poral stability (Gómez-Plaza *et al.*, 2000; Schneider *et al.*, 2008). Yet, sampling measurements during the wet stage show relatively high correlation (r_s above 0.65), implying that hydrological processes influencing soil moisture patterns might be temporally stable. On the contrary, time stability of soil moisture patterns within dry stage tend to decrease. Nevertheless it is as well interesting to observe that time stability increases under wetter conditions.

Controlling factors on temporal stability of soil moisture

Figure 3 shows the time-average plot of the relative soil moisture differences ($\overline{\delta_i}$, are solid circles and $\sigma(\delta_i)$ are gray bars) and associated ITS (green line). Moreover the $\overline{\delta_i}$ -values are associated to the corresponding soil-landcsape units (VAG1, VAG2, VAG3, VAR3 and VAI1 and CAG) as presented in a similar fashion by Wang *et al.* (2015). The $\overline{\delta_i}$ -values, referred to an area of about 37 km^2, span from –46% to +50% which are values surprisingly larger than those obtained in previous studies applied in more extended catchments (Martínez-Fernández and Ceballos, 2003; Brocca *et al.*, 2010; Brocca *et al.*, 2012; Wei *et al.*, 2017). The time-average plot of the relative soil moisture differences shows locations that systematically overestimate ($\overline{\delta_i}$ >0) or underestimate ($\overline{\delta_i}$ <0) the spatial-average soil moisture (Coppola *et al.*, 2011). It is evident that the wetter-than-average zones belong to the dominant soil-landscape unit, VAG (as visually indicated by the clustering of bluish circles on the right part of the plot) and soil moisture patterns are characterized by large standard deviations (from 9% to 58%). On the other hand the drier-than-average zones in the remaining soil-landscape units are characterized by values of $\sigma(\delta_i)$ ranging from 7% up to 31% (Hu *et al.*, 2010; Wei *et al.*, 2017). Nonetheless, temporal stability is assessed through the ITS-index which is maximum for wettest and driest conditions and minimizes toward the centre of the plot corresponding to the ideal point $\overline{\delta_i}$ =0. There are two local minima with ITS=8.8 and ITS =10.1 at locations 38 ($\overline{\delta_i}$ = –4.6%) and 46 ($\overline{\delta_i}$ =+2.3 %), respectively, indicating the highest degree of temporal stability. Both locations belong to the VAG unit and can be both considered as representive points of the study area. Nevertheless, additional analysis of temporal stability should be based on the replacement of spatial mean soil moisture with field capacity to distinguish between fast-flow and capillary-flow locations as recently recommended by Lai *et al.* (2018). Below, we examine the role exerted by soil (clay, silt, sand contents, soil organic matter, and soil bulk density) and topographical (aspect, slope, planar and tangential curvature, contributing area) characteristics in determinining the spatial organization of soil moisture. However, we caution the reader that the most probable influence of vegetation is neglected in this study for lack of direct measurements. Table 3 lists the Pearson's correlation coefficients between $\overline{\delta_i}$ and the environmental controls. Only five correlation coefficients are significant at the *p*-level <0.05. Soil moisture patterns are more sensitive to clay content (positive correlation) and slope (negative correlation). In other words, wetter-than-average zones (corresponding to VAG units) are determined by clayey soils on hillslopes with moderate slopes. The non-dominant soil-landscape units are characterized by arenaceous soils (sandy texture), steep slopes and forest cover. In order to corroborate these observations, Figure 4 shows an illustrative example on the relationship between clay content and δ-values. Clay content is expressed as relative difference (RD_{clay}) between clay at location *i* and clay content at location 38, considered as benchmark point with lowest ITS-value (white square that is almost at the centre of the plot where both RD_{clay} and δ are zero). Figure 4 presents also a regression line expressing the relationship between clay and δ

