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Temporal stability of soil water content in typical paddy soil at Taihu Lake region of China

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ABSTRACT

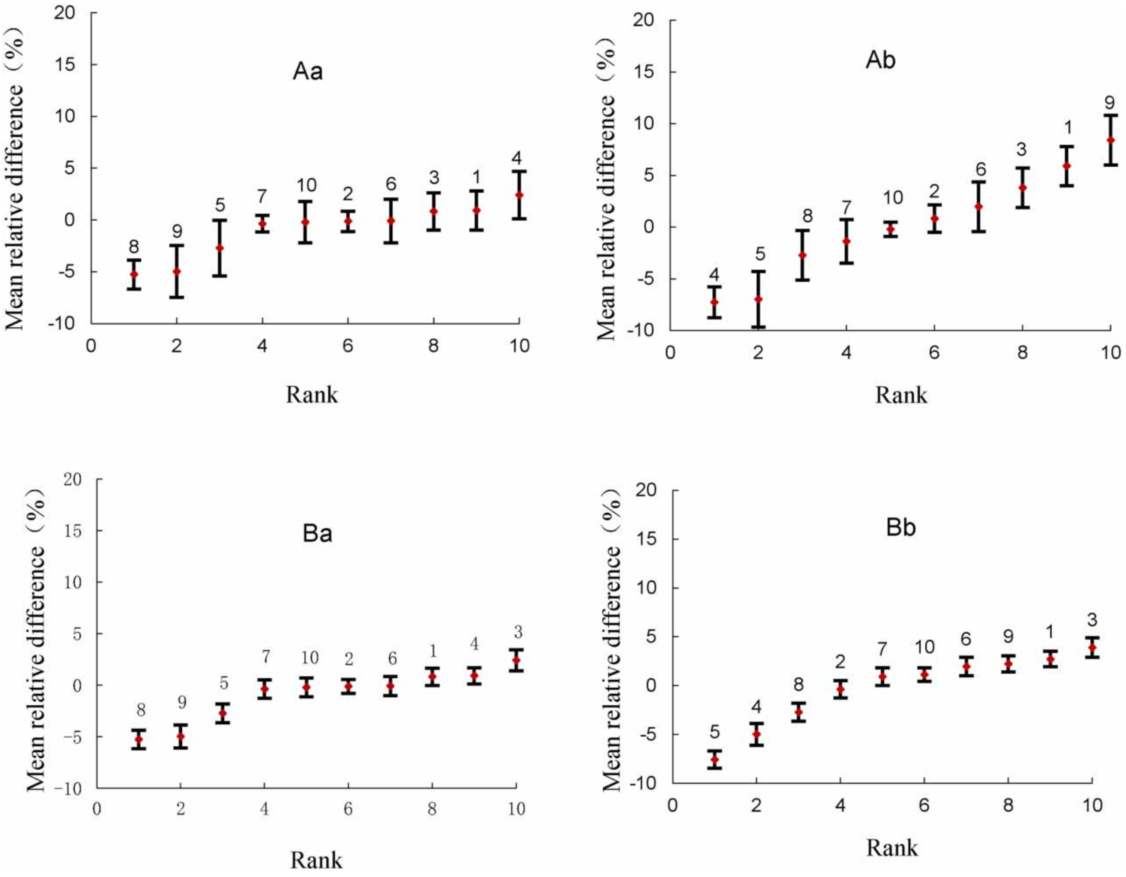
Soil water content plays an important role in crop production, especially in the main rice production areas of China. The temporal stability of soil water content was studied in a paddy field of Taihu Lake region, southeast China. There were two treatments in this experiment, one was mulch with rice straw and the other was without mulch. Soil water content of the two treatments was monitored at the interval of 10 days by the Time Domain Reflectometer probes which were installed *in situ*, and measured both at 14 and 33 cm soil layers. The data were evaluated by temporal stability methods and Spearman's correlation. Results showed that mulching with rice straw proved to be efficient in retaining the soil water at the 14 cm soil layer. Based on the relative difference method, the representative positions of the experiment field were identified, which accurately represented the field-mean soil water at the experiment field was detected in terms of root mean square error, less than 2.18%. The Spearman's correlation values were high, which indicates temporal dependence along the experiment period. The data of soil water temporal stability could provide scientific basis for adequate water management in paddy field.

