SPATIAL VARIABILITY

Management, Topographical, and Weather Effects on Spatial Variability of Crop Grain Yields

A. N. Kravchenko,* G. P. Robertson, K. D. Thelen, and R. R. Harwood

ABSTRACT

The quantitative characterization of spatiotemporal variability in crop grain yields is an important component for successful precision-agriculture applications. The objective of this study was to analyze and quantify effects of management practices, topographical features, and weather conditions on spatial variability of crop yields. A one-factor randomized complete block design experiment with six replications was established at the Long Term Ecological Research site in southwest Michigan in 1988. The treatments used in this study were two treatments with conventional chemical inputs (chisel plow and no-till) and two organic-based chisel-plowed treatments with a winter leguminous cover crop (low chemical input and zero chemical input). The data consisted of corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.]–wheat (*Triticum aestivum* L.) yields collected via combine monitors from 1996 to 2001. We observed that stressful conditions, regardless of the stress origin, were associated with increase in the overall yield variability (coefficient of variation) as well as the small-scale yield variability (variogram values at short lag distances and variogram slopes near the origin) with yields probably being more sensitive to the small-scale variations in growth conditions due to soil and microtopographical differences. Coefficients of variation were as high as 45% in years with low precipitation and as low as 14% in years with above-average precipitation. During the years with low precipitation, both the coefficients of variation and the small-scale variability were often significantly higher in the zero chemical input treatment than in the treatments that received fertilizer inputs. The coefficients of variation and the small-scale variability parameters also tended to be higher in corn stressed by antagonism from previous wheat crop in the no-till treatment.

The quantitative characterization of spatiotemporal variability in crop grain yields is an important input for precision-agriculture applications. Crop yields are highly variable across fields as a result of complex interactions among different factors, such as topography, soil properties, and management practices. Topography has been found to be among the major sources of yield variability in a number of studies (e.g., Simmons et al., 1989; Changere and Lal, 1997; McConkey et al., 1997; Timlin et al., 1998; Kravchenko and Bullock, 2000; Kaspar et al., 2003; Si and Farrell, 2004; Jiang and Thelen, 2004; Schepers et al., 2004). However, yield/topography relationships vary substantially from year to year and from field to field (Lamb et al., 1997; Kravchenko and Bullock, 2000; Lark, 2001; Machado et al., 2002; Kaspar et al., 2003). These variations are often associated with the prevailing weather conditions during the growing season of each particular year, such as spring and summer precipitation (Kravchenko and Bullock, 2000; Jaynes and Colvin, 1997) or total growing degree days (Lamb et al., 1997), indicating that in well-managed fields, moisture availability is often the main yield-affecting factor.

Not only the overall yields but also yield variability has been reported to vary from year to year depending on weather conditions. Whelan and McBratney (2000) observed coefficients of variation of yield ranging from 13 to 83% for wheat and from 12 to 44% for sorghum [*Sorghum bicolor* (L.) Moench] in two consecutive years. Porter et al. (1998) reported coefficients of variation from field plots for corn and soybean yields ranging from 2 to 19% over 10 studied years. Noticeable differences in spatial variability patterns were observed by Jaynes and Colvin (1997) in a study of 6 yr of corn–soybean grain yields in central Iowa and by Tawainga et al. (2003) in a 3-yr study in central New York. Schepers et al. (2004) observed variations in spatial variability patterns and variogram parameters of crop yields over five studied years in an irrigated field in Nebraska. These and other researchers commented on the difficulties of predicting future yield and developing site-specific management practices based on the spatial variability of historic yields (Lamb et al., 1997). Emerging applications of advanced statistical procedures, such as cluster analysis, have been used to identify management zones, that is, areas within fields with similar temporal yield patterns that could be managed on a uniform basis (Lark, 2001; Jaynes et al., 2003, Roel and Plant, 2004).

