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Assessing the time stability of soil moisture patterns using statistical and geostatistical approaches

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ABSTRACT

Understanding the variation of soil moisture patterns over time can support field investigative efforts specific to managing irrigation input, environmental risk assessment, or water resource planning. The objective of this study was to apply an integrated suite of traditional (e.g. Vachaud's time stability analysis) and less common techniques (e.g. confusion matrix, Castrignanò's average of the differences, cross correlogram analysis, and polygon kriging) to gain deeper insight into the temporal persistence of soil moisture patterns, especially for site-specific water management purposes. This study used soil moisture estimates generated in previous work that was carried out in a field in Central Kentucky for three dates ranging from permanent wilting point up to field capacity. The results obtained from this study provide richer evidence of time stable soil moisture patterns and lend greater insight into the controlling factors of spatial and temporal variation, including soil moisture status, soil physicochemical properties, and landscape position, that otherwise would not be attainable using a single metric alone.

1. Introduction

Soil moisture distribution over a field, landscape, or watershed often exhibits spatial patterns mirroring those of soil properties and terrain features (Grayson et al., 1997; Western et al., 1999; Gómez-Plaza et al., 2000; Grayson and Western, 2001; Grayson et al., 2002; Lin et al., 2008). The time stability, also referenced herein as temporal stability (Chen, 2006; Lin, 2006; Vanderlinden et al., 2012), of such spatial patterns is commonly studied using the approach proposed by Vachaud et al. (1985). Such approach was prompted by the large number of observations required to obtain soil moisture's time dependent statistical properties (e.g. mean and standard deviation) across an observation domain, such as a field or watershed. The importance of time stability resides in the fact that it can identify locations where soil moisture data distributions maintain their statistical relevance through time. These locations require less frequent sampling thereby saving time, labor, and cost associated with field investigation efforts (Lin, 2006; Guber et al., 2008). Minimizing these efforts are attractive to real-world practices including precision agriculture, environmental risk assessment, and water resource planning.

Vachaud et al. (1985) introduced two metrics commonly cited within the literature. The first is the mean relative difference (MRD), which identifies locations that are persistently greater or less than the field average. The second is the nonparametric Spearman rank coefficient, which assesses how locations maintain their rank with changes in soil moisture content over time. The closer the rank coefficient is to 1.0 the stronger the time stability between observation dates. Vachaud et al.'s (1985) analysis is classified here as a traditional approach because it does not take into account the spatial association between observations in georeferenced space (2D or 3D), therefore, making it difficult to recognize the temporal stability of the spatial dependence of soil moisture. Moreover, Vachaud et al.'s (1985) approach does not inform practitioners of the environmental factors controlling time stable soil moisture patterns. These limitations reduce the utility of their approach for executing site-specific management practices unique to farmers, remediation specialists, and water resource conservationists.

Several empirical adaptations have evolved to overcome the shortcomings associated with time stability analysis first pioneered by Vachaud et al. (1985) to include spatial autocorrelation and scale. For example, Kachanoski and De Jong (1988) introduced spatial coherence analysis, which employs a spatial power spectrum to

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study scale-dependent time stable soil moisture patterns. Chio et al. (2007) expanded on Jacobs et al.'s (2004) work by applying principal component analysis to understand how pre-defined empirical parameters (Jacobs et al., 2004), including climate, soil, and vegetation, influenced soil moisture patterns across multiple spatial scales (e.g. the field, watershed, and basin). More recent literature has tied Vachaud et al.'s (1985) statistical approach to multivariate geostatistics (Buttafuoco et al., 2011; Vanderlinden et al., 2012). Geostatistics assumes that a set of observations represents one realization of a random function defined in a region R^n, which exhibits both autocorrelated (spatially structured) and erratic (non-spatially structured) variation. For example, Buttafuoco et al. (2011) used a multivariate geostatistical approach, factorial cokriging analysis (FCA), to analyze the scale-dependent correlation structure of mean annual precipitation across multiple decades. Their results suggested different factors drive the scale-dependent spatiotemporal variability in mean annual precipitation across southern Italy, including short-range orographic configurations and long-range global atmospheric circulation processes. FCA is a powerful tool because it combines the efforts made by Kachanoski and De Jong (1988) and Chio et al. (2007) into an integrated system of geostatistical techniques aimed at assessing spatiotemporal scale-dependent variation in addition to suggesting the potential environmental attributes influencing this variation. Vanderlinden et al. (2012) later discussed a stochastic model that decomposes the MRD into two components, a deterministic mean and a second order stationary residual with zero mean, where each component is a function of location, in a 2-D sampling space, and time (Vereecken et al., 2014). Their approach aims to characterize the spatiotemporal variation in soil moisture and identify main controls of this variation (Vereecken et al., 2014).