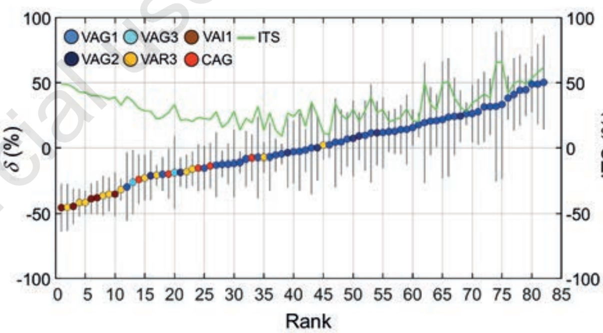

Figure 3. Ranked time average relative difference, $\overline{\delta_i}$ (solid circles) and index of time stability, ITS (green line) for the 82 sampling points. Solid circles are colored according to soil-landscape units. Error bars indicate ±1 standard deviation of relative difference at each location i, δ_i.

Table 2. Matrix of nonparametric Spearman's correlation coefficients among soil moisture data collected during the ten sampling campaigns in the study area.

	7-ott-04	20-ott-04	29-ott-04	5-nov-04	11-nov-04	16-nov-04	30-nov-04	7-dic-04	19-dic-04	11-gen-05
7-ott-04	1***									
20-ott-04	0.305*	1***								
29-ott-04	0.294*	0.777*	1***							
5-nov-04	0.210*	0.718*	0.809*	1***						
11-nov-04	0.337***	0.818***	0.737***	0.733***	1***					
16-nov-04	0.303***	0.784***	0.753***	0.710***	0.885**	1***				
30-nov-04	0.303***	0.831***	0.736***	0.767***	0.888**	0.851**	1***			
7-dic-04	0.447***	0.775***	0.771***	0.779***	0.837**	0.830**	0.833**	1***		
19-dic-04	0.218***	0.672***	0.669***	0.746***	0.651**	0.671**	0.760**	0.776**	1***	
11-gen-05	0.361***	0.751***	0.655***	0.668***	0.808**	0.874**	0.771**	0.809**	0.696**	1***

*, ** and *** values indicate correlations within dry stage, within wet stage and between dry and wet stages, respectively.

(R^2=0.52). Even though the linear regression suffers from heteroschedasticity, it expresses the dominant role of soil texture. Once again we remind that south-facing slope is classified as VAG unit that is characterized by the typical clayey *Cilento Flysch* of this area (Nasta *et al.*, 2017). We report a reduction in δ of approximately 50% when decreasing clay content by almost 100%. Data belonging to north-facing hillslope align along the regression line which indicates larger dependence of soil moisture on sand content in the north-facing hillslope (classified as VAI and VAR soil-landscape units). All of the other remaining factors are generally minor except for the soil organic matter. Hu *et al.* (2009) observed that soil texture and soil organic matter were the main controlling factors on temporal variation of soil moisture. Yet, this indicator can be considered as a proxy for vegetation cover and it is interestingly negatively correlated to soil moisture patterns (Ruiz-Sinoga *et al.*, 2011). The standard deviation of δ and ITS values are weakly correlated with environmental controlling factors that therefore do not influence temporal stability. Only exceptions are the *weak* roles of clay content and aspect on the $\sigma(\delta_i)$ as representative for soil and topography, respectively. The low spatial density of measurement locations and the direction of the six transects along the main slope gradients might favor the effect of non-local controls on soil moisture patterns as stated by Vanderlinden *et al.* (2012).

To examine whether or not the sampling strategy was based on a sufficient number of measurement data, we provide the ideal number of samples through prescribed percentage confidence errors (*E*=5% and *E*=10%) given in Eq. (3). Figure 5A shows the relationship between spatial-average soil moisture, $\overline{\theta}_i$ and its corresponding coefficient of variation, CV_j at time *j* that is then used to calculate the minimum number of samples (MNS) required to guarantee an acceptable pre-fixed level of uncertainty. In accordance to previous studies, the relationship between $\overline{\theta}_i$ and CVj is expressed through an exponential law instead of a linear regression line (Famiglietti *et al.*, 2008; Brocca *et al.*, 2010; Brocca *et al.*, 2012; Korres *et al.*, 2015). We observe that spatial variability of soil moisture is higher under dry conditions and nonlinearly decreases with increasing $\overline{\theta}_i$. Previous studies present similar regression coefficients reported in Figure 5A in areas with different environmental conditions (Famiglietti *et al.*, 2008; Brocca *et al.*, 2012). Nonlinear increase of MNS calculated by using Eq. (3) is related to sampling accuracy when spatial variability (in terms of *CV* values) increases (Figure 5B). The conversion of CV_j into $\overline{\theta}_i$ is straightforward. The observed CVj-values span from 21% to 59% and are associated to MNS of 2 to 11 by accepting *E*=10% and of 7 to 52 by accepting *E*=5%.