Key words: paddy soil, soil water content, Spearman's correlation analysis, temporal stability

HIGHLIGHTS

- The deeper the soil layer, the better the temporal stability of soil moisture.
- Temporal stability of soil moisture affects agricultural production.
- The temporal stability of soil moisture can provide information in large area.
- Straw mulching had significant effect on temporal stability of soil surface water.
- The use of field water stability can reduce the number of observations required for soil water management.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The variability of soil water content is a major obstacle for soil water management, which demands reliable estimates of the soil water status and hydraulic properties. Since the early 1950s, soil moisture variability has frequently been studied after the development of tensiometers and neutron probes that allowed quick non-destructive measurement of soil water content (Hillel 2004). In the 1970s, easier access to computing facilities and application of geostatistics in soil physics have spurred more research on soil water variability.

From an applied point of view, knowledge of soil water dynamics is crucial for prediction of flood discharge, estimation of aquifer recharge, and risk evaluation of pollution migration. Enhanced soil water may induce secondary effects on soil ecology, such as stimulation of soil microbial processes and alteration of litter decomposition and nutrient mineralization. This may in turn improve nutrient availability for plant growth, as mentioned above, and cause nutrient losses via leaching (Vereecken *et al.* 2014). From an agricultural point of view, soil water content is also an important variable, as optimization of water resources and agricultural production largely depends on good understanding of the real-time soil water status (Martinez & Ceballos 2003). Under natural conditions, water fluxes from an ecosystem to the atmosphere via transpiration through stomata or direct evaporation from soil and plant surfaces. Soil water is a key state variable for a wide variety of hydrological processes acting over a range of spatial and temporal scales (Hupet & Vanclooster 2002). Furthermore, these studies are conducted in a large variety of hydrological and climate conditions (Guber *et al.* 2008; Brocca *et al.* 2009; Duan *et al.* 2017). Nevertheless, it attracts more interest in the analysis of the temporal dynamics of soil water content in recent years (Albertson & Montaldo 2002; Thierfelder *et al.* 2003; Zhao *et al.* 2017a, 2017b). There are many studies investigating the spatial variability of soil properties, however, little is known about their temporal variability (Martinez & Ceballos 2005). Vachaud *et al.* (1985) introduced the concept of temporal stability as the preservation of spatial patterns of soil water content over time. The mean soil water content at a site can be accurately represented by a minimum number of ground-based soil water content measurements. Analyses of the temporal stability and variability of soil water content have been particularly useful in the fields of soil science and hydrology. The temporal stability may be used to answer a number of questions related to soil properties sampling designs in highly variable fields, addressing both economic and technical aspects. Moreover, the verification of temporal stability may generate clearer and more precise scientific information (Fry & Guber 2020).

The temporal stability of soil water content is a reflection of the temporal persistence of the spatial structure (Kachanoski & Jong 1988). In practice, if the spatial distribution of soil water content exhibits temporal stability then its estimation over large areas through a limited number of measurements would be possible. Goovaerts & Chiang (1993) analyzed the temporal dynamics of different soil properties and hydrological properties. Jaynes & Hunsaker (1989) studied the temporal stability of infiltration and its application to irrigation. Wang *et al.* (2015) analyzed the temporal stability of the soil matric potential with a view to optimizing sampling strategies. Soil water temporal stability should be evaluated for different climate conditions, crops, soil classes, topographic elevation, and soil cover characteristics (Rodriguez *et al.* 2011). Because of the importance of soil water dynamics to agricultural production, mainly in key area for food production with large area, the goal of identifying and reducing the sampling number of measurements is necessary. However, little information has addressed the analysis of temporal stability of soil water in field-scale of typical paddy soil.