Since water redistribution within a field is a function of combined effects of field topography, soil properties, and weather conditions, the spatial variability of crop yields as affected by moisture is an outcome of topography–soil–weather interactions. Quantitative description of these interactive effects is an important component for further advancement in precision agriculture, e.g., for development of management zone strategies. For

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Abbreviations: ChiselConv-T1, chisel-plowed treatment with conventional chemical inputs; ChiselLow-T3, chisel-plowed treatment with low chemical input and a winter leguminous cover crop; ChiselNoChem-T4, organic-based chisel plowed with zero chemical input and a winter leguminous cover crop; CV, coefficient of variation; LTER, Long Term Ecological Research (site); NoTillConv-T2, no-till treatment with conventional chemical inputs; Var1.5, general relative variogram value at lag distance 1.5 m.

example, predicting early in the season the extent and strength of spatial continuity in crop yield distribution can add supplementary considerations to producers' decisions regarding size and location of potential management zones.

Another factor that can influence the spatial variability of yield, not yet addressed, is the management practice. Comparisons of management effects on soil properties indicate that not only the values of soil properties but also their variability characteristics might be affected by management. For example, Perfect and Caron (2002) observed higher spatial variability in soil water contents, bulk density, and total C values in no-till soil management than in conventional-till soil management. Robertson et al. (1993) observed that the ranges of spatial correlation for soil moisture, P, and total C values were shorter in a never-cultivated site than those in an adjacent tilled site. Tsegaye and Hill (1998) reported weaker spatial correlation in distributions of bulk density, soil strength, and mean pore size in the top 6- to 9-cm portion of the soil profile than in the 27- to 30-cm portion and ascribed differences to disturbance of the upper portion by tillage. Management might thus interact with and possibly buffer—or alternatively accentuate— the influence of biophysical factors on yield variability. Prior studies cannot be used to evaluate these potentials because of a limited number of field replicates or management regimes. In the present study, we take advantage of 6 yr of yield monitoring on a set of replicated crop rotations managed with conventional tillage, with no-till, and with reduced or zero chemical inputs to address the question "to what extent can agronomic management influence yield variability over and above the influence of topography, soil properties, and weather?"

The specific objectives of this study were first, to determine how topographical features, management practices, and weather conditions influence spatial variability of crop yields and, second, to quantify the influences of these factors on selected spatial variability characteristics.

MATERIALS AND METHODS

Site Description and Data Collection[1]

The data were collected at the Long Term Ecological Research (LTER) site located at Kellogg Biological Station (KBS) in southwest Michigan (85°24′ W, 42°24′ N). Soils are well-drained Typic Hapludalfs of the Kalamazoo (fine-loamy, mixed, mesic) and Oshtemo (coarse-loamy, mixed, mesic) series, developed on glacial outwash. Mean annual precipitation (30-yr mean) is 860 mm, about half of which falls in the winter months. Mean annual temperature of the site is 9.4°C.

A one-factor randomized complete block design experiment with six replications was established at the site in 1988 (Fig. 1). The experiment consisted of a total of seven treatments, only four of which were agronomic treatments. Thus, this study used the four agronomic treatments of the LTER site, namely, chisel plowed with conventional chemical inputs (ChiselConv-T1), no-till with conventional chemical inputs (NoTillConv-T2), chisel plowed with low chemical input and a winter leguminous cover crop (ChiselLow-T3), and organic-based chisel plowed with zero chemical input and a winter leguminous cover crop (ChiselNoChem-T4). All of the annual crops were managed as corn–soybean–wheat rotations according to best management practices by treatment.

Crop yield data included corn, soybean, and wheat grain yields collected via yield monitors from all six replications of each treatment during 1996 to 2001. We followed Drummond and Sudduth's (2003) recommendations for cleaning and processing yield data. Border effects were eliminated so that only the yield data from the central 60- by 80-m portion of each plot were used in the analysis. The yield files were adjusted for delays in yield recoding in combine sensors. Also, the few observations with erroneous grain moisture values, lower number of satellites for GPS receiving, and near-zero combine travel times were deleted from the data sets. The number of yield data points remained in each plot after data processing ranged from at least 500 for wheat data to as much as 1600 for corn and soybean data. The planting rows were oriented in north–south direction. The distance between the yield measurement points in north–south direction was approximately 1.5 m, and the distance in west–east direction was approximately 3 to 4 m for corn and soybean and approximately 2 to 3 m for wheat. From here on, we will refer to the "plot" as only the corrected harvest area of each experimental plot with borders removed. The relatively large size of the plots and large number of yield data points per plot allowed for meaningful spatial variability characterizations of crop yields within each plot.

