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Temporal stability in soil water content patterns across agricultural fields

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Abstract

When a field or a small watershed is repeatedly surveyed for soil water content, locations can often be identified where soil water contents are either consistently larger or consistently less than the study area average. This phenomenon has been called temporal stability, time stability, temporal persistence, or rank stability in spatial patterns of soil water contents. Temporal stability is of considerable interest in terms of facilitating upscaling of observed soil water contents to obtain average values across the observation area, improving soil water monitoring strategies, and correcting the monitoring results for missing data. The objective of this work was to contribute to the existing knowledge base on temporal stability in soil water patterns using frequent multi-depth measurements with Multisensor Capacitance Probes (MCPs) installed in a coarse-texture soil under multi-year corn production. Water contents at 10, 30, 50, and 80 cm depths were measured every 10 min for 20 months of continuous observation from May 2001 to December 2002. The MCPs revealed temporal stability in soil water content patterns. Temporal stability was found to increase with depth. The statistical hypothesis could not be rejected ($P<0.0001$) that data collected each 10 min, each 2 h, each day, and each week had the same temporal stability. The locations that were best for estimating the average water contents were different for different depths. The best three locations for the whole observation period were the same as the best locations for a month of observations in about 60% of the cases. Temporal stability for a specific location and depth could serve as a good predictor of the utility of this location for estimating the area-average soil water content for that depth. Temporal stability could be efficiently used to correct area-average water contents for missing data. Soil water contents can be upscaled and efficiently monitored using the temporal stability of soil water content patterns.
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Keywords: Temporal stability; Multisensor capacitance probe; Soil water content; Spatial pattern; Upscaling; Measurement frequency

1. Introduction

When a field or a small watershed is repeatedly surveyed for soil water content, locations can be often identified where soil water contents are either consistently larger or consistently less than the study area average. This phenomenon has been called time stability or temporal stability (Vachaud et al., 1985), temporal persistence (Kachanoski and de Jong, 1988), or rank stability (Tallon and Si, 2003) in soil moisture spatial patterns. Soil water content temporal stability has been demonstrated for three different time-dependent characteristics of soil water dynamics, namely: (a) water contents at specific depths; (b) soil water storage usually interpreted as the total amount of soil water within a range of depths; and (c) soil water fluxes estimated at specific depths. Temporal stability causes time series of soil water contents or fluxes at different locations to have similar shapes while being offset from each other. Although a mechanistic explanation of temporal stability in spatial soil water patterns has never been given, its presence has been routinely observed in widely different environments, provided measurement locations did not change in time.

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Several consequences of temporal stability in soil water patterns (TSSWP) have caused more interest recently in this feature. One consequence is that one or more locations can often be found that have a time series of the soil water content (or of the soil water storage or the estimated soil water flux) very similar to the time series of the average value of the soil water content (or soil water storage or soil water flux) across the study area. Once such locations are found, only a small number of soil moisture sensors at those locations are needed to monitor the average soil water content across relatively large areas. This aspect of TSSWP has been actively used in remote sensing of soil moisture because of the possibility to upscale water contents from several or even single point measurements to the average soil water content across a footprint area (Mohanty and Skaggs, 2001; Cosh et al., 2003; Jacobs et al., 2004). Other applications include establishing field- or catchment-wide antecedent moisture conditions for runoff simulations (Western et al., 2003), relating spatio-temporal variations in soil water to the onset of subsurface flow as measured with a network of piezometers (Penna et al., 2006), and upscaling soil moisture data in irrigated and dryland crops (Rolston et al., 1991; Rocha et al., 2005).

Another consequence of TSSWP is that relative differences between average soil water contents across the study area and water contents at specific points within this area, may remain relatively constant. In other words, the pattern of variation across the study area remains more or less the same, even though the average soil water content changes. This aspect of TSSWP has been used to estimate time series of the soil moisture content at locations for which only a few data are available, but with continuous records available from nearby locations (Pachepsky et al., 2005; Fernández-Gálvez et al., 2006). Downscaling of remote sensing data of soil moisture based on the stability of patterns has also been suggested (Narayan and Lakshmi, 2005). Spatial patterns of moisture-affected soil properties have similarly demonstrated temporal stability (Goovaerts and Chiang, 1993; Douaik et al., 2006), a feature that was further used to explain spatial variability in crop yield (Cassel et al., 2000; King et al., 2005; Starr, 2005).

Although information on TSSWP has been steadily accumulating, several contentious questions require more insight. The use of TSSWP to decrease the number of monitoring devices requires the selection of a time period to identify locations that can be used to estimate time series of the average soil water content, soil water storage, or flux measurements. Grayson and Western (1998), among others, recognized that the observation time span has to be split into a training period during which the best locations for representing the averaged soil water patterns are identified, and a validation period for testing the “best” locations. Martínez-Fernández and Ceballos (2005) recommended using one year as a training period. Soil water contents in their study were measured every two weeks. Unfortunately, currently it is not known how the frequency of soil moisture measurements affects the selection of the training period.