The main objectives of this study are: (1) identifying which points are representative of the mean soil water content value throughout the field; (2) evaluating the effect of the rice straw on the soil water temporal stability; (3) analyzing the temporal pattern of the field-mean soil water of the studied site and providing information to monitor soil water content over large areas.

2. MATERIALS AND METHODS

2.1. Experimental area

The field experiment was carried out at Changshuo experimental station (31 °30′N, 120 °33′E, Jiangsu province, Taihu Lake region of China), and the experimental field area was about 1.5 ha. This field has not suffered any substantial agronomic changes in the past 50 years and represents the majority of agricultural lands in Jiangsu province, a key area for rice production. Under a subtropical monsoon climate, the local area has a mean annual precipitation of 1,100–1,200 mm and annual average temperature of 16 °C. The annual sunshine time is longer than 2,000 h. The frost-free days in a year are more than 230 d. Local farmers use conventional tillage with rice–wheat rotation. Soil at the study site was typical paddy soil. Its basic properties were listed in Table 1.

2.2. Experimental designs

Cropping system of this experimental site was rice–wheat rotation. This study was focused on the water stability in wheat cropping season. The experimental area was divided into two equal parts (Figure 1). Two treatments have been designed: one was mulched with rice straw (Treatment 1), the other was not mulched rice straw (Treatment 2). There was no irrigation during the experimental period. The field experiment was carried out from jointing stage (13 March) to ripening stage (20 June) during the wheat growth period in 2019. Daily values of rainfall and evaporation were shown in Figure 2. The data were obtained every 10 days during the experimental period, comprising 10 measurements campaigns. Time Domain Reflectometry (AQUA – TEL – TDR, USA) probes which were connected to a data logger to record soil water content were installed 14 and 33 cm in the soil layers. To calibrate the sensor, soil water content was measured by drying method. The signal from the data logger was linearly related to drying method ($r^2 = 0.9903$). During the experimental stage, datasets of soil water content (14 and 33 cm in the soil layers) were collected using Time Domain Reflectometry (TDR).

Table 1 | The basic properties of the studied soil

						Mechanical composition ($g \cdot kg^{-1}$)		
Soil layer	**Depth (cm)**	**Saturated hydraulic conductivity ($cm \cdot s^{-1}$)**	**Bulk density ($g \cdot cm^{-3}$)**	**pH**	**Porosity (%)**	**Sand**	**Silt**	**Clay**
Cultivated layer	0–14	7.04×10^{-4}	1.21	7.0	54.34	337.4	386.2	276.4
Plowpan layer	14–33	1.26×10^{-4}	1.47	7.2	44.53	278.6	392.6	328.8

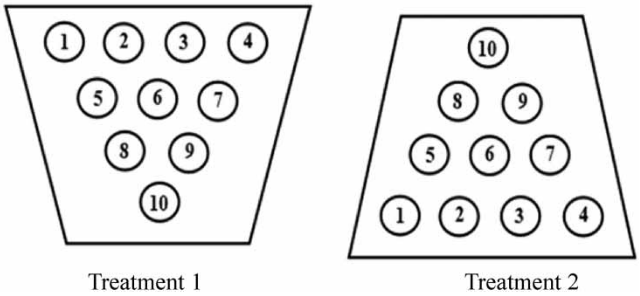


Figure 1 | Samples distribution.

