Research Progress on Temporal Stability of Soil Moisture (Postprint)

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Abstract

Soil moisture is an indispensable component of terrestrial ecosystems, playing a critical role in surface hydrological processes, connecting a series of hydrological, ecological, climatic, and geological processes, and is crucial for the healthy functioning of terrestrial ecosystems. Centering on the concept of soil moisture temporal stability, this study systematically reviews recent research progress from the perspectives of the temporal stability concept, research methods, applications, and influencing factors, and discusses the selection criteria for representative measurement sites and the influencing factors of soil moisture temporal stability. Based on current research progress, future research priorities are proposed: strengthening research on the combined effects of multiple factors on soil moisture temporal stability; combining "3S" technology, computer simulation, and field measurements to study scale issues of temporal stability; how to efficiently select representative measurement sites; and exploring the research and application of the temporal stability concept in vegetation restoration areas and climate-sensitive zones.

Full Text

Preamble

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Research Progress on Soil Moisture Temporal Stability

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Abstract

Soil moisture is an integral component of terrestrial ecosystems and the core of surface hydrological cycles, connecting a series of hydrological, geological, climatic, and ecological processes. It is essential for the healthy functioning of terrestrial ecosystems. Focusing on the concept of soil moisture temporal stability, this paper systematically reviews recent research progress from the perspectives of the temporal stability concept, research methods, applications, and influencing factors. We analyze the selection criteria for representative sites and the factors affecting soil moisture temporal stability. Based on current research progress, we propose future research priorities: (1) investigating scale issues of temporal stability by combining "3S" technology, computer simulation, and field measurements; (2) strengthening research on the combined effects of multiple factors on soil moisture temporal stability; (3) developing methods for efficient selection of representative sites; and (4) exploring the application of temporal stability concepts in vegetation restoration areas and climate-sensitive regions.

Keywords: soil water content; temporal stability; representative sites; applications; influencing factors

1. Conceptual Development of Temporal Stability

Over the past half-century, soil moisture spatiotemporal variability has been extensively studied across different scales and ecosystem types. Researchers have long recognized that due to strong spatiotemporal variability, obtaining regional mean soil moisture conditions through classical statistical theory requires extensive sampling, which is time-consuming, labor-intensive, and costly. This practical need led to the emergence of the temporal stability concept from numerous spatiotemporal variability studies. Vachaud et al. [45] first discovered and proposed the concept of temporal stability during soil moisture studies of olive trees and wheat. They observed that when all measurement points were ranked from low to high, some sites consistently represented the mean soil moisture of the experimental area, while others were consistently above or below the mean. This similarity of soil moisture spatial patterns over time is termed the temporal stability phenomenon. Although some scholars have used the temporal stability concept to test whether soil moisture spatial patterns persist over time [46-47], the phenomenon has been widely recognized by numerous researchers [37, 48-51]. Similar terms such as "temporal persistence," "order stability," and "rank stability" have also been used in related studies [12, 52-53], but subsequent research has predominantly adopted the term "temporal stability" [37, 54-56].

2. Methodological Approaches for Temporal Stability Analysis

Three primary methods exist for analyzing temporal stability. The first is the relative difference method [45], where ijk represents the relative difference value of site i at time j for soil layer k, calculated as (ijk - jk)/ jk, where ijk is the soil moisture at site i, time j, and layer k, and jk is the mean soil moisture across all sites at time j for layer k. The mean relative difference (MRD) ik and its standard deviation (SDRD) (ik) are then computed across all measurement times. By ranking all sites according to MRD and annotating each site' s SDRD, one can easily identify which sites consistently exceed the mean, which fall below it, and which reliably represent the regional mean. The second method is the Spearman rank correlation coefficient method, which primarily reflects the temporal similarity of measurement sites' spatial patterns. By calculating the rank correlation coefficient rs between different measurement times, we can assess temporal stability—higher rs values indicate greater similarity in soil moisture spatial patterns across time [58]. The third method is the cumulative probability function approach [45], which analyzes temporal stability by examining the similarity of soil moisture cumulative probability distributions across different measurement times. If certain sites' moisture content equals or approximates the mean under various moisture conditions, these sites can serve as representative sites for estimating mean soil moisture conditions. Zhao Peipei [57] also applied spectral analysis to study temporal stability, finding that data gaps do not affect spectral characteristics. Among these methods, the Spearman rank correlation coefficient and relative difference methods are most widely used [1, 37, 51, 56]. While both SDRD and rs are crucial indicators for determining temporal stability, they differ significantly: SDRD represents the temporal stability of individual sites (smaller values indicate stronger stability), whereas rs reflects the temporal similarity of spatial patterns across all sites (values closer to 1 indicate greater similarity) [58].

