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Identification of Optimal Sampling Locations and Grid Size for Soil Moisture Mapping

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Abstract

The most robust site-specific management system is based in part on high quality maps of soil data. However, creating useful, accurate maps of soil information can be complicated by the natural variability of soil characteristics. This study addresses optimal sampling locations and grid sizes for soil moisture mapping, which is a valuable input for site-specific applications that depend on moisture status, such as precision irrigation and application of chemicals which require moisture transport into the root zone. Variogram analysis of surface moisture data for a central Illinois field revealed that the geospatial characteristics of the soil moisture patterns are similar from one date to another, which may allow for a single, rather than temporally variable, variogram to describe the spatial structure. For this field, a maximum cell size of 13 meters was found to be appropriate for soil moisture. This could indicate an appropriate scale for precision farming operations or for intensive ground sampling. The temporal stability of moisture patterns was studied in order to identify optimal sampling points for field-average soil moisture. Such points were identified by calculating their deviation over time from field average. Topographic data were analyzed to determine if these sampling points could be identified from time-invariant data. While no topographic indices were identified as being strong indicators of these locations, the points tended to be located in areas that were neutral in plan curvature compared to the field average.

Keywords

Soil moisture, sampling design, spatial variability, variogram

Disciplines

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Comments

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Abstract. *The most robust site-specific management system is based in part on high quality maps of soil data. However, creating useful, accurate maps of soil information can be complicated by the natural variability of soil characteristics. This study addresses optimal sampling locations and grid sizes for soil moisture mapping, which is a valuable input for site-specific applications that depend on moisture status, such as precision irrigation and application of chemicals which require moisture transport into the root zone. Variogram analysis of surface moisture data for a central Illinois field revealed that the geospatial characteristics of the soil moisture patterns are similar from one date to another, which may allow for a single, rather than temporally variable, variogram to describe the spatial structure. For this field, a maximum cell size of 13 meters was found to be appropriate for soil moisture. This could indicate an appropriate scale for precision farming operations or for intensive ground sampling. The temporal stability of moisture patterns was studied in order to identify optimal sampling points for field-average soil moisture. Such points were identified by calculating their deviation over time from field average. Topographic data were analyzed to determine if these sampling points could be identified from time-invariant data. While no topographic indices were* *identified as being strong indicators of these locations, the points tended to be located in areas that were neutral in plan curvature compared to the field average.*

Keywords. Soil moisture, sampling design, spatial variability, variogram.

Introduction

Soil moisture is a critical component of many systems, including agriculture and field-scale hydrology. As such, understanding the variability of soil moisture across a field can provide useful management information, and can aid in sampling system design.

The extent to which surface soil moisture varies within a given region and over time is difficult to quantify, yet understanding the variability is critical for determining an optimal sampling resolution both in space and in time. Quantification of spatial variability in soil moisture is also important for determining optimal management zones for agricultural applications that depend on moisture status, such as precision irrigation and application of chemicals which require moisture transport into the root zone.

Another application of studying within-field soil moisture variability is identification of what some researchers have called catchment average soil moisture monitoring (CASMM) sites (Grayson and Western, 1998). These sites are defined as locations within a catchment that are observed to have consistent behavior over time with respect to the catchment average (Vachaud et al., 1985). Such information could be useful for identifying the most advantageous sampling locations for an area in which intense monitoring is not possible, as well as for providing ground truth information for large-scale remote sensing imagery. Grayson and Western (1998) noted that more research was needed to develop methodologies for determining CASMM sites from topographic and soil characteristics.