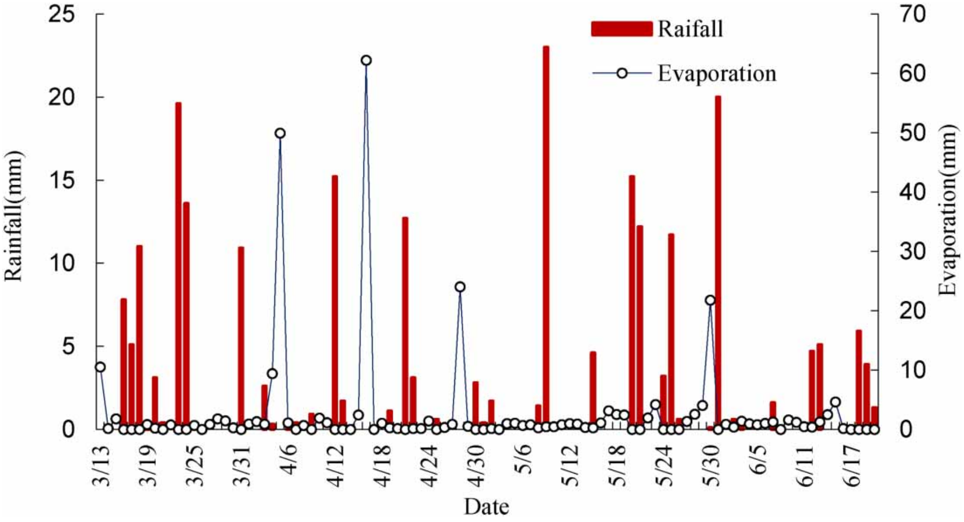


Figure 2 | The rainfall and evaporation during the experiment period.

2.3. Statistical analysis

Temporal stability was defined by Vachaud *et al.* (1985) on the basis of the time-invariant association between spatial location and classical statistical parametric values of a given soil property. The statistical techniques were employed to analyze the temporal stability of the spatial patterns of soil water in the present work.

The temporal stability analysis was based on the parametric test of relative differences (Vachaud *et al.* 1985). It was briefly described. The relative difference, δ_{ij} at point i and day j is given by:

$$\delta_{ij} = \frac{\theta_{ij} - \overline{\theta_j}}{\overline{\theta_j}} \tag{1}$$

where θ_{ij} is the soil water content at point i $(i = 1,\ldots, \mathrm{n})$ at time j $(j = 1,\ldots, \mathrm{m})$, and $\overline{\theta_j}$ is the mean for each sampling day:

$$\overline{\theta_j} = \frac{1}{n}\sum_{i=1}^{n} \theta_{ij} \tag{2}$$

For each point i, the mean, $\overline{\delta_i}$, and standard deviation $\sigma(\delta_i)$, of the relative differences are given by:

$$\overline{\delta_i} = \frac{1}{M}\sum_{j=1}^{M} \delta_{ij} \tag{3}$$

$$\sigma(\delta_i) = \sqrt{\frac{1}{M-1}\sum_{j=1}^{M} (\delta_{ij} - \overline{\delta_i})^2} \tag{4}$$

In several studies (e.g., Jacobs *et al.* 2004; Zhao *et al.* 2010; Jia & Shao 2013), the index of temporal stability at location i (ITS_i) was used to compare the stability among sampling locations, with Jacobs *et al.* (2004) suggesting that those locations having the lowest ITS_i value be considered the most 'time-stable representative location' to evaluate average soil water content, defined as follows:

$$ITS_i = \sqrt{\delta_i^2 + \sigma(\delta_i)^2} \tag{5}$$

The sampling point with the lowest ITS_i is thus the most temporally stable, whereas points with high values of ITS_i are the wettest and driest field locations.

The persistence of soil water content spatial patterns over time can also be evaluated using Spearman rank correlation, and the Spearman's rank correlation coefficient r_s, defined by:

$$r_s = 1 - \frac{6\sum_{i=1}^{n}(R_{ij} - R_{ik})^2}{n(n^2 - 1)} \tag{6}$$

where R_{ij} is the rank of θ_{ij} in a plot, and R_{ik} is the rank of soil water content observation at the same point, but for measurement campaign k. The closer the r_s value is to 1, the more similar was soil moisture spatial pattern between dates i and k. n is the number of observations.

The SPSS software was used for statistical treatment of the data. The Spearman's correlation test was performed to analyze the correlation between gravimetric water content and measurement campaigns of soil water monitoring.