No conclusive results have been obtained on how and where to identify the “best” locations for the purpose of demonstrating and using TSSWP. Da Silva et al. (2001) found that clay content and organic matter can serve as good explanatory variables, whereas topographic variables cannot. On the contrary, topography and vegetation rather than soil properties appeared to be leadings factors of TSSWP in a study of Gomez-Plaza et al. (2000), while Jacobs et al. (2004) indicated that locations with mild slopes consistently exhibited time stable features. Grayson and Western (1998) found that the “best” sites to represent catchment average soil moisture were located in areas that were neither strongly convergent nor divergent, and tended to be near the mid-slopes or in areas that had topographic aspects close to the average. Jacobs et al. (2004) observed that sampling sites with the highest sand content tended to generate the least time stability, whereas Mohanty and Skaggs (2001) found better time stability on a sandy loam soil than a silt loam. Tallon and Si (2003) observed that time stable sites showed poor relationships to soil and topographic properties, thus suggesting the absence of a single dominant control.

Several studies indicate that TSSWP may be affected by the type of soil water sensor used. Kirda and Reichardt (1992) found that spatial patterns in soil water demonstrated temporal stability when measured with neutron probes, but not when tensiometers or gypsum blocks had been used. These authors hypothesized that the soil water sensor has to average over a sufficient soil volume to uncover temporal stability. Van Pelt and Wierenga (2001) demonstrated temporal stability in pressure heads measured with tensiometers. Mohanty et al. (2000) found little or no temporal stability in measurements of surface soil water contents in the Little Washita watershed with theta probes that were inserted anew at each location for each sampling. However, they demonstrated excellent temporal stability using the same measurement technique in the Walnut Creek watershed (Jacobs et al., 2004). Although multisensor capacitance probes (MCPs) have recently become more popular for measuring soil moisture contents (Starr and Paltineanu, 2002), little is known about TSSWP assessment using MCPs. We were aware only of one study, by Tallon and Si (2003), in which MCPs had been used to investigate temporal stability in the soil water contents of Chernozem and Regosol.

Whereas temporal stability in soil water contents has been amply demonstrated, the presence of temporal stability in estimated soil water fluxes is less obvious. Reichardt et al. (1993) concluded that it was not feasible to estimate mean field behavior with respect to soil water fluxes due to soil variability, if field-measured hydraulic conductivities and pressure heads are used to estimate water fluxes and pressure gradients. It is not known if temporal stability in estimated soil water fluxes can be demonstrated, and whether the same locations can be used to estimate time series of average soil water contents and average soil water fluxes.

The objective of this study was to contribute to existing knowledge on temporal stability in soil water patterns using extremely frequent multi-depth measurements with Multisensor Capacitance Probes installed in a soil profile under multi-year corn production. In this paper we investigate: (a) the effect of monitoring frequency on temporal stability and selection of the best locations to estimate the area-average soil water content; and

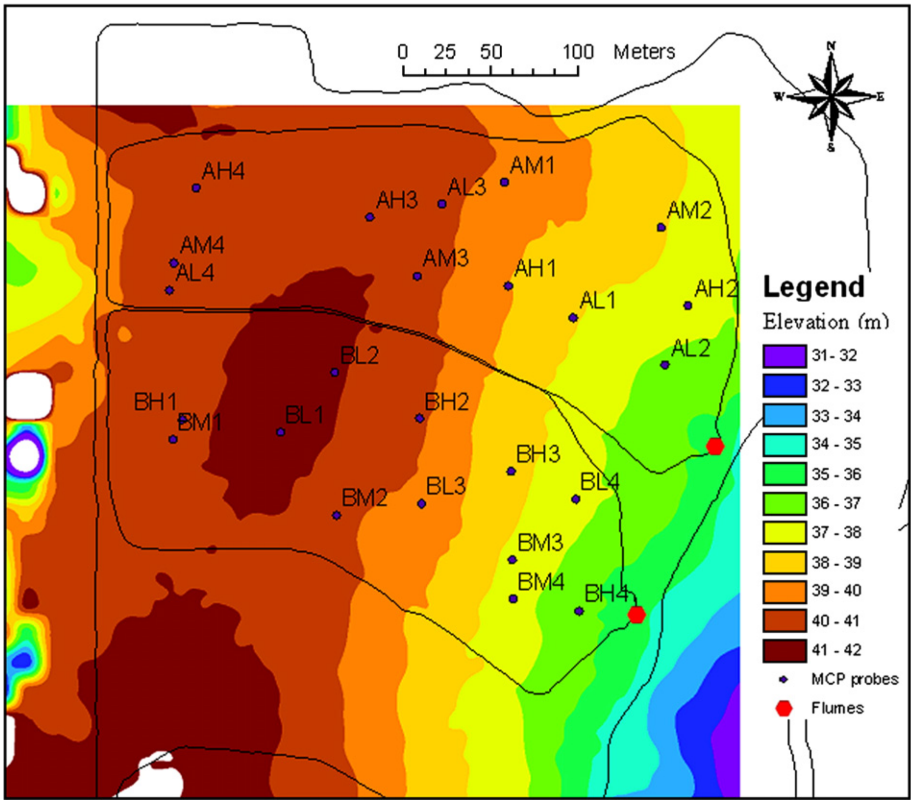

Fig. 1. Layout of fields, elevation map, and soil water probe locations; A, B — the field code, H, M, and L — range of distances (high, medium, low) to the impermeable layer, 1 to 4 — replication number.