Furthermore, for a number of applications, understanding how the variability of soil moisture relates to variation in topographic factors such as slope, curvature, and aspect, is desirable. As explained by Qiu et al. (2001), a “comprehensive knowledge of soil moisture variations in relation to land use and topography can provide a simple approach for subdivision of a watershed into spatial units with homogeneous hydrologic response.” An understanding of the inter-relationships in variation in soil moisture and topographic parameters can provide a method for distributed estimations of soil moisture based on a limited number of samples (Grayson and Western, 1998). Some research has been done into the variation of soil moisture as it relates to topographic or topography-related variables. Pachepsky et al. (2001) found that sand, silt, and clay contents were related to slope and curvatures and, not surprisingly, impacted soil water retention. They also found that a regression model using slope, profile curvature, and tangential curvature explained over 60\% of the variation in soil water content in the upper soil layers (10 and 33 kPa).

Han et al. (1994) used geostatistical analysis to determine an optimal cell size for site-specific crop management. For field applications that are based on soil moisture, they used a single day's set of moisture data to determine a maximum cell size of 52 m from a variogram analysis. However, since the variability in soil moisture can change over time, one sampling of data may not be sufficient to adequately determine an overall optimal cell size. Rahman et al. (2003) used a similar approach to recommend an optimal pixel size for hyperspectral remote sensing images to be used for vegetation indices, one of which was a plant water index.

The purpose of this study was to analyze soil moisture variability in space and time, towards understanding how this variability affects management grid size and optimal sampling scheme design.

Location and Methods

A University of Illinois research farm field in southeast Urbana, IL was used in this study, which was done during the 2002 growing season. The Grein field is an 8.2-acre corn field with moderate topographic variation. Grein has two soil types, one a grayish-brown, moderately well drained silt loam typically found on till plains and moraines, and the other a blackish, poorly drained, moderately permeable silty clay loam (Mount, 1982). No drainage tile lines are known to be located within Grein. The field was tilled after harvest the previous fall, and cultivated in the spring just prior to planting. During the 2002 season, the field was planted so that there were alternating strips of corn (16 rows at 76.2 cm spacing) and bare soil (6.1 m wide). The sampling locations are shown in figure 1, and dates for the study are given in table 1. Samples were taken on a large grid in the bare swaths, and three smaller sections of more dense grids were sampled within the crop rows.