A total of 597 elevation measurements were collected in the first five replications using land-based laser in 1988 (Robertson et al., 1997). Distance between measurements ranged from 4 to 20 m, and approximately eight to nine elevation measurements were available for each plot (Fig. 1). The elevation measurements were converted into a cell-based terrain map on a 15- by 15-m grid by means of inverse distance weighting with power of 2 and 6 nearest neighbors using ArcView GIS Spatial Analyst (ESRI, 1996). Slope, curvature, flow accumulation, and soil wetness index (Moore et al., 1993; Schmidt and Persson, 2003) were derived from the elevation data using surface hydrologic analysis of ArcInfo GRID. The grid size for the terrain map was selected such as to ensure that every cell contains at least one elevation data point. It allowed us to obtain a realistic level of detail in the terrain map and at the same time to avoid artificially high values of slopes, curvatures, and the other terrain map derivatives that occur in terrain maps with cell sizes substantially smaller than the distance between the elevation measurement points.

Daily precipitation and temperature data were obtained from an automated weather station located at the LTER site. Average daily precipitation values from March through June for 1996 to 2001 are shown in Fig. 2. The weather variables used in the study included average daily precipitations and temperatures of the individual months from March through June, as well as average daily precipitations and temperatures for the whole March through May and March through June periods.

Data Analysis

Variability Characterization in Individual Plots

All crop yield variability characteristics were calculated separately for each experimental plot and then used as dependent variables in subsequent statistical analysis. Coefficient of variation (CV), calculated as a ratio of standard deviation of

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[1] Please see http://lter.kbs.msu.edu (verified 20 Dec. 2004) for complete site description, experimental design, and protocols.