(b) using temporal stability to correct the average soil water contents for missing data from individual locations.

2. Materials and methods

2.1. Soil water monitoring

The research site is part of the Optimizing Production inputs for Economic and Environmental Enhancement (OPE3) research site located at the USDA-ARS Beltsville Agricultural Research Center, in Beltsville, Maryland (39° 01′ 00″ N, 76° 52′ 00″ W). The site is part of a 25-ha watershed formed from fluvial deposits with slopes ranging from 1 to 4% (Gish, 2002). Data from two fields at the site with a total area of 6 ha were used in this study (Fig. 1). The fields were under continuous corn production. Each year the tillage practices were the same, with fields being disked about one month prior to a second disking operation, followed by planting. Soils at these fields have been classified as a coarse loamy, siliceous, mesic Typic Hapludults, and the fine–loamy, siliceous, semiactive, mesic Aquic Hapludults with either well or excessively well drainage. On average, the soil has a coarse loamy sand surface horizon (0–25 cm, organic matter 1.2–5.1%), followed by a sandy loam horizon (25–80 cm), and a loam horizon (80 –120 cm), with loamy sand and fine-textured clay loam lenses between 120 and 250 cm. The lenses in the latter form a nearly impermeable layer in this soil (Gish et al., 2002) that prevents deep leaching and causes lateral movement of water and solutes. This subsurface layer furthermore has numerous localized depressions that form braided flow pathways throughout the field causing drainage toward a riparian wetland and a first-order stream.

The capacitance probes (EnviroSCAN, SENTEK Pty Ltd., South Australia) were installed in the spring of 1998 to better understand surface and subsurface soil water dynamics. For details on sensor location and installation, see Gish et al. (2002). Each sensor was calibrated before installation (Paltineanu and Starr, 1997). In this study we used data from 24 soil moisture multisensor capacitance probes (Fig. 1) that were installed at depths of 10, 30, 50, 80, 120, 150, and 180 cm, with water contents recorded each 10 min for 610 days from May 1, 2001 to December 31, 2002. Depths of sensor installation at different locations are shown in Table 1.

Table 1
Depths of sensor installation by locations, "+" — sensors are installed, "–" no sensors at this depth

k	Depth, cm	Location		
		AH1, AH2, AH3, AH4, BH1, BH2, BH3, BH4	AM1, AM2, AM3, AM4, BM1, BM2, BM3, BM4	AL1, AL2, AL3, AL4, BL1, BL2, BL3, BL4
1	10	+	+	+
2	30	+	+	+
3	50	−	+	+
4	80	+	−	+
5	120	−	+	+
6	150	−	+	+
7	180	−	+	+