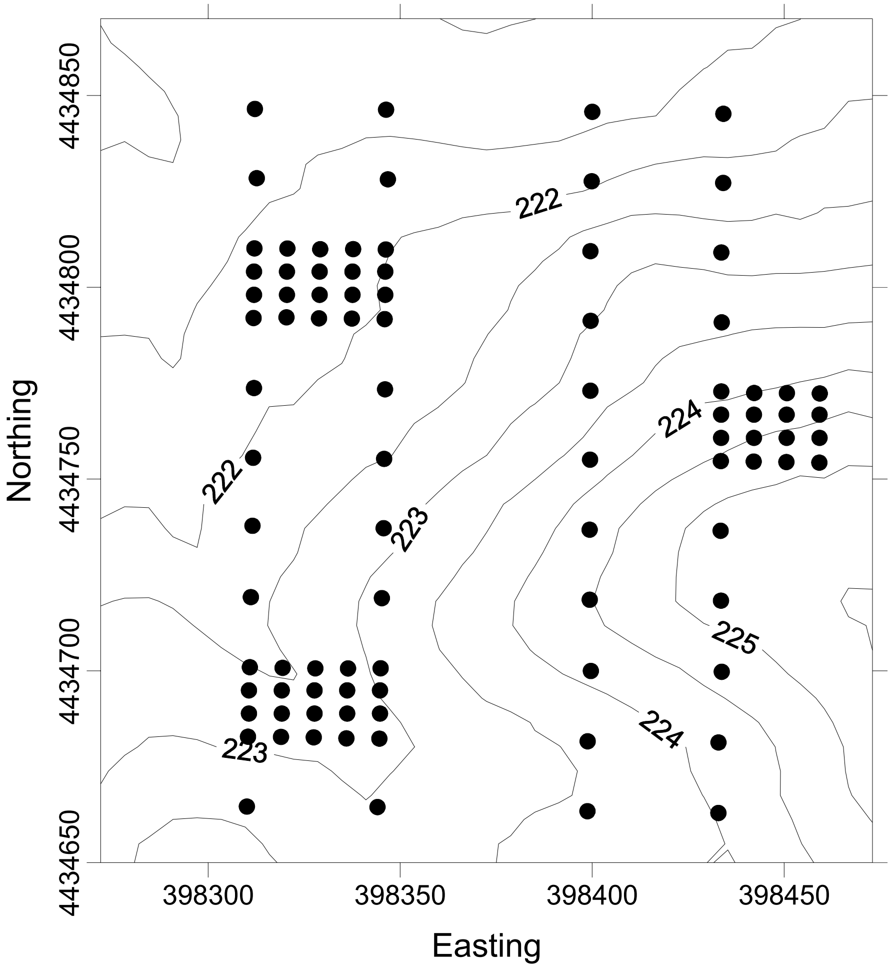

Figure 1. Sampling locations and topography at the Grein field. The contour lines represent elevation in meters. The dots represent sampling locations. Easting and Northing are given in UTM.

Table 1. Summary of 2002 data collection.

Date	Number of locations (outer grid, nested grid)	Problems encountered or management issues
6/17/02	43, 4	Too few sample containers to complete nested grids
6/18/02	44, 28	Too few sample containers to complete nested grids
6/19/02	43, 46	None
7/19/02	40, 18	Interior (crop row) locations in nested grids no longer sampled
7/20/02	44, 17	None
7/21/02	44, 16	None
8/15/02	44, 12	Onset of precipitation prevented collecting all samples
8/20/02	44, 18	None
9/12/02	44, 18	None
9/26/02	44, 0	Nested grids not sampled

Markers were put in the field at each of the sampling locations in the bare strips, and GPS data were collected using a Leica GPS system giving geographic location accurate to 2 cm. For the nested grid locations in the planted strips, the crop rows were used for orientation in the north-south direction, and the markers were used for visual alignment for the east-west orientation.

Surface soil moisture measurements were done using gravimetric sampling. At each location, two 3.8 cm diameter, 7.6 cm deep soil cores were taken and placed in a zip-seal plastic bag and labeled. After sampling of the entire field was completed, the samples were taken back to the laboratory, where they were removed from the bags and weighed. The samples were then baked at 100 ^{o}C for 23 hours, removed from the oven and re-weighed. Dry-based gravimetric soil moisture for each sample was then calculated.

Analysis

Quantifying spatial variability

For the purposes of determining optimal management grid size, the spatial variability must be quantified. One way to do this is to compute the semivariogram of the spatially distributed data, which gives a measure of the average dissimilarity between data separated by some distance h. The semivariogram estimate for a given dataset is described by the equation

$$\gamma(h) = \frac{1}{2N(h)} \sum_{\alpha=1}^{N(h)} \left[z(u_\alpha) - z(u_{\alpha+h}) \right]^2$$

where $\gamma(h)$ is the sample semivariogram, $N(h)$ is the number of pairs of data locations which are separated by the lag h, and $z(u_\alpha)$ is the data value at location u_α. In many cases, at a certain distance or range, the semivariogram stops increasing and fluctuates around a sill value. By definition, $\gamma(h) = 0$, but in practice the estimated semivariogram may not approach zero as h decreases. This is called a nugget effect, and is a function of measurement error and/or spatial variation at smaller than measured scales. A full discussion of the semivariogram can be found in Goovaerts (1997).

In order to analyze the spatial statistics of the moisture data, semivariograms were computed, and subsequently a model was visually fitted to each date's results. Table 2 lists the variogram model properties for each date. In general, two models were sufficient to describe all of the semivariograms: the spherical model, and the nugget. The spherical model is described by the equation

$$g(h) = C\left\{\begin{matrix} 1.5\frac{h}{a} - 0.5\left(\frac{h}{a}\right)^3 & \text{if } h \le a \\ 0 & \text{otherwise} \end{matrix}\right\}$$

where C is the estimated semivariogram sill and a is the range. The nugget effect is described by the equation

$$g(h) = C_0\left\{\begin{matrix} 0 & \text{if } h = 0 \\ 1 & \text{otherwise} \end{matrix}\right\}$$

Table 2. Semivariogram model data.