Several technical adaptations have also evolved to overcome the shortcomings associated with Vachaud et al.'s (1985) pioneering work. These adaptations include integrating sparse direct observations with dense proximal sensing observations. Fusing data with different sampling supports and density allows field investigators to capture richer spatial detail that otherwise might not be attainable using sparse direct observations alone (Landrum 2013; Landrum et al., 2015). Point observations (e.g. soil coring, capacitance probing, etc.) often lack the appropriate sampling support and are too costly to adequately assess soil moisture variation at management scales typical for famers, watershed planners, and remediation specialists (e.g. field scale and above) (Lin 2003; Zhu et al., 2012; Vereecken et al., 2014).

Over the last several decades hydrogeophysical applications have become widely used to study time stability and can include applications such as electrical resistivity (ER) (Amidu and Dunbar, 2007; Besson et al., 2010; Landrum et al., 2015), ground penetrating radar (GPR) (Minet et al., 2013; Cafarelli et al., 2015), and electromagnetic induction (EMI) (Zhu et al., 2010; Castrignanò et al., 2012). Landrum et al. (2015) combined sparse soil coring with high resolution apparent electrical conductivity measurements using a multivariate geostatistical approach, called multicollocated factorial cokriging, to analyze and map the scale-dependent interactions between soil moisture and associated soil-terrain attributes during an unusually dry period for central Kentucky (Landrum, 2013; Landrum et al., 2015). Their results indicated soil moisture variation was time stable at a long-range (~250 m), in comparison to a short-range (~40 m), and that soil moisture's interaction with soil physicochemical properties overshadowed the interaction with terrain attributes during this period. Their study demonstrated that apparent electrical resistivity was a preferred proximal sensing technology over LiDAR generated digital terrain attributes to capture and map (e.g. downscale) the cumulative scale-dependent variability of soil moisture and associated environmental attributes.

It has been recommended to combine more approaches to study the temporal stability of soil moisture patterns to optimize field investigative and management efforts (Guber et al., 2008). The objective of this research was to apply an integrated suite of both traditional (Vachaud et al.'s analysis) and less commonly used (confusion matrix, average of the differences, cross correlogram analysis, and polygon kriging) techniques to provide more informative evidence of time stable soil moisture variation that otherwise would not be possible using a single approach alone.

2. Materials and methods

The site investigated is at Spindletop Farm in Kentucky's Inner Bluegrass physiographic region, Fayette County, Lexington, KY (38.116030 N, −84.491093 W), a part of the University of Kentucky Agricultural Experiment Station. The Inner Bluegrass region is underlain by Ordovician phosphatic limestone, calcareous shales, and interbedded limestone shales (USDA-NRCS 2013). The site spans approximately 40 ha and is dominated by forage grasses and silt loam and silty clay loam soils (Landrum et al., 2015). A meandering creek is located to the north and a drainageway transects the site. The reader is referred to Landrum (2013) and Landrum et al. (2015) for additional information regarding site characteristics.

Soil moisture sampling occured during the summer and fall of 2012. The U.S. Drought Monitor declared a Level 1 (moderate) drought for Central Kentucky during June and July 2012 and the remainder of the sampling season was classified as abnormally dry. Due to lack of sufficient rainfall only three dates, July 17th, September 11th, and October 5th 2012, were sampled during this period. Soil moisture contents amid the three dates ranged from the permanent wilting point (July) to field capacity (October) for the silt loam soils (Saxton and Rawls, 2006). Soil moisture estimates (vol./vol.) for the top 30 cm of the soil profile were generated using multicollocated cokriging at each grid node on a 5 × 5 m mesh grid that resulted in a total of 8734 estimates for each date. The reader is referred to Landrum (2013) and Landrum et al. (2015) for more details on the geostatistical techniques used to generate soil moisture estimates.

Soil moisture estimates were subjected to a suite of analytical techniques, including confusion matrix, Vachaud's analysis, average of the differences, cross correlogram analysis, and polygon kriging, to ascertain if the three soil moisture dates exhibited time stable soil moisture variation across the field. The analytical techniques were split into two categories: traditional statistics and geostatistics.

2.1. Traditional statistics

2.1.1. Confusion matrix

The confusion matrix produces a value, identified here as the observed accordance, indicating the overall agreement between soil moisture classes for two observation dates (Lauenroth et al., 2003; Mather, 2004). It is possible in some cases that the observed accordance arises from mere chance. The Kappa statistic is a measure of the accordance corrected for chance occurrence. If the Kappa statistic is significant, it means that the observed association cannot be attributed to chance. Prior to calculating the confusion matrix, each soil moisture estimate (n = 8734) was ranked from lowest to highest and classified into four iso-frequency classes (1 being the lowest soil moisture content and 4 being the highest) for each observation date. Four classes were chosen for data management purposes. If a soil moisture estimate at a given point held its classification through time it was considered time stable. This study employed R (version 2.15.2, caret package) to calculate the confu-