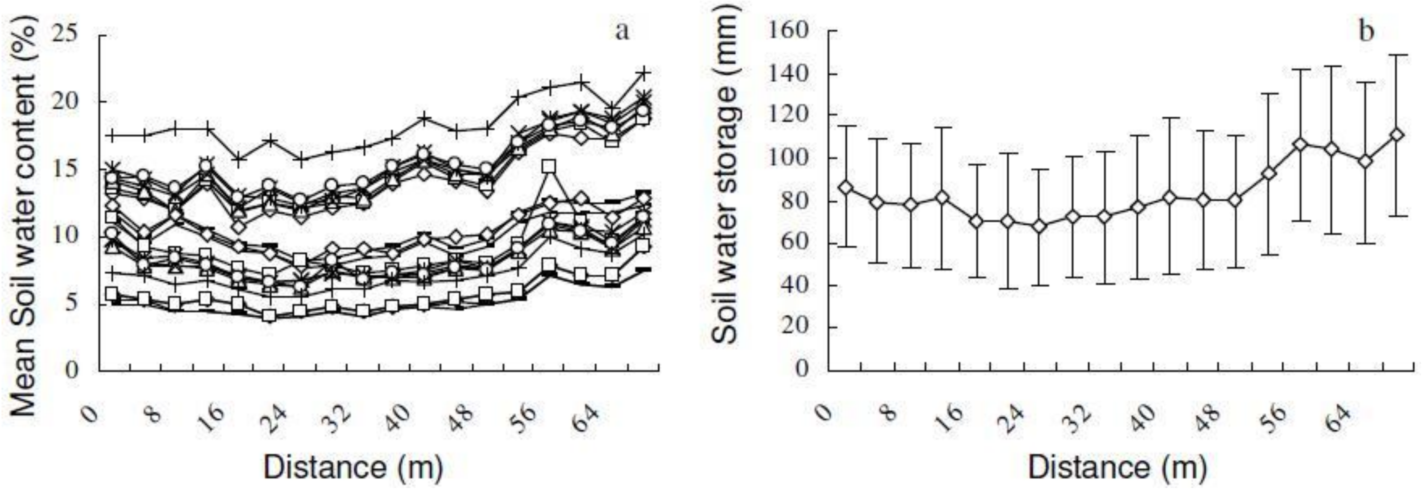

Figure 3. The distributions of mean soil water content (a) and soil water storage (b) along the silting direction in 2008 (error bar represents standard deviation; 0-68 m represents the silting direction).

and 0.308 to 0.345, respectively. These values were relatively lower than the result of Ping et al. (2004) who focused on the crop yield in their plots. Consequently, SWS at the DF may have low spatial dependence for the DF was formed by layered sediment. Another explanation is that the sites were spaced 3.5 m which is farer than the sampling distance in the research of Ping et al. (2004). Anyway, there existed positive spatial correlations for SWS in this kind of farmland. Positive values of Moran's *I* indicated that SWS were clustered together such that high storage tended to be surrounded by higher storage neighbors and low storage companied by lower storage neighbors. This might suggest that SWS at DF were strongly related to their locations under natural silting conditions. Appearances of SWS in a clustered manner, however, are desirable in precision agriculture since managing spatial variability is one of the advantages of precision agriculture. As water is the most limited factor for high crop yield in this region, the recognition of the clustered manner was helpful to the soil water management at the DF.

Equation 3 is used to calculate the spatial autocorrelation values *ρ(h)*of SWS along the sampling line at the DF. The correlogram is shown in Figure 4. The value of 1.0 obtained at *h*=0 is included for completeness, but for a small positive non-zero value of *h*, the *ρ(h)* value is 0.846, gradually decreasing towards zero at about *h*=16 m. From the data set, SWS at DF has bigger *ρ(h)* value than critical values at *h* =3.5 m. That means SWS has autocorrelation relationship in the range of minimum sample distance (4 m). For *h* values of 14-60 m, estimated autocorrelation values are slightly negative but not significant. For *h* values of 0-16 m, the ACF value decreases gradually and approaching to zero. The spatial dependence of SWC no longer existed at the range of 16 m far. The analysis of SWS on all the observations on line 1 and 2 using autocorrelation tools have similar results of the example with significant value at one lag (data not show). Consequently, SWS at the DF had spatial dependence from the results of Moran's *I* and ACF at a lag distance of 4 m.