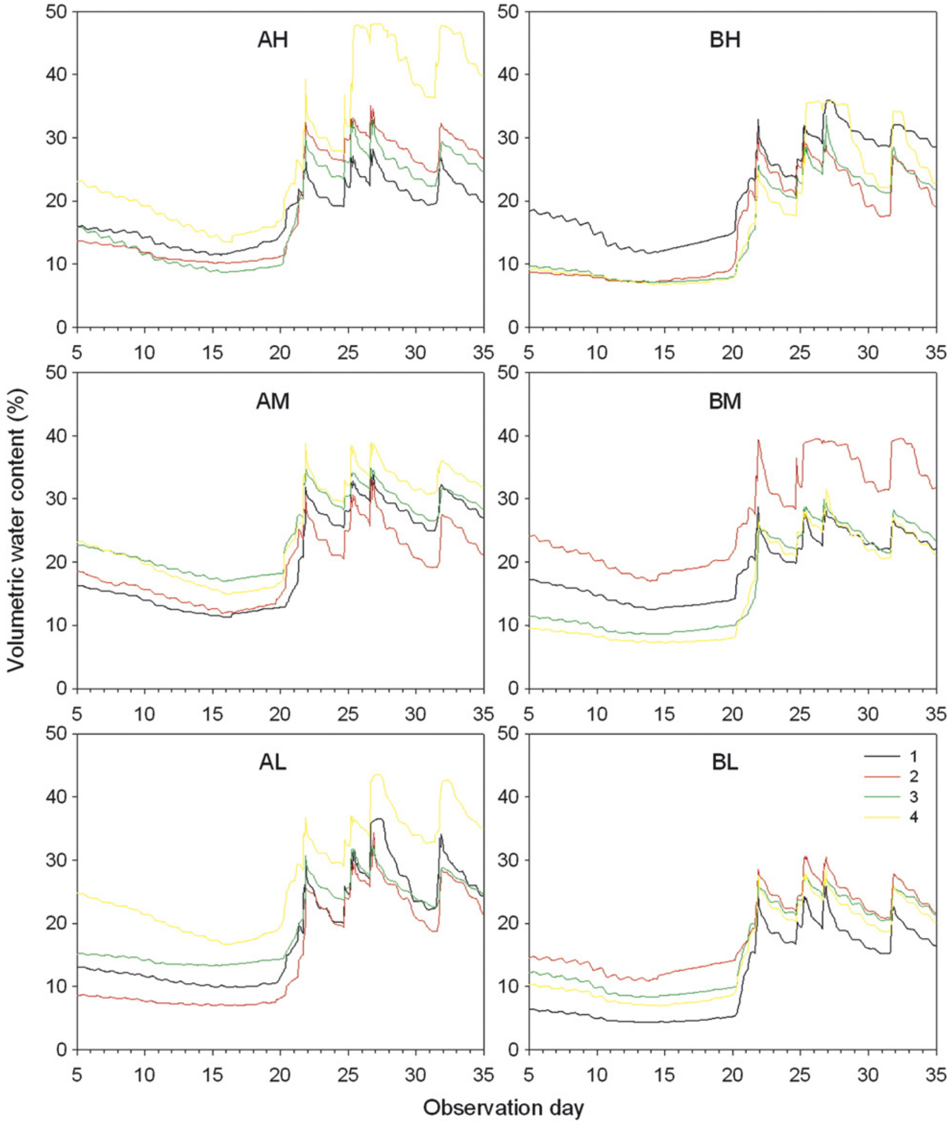

Fig. 2. Example of monthly soil water dynamics measured with the MCP probes at a depth of 10 cm. Combine the letters on a panel with the curve number in the legend to obtain the MCP ID of for the individual curve (e.g., red curve of top left panel shows data from the AH2 MCP).

2.2. Evaluating temporal stability in soil water patterns

Temporal stability was quantified using the approach of Pachepsky et al. (2005), which is similar to one proposed earlier by Vachaud et al. (1985). The relative water contents β_{ikj} for each sampling location i at depth k for measurement time j were computed as:

$$\beta_{ikj} = \frac{\theta_{ikj}}{\overline{\theta}_{kj}} \tag{1}$$

where θ_{ikj} is the water content measured at location i at the jth measurement time at the kth depth, and $\overline{\theta}_{kj}$ is the average water content at the jth measurement time at the kth depth:

$$\overline{\theta}_{kj} = \frac{1}{N_k} \sum\nolimits_{i=1}^{N_k} \theta_{ikj} \tag{2}$$

in which N_k is the total number of probes at depth k (Table 1). Temporal stability in the water content patterns was characterized separately for each observation depth k and each location i by using empirical probability distribution functions, β_{ikj}. The temporal stability index T_{ik}, computed as the width of the 90% empirical tolerance interval, i.e., $\beta_{ik}(P=0.95)-\beta_{ik}(P=0.05)$, was used as a measure of the temporal stability in soil water content of sampling location i at depth k. Larger values of T_{ik} correspond to lower temporal stability. The two-sample Kolmogorov–Smirnov goodness of fit test as implemented in the S-PLUS200 software (Mathsoft, 1999) was used to test whether values of β_{ik} obtained with different observation frequencies could have come from the same distribution.

Locations were ranked by their utility to estimate average soil water contents using the χ^2 statistic:

$$\chi^2_{ik} = \sum_j \left(\frac{\overline{\theta}_{jk} - \theta_{ikj} / \overline{\beta}_{ik}}{\sigma_{jk}} \right)^2 \tag{3}$$

where summation runs over all observation times, σ_{jk} is the standard deviation of the average soil water content $\overline{\theta}_{jk}$ for observation time j

at depth k (i.e., the standard error of observed water contents at this time and depth), and $\overline{\beta}_{ik}$ is the average value of the relative water content at location i and depth k. Root-mean-squared differences

$$D_{ik} = \sqrt{\frac{\sum_j^{N_{ik}}\left(\overline{\theta}_{jk} - \theta_{ikj}/\overline{\beta}_{ik}\right)^2}{N_{ik}-1}} \tag{4}$$

were also computed, with N_{ik} being the total number of observations at depth k and location i in the field. We note that Eqs. (3) and (4) both use measurements at a particular location, corrected by the average relative water content rather than uncorrected measurements that are invoked to represent the average water content (Gomez-Plaza et al., 2000; Kaleita et al., 2004).