Date	Model	Sill	Range	MCD
6/17/02	Spherical	3.0E-4	60	22.5
6/18/02	Spherical	2.5E-4	35	13.1
6/19/02	Spherical	2.5E-4	35	13.1
7/19/02	Nugget	2.0E-4	--	6.9
	Spherical	2.2E-4	35	
7/20/02	Spherical	3.2E-4	35	13.1
7/21/02	Spherical	3.5E-4	35	13.1
8/15/02	Nugget	2.0E-4	--	--
8/20/02	Spherical	1.2E-4	35	13.1
9/12/02	Nugget	1.6E-4	--	--
9/26/02	Spherical	1.6E-4	35	13.1

Aside from 8/15/02 and 9/12/02, the dates are similar in semivariogram shape, most being well-described by a simple spherical model. In the case of 8/15/02, no clear model is evident, whereas in the case of 9/12/02, the semivariogram is best described by a pure nugget model. The 7/19/02 data are well described by a combination of spherical and nugget models. The ranges for the moisture data are quite consistent. For all the spherical models except 6/17/02, the range is 35 m; the range for the 6/17/02 data is 60 m. Also, the sills for the moisture data are similar for the June and July dates (2.5E-4 to 4.2E-4) but are decreased for the August and September dates (1.2E-4 to 2.0E-4).

The consistency in the estimated semivariogram range for the surface moisture data suggests that for this field, a single, rather than dynamic or temporally variable, optimal cell size for precision management is appropriate. Han et al. (1994) computed the maximum cell size equivalent to the mean correlation distance, which is expressed as

$$MCD = \int_{0}^{h_{\max}} \rho(h)\, dh$$

where $h_{\max}$ is the maximum distance between sampled locations. The normalized complement function $\rho(h)$ is related to the semivariogram $\gamma(h)$ through the equation

$$\rho(h) = \frac{(C_0 + C) - \gamma(h)}{C_0 + C}.$$

For situations in which $h_{\max}$ exceeds the semivariogram range a, the preceding equations reduce to the following equation for a spherical semivariogram model,

$$MCD = \frac{3Ca}{8(C_0 + C)}$$

Applying this equation to the semivariogram data presented in table 2 reveals that the maximum cell size varies from 6.9 m to 22.5 m. For the dates which are modeled with a pure nugget semivariogram, computation of a maximum cell size is not possible. Theoretically, these dates have an infinitely small maximum cell size. MCD computations suggest that a cell size of 13.1 m would be sufficient for seven of the ten dates.

The difference between these results and those reported by Han et al. (1994), which found a maximum cell size of 52 m for a field on the University of Illinois agricultural engineering farm, which is within a mile of the Grein field, indicates that each field or area, even within the same geographic region, likely has a different optimal management zone size. Furthermore, optimal management zone size is temporally variable. In the case of the Grein field, however, the MCD is not widely varying.

Identification of optimal sampling locations

It is desirable to identify locations that are advantageous to sample, or that will provide the most information about the moisture status of the field with the smallest amounts of necessary ground sampling. Sampling recommendations often assume a grid sampling scheme is the most appropriate. However, it is possible that judicious sampling in a non-grid scheme could provide for better estimation of moisture across the field from limited samples, particularly when there are restrictions on the number of locations it is feasible to sample. As discussed previously, Vachaud et al. (1985) and Grayson and Western (1998) observed that some locations within a field have consistent moisture behavior over time with respect to the field average.