3. Selection Criteria for Representative Sites

Representative sites typically refer to locations where soil moisture approximates the mean moisture content of the entire observation area or where mean soil moisture can be easily obtained [59]. Using representative sites to predict regional mean moisture is among the most important applications of temporal stability concepts, making accurate and convenient site selection critical. Schneider et al. [55] further noted that selected representative sites can be used for multi-year predictions of regional soil moisture conditions. Four main criteria exist for selecting representative sites. The first method identifies sites with MRD values close to zero and small SDRD values as representative [45]. However, this process involves some subjectivity, and sites with MRD near zero do not necessarily have small SDRD, nor does this indicator directly provide prediction accuracy [60]. The second method identifies sites with MRD close to zero as representative, then estimates regional mean moisture through ik transformation [17, 62]. The third approach, proposed by Hu et al. [60] from a minimum error perspective, uses the Mean Absolute Bias Error (MABE) to evaluate representative sites, where MABEik = (1/N) Σ| ijk - ik|. Lower MABE values indicate higher prediction accuracy. To overcome limitations of the first two methods, some scholars [63-64] proposed combining both indicators into a new index called Integrated Time Stability (ITS), calculated as $\mathrm{ITSIk} = \mathrm{ik}^2 + (\mathrm{ik})^2$. Gao Lei [65] considered this method a useful supplement for optimizing representative site selection, though treating the effects of MRD and SDRD equally remains debatable. Currently, most researchers use the first method, and no universally accepted standard exists. While the first method has been successfully applied across various study areas [37, 49, 66-67], the other three methods, despite their advantages, have not been widely validated for superior prediction accuracy. All four methods require extensive preliminary soil moisture measurements, which should be evenly distributed throughout a year-long measurement cycle. Consequently, researchers have paid special attention to characteristics of selected representative sites, such as soil texture, slope position, and topographic location, hoping to identify common features through simple observations that could eliminate extensive preliminary measurements—a highly practical approach [61, 63, 68].

2. Applications of Soil Moisture Temporal Stability

Temporal stability concepts have been widely recognized and applied in soil moisture research [13, 39, 49, 63, 68]. Beyond soil water content, soil water storage and soil water potential also exhibit temporal stability characteristics [45, 54, 68-70]. The concept has three primary applications: (1) identifying stable representative sites within a study area to directly or indirectly predict or estimate mean soil moisture conditions and upscale soil moisture data [13, 49, 56, 58, 61, 71-73]; (2) interpolating missing soil moisture data due to instrument failure [57, 74-75]; and (3) validating or calibrating remotely sensed soil moisture data [1, 25, 55, 64]. Temporal stability has been applied across various land use types, including grassland [45, 55, 63], cropland [51, 54], forest [76], and agroforestry ecosystems [77-78], as well as different climatic zones such as arid/semi-arid [31, 63, 68, 79], semi-humid [37, 62], and humid regions [64]. Liwata et al. [80] even studied soil moisture stability across a boreal gradient (60-68°N). The concept has also been applied to different soil depths [62, 80], scales [31, 51, 56, 81], measurement periods [54, 63, 82-83], and instruments [8, 64, 72, 84], yielding significant progress.

Identifying representative sites to predict mean soil moisture has become the most important application [60]. Since representative sites can predict regional mean moisture, extensive sampling becomes unnecessary—only periodic measurements at representative sites are needed, saving substantial resources. Hu et al. [85] developed a quantitative relationship between soil moisture at various sites and typical monitoring sites using stepwise multiple linear regression based on temporal stability and hierarchical cluster analysis, enabling prediction of soil moisture across sites at different times. Vanderlinden et al. [47] compared three methods for determining the minimum sample size needed to predict mean soil water storage in a 12 m × 15 m plot, finding that the first method required 20 samples while the second needed only 12. However, the number of representative sites varies by study area, sometimes requiring multiple sites [48, 60, 86]. Studies show that finding a single site representing multiple soil depths is challenging. Tallon and Si [12] found only one site that could represent two soil layers, while Kamgar et al. [70] found none representing three layers. Guber et al. [54] discovered that representative sites vary with soil depth. Jia et al. [81] found a single representative site could represent three depths (0-1, 1-2, and 2-3 m) on a typical loess slope, while Penna et al. [84] and Mohanty et al. [1] also found sites representing multiple depths. Generally, optimal sites have relatively high clay content and smooth surfaces [56, 64]. Mohanty and Skaggs [1] found that in sandier soils, the best sites had medium to high clay content (28%-30%). Jacobs et al. [64] and Martinez et al. [59] confirmed that the most stable sites have medium to high clay content. However, findings among researchers are sometimes contradictory. Da Silva et al. [50] found that clay and organic matter content better identified representative sites than topographic variables, while other studies [68, 73] found topography and vegetation more important than soil texture. Mohanty et al. [1] concluded that soil moisture has better temporal stability in sandy loam than silt loam, while Zhao et al. [31] found sand had significantly stronger temporal stability than sandy loam and silt loam at the watershed scale. Schneider et al. [55] argued that soil properties alone cannot fully reflect representative site characteristics. Since temporally stable sites have proven valuable for soil moisture monitoring, developing more efficient methods for optimal site selection represents a key future research direction.