Predication soil water storage by spatial dependence

The ACF of Figure 4 and the positive values of Moran's *I* for the SWS at the DF illustrate the well spatial dependence or correlation along the silting direction. This dependence or correlation means the cluster characteristics of SWS which could be used to predicate SWS of neighboring location. A simple linear relationship was applied here. As the layered feature of deposited soil, there is a possibility that the topsoil water content of a position has a good relationship with the SWC of a certain depth (80 cm in this research). Figure 5 shows the well linear relationship of topsoil water content and SWS (80 cm) of an example. From the research of Kilic (2009), the indicative function of topsoil was believed to be applicable in evaluating the classes of soil drainage. Consequently, the topsoil water content was introduced to predicate SWS as an indicator in this research. As a result, SWS of point *i* and the SWC of topsoil at location *i+1* were used to estimate SWS of point *i+1*. The mean R^2 of linear fitting was 0.687 for line 1 and 0.740 for line 2. Consequently, the spatial correlation could be well used to estimate SWS at the DF for saving time and labor, and developing precision agriculture.

Since the topsoil water content could be a spatial indicator to predicate the SWS on space, it was believed that it can well predicate SWS over time. Then the SWS can be predicated by a simple linear relationship which the slope was calculated by the topsoil water content

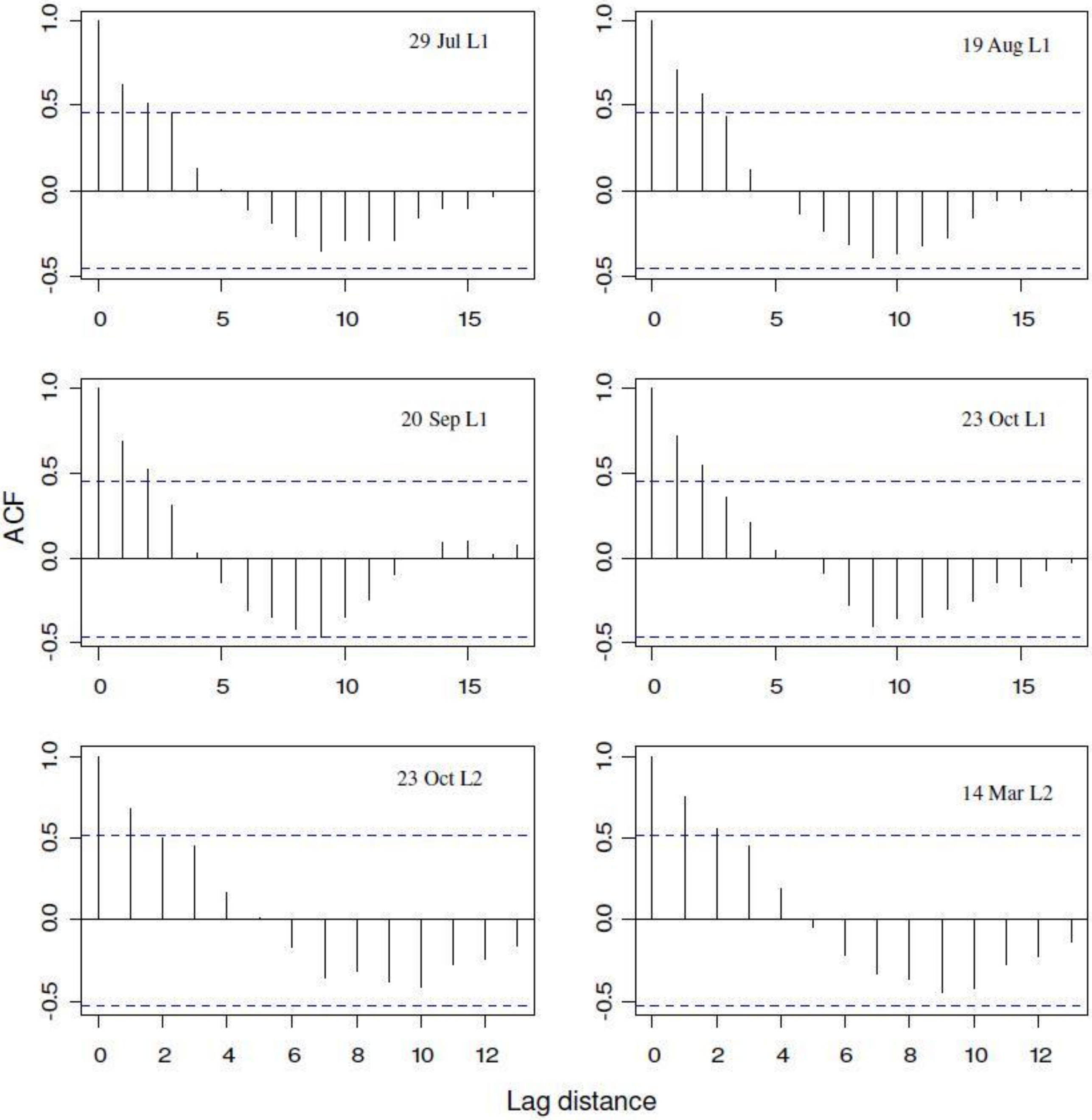

Figure 4. Auto-correlation correlograms of soil water storage at the deposited soil farmland on some random days.