3. RESULTS

3.1. The meteorological factors

The daily data of rainfall and evaporation were shown in Figure 2. Mean rainfall and evaporation were 2.32 mm and 3.67 mm during the experiment period, respectively. Maximum rainfall and evaporation were 23 mm and 62.24 mm at 9 May and 16 April, respectively.

3.2. Soil water content

The soil water content between the two treatments was listed in Table 2. Mean soil water content in treatment 1 was higher than that in treatment 2 at the 14 cm soil layer. However, the mean of soil water content at the 33 cm soil layer had no significant change in two treatments. The coefficient of variation in treatment 1 was lower than that in treatment 2 at 14 cm the soil layer.

3.3. Soil water temporal stability

The mean inter-temporal relative difference and standard deviation of soil water content in 14 and 33 cm soil layers were shown in Figure 3. In Figure 3(Aa), the 7th point presents the relative difference closest to zero in treatment 1 in 14 cm soil layer. The mean relative difference (MRD) value and the standard deviation (SD) of 7th point were 0.23%, and 0.89. Similarly, the points that underestimated or overestimated the soil water average value during the study stage were determined. The MRD and SD values at the undervalued mean (point 8) and overestimated mean (point 4) positions are −5.01% and 1.59, 4.21% and 2.21, respectively. The 10th point in the treatment 2 of 14 cm soil layer showed the relative difference closest

Table 2 | Soil water content in different soil layers under different treatments at study area

	14 cm (g·kg^{-1})				33 cm (g·kg^{-1})			
Soil layers	**Max**	**Min**	**Mean**	**C.V.**	**Max**	**Min**	**Mean**	**C.V.**
Treatment 1	323.82	228.08	279.37	12.93	325.34	238.73	284.81	9.98
Treatment 2	317.69	220.37	253.73	16.67	324.86	276.71	289.18	10.12

Note: C.V. means coefficient of variations.
Treatment 1: mulched with wheat straw; Treatment 2: without mulched with wheat straw.