3. Factors Influencing Soil Moisture Temporal Stability

Sites that accurately predict mean soil moisture typically represent watershed-average characteristics, particularly those closely related to soil moisture [25, 61]. Because correlations between soil moisture and different characteristics vary, identifying factors influencing temporal stability is prerequisite for a priori identification of representative sites. Soil moisture temporal stability is affected by multiple factors including soil properties, topography, vegetation, and climate [37, 60-61, 68, 73]. Revealing relationships between temporal stability and these factors at different scales aids in identifying stable sites and predicting soil moisture in other regions [70]. Due to differences in study areas and sampling times, no unified conclusions exist regarding these effects [87]. In topographically complex regions, relative elevation strongly influences temporal stability [25, 37, 58, 61, 81], while in flat areas, topography has minimal or no effect [49, 63]. Soil properties affect soil moisture primarily through particle composition, organic matter content, and structure, which alter water retention and conductivity. While soil properties show little temporal variability, they exhibit strong spatial variability—saturated hydraulic conductivity can vary by several orders of magnitude over short distances [88], inevitably causing spatial variation in soil moisture. Mohanty et al. [1] used remote sensing footprint data to study temporal stability under different soil types, finding better stability in sandy loam than silt loam for 0-5 cm soil moisture. At the watershed scale, Zhao et al. [31] found soil texture was the main control factor. Gao et al. [56] analyzed temporal stability of jujube orchards on the Loess Plateau, identifying sites with relatively high clay content and smooth surfaces as optimal representatives. Hawley et al. [89] found soil texture significantly influenced soil moisture at the watershed scale. However, Jacobs et al. [64] and Western et al. [61] found topography and vegetation, rather than soil texture, were more important for identifying representative sites.

Vegetation significantly influences soil moisture dynamics by altering infiltration, water holding capacity, evaporation, and root water uptake [90-91]. Compared to soil and topography, vegetation changes more temporally, and its effects show strong seasonal dependence. Hupet and Vanclooster [90] found that during corn growth, vegetation contributed non-negligibly to soil moisture variability. Hawley et al. [89] found vegetation reduced topographic effects on soil moisture variability. Schneider et al. [55] found grazing management and vegetation cover were primary factors controlling soil moisture stability in relatively flat semi-arid grasslands. At larger scales, land cover or vegetation has limited influence on soil moisture spatial distribution [21], and the relationship between vegetation and soil moisture variability becomes more complex due to feedback mechanisms [92-93]. Teuling and Troch [94] found that under non-stressed conditions, vegetation increases soil moisture variability, but when soil moisture falls below a threshold and evapotranspiration is supply-limited, vegetation reduces variability. Gómez-Plaza et al. [68] found vegetation cover changes reduce temporal stability—during growing seasons, temporal patterns are weaker, while stability increases when vegetation is dormant in winter. Mohanty and Skaggs [1] found the degree of temporal stability change depends on vegetation cover and topography. Jia et al. [73] analyzed temporal stability of soil water storage under three vegetation types (alfalfa, caragana, and grass) in a small watershed, finding alfalfa had the weakest stability while vegetation cover and aboveground biomass were main influencing factors. Zhao et al. [81] found that besides soil texture, vegetation biomass and litter also significantly affected profile soil water storage stability. However, in relatively stable ecosystems with consistent measurement periods, vegetation effects on stability diminish. Hu et al. [31] found no significant difference in temporal stability indices between two vegetation types (Stipa bungeana and Caragana) in sandy loam and silt loam soils at the watershed scale. Vachaud et al. [45] observed strong temporal stability in a uniform grassland with minimal seasonal variation.