using Equation (2). The data are used to predict SWS of 80 cm soil depth in year 2009. The comparison of true value and fitted results can be seen in Figure 6. The similar distribution characteristics of the true value and fitted values lines illustrate the well fitting performance. The intercept, slope, and R^2 for each point are shown in Table 3. The R^2 values also show that the fitting results are good. From Table 3, there is also a trend that the R^2 decreased from the silting beginning to the middle part and increase to the end. The trend is similar with the distribution of mean water content. The middle location performed worse in the predication process than other parts. From the above-mentioned results, the DF should be divided into three parts: front position which is the part bordering the check-dam body; median position which locates on the middle part of the whole land; back position which is the silting beginning of the DF and the farthest place to the check-dam body. For example, Wang et al. (2008) stated that the DF contributed soil carbon sequestration by analyzing the samples taken

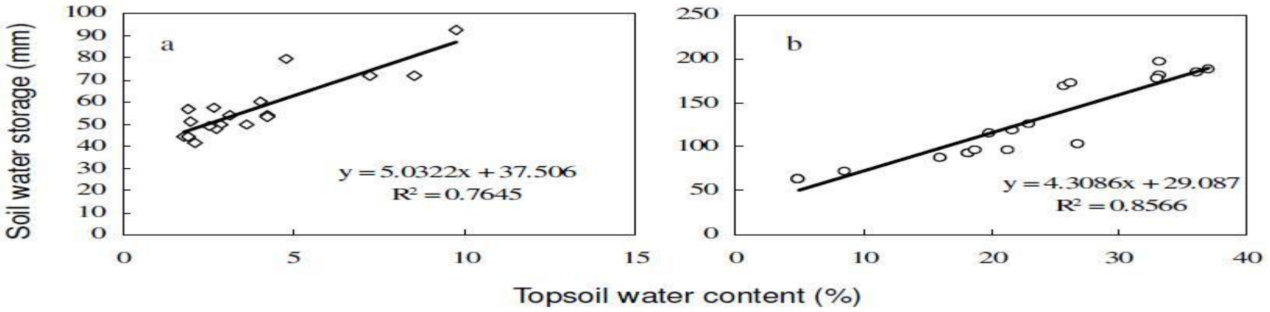

Figure 5. The relationship between topsoil water content (10 cm) and soil water storage (80 cm) of line 1 on July 29 (a) and line 2 on 23 Mar (b).