The use of temporal stability in soil water contents to correct the average soil water content for missing data was studied by applying the equation (Pachepsky et al., 2005)

$$\overline{\theta}_{jk} \approx \sum_i \theta_{ikj} \Big/ \sum_i \overline{\beta}_{ik} \tag{7}$$

where $\overline{\beta}_{ik}$ is the average relative water content at depth k at location i. Eq. (7) is summed over all locations for which measurements are available at observation time j.

3. Results and discussion

3.1. Temporal stability in soil water contents

The MCPs revealed considerable temporal stability in the soil water contents. Fig. 2 shows an example of monthly soil water dynamics measured with MCPs at the 10-cm depth. Temporal changes in soil water contents at different locations were very similar in that the graphs of the water contents at different locations were mostly only shifted relative to each other. These similarities translated into water content profiles characterized in Fig. 3 by the average and the 5% and 95% quantiles of the distribution individual soil water contents which were significantly ($P<0.05$) different from the average soil water content in 9 of 24 locations at the 10 cm depth, in 17 of 24 locations at 30 cm, in 12 of 16 locations at 50 cm, and in 11 of 16 locations at the 80 cm depth. The number of locations with water contents significantly different from the average was much larger than, for example, in the study of Comegna and Basile (1994) where soil homogeneity prevented large differences between water contents at different locations. Also, we did not observe a dependency of temporal stability on the average water content at a particular location, as was reported in earlier studies. For example, Martínez-Fernández and Ceballos (2003) and Jacobs et al. (2004) found that relative water contents of drier locations tended to have less variability than the wetter locations.

The temporal stability index T_{ik} is shown in Fig. 3 as the width of the interval between the error bars. The index decreased with depth between 0 and 60 cm, which reflects increased stability with depth. Average values of T_{ik} over 24 locations were 0.42, 0.23, and 0.24 at depths of 10 cm, 30 cm, and 50 cm, respectively. A similar increase in temporal stability with depth was observed by Cassel et al. (2000) for cropland and by Lin (2006) for forest watersheds. A similar result was also reported by Kamgar et al. (1992) who suggested that

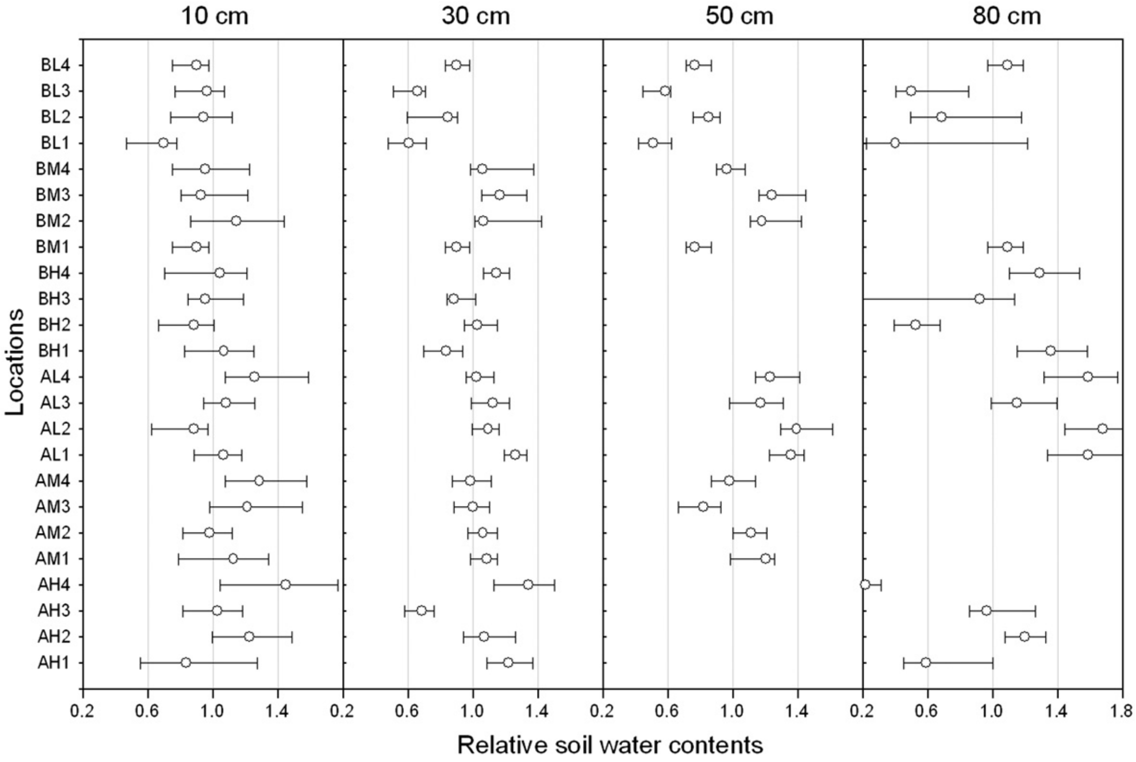

Fig. 3. Variations in relative soil water contents at four depths during the observation period from May 1, 2001 to Dec 31, 2002. Symbols show the median value, error bars show values at the 5% and 95% probability levels.

temporal stability in soil water storage was less pronounced in shallow soil layers owing to the impact of crop root water uptake, whereas pedogenetically derived variations at deeper layers conserved a relatively stable pattern in spatial variation through time. Another possible reason for the increased temporal stability with depth may be the dynamics in soil structure and its ability to retain water, which is much more pronounced at lower depths (Korsunskaya et al., 1995). The water table at some locations in our study was less than 80 cm, which explains the considerable variability in relative water contents as seen in Fig. 2. The temporal stability index for these reasons varied widely at this depth.