Table 3. Pearson's correlation coefficients of $\overline{\delta}_i$, $\sigma(\delta_i)$, ITS with soil and topography controlling factors.

	$\overline{\delta}_i$	$\sigma(\delta_i)$	ITS
Clay	0.72*	0.48*	0.10
SOM	–0.21**	0.06	0.08
ρ_b	–0.08	–0.12	–0.11
Aspect	–0.14	–0.28**	–0.07
Slope	–0.55*	–0.23	0.07
Tang. curvature	0.01	0.07	–0.09
Plan. curvature	0.11	0.05	0.06
Ac	0.04	0.08	–0.03

*P<0.001; **P<0.05.

Role of soil-landscape units in explaining space-time variation in soil moisture

To provide some responses to the scientific questions posed in the Introdution section, we assume the soil-landscape units as hydrotopes (*i.e.* hydrologically similar units). We therefore partition the data set of soil moisture values in two sub-groups in order to test this hypothesis. We distinguish between those values belonging to the dominant unit (VAG) with 60 soil moisture locations and those ones belonging to the remaining units (VAI, VAR and CAG) with 22 soil moisture locations. Once again, we caution that the limited number of sampling locations was determined by several logistic constraints and impediments. The new sub-groups will be referred to as *VAG* and *MIX* for the dominant and subordinate data sets, respectively.

The predictive ability of the easily-available environmental controls was tested through the PLSR analysis for both groups. Figure 6A shows the new spatial distributions of soil moisture values (VAG and MIX are represented by green and orange colors, respectively). A preliminary analysis of variance (ANOVA) test

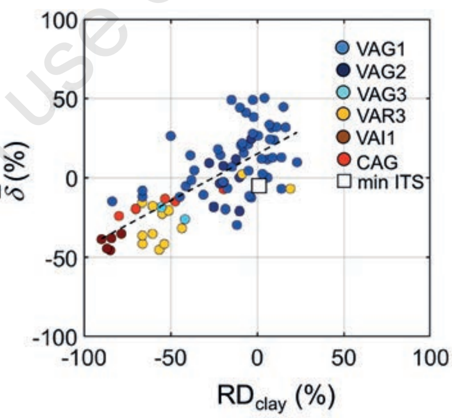

Figure 4. Relationship between relative difference in clay content (RD_{clay}) and relative difference in soil moisture. The markers in the scatter plot are colored according to soil-landscape units. The white square is the representative point of the study area (location 38).

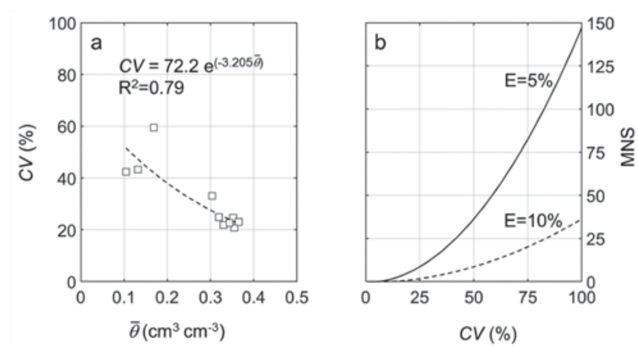

Figure 5. Relationship between: a) soil moisture areal mean and coefficient of variation (CV); and b) coefficient of variation (CV) and minimum number of samples (MNS) for prescribed E=5% (solid line) and E=10% (dashed line).