In order to determine if this was also the case for the Grein field, the point-field standard deviation (PFSD) at each location on the large grid was calculated as

$$\sigma_i = \frac{1}{m-1}\sqrt{\sum_{j=1}^{m}\left(\delta_{i,j} - \bar{\delta}_{i,j}\right)^2}$$

where m is the number of sampling occasions, and i is the sample location. The moisture deviations at each location and their averages over time, $\delta_{i,j}$ and $\bar{\delta}_{i,j}$, were calculated by the equations

$$\delta_{i,j} = \frac{S_i - \bar{S}_j}{\bar{S}_j}$$

$$\bar{\delta}_{i,j} = \frac{1}{m}\sum_{j=1}^{m}\delta_{i,j}$$

where S_i is the moisture at the i th point, and $\bar{S}_j$ is the field average of all S_i on the j th sampling occasion.

The results of this analysis, shown as an interpolated image with elevation contours in figure 2, reveal that there is a sampling location in the Grein field with very low point-field variance. This point is located at (398399.5 E, 4434809 N), and has a PFSD of 0.016, whereas the average PFSD is 0.067 and the maximum is 0.15. Therefore, this point has very consistent behavior with respect to the field average moisture. In fact, further analysis reveals that the moisture of this point is generally nearly equivalent to the field average moisture.