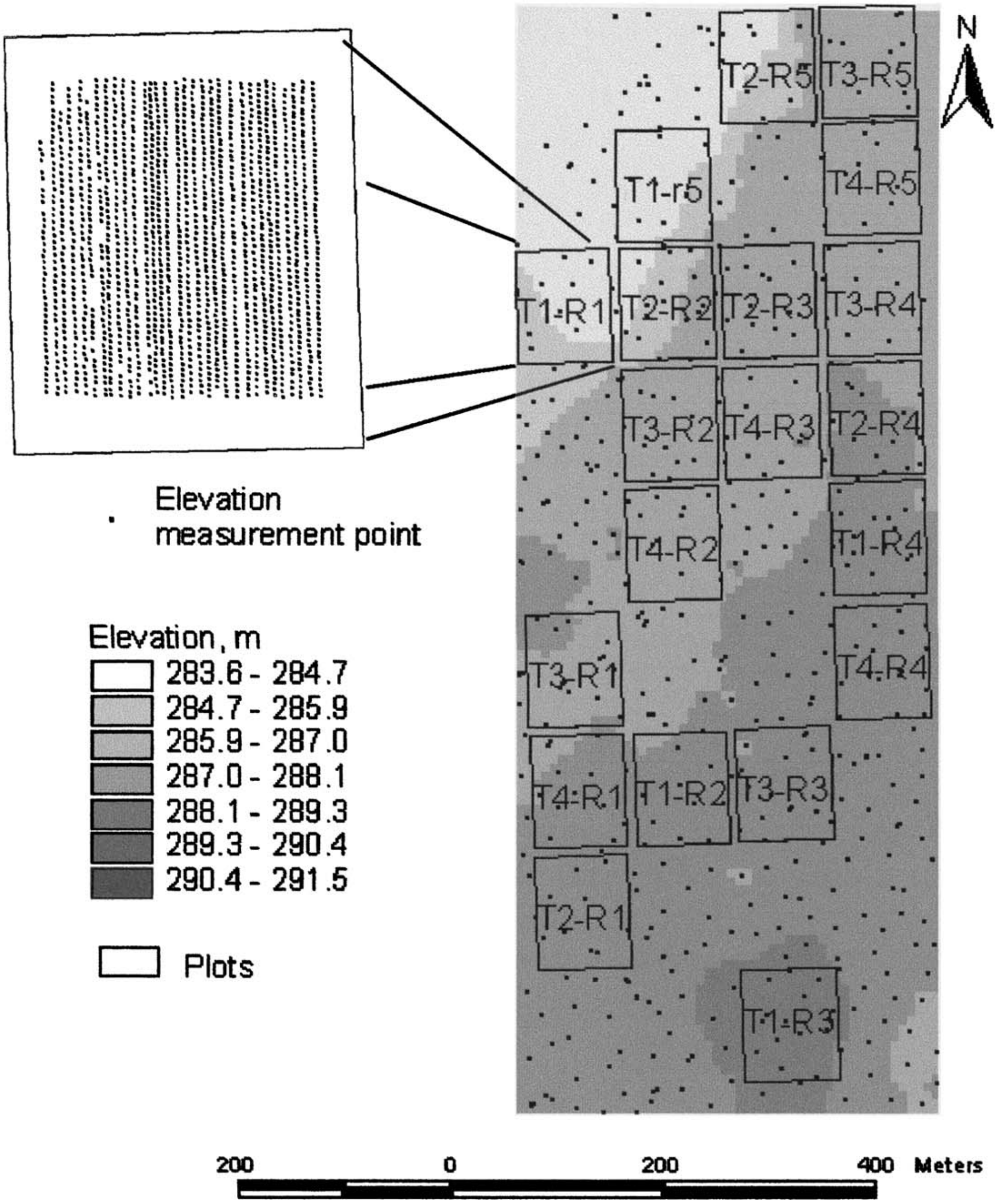


Fig. 1. Layout of the first five replications (blocks) of the experimental site with locations of the elevation measurements, locations of the experimental plots from the four treatments used in the study, and the 15- by 15-m interpolated elevation map. The plots are labeled with the last two letters from their treatment names and respective replication numbers, e.g., T2-R1 is the plot from Replication 1 that received treatment NoTillConv-T2. Inclusion represents an example of yield data points collected from each experimental plot via combine monitor.

plot yield to the average yield from that plot, was used to characterize the overall variability. General relative variograms and correlograms were used to characterize spatial components of the yield variability within each plot and were computed using GSLIB software (Deutsch and Journel, 1998).

A general relative variogram was calculated by standardizing the regular semivariogram using the square mean of the data for each lag distance (Deutsch and Journel, 1998):

$$\gamma_{\mathrm{GR}}(h) = \frac{\dfrac{1}{2N(h)}\displaystyle\sum_{i=1}^{N(h)}(x_i - y_i)^2}{\left(\dfrac{m_{-h} + m_{+h}}{2}\right)^2}$$

where $N(h)$ is the number of data pairs for a separation lag h, x_i is the first value from the data pair (tail value), y_i is the second value of the data pair (head value), m_{-h} is the mean of the tail values, and m_{+h} is the mean of the head values. We decided to use general relative variograms instead of traditional semivariograms in this study because standardizing by the means reduces proportional effect and results in less erratic variogram values, hence providing a more accurate view of the spatial variability structure (Isaaks and Srivastava, 1989). At the same time, the general relative variograms allow for comparisons between spatial variability patterns of different treatments that account not only for the shape but also the magnitude of the variogram values. The components of the general relative variograms that were studied included range

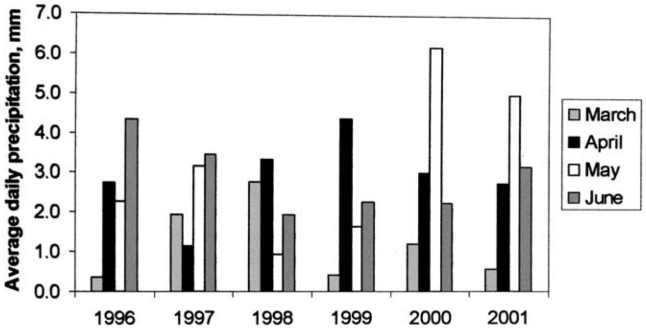


Fig. 2. Average daily precipitation values for the period March–June of the studied years.

and behavior near the origin. The range was determined by visual inspection of the variogram. The behavior near the origin was characterized, first, using the slope of a line fitted to the variogram values at the first three lag distances, i.e., 1.5, 5, and 10 m, and, second, using variogram value at the shortest lag distance of 1.5 m (Var1.5). Example of the general relative variogram for the 1996 corn yield data from Replication 3 plot of the treatment ChiselNoChem-T4 with regression line used to obtain the variogram slope near origin and Var1.5 value highlighted is shown in Fig. 3.