established that the spatial-average soil moisture values of the two sub-groups are significantly different at 1% confidence level at each sampling date. The spatial variation of soil moisture patterns explained by the environmental controlling factors is illustrated in Figure 6B. We expect interwined influences of topography and soil properties on soil moisture patterns (Zhu and Lin, 2011). It is worth noting that the soil moisture patterns belonging to the MIX group are well-explained (70% in average) by soil and topography features (percentages consistently above 50% except for the 3rd sampling date). On the one hand the explained variability reaches about 87% in two occasions under wet conditions. On the other hand the spatial organization of soil moisture patterns pertaining to the dominant soil-landscape unit is less effectively (45% in average) explained by soil and topography. Since the VAG unit is mostly covered by arable and pasture lands, additional *disturbing* factors influencing spatial variation of soil moisture patterns are mostly related to anthropogenic actions such as soil tillage practices that favor water infiltration during the growing season and surface lateral flow during the dormant season (Nasta *et al.*, 2017). Hébrard *et al.* (2006) evidence the effect of landscape management induced by farmers who reshaped the landform with terraces and ditches in Mediterranean catchment located in southern France.

The predictive ability of the soil-topography controlling factors in the two sub-sets of data is showed in Figure 7. The comparison between observed and PLSR-modeled soil moisture is expressed through the R^2 and RMSE. The environmental factors in the dominant unit (VAG) are fairly able to reproduce predicted soil moisture patterns (R^2=0.79). Yet data pairs cluster around the identity line (1:1 line) and model performance is not satisfactory (RMSE=0.056 cm^3 cm^{-3}). In contrast, the simulated soil moisture patterns are very close to observed ones in the MIX group as corroborated by high R^2 and low RMSE. Data pairs in Figure 6B align well around the identity line demonstrating low discrepancy between observed and predicted soil moisture patterns.

Table 4 lists the spatial-average values of environmental factors pertaining to the VAG and MIX groups. The main difference is evident in sand and clay contents and slope for soil and terrain characteristics, respectively. Group MIX has sand content and slope that double those belonging to VAG. Moreover the role of land use is important because MIX unit is covered by dense forest while VAG is dominated by arable and pasture lands.

Table 4. Spatial-average values of soil and topography controlling factors in the VAG and MIX sub-groups.

	Units	VAG	MIX
I	-	60	22
Sand	%	19.93	43.55
Silt	%	35.81	34.62
Clay	%	44.26	21.83
SOM	%	1.91	1.75
ρ_b	g cm^{-3}	1.28	1.33
Aspect	Degree	216.54	254.66
Slope	Degree	10.21	17.19
Tang. curvature	m^{-1}	–0.05	–0.08
Plan. curvature	m^{-1}	0.05	–0.01
ln(A$_c$)	m^2	5.46	5.07

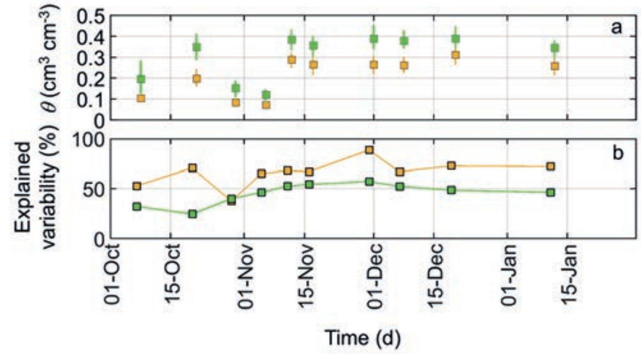

Figure 6. Daily values of a) spatial-average soil moisture values in VAG (green squares) and MIX (orange squares) sub-groups, vertical bars indicate ±1 standard deviation of soil moisture values; b) spatial variation of soil moisture patterns explained by soil and topography factors by using the PLSR technique.