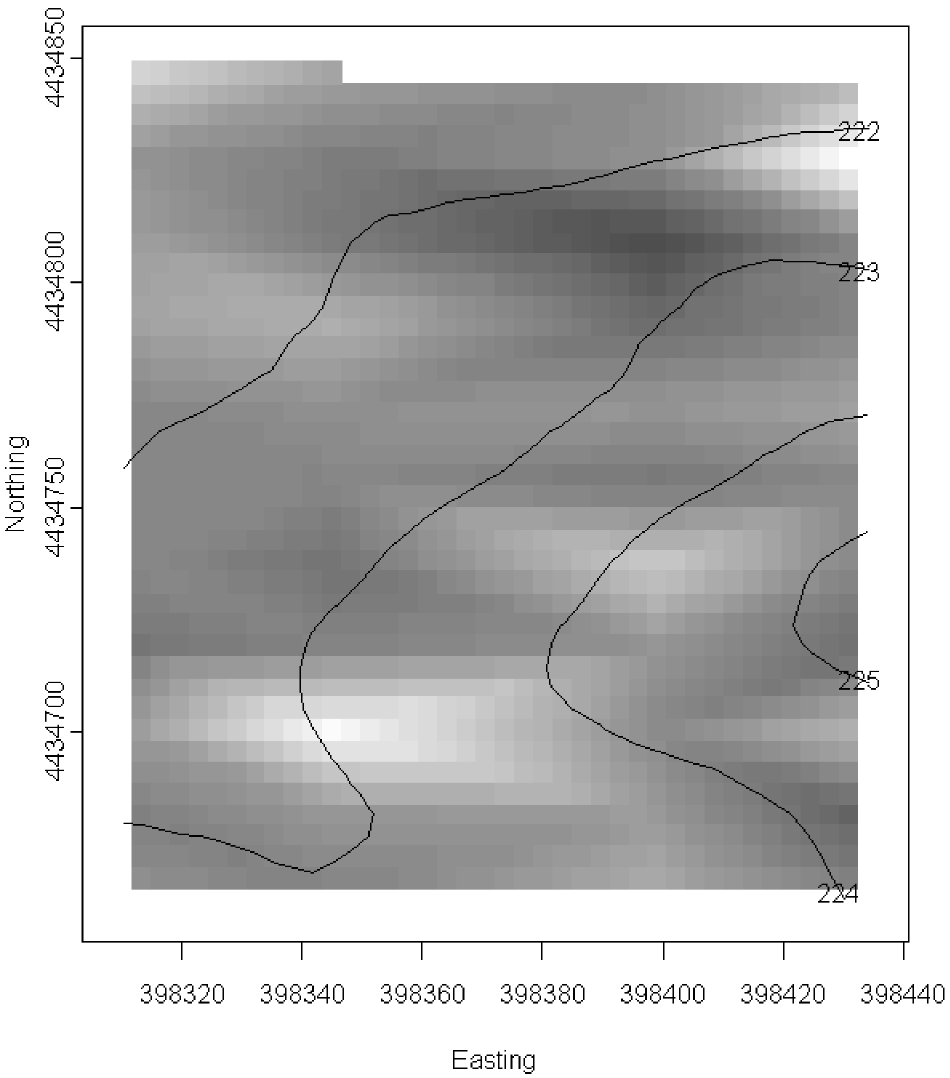

Figure 2. Interpolated image plot of point-field standard deviations of Grein soil moisture. Contours represent elevation in meters. Easting and Northing are given in UTM. The location with the lowest PFSD is located in the northeast quadrant of the field at (398399.5 E, 4434809 N).

The locations of points with low point-field standard deviation are useful for monitoring average soil moisture, since it means that only a limited number of sites need to be sampled. Is it necessary to exhaustively sample the field for moisture over time in order to perform the above statistical analysis for identification of low-PFSD locations, or can these points be identified from analysis of temporally stable factors such as topographic indices? Grayson and Western (1998), suggest that areas of little convergence or divergence of flow and that are “aspect neutral”, where radiative exposure is close to the field average, are likely candidates for the these locations. Their study focused on an entire catchment, but it is possible that the same guidelines are true for an individual field.

High resolution elevation data for the Grein field were used to investigate these relationships. Several topographic indices were computed from the elevation data: slope, aspect (also known as flow direction), plan curvature (the curvature along a contour line, perpendicular to the slope), profile curvature (the curvature in the direction of the slope), and tangential curvature (the curvature along a vertical plane teangential to a contour line). “Neutrality” values were calculated by taking the absolute value of the deviation of a given topographic index at each large grid sampling location from the field average of said index. In this way, neutrality is characterized by values close to zero. Figure 3 is a plot of aspect neutrality versus PFSD. Figures 4 and 5 are bar plots of the correlations for all topographic indices and index neutrality, respectively. It can be seen that the point with the lowest value of PFSD also is fairly aspect neutral. However, some other areas with low PFSD are among the least aspect neutral in the field, and some areas that are quite aspect neutral have high PFSD. As a result, it is probable that aspect neutrality alone is not a good indicator for low-PFSD sites, at least at the Grein field. For the most part, the study areas used by Grayson and Western were hillslopes, and it is probable that aspect plays a greater role in these areas than areas which are flatter.