Soil moisture temporal stability also exhibits depth dependence and spatial scale dependence. Typically, deep soil moisture shows stronger temporal stability than shallow layers [31, 54, 58, 81]. Ran et al. [95] found surface soil moisture (0-20 cm) was most variable in the Heihe River Basin, stabilizing below 40 cm. Heathman et al. [62] similarly found surface moisture stability was weaker than profile moisture in the southern Great Plains. However, Jia et al. [81] found surface soil had stronger temporal stability than deep layers on a typical Loess Plateau slope, possibly due to scale and seasonal differences. Temporal stability also depends on study scale [52, 68, 82]—sampling density and area affect which factors dominate stability. Kachanoski and de Jong [52] first proposed the scale issue of temporal stability, analyzing controls on soil water storage at different spatial scales within a transect. Using wavelet analysis, Gómez-Plaza et al. [68] studied controls on soil water storage at various scales within a transect, finding elevation was most important at every scale. Two-dimensional scale effects have also been widely studied, though conclusions vary. Schneider et al. [55] and Brocca et al. [37] found that increasing sampling scale adds variability from soil and vegetation, reducing temporal stability. Basile et al. [46] found MRD ranges were less than 2% in small study areas but exceeded 100% in larger watersheds. Cosgrove et al. [49] and Martínez-Fernández and Ceballos [51] found similar results. These differences are attributed to varying experimental designs, measurement techniques, and differences in topography and vegetation [68, 70]. Since multiple soil moisture-related factors change with location and time, isolating scale effects from other influences remains challenging.

4. Future Research Directions

Since Vachaud et al. [45] introduced the temporal stability concept, it has been widely recognized and applied to soil moisture research across different scales, ecosystem types, and climate zones, yielding significant progress. However, due to complex influencing factors and strong seasonal, depth, and spatial scale dependencies, research results show regional differences and sometimes contradictions. Based on existing problems and current eco-hydrology development needs, we propose several future research directions:

Comprehensive Multi-factor Studies: Soil moisture temporal stability is jointly affected by climate, vegetation, and soil properties, yet some studies present contradictory conclusions. Potential controlling factors like soil hydraulic properties and boundary conditions (precipitation and evapotranspiration heterogeneity/homogeneity) during measurement periods require further exploration [70]. Many studies indicate that stability results from combined rather than single factors. Future research should employ statistical and spatiotemporal models to explore interactions among various factors and distinguish their spatiotemporal components.

Scale Issues: Temporal stability shows strong spatial scale dependence, making scale a focus and challenge in eco-hydrology. Upscaling findings from hillslope or small watershed scales to larger watersheds is crucial for validating remote sensing data and estimating regional soil moisture. Recent studies have developed cross-scale upscaling methods including random sampling analysis, optimal combination analysis, temporal stability analysis, and temporal smoothing correlation analysis [97], which effectively solve information collection, processing, and validation issues at larger spatiotemporal scales. However, collecting large-scale data remains difficult, consuming substantial resources and time. Combining 3S technology, computer simulation, and field measurement represents a future direction for scale research.

Efficient Selection of Representative Sites: No consensus exists on a priori identification of representative sites based on soil moisture-related variables, and findings are sometimes contradictory. While spatial variability of relative differences typically increases with sampling extent, whether optimal representative sites for estimating mean moisture remain spatially constant with increasing scale remains unresolved [70]. Future research should focus on rapidly and efficiently identifying representative sites under data-limited conditions.

Application in Vegetation Restoration and Climate-Sensitive Areas: Temporal stability concepts have been studied across various vegetation types and climate zones. However, with global climate change, soil moisture near timberlines is particularly sensitive. Studying soil moisture stability in these areas can provide theoretical guidance for evaluating vegetation suitability under climate change and predicting future developments. With large-scale vegetation restoration projects implemented across China, researching temporal stability in suitable restoration areas to efficiently locate representative sites will be a future research hotspot, providing guidance for vegetation restoration and reconstruction efforts.