Sensors at different locations in the field often showed consistently lower or higher water contents than the average water content at a particular depth. The AL2 location presents an example (Fig. 2) for which water contents at 10 cm (30 cm) depth were significantly less than (greater than) the average water content. This may be the result of considerable soil heterogeneity that was demonstrated for this site with data from a ground penetration radar survey (Gish et al., 2002).

To evaluate the effect of the sampling frequency on temporal stability characteristics, the data were sequentially reduced. Data obtained at time intervals of 2 h, 1 day and 7 days were selected by retaining each 12th, 144th and 1008th measurement, respectively. We next compared probability distribution functions, β_{ik}, of the relative water contents. The statistical hypothesis that values of β_{ikj} at four different measurement time intervals (10 min, 2 h, 1 day, 7 days) for the same depth and location belonged to the same distribution could not be rejected ($P<0.0001$). An important implication of this result is that temporal stability in soil water contents can be revealed equally well with a low frequency of observations as with high frequency.

3.2. Selection of soil water monitoring locations

Locations BM1, AH3, and BM3 appeared to be the best for estimating the average water contents at depths of 10 cm, 30 cm, and 50 cm, respectively, having root-mean-squared differences D_{ik} of 1.16, 0.77 and 0.98%, respectively. Given that the observed average soil water contents at these depths ranged from 2 to 31%, from 7 to 25%, and from 5 to 20%, respectively, the accuracy of the estimated average may well be sufficient for many applications. Location AH1 was the worst estimator of the average at depths of 10 cm and 30 cm, having errors of 3.7 vol.% and 1.8 vol.%, respectively. Our results concur with the observation by Tallon and Si (2003) that within the same field, time stable sites can be different at different depths. This observation does not seem to be universal. For example, Cassel et al. (2000) found that the ranking of the various locations was similar at different depths. The small errors in estimated average water contents indicate that a two-stage monitoring method as suggested by Rolston et al. (1991) and later by Gomez-Plaza et al. (2000) is very much feasible at our study site. The method consists of initial intensive sampling in order to identify locations giving mean soil water storage. Only these locations could subsequently be sampled for changes in soil water. Several best locations can be selected if no statistically significant differences exist between the root-mean-squared differences D_{ik}.

Table 2
Utility of locations to estimate the average soil water contents at the depth of 10 cm across the field B over the whole observation period and over the calendar month observation periods

Location, sorted by the χ^2 statistic for the 19-month observation period	The χ^2 statistic for the 19-month observation period	The root-mean-squared difference D for the whole observation period, vol.%	The number of monthly observation periods over which the location had the lowest χ^2 statistic
BL3	139	1.34	4
BL1	146	1.42	5
BL4	155	1.18	3
BL2	167	1.77	1
BH3	171	1.84	2
BH1	175	2.04	1
BM4	199	1.79	3
BM1	207	1.91	0
BH2	210	2.00	0
BM3	232	2.12	0
BM2	236	2.58	0
BH4	270	2.52	0

A change in the duration of the observation period was found to affect the selection of the best monitoring locations. An example of data for monthly observations periods is presented in Table 2 for the 10 cm depth across field B. Only data from field B were used since some locations of field A had a large number of missing data. The best three locations to estimate the average soil water content over the whole observation period were the best locations over a month-long period of observations in about 60% of cases. The worst six locations over the entire observation period never were the best over a month of observations. The lowest values of χ^2 for May, June and July were about two times larger than the lowest χ^2 for other months. These results are consistent with the observation by Da Silva et al. (2001) that the relative importance of different factors affecting temporal stability varies during the growing season and between seasons. The May–June period was a period of active vegetative growth of corn for both years of observations. Zhang and Berndtsson (1988) and Hupet and Vanclooster (2002) also observed weaker temporal stability during dry periods compared with wet periods.

The sequential data reduction technique was used to evaluate the effect of sampling frequency on the utility of locations to estimate the field average soil water content. Table 3 shows the effect of sampling frequency across Field B at three depths. We encountered only slight changes in the root-mean-squared differences D_{i1} when the sampling frequency was changed from 10 min to 2 h, 1 day, and 7 days. No changes in location ranking by the χ^2 statistic were found. The implication of this result is that the utility of a location to estimate the field average soil water content can be evaluated with the same accuracy using a low frequency of observations as compared to a high frequency.