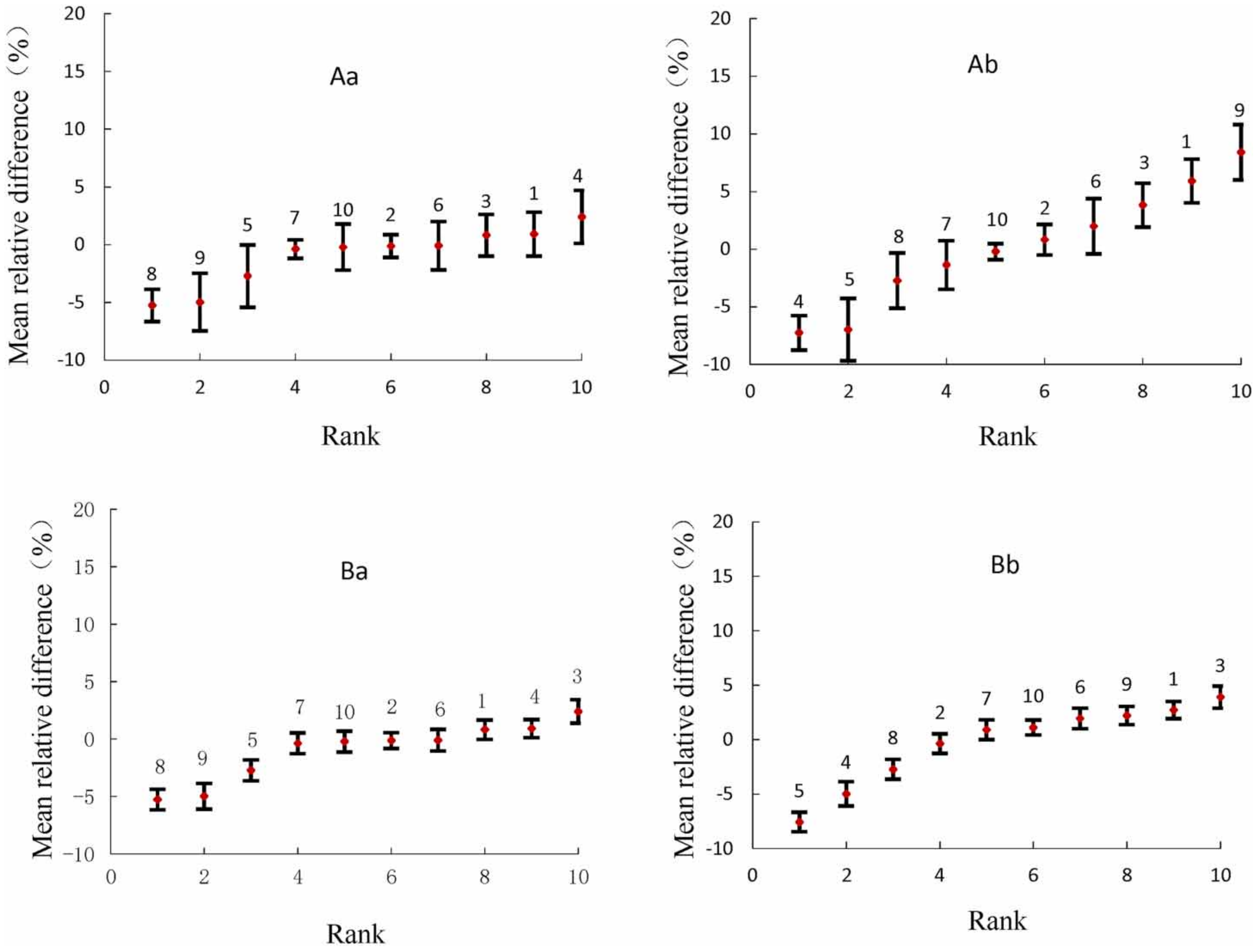


Figure 3 | Ranked mean relative difference of soil water content at two soil layers. Note: A: 14 cm; B: 33 cm. a: Treatment 1; b: Treatment 2.

to zero. The MRD value and SD of 10th point were 0.34% and 0.67, which was shown in Figure 3(Ba). The 7th point in treatment 1 indicated the mean soil water content, the MRD was −0.18% and SD was 2.63. On the other hand, the most representative point was the 2th point, with a MRD of 0.13% and SD of 2.71. Locations in the experiment field can be viewed in Figure 1.

The mean soil water content during the experimental period was compared to the representative points calculated by relative difference (Figure 4). Although some points did not exactly match the mean value, the differences were minimum. The root mean square error between mean values (in different treatments and at different soil layers) and representative points (Aa: point 7 and Ab: point10, Ba: point 7 and Bb: point 2) values were 2.03%, 2.18%, 1.04%, and 1.98%, respectively. The technique proposed by Vachaud *et al.* (1985) produced satisfactory results and identified the position in the field which was the best representation of the mean soil water content during the experimental period. Thus, allowing reduction of the number of samples required analyzing soil water behavior with high accuracy and reduced sampling efforts.

3.4. Spearman's correlation analysis of temporal stability of soil water

The temporal stability was investigated through the Spearman's rank correlation coefficient (r_s). In order to make further understanding of the soil water temporal stability at the experimental area, Spearman's correlation coefficient in different treatments at 14 cm soil layer were presented in Table 3 (mulch with rice straw) and Table 4 (without rice straw). With the increase of time and distance, the correlation coefficient increases. The temporal stability of soil water content in 14 cm soil layer was good, and the Spearman rank correlation coefficient of soil water content reached significant level ($p < 0.05$). The Spearman rank correlation coefficient of temporal stability of soil water content in 33 cm soil layer reached extremely significant level. ($p < 0.01$).