References

[1] Mohanty B P, Skaggs T H. Spatio-temporal evolution and time-stable characteristics of soil moisture within remote sensing footprints with varying soil, slope, and vegetation. Advances in Water Resources, 2001, 24(9/10): 1051-1067. [2] Seneviratne S I, Corti T, Davin E L, Hirschi M, Jaeger E B, Lehner I, Orlowsky B, Teuling A J. Investigating soil moisture-climate interactions in a changing climate: a review. Earth-Science Reviews, 2010, 99(3/4): 125-161. [3] [Chinese reference on soil moisture remote sensing monitoring] [4] Cheema M J M, Bastiaanssen W G M, Rutten M M. Validation of surface soil moisture from AMSR-E using auxiliary spatial data in the transboundary Indus Basin. Journal of Hydrology, 2011, 405(1/2): 137-149. [5] Legates D R, Mahmood R, Levia D F, DeLiberty T L, Quiring S M, Houser C, Nelson F E. Soil moisture: a central and unifying theme in physical geography. Progress in Physical Geography, 2011, 35(1): 65-86. [6] Lü Y H, Fu B J, Wei W, Yu X B, Sun R H. Major ecosystems in China: dynamics and challenges for sustainable management. Environmental Management, 2011, 48(1): 13-27. [7] Wang L, D' Odorico P, Evans J P, Eldridge D J, McCabe M F, Caylor K K, King E G. Dryland ecohydrology and climate change: critical issues and technical advances. Hydrology and Earth System Sciences, 2012, 16(8): 2585-2603. [8] Wang X P, Pan Y X, Zhang Y F, Dou D Q, Hu R, Zhang H. Temporal stability analysis of surface and subsurface soil moisture for a transect in artificial revegetation desert area, China. Journal of Hydrology, 2013, 507: 100-109. [9] Zhao W W, Fu B J, Qiu Y. An upscaling method for cover-management factor and its application in the Loess Plateau of China. International Journal of Environmental Research and Public Health, 2013, 10(10): 4752-4766. [10] Yang L, Wei W, Chen L, Jia F, Mo B. Spatial variations of shallow and deep soil moisture in the semi-arid Loess Plateau, China. Hydrology and Earth System Sciences, 2012, 16(9): 3199-3217. [11] Noy-Meir

I. Desert ecosystems: environment and producers. Annual Review of Ecology and Systematics, 1973, 4: 25-51. [12] Tallon L K, Si B C. Representative soil water benchmarking for environmental monitoring. Journal of Environmental Informatics, 2004, 4(1): 28-36. [13] Hu W, Shao M A, Wang Q J, Reichardt K. Time stability of soil water storage measured by neutron probe and the effects of calibration procedures in a small watershed. CATENA, 2009, 79(1): 72-82. [14] He Z B, Zhao W Z, Liu H, Chang X X. The response of soil moisture to rainfall event size in subalpine grassland and meadows in a semi-arid mountain range: a case study in northwestern China' s Qilian Mountains. Journal of Hydrology, 2012, 420-421: 183-190. [15] Ivanov V Y, Fatichi S, Jenerette G D, Espana J F, Troch P A, Huxman T E. Hysteresis of soil moisture spatial heterogeneity and the "homogenizing" effect of vegetation. Water Resources Research, 2010, 46(9): W09521. [16] Yang L, Chen L D, Wei W. Effects of vegetation restoration on the spatial distribution of soil moisture at the hillslope scale in semi-arid regions. CATENA, 2015, 124: 138-146. [17] Starks P J, Heathman G C, Jackson T J, Cosh M H. Temporal stability of soil moisture profile. Journal of Hydrology, 2006, 324(1/4): 400-411. [18] Longobardi A. Observing soil moisture temporal variability under fluctuating climatic conditions. Hydrology and Earth System Sciences Discussions, 2008, 5(2): 935-969. [19] Jin T T, Fu B J, Liu G H, Wang Z. Hydrologic feasibility of artificial afforestation in the semi-arid Loess Plateau of China. Hydrology and Earth System Sciences, 2011, 15(8): 2519-2530. [20] Wilson D J, Western A W, Grayson R B. A terrain and data-based method for generating the spatial distribution of soil moisture. Advances in Water Resources, 2005, 28(1): 43-54. [21] Venkatesh B, Lakshman N, Purandara B K, Reddy V B. Analysis of observed soil moisture patterns under different land covers in western Ghats, India. Journal of Hydrology, 2011, 397(3/4): 281-294. [22] Jia Y H, Shao M A. Dynamics of deep soil moisture in response to vegetation restoration on the Loess Plateau of China. Journal of Hydrology, 2014, 519: 523-531. [23] Brown A E, Zhang L, McMahon T A, Western A W, Vertessy R A. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. Journal of Hydrology, 2005, 310(1/4): 28-61. [24] Ursino N, Contarini S. Stability of banded vegetation patterns under seasonal rainfall and limited soil moisture storage capacity. Advances in Water Resources, 2006, 29(10): 1556-1564. [25] Vivoni E R, Gebremichael M, Watts C J, Bindlish R, Jackson T J. Comparison of ground-based and remotely-sensed surface soil moisture estimates over complex terrain during SMEX04. Remote Sensing of Environment, 2008, 112(2): 314-325. [26] [Chinese reference on soil moisture spatial variability] [27] Fu B J, Wang J, Chen L D, Qiu Y. The effects of land use on soil moisture variation in the Danangou catchment of the Loess Plateau, China. CATENA, 2003, 54(1/2): 197-213. [28] Jackson R B, Jobbágy E G, Avissar R, Roy S B, Barrett D J, Cook C W, Farley K A, Le Maitre D C, McCarl B A, Murray B C. Trading water for carbon with biological carbon sequestration. Science, 2005, 310(5756): 1944-1947. [29] [Chinese reference on deep soil moisture] [30] [Chinese reference on soil moisture zonation] [31] Hu W, Shao M G, Han F P, Reichardt K, Tan J. Watershed scale temporal stability of soil water content. Geoderma, 2010, 158(3/4): 181-198. [32] Heathman G