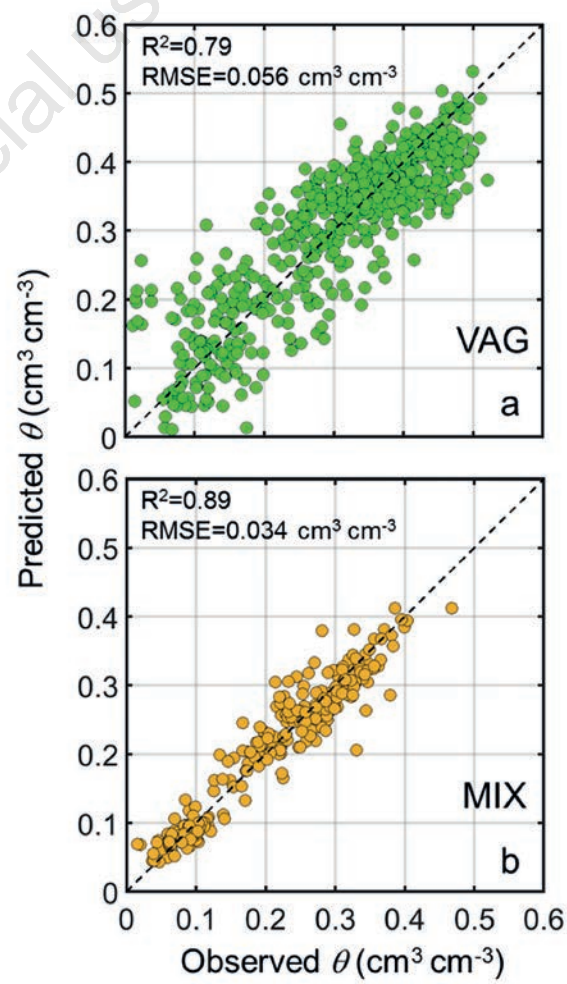

Figure 7. Comparison between observed and predicted soil moisture values a) for the VAG sub-group; b) for the MIX sub-group.

Conclusions

In this study we evaluated how soil textural characteristics and topographical features control temporal stability of soil moisture patterns in a sub-catchment of southern Italy, which can be viewed as representative of hilly zones of the Mediterranean Belt. The soil-landscape map was the available tool providing basic soil information on the study area. This classification proved to be a suitable tool to identify two different groups of soil moisture data with specific hydrologic behavior. The south-facing hillslope is classified as VAG unit because it is characterized by clayey soil and pasture and arable land. The north-facing hillslope has a steep profile, arenaceous soil and is covered by forest. The soil-landscape units can be considered as hydrotopes and represent a statistical tool that assist in deriving representative spatial-average soil moisture estimates.

The successful organization of ideal sampling schemes in longterm observatories largely depends on an in-depth understanding of spatio-temporal variability of soil moisture patterns retrieved during preliminary surveys like the one presented in this study. More specifically, we can design optimal soil moisture sensor distributions if we gain at least coarse information on temporal stability of soil moisture and its spatial covariation with environmental controlling factors. This prognostic analysis will serve for the installation of cosmic ray sensors and wireless sensor network in representative areas with different environmental features. The location of this instrumentation will be placed in light of the precious results given in this study.

References

Beaudette D.E., Dahlgren R.A., O'Geen A.T. 2013. Terrain-shape indeces for modeling soil moisture dynamics. Soil Sci Soc Am J. 77:1696-710.

Brocca L., Melone F., Moramarco T., Morbidelli R. 2009. Soil moisture temporal stability over experimental areas in central Italy. Geoderma. 148:364-74.

Brocca L., Melone F., Moramarco T., Morbidelli R. 2010. Spatial-temporal variability of soil moisture and its estimation across scales. Water Resourc. Res. 46 W02516.

Brocca L., Tullo T., Melone F., Moramarco T., Morbidelli R. 2012. Catchment scale soil moisture spatial-temporal variability. J. Hydrol. 422-423:63-75.

Chaney N.W., Roundy J.K., Herrera-Estrada J.E., Wood E.F. 2015. High-resolution modeling of the spatial heterogeneity of soil moisture: applications in network design. Water Resour. Res. 51:619-38.

Comegna V., Basile A. 1994. Temporal stability of spatial patterns of soil water storage in a cultivated Vesuvian soil. Geoderma 62:299-310.