3.3. Correction for missing data using temporal stability

To evaluate the efficiency of correcting the average soil water content for missing data at some locations, we first performed a simulation experiment. All hourly measurements were used over

Table 3
Root-mean-squared deviations ($cm^3\ cm^{-3}$) of corrected location water contents from the average soil water content across the field B

Location	Time interval between measurements			
	10 min	2 h	1 day	7 days
Depth 10 cm				
BM1	1.18	1.17	1.15	1.06
BL3	1.34	1.35	1.35	1.27
BL1	1.42	1.43	1.49	1.30
BL2	1.77	1.78	1.86	1.56
BM4	1.79	1.79	1.79	1.69
BL4	1.91	1.92	1.95	1.90
BH3	1.84	1.84	1.82	1.71
BH2	2.00	1.99	1.94	1.88
BH1	2.04	2.06	2.13	2.01
BM3	2.12	2.13	2.20	2.19
BH4	2.52	2.51	2.52	2.58
BM2	2.58	2.59	2.64	2.65
Depth 30 cm				
BM1	0.89	0.90	0.91	0.88
BH4	0.97	0.98	1.00	0.94
BH3	1.09	1.10	1.14	0.94
BH2	1.17	1.17	1.20	1.13
BL4	1.24	1.23	1.22	1.18
BM3	1.37	1.38	1.38	1.39
BM4	1.37	1.39	1.44	1.42
BL3	1.50	1.49	1.49	1.36
BM2	1.55	1.58	1.69	1.63
BH1	1.64	1.66	1.73	1.79
BL2	1.66	1.70	1.84	1.76
BL1	2.31	2.32	2.40	2.16
Depth 50 cm				
BM4	0.95	0.96	0.98	0.85
BM1	1.03	1.02	1.09	0.68
BL4	1.03	1.02	1.09	0.68
BM3	1.05	1.05	1.06	0.96
BL2	1.09	1.11	1.16	1.15
BM2	1.33	1.34	1.39	1.30
BL3	1.44	1.45	1.45	1.39
BL1	2.83	2.88	3.01	2.88

the period when all 24 probes worked at the 10-cm depth. Data from 1 to 22 probes were removed for each sampling time, and the average water content was estimated in two ways: (a) as the average water content over remaining probes (assumed to be working); and (b) as the corrected value of the average water content according to Eq. (7). The efficiency of the correction was evaluated by computing the root-mean-squared difference, RMSD, between the actual and estimated average soil water content. The probability distribution of RMSD from this simulation is shown in the Fig. 4. The improvement depended on the total number of working probes. The fewer the number of working probes, the more efficient was the correction.

Fernández-Gálvez et al. (2006) investigated how to use temporal stability in soil water patterns to estimate soil water contents at rarely sampled locations from soil water contents at densely monitored locations. This problem is closely related to the problem of estimating missing data. Fernández-Gálvez et al. (2006) found that their interpolation procedure appeared to be least successful during infiltration events. We did not find such an effect when estimating the average water content. This may be related to the fact that we used average values of the relative water contents, rather than relative water contents at specific times.

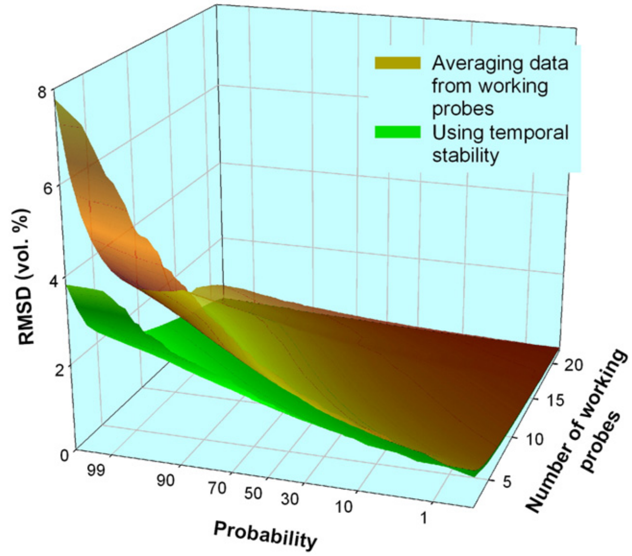

Fig. 4. Probability distributions of the root-mean-squared difference RMSD between actual and estimated average soil water contents.

Substantial corrections for the missing data were obtained at some observation times within the entire observation period of 610 days when the missing data log was used (Fig. 5). The water content corrections generally decreased with an increase in the number of working probes (Fig. 6). The maximum correction was equal to 2.5 vol.% at an average water content of 19.2 vol. %, corresponding to a time interval when 10 probes functioned properly. The advantage of correcting for missing data may be even more substantial if the effect of the number of probes on the accuracy of the average is considered (Teuling et al., 2006).