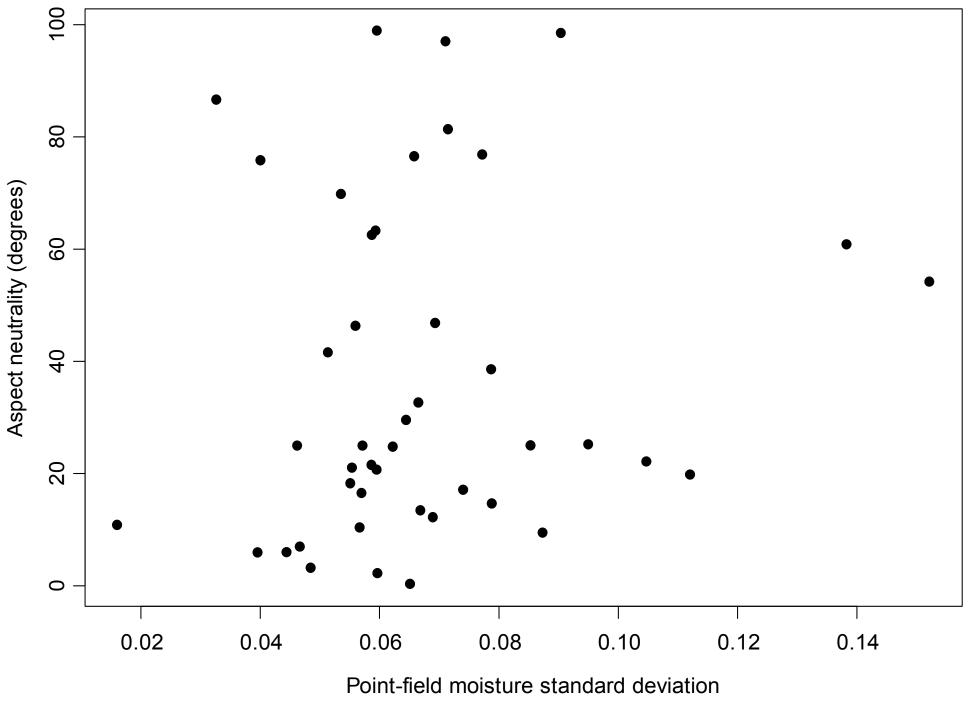

Figure 3. Aspect neutrality versus point-field moisture standard deviation. Aspect neutrality is a measure of the absolute difference between the topographic aspect of the location and the field average aspect.

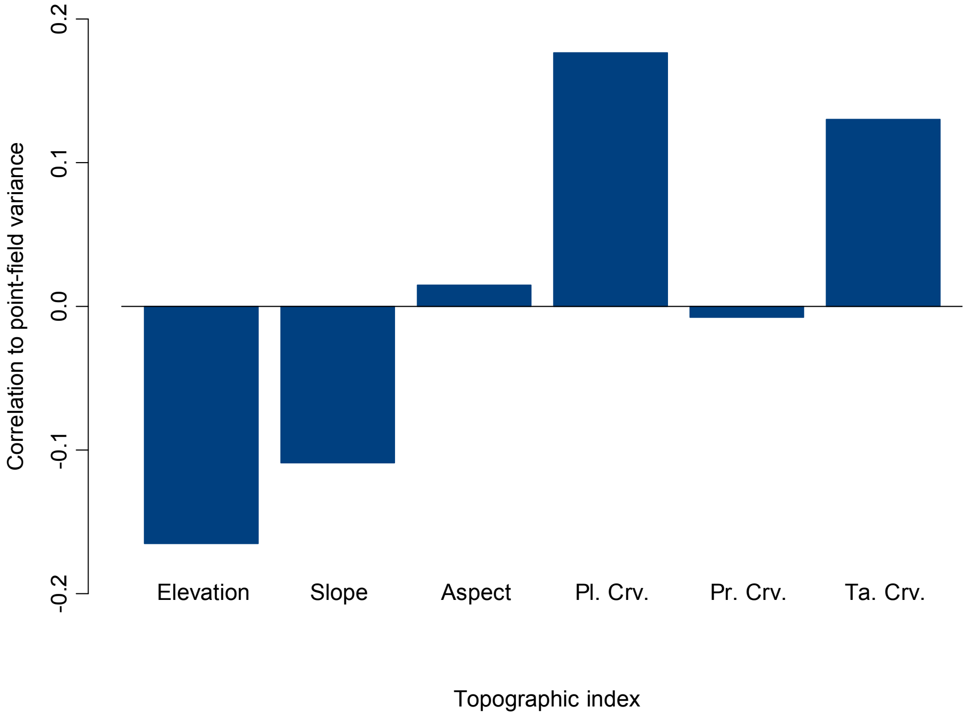

Figure 4. Correlations between point-field moisture standard deviation and topographic indices.