C, Cosh M H, Merwade V, Han E J. Multi-scale temporal stability analysis of surface and subsurface soil moisture within the Upper Cedar Creek Watershed, Indiana. CATENA, 2012, 95: 91-103. [33] Vereecken H, Kamai T, Harter T, Kasteel R, Hopmans J, Vandeborght J. Explaining soil moisture variability as a function of mean soil moisture: a stochastic unsaturated flow perspective. Geophysical Research Letters, 2007, 34(22): L22402. [34] Famiglietti J S, Rudnicki J W, Rodell M. Variability in surface moisture content along a hillslope transect: Rattlesnake Hill, Texas. Journal of Hydrology, 1998, 210(1/4): 259-281. [35] Pietroniro A, Soulis E D, Kouwen N. Deriving antecedent moisture conditions from airborne SAR for input into a flood forecasting model. Proceedings of International Geoscience and Remote Sensing Symposium. Pasadena, CA, USA: IEEE, 1994, 3: 1435-1438. [36] Wagner W, Blöschl G, Pampaloni P, Calvet J C, Bizzarri B, Wigneron J P, Kerr Y. Operational readiness of microwave remote sensing of soil moisture for hydrologic applications. Hydrology Research, 2007, 38(1): 1-20. [37] Brocca L, Melone F, Moramarco T, Morbidelli R. Soil moisture temporal stability over experimental areas in Central Italy. Geoderma, 2009, 148(3/4): 364-374. [38] Brocca L, Melone F, Moramarco T, Morbidelli R. Spatial variability of soil moisture and its estimation across scales. Water Resources Research, 2010, 46(2): W02516. [39] Brocca L, Tullo T, Melone F, Moramarco T, Morbidelli R. Catchment scale soil moisture spatial-temporal variability. Journal of Hydrology, 2012, 422-423: 63-75. [40] Zucco G, Brocca L, Moramarco T, Morbidelli R. Influence of land use on soil moisture spatial-temporal variability and monitoring. Journal of Hydrology, 2014, 516: 193-199. [41] Brocca L, Morbidelli R, Melone F, Moramarco T. Soil moisture spatial variability in experimental areas of central Italy. Journal of Hydrology, 2007, 333(2/4): 356-373. [42] Henniger D L, Peterson G W, Engman E T. Surface soil moisture within a watershed—variations, factors influencing, and relationship to surface runoff. Soil Science Society of America Journal, 1976, 40(5): 773-776. [43] Qiu Y, Fu B J, Wang J, Chen L D. Soil moisture variation in relation to topography and land use in a hillslope catchment of the Loess Plateau, China. Journal of Hydrology, 2001, 240(3/4): 243-263. [44] Ibrahim H M, Huggins D R. Spatio-temporal patterns of soil water storage under dryland agriculture at the watershed scale. Journal of Hydrology, 2011, 404(3/4): 186-197. [45] Vachaud G, De Silans A P, Balabani P, Vauclin M. Temporal stability of spatially measured soil water probability density function. Soil Science Society of America Journal, 1985, 49(4): 822-828. [46] Comegna V, Basile A. Temporal stability of spatial patterns of soil water storage in a cultivated Vesuvian soil. Geoderma, 1994, 62(1/3): 299-310. [47] Kamgar A, Hopmans J W, Wallender W W, Wendroth O. Plot size and sample number for neutron probe measurements in small field trials. Soil Science, 1993, 156(4): 213-224. [48] Coppola A, Comegna A, Dragonetti G, Lamaddalena N, Kader A M, Comegna V. Average moisture saturation effects on temporal stability of soil water spatial distribution at field scale. Soil and Tillage Research, 2011, 114(2): 155-164. [49] Cosh M H, Jackson T J, Moran S, Bindlish R. Temporal persistence and stability of surface soil moisture in a semi-arid watershed. Remote Sensing of Environment, 2008, 112(2): 304-313. [50] Da Silva A P, Nadler A, Kay B D. Factors contributing to temporal stability in spatial patterns of water content in the tillage zone. Soil and Tillage Research, 2001, 58(3/4): 207-218. [51] Martínez-Fernández J, Ceballos A. Temporal stability of soil moisture in a large-field experiment in Spain. Soil Science Society