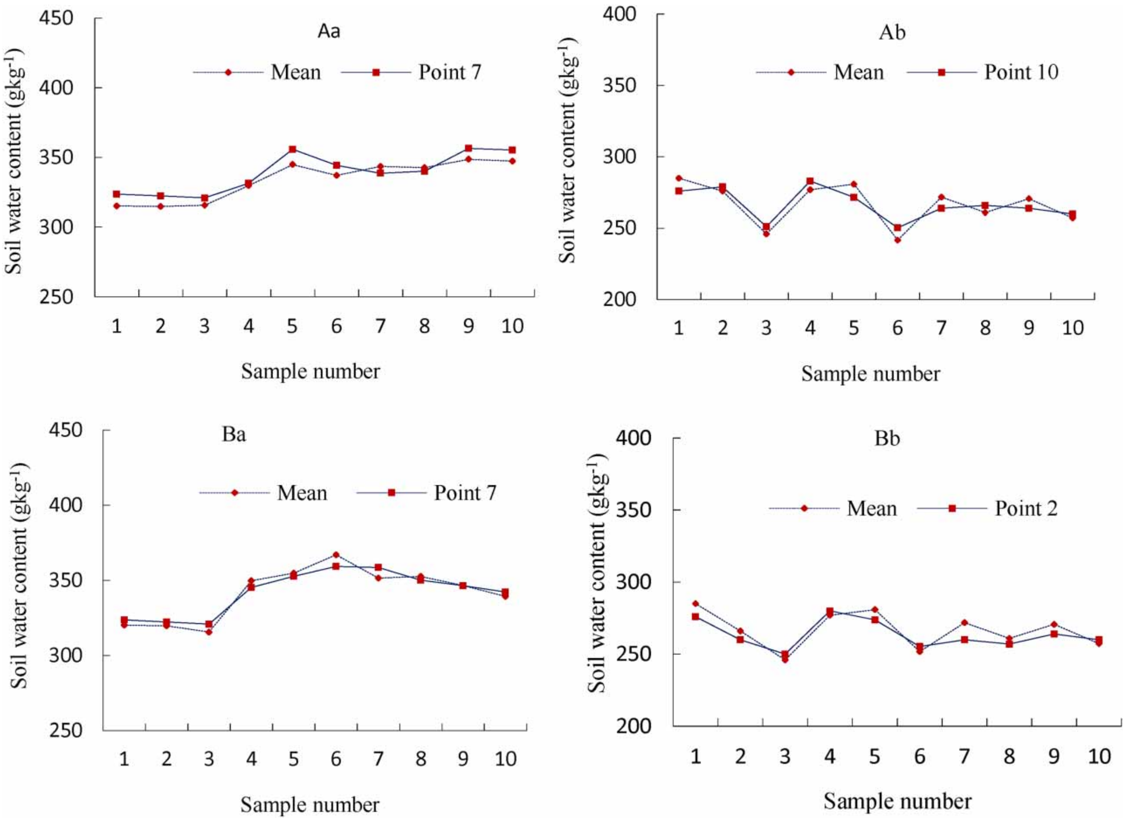


Figure 4 | Comparison between the average soil water contents and water contents at positions with temporal stability. Note: A: 14 cm; B: 33 cm. a: Treatment 1; b: Treatment 2.

Table 3 | Matrix of Spearman's correlation coefficients corresponding to soil water content at the soil layer of 14 cm, mulched with wheat straw

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	1									
2	0.653**	1								
3	0.516	0.711**	1							
4	0.414	0.058	0.703**	1						
5	0.576*	0.701	0.696*	0.910**	1					
6	0.766**	0.508	0.719**	0.512	0.476	1				
7	0.137	0.568*	0.401	0.687*	0.730**	0.934**	1			
8	0.584*	0.601*	0.681*	0.574*	0.463	0.940**	0.507	1		
9	0.433	0.422	0.232	0.458	0.446	0.850**	0.808**	0.704**	1	
10	0.008	0.787**	0.573*	0.753**	0.574*	0.819**	0.730**	0.942**	0.626*	1

*Correlation is significant at the 0.05 level; **Correlation is extremely significant at the 0.01 level.