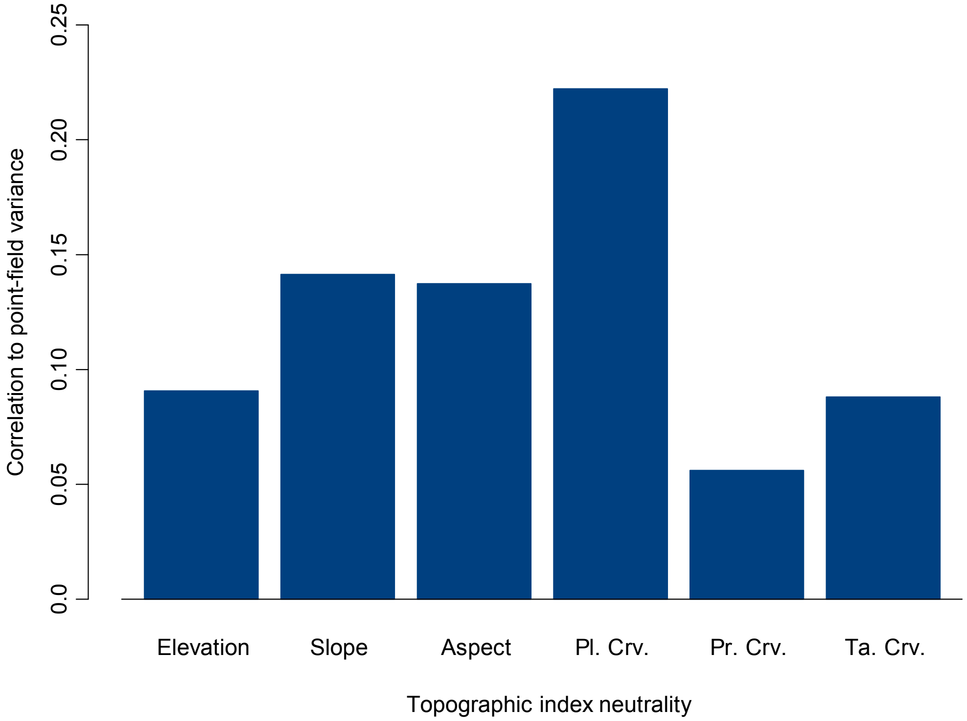

Figure 5. Correlations between point-field moisture standard deviation and topographic index neutrality.

Plan curvature shows the most correlation to PFSD of all the topographic indices. This is true for both the straight topographic index data, where the plan curvature correlation (r=0.18) is slightly higher than the elevation correlation (r=-0.17), and the index neutrality data, where the plan curvature correlation (r=0.22) is distinctly larger than the correlations for any of the other indices. This echoes the Grayson and Western (1998) conclusion that soil moisture in areas of no flow convergence or divergence were more likely to behave like the catchment average. Looking closer at the topographic and PFSD data for each point reveals that the four points with the lowest PFSD values have plan curvature neutrality less than 0.04, and have slopes between 1.66% and 1.77%, which is slightly higher than the field average of 1.41%. However, other points with only slightly higher values of PFSD do not follow this pattern, and there are several other points which fit the preceding criteria but have high values of PFSD. Nonetheless, for fields like Grein this may provide a general guideline for identifying sites to sample for their potential to be low-PFSD sites.

Conclusion

Variogram analysis of surface moisture data for a central Illinois cornfield revealed that the geospatial characteristics of the soil moisture patterns are similar from one date to another, which may allow for a single, rather than temporally variable, variogram to describe the spatial structure. In the case of a strong relationship between mean and variance, it may also be possible to determine a stable relationship between mean and variogram.

The relationship between moisture patterns and topographic indices was also investigated for this field, which had moderate topographic variation. While there was no strong correlation between the moisture patterns and topographic indices, the results indicated that plan curvature may be an important topographic indicator for understanding surface moisture spatial variation.

For the same field, a maximum cell size of 13 meters was found to be appropriate for moisture studies. This could indicate an appropriate scale for precision farming operations, or could indicate a maximum pixel size for remotely sensed studies of field-level moisture status.

The temporal stability of moisture patterns was studied in order to identify optimal sampling points for field-average soil moisture. Such points were identified by calculating their deviation over time from field average, indicating that the concept of catchment average soil moisture monitoring sites can be scaled down to the field level as well. Topographic data were analyzed to determine if these sampling points could be identified from time-invariant data. While no topographic indices were identified as being strong indicators of these locations, the points tended to be located in areas that were neutral in plan curvature compared to the field average.

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