Correlograms were calculated as

$$\rho(h) = \frac{\dfrac{1}{N(h)}\sum_{i=1}^{N(h)} x_i y_i - m_{-h}m_{+h}}{\sigma_{-h}\sigma_{+h}}$$

where σ_{-h} and σ_{+h} are the standard deviations of the tail and head values.

We used the integral scale as a characteristic of the overall spatial correlation strength in yield data of a given plot (Gajem et al., 1981; Warrick et al., 1986; Yates et al., 1988):

$$\lambda^* = \left[2\int_0^\infty h\rho(h)dh\right]^{1/2}$$

The integral scale defines the range of influences beyond which the values are independent from each other. It provides a concise and convenient characterization of the spatial variability pattern since it takes into account both the spatial correlation range and the correlogram's shape.

To obtain the integral scale, we fitted the experimental correlograms with polynomial equations. The highest-order polynomial used was equal to 4, and adjusted R^2 was used as a criterion for choosing the order of the polynomial. The polynomial function was integrated as:

$$\begin{aligned}\lambda^* &= \left[2\int_0^a h\rho(h)dh\right]^{1/2} \\ &= \left[2\int_0^a h(\beta_0 + \beta_1 h + \cdots + \beta_k h^k)dh\right]^{1/2} \\ &= \left[\beta_0 a^2 + \beta_1\frac{2a^3}{3} + \cdots + \beta_k\frac{2a^{k+2}}{k+2}\right]^{1/2}\end{aligned}$$

where β_k is the coefficient of the polynomial equation, k is the order of the polynomial, and a is the distance at which the correlogram value approaches zero.

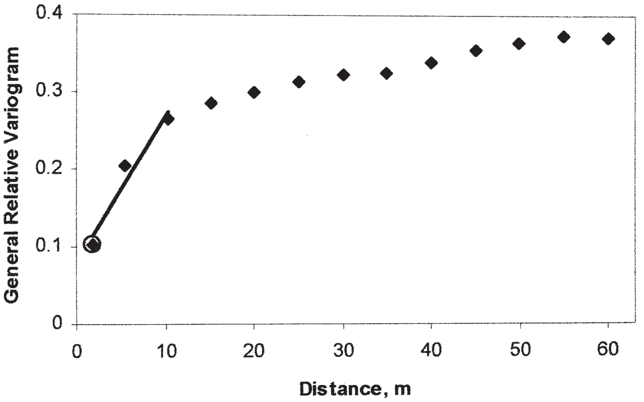


Fig. 3. Example of a general relative variogram calculated for the 1996 corn yield data from the Replication 3 plot of ChiselNoChem-T4 treatment. Variogram slope near origin (0.0191) was obtained by fitting linear regression line (solid line) to the variogram values at the first three lag distances. Variogram value at the shortest lag distance (Var1.5) is marked with an open circle.

Statistical Analysis

Variability characteristics calculated for individual plots were further used as dependent variables in the statistical analysis. The statistical model for studying treatment and year effects on yield variability characteristics, y_{ijk}, was specified as

$$y_{ijk} = \mu + \text{block}_j + \text{trt}_i + \text{plot}_{ij} + \text{year}_k + \text{year}_k \times \text{trt}_i + \beta_{ik}X_{ij} + \text{e}_{ijk}$$

where μ is the overall mean, block is the random effect of the replications (blocks), trt is the fixed effect of treatments, plot is a random effect of a plot used as an error term to test treatment effects, year is the fixed effect of year, year*trt is the interaction between year and treatment effect, βX is a topographical covariate and its interaction with treatments and/or years, and e is the residual. The effect of crop type was initially included in the statistical model as a fixed effect with years used as an error term. However, the crop effect and all the interaction terms with crop were negligible for all studied variability characteristics. Hence, we decided not to include the crop effect in the final statistical model. The nonsignificant crop effect was most likely a result of only 2 yr of data available for each crop.