of America Journal, 2003, 67(6): 1647-1656. [52] Kachanoski R G, de Jong E. Scale dependence and the temporal persistence of spatial patterns of soil water storage. Water Resources Research, 1988, 24(1): 85-91. [53] Chen Y J. Letter to the editor on "rank stability or temporal stability" . Soil Science Society of America Journal, 2006, 70(1): 306-306. [54] Guber A K, Gish T J, Pachepsky Y A, van Genuchten M T, Daughtry C S T, Nicholson T J, Cady R E. Temporal stability of soil water content patterns across agricultural fields. CATENA, 2008, 73(1): 125-133. [55] Schneider K, Huisman J A, Breuer L, Zhao Y, Frede H G. Temporal stability of soil moisture in various semi-arid steppe ecosystems and its application in remote sensing. Journal of Hydrology, 2008, 359(1/2): 16-29. [56] Gao X D, Wu P T, Zhao X N, Shi Y G, Wang J W. Estimating spatial mean soil water contents of sloping jujube orchards using temporal stability. Agricultural Water Management, 2011, 102(1): 66-73. [57] [Chinese reference on spectral analysis] [58] Gao L, Shao M G. Temporal stability of soil water storage in diverse soil layers. CATENA, 2012, 95: 24-32. [59] Martinez G, Pachepsky Y A, Vereecken H. Temporal stability of soil water content as affected by climate and soil hydraulic properties: a simulation study. Hydrological Processes, 2014, 28(4): 1899-1915. [60] Hu W, Shao M G, Reichardt K. Using a new criterion to identify sites for mean soil water storage evaluation. Soil Science Society of America Journal, 2010, 74(3): 762-773. [61] Grayson R B, Western A W. Towards areal estimation of soil water content from point measurements: time and space stability of mean response. Journal of Hydrology, 1998, 207(1/2): 68-82. [62] Heathman G C, Larose M, Cosh M H, Bindlish R. Surface and profile soil moisture spatio-temporal analysis during an excessive rainfall period in the Southern Great Plains, USA. CATENA, 2009, 78(2): 159-169. [63] Zhao Y, Peth S, Wang X Y, Lin H, Horn R. Controls of surface soil moisture spatial patterns and their temporal stability in a semi-arid steppe. Hydrological Processes, 2010, 24(18): 2507-2519. [64] Jacobs J M, Mohanty B P, Hsu E C, Miller D. SMEX02: field scale variability, time stability and similarity of soil moisture. Remote Sensing of Environment, 2004, 92(4): 436-446. [65] [Chinese reference on integrated time stability] [66] Van Pelt R S, Wierenga P J. Temporal stability of spatially measured soil matric potential probability density function. Soil Science Society of America Journal, 2001, 65(3): 668-677. [67] Martínez-Fernández J, Ceballos A. Mean soil moisture estimation using temporal stability analysis. Journal of Hydrology, 2005, 312(1/4): 28-38. [68] Gómez-Plaza A, Alvarez-Rogel J, Albaladejo J, Castillo V M. Spatial patterns and temporal stability of soil moisture across a range of scales in a semi-arid environment. Hydrological Processes, 2000, 14(7): 1261-1277. [69] Rolston D E, Biggar J W, Nightingale H I. Temporal persistence of spatial soil-water patterns under trickle irrigation. Irrigation Science, 1991, 12(4): 181-186. [70] Vanderlinden K, Vereecken H, Hardelauf H, Herbst M, Martinez G, Cosh M H, Pachepsky Y A. Temporal stability of soil water contents: a review of data and analyses. Vadose Zone Journal, 2012, 11(4): 1-12. [71] de Rosnay P, Gruhier C, Timouk F, Baup F, Mougin E, Hiernaux P, Kergoat L, LeDantec V. Multi-scale soil moisture measurements at the Gourma meso-scale site in Mali. Journal of Hydrology, 2009, 375(1/2): 241-252. [72] Gao L, Shao M A. Temporal stability of shallow soil water content for three adjacent transects on a hillslope. Agricultural Water Management, 2012, 110: 41-54. [73] Jia X X, Shao M A, Wei X R, Wang Y Q. Hillslope scale temporal stability of soil water storage in diverse soil layers. Journal