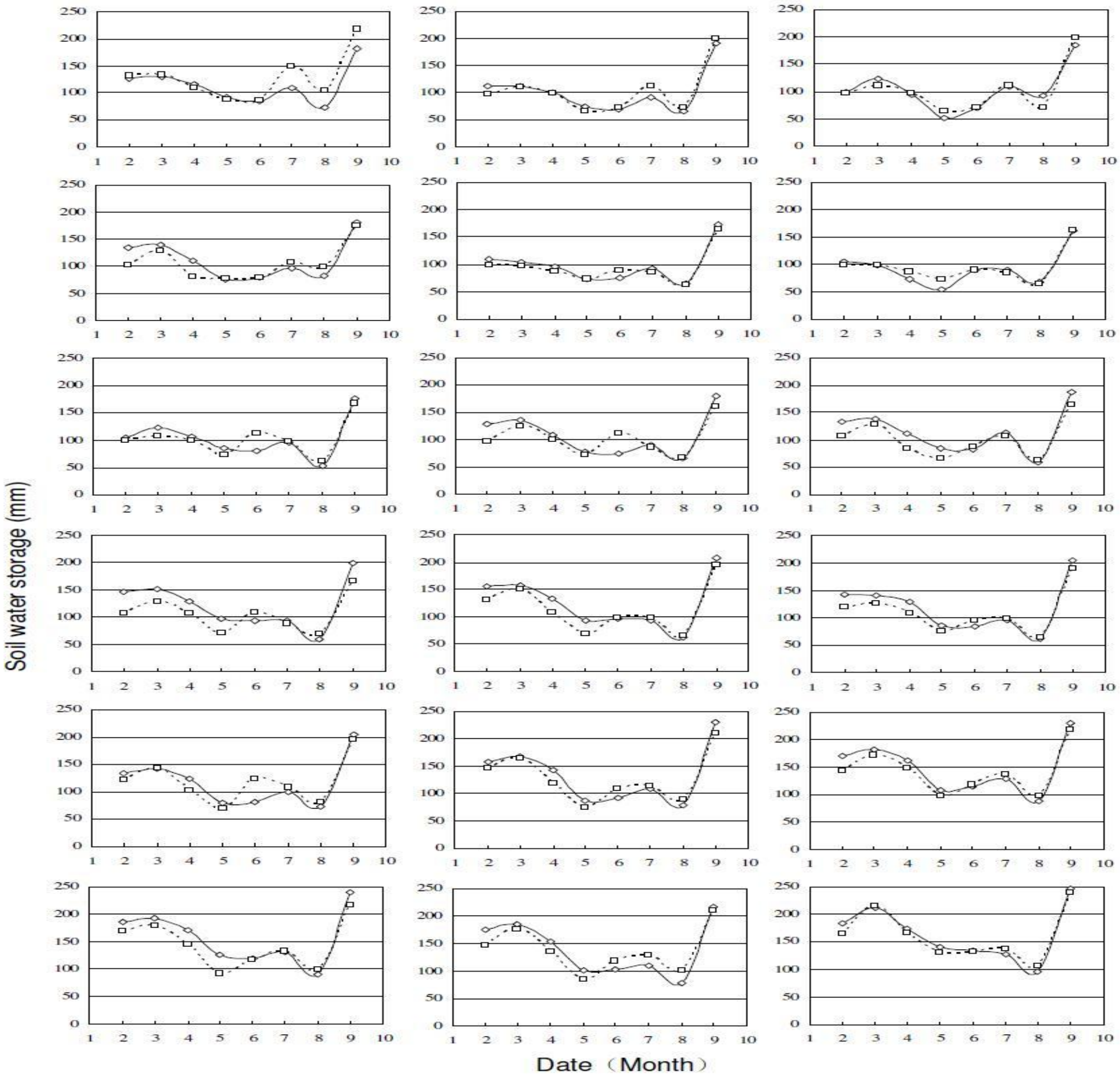

Figure 6. The predication soil water storage for each point on line 1 in 09 by spatial dependence.

Table 3. The slope, intercept, and R2 for the linear fitting in Figure. 5.

Point number	Slope	Intercept	R^2
1	4.2453	55.10	0.8494
2	4.5768	27.784	0.8262
3	5.8733	25.332	0.8025
4	5.2071	15.961	0.7513
5	6.0484	27.022	0.6843
6	7.0358	24.847	0.6623
7	7.2325	26.777	0.6968
8	5.9027	23.617	0.6507
9	7.0252	25.821	0.6544
10	8.4006	18.947	0.6282
11	7.0923	19.93	0.7816
12	6.0726	22.859	0.8095
13	5.9735	27.249	0.8194
14	5.7195	22.388	0.8215
15	4.5302	46.089	0.8315
16	4.0614	30.286	0.8679
17	4.3086	29.087	0.8856
18	4.3857	33.785	0.9027

only from two locations: front and back positions. If middle position was also considered, the results would be more reliable.

Conclusions

Soil water patterns based mainly on the neutron tube measurements at the deposited soil farmland (DF) were observed. Along the silting direction, the mean soil water content (SWC) decreased firstly and then increased at a relative longer distance. The coefficient of variation (CV) and skewness presented exponentially decreased and increased relationships with mean SWC in this study, respectively. The Moran's *I* and ACF could describe the existence of spatial dependence of soil water storage (SWS) along the silting direction. The positive value of Moran's *I* and significant values of ACF illustrate the cluster characteristics of SWS of 80 cm soil depth at the DF. The topsoil water content was introduced as an indicator to predicate SWS over space and time. The layered characteristics of deposited soils at the DF achieved the importance of topsoil in predicating SWS. Moreover, the indicative characteristic of topsoil was also believed to be applicable in evaluating other soil properties, such as soil organic matter. The results suggested three plots would be more reliable in the field at DF. Since managing variability was an objective in precision agriculture, the recognition of spatial dependence and the importance of topsoil variable should be useful to increase crop yield and manage soil water resource. However, only the SWCs on two lines were analyzed in this research. In the future, more data should be applied to recognize the spatial dependence of soil properties at DF for the interpolation of the spatial data and the knowledge of spatial distribution of the soil variables on this kind farmland.

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