The MCPs were installed at temporally unchanged sampling locations at the OPE3 site. Since small-scale variability can be substantial, we concur with Kirda and Reichardt (1992) and Hupet and Vanclooster (2002) that temporally unchanged locations are preferable to establishing and using temporal stability relationships. In spite of the stable location of probes,

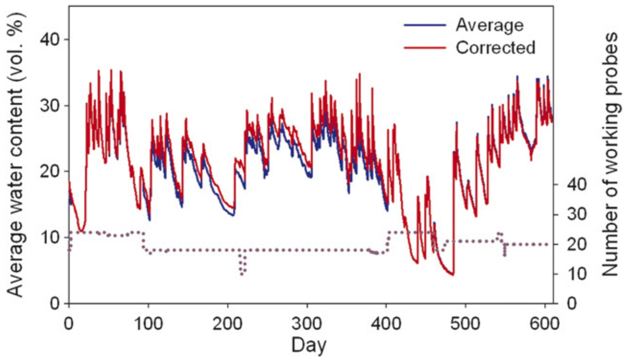

Fig. 5. Temporal stability-based corrections for missing data to the average soil water content at the 10 cm depth. The number of working probes is shown by the dotted line.

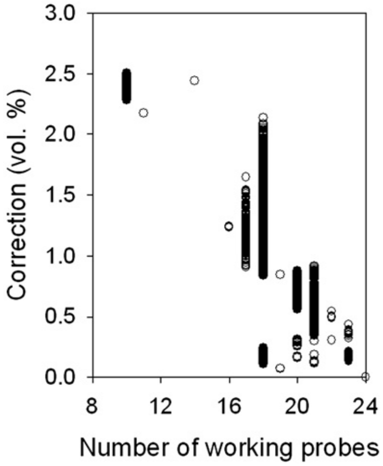

Fig. 6. Relationship between the temporal stability-based correction and the average soil water content at the 10 cm depth and the number of working probes.

considerable variability existed between sites in terms of the temporal stability index (Fig. 3). This implies that the overall spatial pattern in moisture changed dynamically but that some locations within that overall pattern remained at a consistent proportion of the mean.

Several methods have been suggested to characterize consistency in temporal patterns of the soil water contents. In particular, temporal persistence in soil water series can be quantified along with temporal stability. Whereas temporal stability analysis uses statistics of relative water contents as defined by Eq. (1) or statistics of relative differences in water contents as defined by Vachaud et al. (1985), the temporal persistence is characterized using autoregression of the soil water content time series as suggested by Kachanoski and de Jong (1988). Lin (2006) developed four conditions of temporal persistence based on the slope and intercept of this autoregression. Several other parameters have been suggested, such as rank stability (Vachaud et al., 1985), spatial coherency (Kachanoski and de Jong, 1988), variance in relative differences (Martínez-Fernández and Ceballos, 2003; Jacobs et al., 2004), and parameters of the soil moisture semivariogram (Kaleita et al., 2004). An interesting avenue for future research would be to somehow combine these alternative characteristics of consistency in temporal patterns for the purpose of selecting monitoring locations or estimating missing data.

Obtaining the average water content across the observation area from point-scale MCP measurements can be interpreted as a method of upscaling. Upscaling in this sense is valuable in many applications, such as for estimating groundwater recharge, modeling contaminant transport in the vadose zone, watershed modeling, and remote sensing of soil moisture. Upscaling of water contents in our study could be accomplished using relatively low temporal resolution. Good locations for upscaling could be found with reasonable probability using only one month of data. Several have suggested a need for longer periods of observations in order to find representative locations for the soil water sensors. Martínez-Fernández and Ceballos (2005) found that one year was needed to identify representative mean soil moisture measuring stations for both a small catchment of 0.62 km^2 with a complex vegetation cover and a large area of 1285 km^2 covered with the soil moisture observation network. Lin (2006) found that temporal stability in soil moisture spatial patterns varied over space and between seasons in complex terrains with heterogeneous soils and landforms. The one-month observation duration used here is probably specific for the location and spatial scale of our study site, and should not be generalized.

4. Concluding remarks

Multisensor capacitance probes can provide soil water content data with high temporal frequency. Using such data, we demonstrated considerable temporal stability in soil water patterns across field in a coarse textured soil for the observation period of 610 days.

By sequentially reducing data, we found that high-frequency data collection did not provide advantages for establishing temporal stability in the soil water contents. Sampling frequencies in the range from 10 min to one week resulted in very similar parameters of temporal stability and in the selection of the same locations as the best for estimating the average water content across the observation area for a single depth.

Temporal stability in soil water contents was found beneficial for correcting measured average soil water contents when some sensors malfunctioned. However, overall, the error resulting from malfunctioning of some sensors was relatively modest in our work.

Although the mechanisms behind temporal stability in soil water patterns need further research, empirical evidence indicates that this phenomenon is widespread and pervasive. We conclude that soil water contents can be monitored and upscaled more efficiently when taking advantage of the temporal stability in soil water patterns.

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