Coppola A., Comegna A., Dragonetti G., Lamaddalena N., Kader A.M., Comegna V. 2011. Average moisture saturation effects on temporal stability of soil water spatial distribution at field scale. Soil & Tillage Res. 114:155-64.

Famiglietti J.S., Ryu D.R., Berg A.A., Rodell M., Jackson T.J. 2008. Field observations of soil moisture variability across scales. Water Resour. Res. 44:W01423.

Friesen J., Rodgers C., Oguntunde P.G., Hendrickx J.M.H., van de Giesen N. 2008. Hydrotope-based protocol to determine average soil moisture over large areas for satellite calibration and validation with results from an observation campaign in the Volta Basin, West Africa. IEEE Trans. Geosci. Remote Sens. 46:1995-2004.

Gómez-Plaza A., Alvarez-Rogel J., Albaladejo J., Castillo V.M. 2000. Spatial patterns and temporal stability of soil moisture across a range of scales in a semi-arid environment. Hydrol. Process. 14:1261-77.

Grayson R.B., Western A.W., Chiew F.H.S., Blöschl G. 1997. Preferred states in spatial soil moisture patterns: local and non-local controls. Water Resour. Res. 33:2897-908.

Hébrard O., Voltz M., Andrieux P., Moussa R. 2006. Spatio-temporal distribution of soil surface moisture in a heterogeneously farmed Mediterranean catchment. J. Hydrol. 329:110-21.

Huang X., Shi Z.H., Zhu H.D., Zhang H.Y., Ai L., Yin W. 2016. Soil moisture dynamics within soil profiles and associated environmental controls. Catena. 136:189-96.

Hu W., Shao M., Wang Q., Reichardt K. 2009. Time stability of soil water storage measured by neutron probe and the effects of calibration procedures in a small watershed. Catena. 79:72-82.

Hu W., Shao M., Han F., Reichardt K., Tan J. 2010. Watershed scale temporal stability of soil water content. Geoderma. 158:181-98.

Jacobs J.M., Mohanty B.P., Hsu E.-C., Miller D. 2004. SMEX02: Field scale variability, time stability and similarity of soil moisture. Remote Sens. Environ. 92:436-46.

Korres W., Reichenau T.G., Fiener P., Koyama C.N., Bogena H.R., Cornelissen T., Baatz R., Herbst M., Diekkrüger B., Vereecken H., Schneider K. 2015. Spatio-temporal soil moisture patterns - A meta-analysis using plot to catchment scale data. J. Hydrol. 520:326-41.

Lai X., Zhou Z., Zhu Q., Liao K. 2018. Comparing the spatio-temporal variations of soil water content and soil free water content at the hillslope scale. Catena. 160:366-75.

Liang W.L., Li S.-L., Hung F.-X. 2017. Analysis of the contributions of topographic, soil, and vegetation features on the spatial distributions of surface soil moisture in a steep natural forested headwater catchment. Hydrol. Process. 31: 3796-809.

Martínez-Fernández J., Ceballos A. 2003. Temporal stability of soil moisture in a large-field experiment in Spain. Soil Sci. Soc. Am. J. 67:1647-56.

Nasta P., Kamai T., Chirico G.B., Hopmans J.W. Romano N. 2009. Scaling soil water retention functions using particle-size distribution. J. Hydrol. 374:223-34.

Nasta P., Palladino M., Ursino N., Saracino A., Sommella A., Romano N. 2017. Assessing long-term impact of land use change on hydrologic ecosystem functions in a Mediterranean upland agro-forestry catchment. Sci. Total Environ. 605-606:1070-82.

Page T., Beven K.J., Freer J., Neal C. 2007. Modelling the chloride signal at Plynlimon, Wales, using a modified dynamic TOPMODEL incorporating conservative chemical mixing (with uncertainty). Hydrol. Process. 21:292-307.

Park S.J., van de Giesen N. 2004. Soil-landscape delineation to define spatial sampling domains for hillslope hydrology. J. Hydrol. 295:28-46.