of Hydrology, 2013, 498: 254-264. [74] Pachepsky Y A, Guber A K, Jacques D. Temporal persistence in vertical distributions of soil moisture content. Soil Science Society of America Journal, 2005, 69(2): 347-352. [75] Dumedah G, Coulibaly P. Evaluation of statistical methods for infilling missing values in high-resolution soil moisture data. Journal of Hydrology, 2011, 400(1/2): 95-102. [76] Lin H. Temporal stability of soil moisture spatial pattern and subsurface preferential flow pathways in the Shale Hills Catchment. Vadose Zone Journal, 2006, 5(1): 317-340. [77] [Chinese reference on agroforestry ecosystems] [78] Shen Q, Gao G Y, Hu W, Fu B J. Spatial-temporal variability of soil water content in a cropland-shelterbelt-desert site in an arid inland river basin of Northwest China. Journal of Hydrology, 2016, 540: 873-885. [79] Zhang P P, Shao M A. Temporal stability of surface soil moisture in a desert area of northwestern China. Journal of Hydrology, 2013, 505: 91-101. [80] Liwata P, Hänninen P, Okkonen J, Sutinen R. Time-stability of soil water through boreal (60-68°N) gradient. Journal of Hydrology, 2014, 519: 1584-1593. [81] Jia Y H, Shao M A, Jia X X. Spatial pattern of soil moisture and its temporal stability within profiles on a loessial slope in northwestern China. Journal of Hydrology, 2013, 495: 150-161. [82] Biswas A, Si B C. Identifying scale specific controls of soil water storage in a hummocky landscape using wavelet coherence. Geoderma, 2011, 165(1): 50-59. [83] Liu B X, Shao M A. Estimation of soil water storage using temporal stability in four land uses over 10 years on the Loess Plateau, China. Journal of Hydrology, 2014, 517: 974-984. [84] Penna D, Brocca L, Borga M, Fontana G D. Soil moisture temporal stability at different depths on two alpine hillslopes during wet and dry periods. Journal of Hydrology, 2013, 477: 55-71. [85] [Chinese reference on optimized soil moisture monitoring] [86] de Souza E R, de Assunção Montenegro A A, Montenegro S M G, de Arimatea de Matos J. Temporal stability of soil moisture in irrigated carrot crops in northeast Brazil. Agricultural Water Management, 2011, 99(1): 26-32. [87] [Chinese reference on soil water distribution] [88] Sobieraj J A, Elsenbeer H, Cameron G. Scale dependency in spatial patterns of saturated hydraulic conductivity. CATENA, 2004, 55(1): 49-77. [89] Hawley M E, Jackson T J, McCuen R H. Surface soil moisture variation on small agricultural watersheds. Journal of Hydrology, 1983, 62(1/4): 179-200. [90] Hupet F, Vanclooster M. Intraseasonal dynamics of soil moisture variability within a small agricultural maize cropped field. Journal of Hydrology, 2002, 261(1/4): 86-101. [91] [Chinese reference on grassland ecosystems] [92] Cantón Y, Solé-Benet A, Domingo F. Temporal and spatial patterns of soil moisture in semiarid badlands of SE Spain. Journal of Hydrology, 2004, 285(1/4): 199-214. [93] Ruiz-Sinoga J D, Martínez-Murillo J F, Gabarrón-Galeote M A, García-Marín R. The effects of soil moisture variability on the vegetation pattern in Mediterranean abandoned fields (Southern

Spain). CATENA, 2011, 85(1): 1-11. [94] Teuling A J, Troch P A. Improved understanding of soil moisture variability dynamics. Geophysical Research Letters, 2005, 32(5): L05404. [95] [Chinese reference on soil moisture temporal stability] [96] Cosh M H, Jackson T J, Bindlish R, Prueger J H. Watershed scale temporal and spatial stability of soil moisture and its role in validating satellite estimates. Remote Sensing of Environment, 2004, 92(4): 427-435. [97] Chen J L, Wen J, Tian H. Representativeness of ground observational sites and upscaling of point soil moisture measurements. Journal of Hydrology, 2016, 533: 62-73.

Note: Figure translations are in progress. See original paper for figures.