4. DISCUSSION

Temporal stability of soil water content is commonly used to identify representative locations for soil water content monitoring, to recover missing monitoring data, to design agronomic experiments, and to validate remote sensing methods (He *et al.* 2019; Fry & Guber 2020). Analyses of the temporal stability and variability of soil water content have been particularly useful in the fields of soil science and hydrology (Zhang & Shao 2017; Zhao *et al.* 2017a, 2017b). In this study, the soil water content

Table 4 | Matrix of Spearman's correlation coefficients corresponding to soil water content at the soil layer of 14 cm without mulched with wheat straw

	1	2	3	4	5	6	7	8	9	10
1	1									
2	0.702**	1								
3	0.510	0.719**	1							
4	0.440	0.602	0.625**	1						
5	0.673	0.548	0.710**	0.588*	1					
6	0.754	0.583	0.389	0.656	0.558*	1				
7	0.559	0.758	0.520	0.744	0.513	0.543	1			
8	0.645	0.762	0.521	0.495	0.831*	0.746**	0.719**	1		
9	0.877	0. 522	0.269	0.526	0.427	0.929**	0.538	0.738**	1	
10	−0.290	−0.425	−0.168	0.234	−0.021	0.581*	0.204	0.278	0.699*	1

*Correlation is significant at the 0.05 level; **Correlation is extremely significant at the 0.01 level.

in deeper soil layer was more temporally stable than that in surface soil layer, which was consistent to the study of Naves *et al.* (2017), who evaluated the temporal stability of soil water content at two different areas in Brazil. The reason may be that surface soil water content was affected easily by precipitation, evaporation, humidity and wind speed, etc., and fluctuated frequently. As it was shown in Figure 3(Aa, Ab). The MRD of soil water content with rice straw mulch was from −6.06% to 5.40%, and the MRD of soil water content without rice straw mulch were from −7.97% to 8.40%, which indicated that soil with rice straw mulch could maintain more soil water. However, the range of soil MRD with rice straw mulch in the 33 cm soil layer (Figure 3(Ba, Bb)) was from −5.49% to 4.89%, which was closest to MRD of without rice straw mulch from −6.07% to 4.42%. These results illustrated that rice straw mulch had no significant effect on maintaining the soil water at 33 cm soil layer. Due to the fact that the 33 cm soil layer was the plowpan layer at the experimental field in Taihu Lake region of China, the wheat roots had no affect to 33 cm soil layer. The soil water content in this soil layer was in the process of dynamic change, and its temporal stability was better than that in the 14 cm soil layer. Therefore, with the deepening of soil layer, the temporal stability of soil water content becomes better. The 33 cm soil layer is less affected by rainfall and irrigation. In addition, the clay content also in this soil layer was higher than cultivated soil layer (14 cm), which is conducive to water retention. Therefore, the soil water in this soil layer shows good temporal stability.

The high Spearman's rank correlation coefficient (r_s) was obtained, which indicates the wettest and driest locations maintained the same pattern during the experimental period at the 14 cm soil layer. The same behavior of temporal stability was found at 33 cm soil layer. The similar results using this methodology to study soil water temporal stability were also observed by Cichota *et al.* (2006) and Brocca *et al.* (2009). Spearman rank correlation coefficient was used to analyze soil water stability and accurately express the correlation between each soil water measurement, so as to timely understand the soil water change and soil variability at each measurement point. The results can be effectively used to design sampling schemes for soil water content measurements and represent valuable support for hydrological and other applications.

5. CONCLUSIONS

In this study, temporal behavior of soil water was investigated in a typical paddy soil in southeast China. Firstly, mulching with rice straw has significant effect on soil water temporal stability at 14 cm soil layer. Secondly, soil water temporal stability presented better at 33 cm soil layer than that at 14 cm soil layer. Thirdly, the Spearman's correlation values were high, which indicates temporal dependence along the experiment period.

The method in this study was used successfully to analyze soil water stability and accurately express the correlation between each soil water measurement, so as to timely understand the variation of soil water at each measurement point and the variability of soil properties in the experimental field. The identification of this position reduces the number of observation required for precise water management in key areas of food production.

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CONFLICT OF INTEREST

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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