Robinson D.A., Campbell C.S., Hopmans J.W., Hornbuckle B.K., Jones S.B., Knight R., Ogden F., Selker J., Wendroth O. 2008. Soil moisture measurement for ecological and hydrological watershed-scale observatories: a review. Vadose Zone J. 7:358-89.

Romano N. 2014. Soil moisture at local scale: measurements and simulations. J. Hydrol. 516:6-20.

Romano N., Nasta P., Bogena H., De Vita P., Stellato L., Vereecken H. 2018. Monitoring hydrological processes for land and water resources management in a Mediterranean ecosystem: The Alento River Catchment Observatory. Vadose Zone J. 17:180042.

Romano N., Chirico G.B. 2004. The role of terrain analysis in using and developing pedotransfer functions. In: Y.A. Pachepsky and W.J. Rawls (Eds.), Development of pedotransfer functions in soil hydrology. Elsevier Science B.V., pp. 273-294.

Ruiz-Sinoga J.D., Martínez-Murillo J.F., Gabarrón-Galeote M.A., García-Marín R. 2011. The e□ects of soil moisture variability on the vegetation pattern in Mediterranean abandoned fields (Southern Spain). Catena 85:1-11.

Santini A., Coppola A., Romano N., Terribile F. 1999. Interpretation of the spatial variability of soil hydraulic properties using a land system analysis. In: J. Feyen and K. Wiyo, (Eds.), Modelling of transport processes in soils at various scales in time and space, 24-26 Nov., Wageningen Pers, Wageningen, The Netherlands, pp. 491-500.

Schneider K., Huisman J.A., Breuer L., Zhao Y., Frede H.-G. 2008. Temporal stability of soil moisture in various semi-arid steppe ecosystems and its application in remote sensing. J. Hydrol. 359:16-29.

Susha Lekshmi S.U., Singh D.N., Tarantino A., Baghini, M.S. 2018. Evaluation of the performance of TDR and capacitance techniques for soil moisture measurement. Geotechn. Testing J. 41:292-306.

USDA. 1996. Keys to soil taxonomy. USDA, Washington, DC, USA.

Vachaud G., Passerat de Silans A., Balabanis P., Vauclin M. 1985. Temporal stability of spatially measured soil water probability density function. Soil Sci. Soc. Am. J. 49:822-8.

Vanderlinden K., Vereecken H., Hardelauf H., Herbs M., Martınez G., Cosh M.H., Pachepsky Y.A. 2012. Temporal stability of soil water contents: a review of data and analyses. Vadose Zone J. 11:1-20.

Vereecken H., Huisman J.A., Bogena H., Vanderborght J., Vrugt J.A., Hopmans J.W. 2008. On the value of soil moisture measurements in vadose zone hydrology: a review. Water Resour. Res. 44:W00D06.

Vereecken H., Huisman J.A., Hendricks Franssen H.J., Brüggemann N., Bogena H.R., Kollet S., Javaux M., van der Kruk J., Vanderborght J. 2015. Soil hydrology: Recent methodological advances, challenges, and perspectives, Water Resour. Res. 51:2616-33.

Vincent S., Lemercier B., Berthier L., Walter C. 2018. Spatial disaggregation of complex Soil Map Units at the regional scale based on soil-landscape relationships. Geoderma. 311:130-42.

Zhu Q., Lin H. 2011. Influences of soil, terrain, and crop growth on soil moisture variation from transect to farm scales. Geoderma. 163:45-54.

Wang T., Wedin D.A., Franz T.E., Hiller J. 2015. Effect of vegetation on the temporal stability of soil moisture in grass-stabilized semi-arid sand dunes. J. Hydrol. 521:447-59.

Wang C., Zuo Q., Zhang R. 2008. Estimating the necessary sampling size of surface soil moisture at different scales using a random combination method. J. Hydrol. 352:309-21.

Wei L., Dong J., Gao M., Chen X. 2017. Factors controlling temporal stability of surface soil moisture: A watershed-scale modeling study. Vadose Zone J. 16 [Epub ahead of print].