To assess the contribution of the studied topographical variables, that is slope, curvature, flow accumulation, and soil wetness index, we included them as covariates in the statistical model (Milliken and Johnson, 2002). The simplest possible expression for the covariate component of the model was obtained by sequentially deleting the higher-order interaction terms involving the covariate. The analysis was conducted using PROC MIXED (SAS Inst., Cary, NC). Normal probability plots of the residuals revealed no deviations from normality. Unequal variances among different treatment and years were accounted for with REPEATED/GROUP option when needed. Then, multiple comparisons between treatments were conducted separately for each year based on the selected statistical model.

The effect of topographical characteristics and weather conditions on crop yield variability characteristics was also studied using multiple regression analysis. The regression models included linear, quadratic, and interaction components for topographical (T) and weather (W) variables:

$$y_{ijk} = \beta_0 + \beta_1 T_{ik} + \beta_2 T_{ik}^2 + \beta_3 W_j + \beta_4 W_j^2 + \beta_5 T_{ik} W_j + e_{ijk}$$

Models were built using Type I sum of squares, and the components significant at 0.05 level were kept in the model. When a quadratic component or an interaction was found to be

Table 1. Means and coefficients of variation for crop yields by year and treatment averaged from the available plots.

		Mean				Coefficient of variation			
Year	**Crop**	**ChiselConv-T1**	**NoTillConv-T2**	**ChiselLow-T3**	**ChiselNoChem-T4**	**ChiselConv-T1**	**NoTillConv-T2**	**ChiselLow-T3**	**ChiselNoChem-T4**
		Mg ha^{-1}				%			
1996	Corn	3.2ab†	3.9bc	4.2c	2.5a	37a	38ab	31a	43b
1997	Soybean	1.5a	2.0c	1.8b	1.6ab	45c	31a	32ab	39bc
1998	Wheat	3.0d	2.8c	2.2b	1.1a	27a	23a	26a	36b
1999	Corn	4.0ab	3.7a	4.4b	4.2ab	31a	39b	23a	28a
2000	Soybean	2.6a	2.9a	2.8a	2.9a	16a	19a	19a	14a
2001	Wheat	4.2c	3.7b	3.7b	2.7a	15a	20a	19a	19a

† Values within the same row for means and coefficients of variation followed by the same letter are not significantly different from each other ($p < 0.1$).

significant, the corresponding linear components were also kept in the model. Because of the limited number of years and topography data, we only included in the model two variables at a time (one topographical and one weather variable). The reported models are those that provided the highest prediction accuracy of the variability characteristics as judged by the lowest mean square for error values. The regression analysis was conducted using PROC REG (SAS Inst., Cary, NC).

RESULTS AND DISCUSSION

The topographical variable that was the most significant covariate for yield variability characteristics was maximum terrain slope of the plot. Hence, only the results of analyses with maximum terrain slope are shown. The weather variable that was most useful as a covariate in predicting yield variability was the average daily precipitation during a period from April to June. Other variables that were somewhat significant in explaining yield variability were average daily precipitations from individual months of March, April, May, and June and the average daily precipitation from April to May. Only the results with the most significant weather variables are shown.

Coefficient of Variation

The effect of treatments on the mean yields and coefficients of variation differed from year to year (Table 1). The CV values depended on the type of management, the diversity of field topography, and on the prevailing weather conditions in different years.

The CV values were significantly higher in the zero-input treatment (ChiselNoChem-T4) than in treatments ChiselConv-T1 and ChiselLow-T3 in 1996, treatment NoTillConv-T2 in 1997, and all the other treatments in 1998 (Table 1). These 3 yr were the years with average (1996 and 1997) or below-average (1998) spring–early-summer precipitations. We hypothesize that in ChiselNoChem-T4, the plants in the sites with lower elevation might have been growing under relatively sufficient nutrient and water regime while plants at the higher-elevation sites might have been severely affected not only by the lack of nutrients, but by lack of water as well. This was most pronounced in 1998 with dry May–June conditions during the critical stage of plant development for wheat. The results are consistent with those reported by Rockström et al. (1999), who observed higher variability in millet [*Pennisetum glaucum* (L.) Br.] yield in nonfertilized compared with fertilized treatments in water-stressed conditions of the Sahel (Niger).

There was no significant difference between CV values of the studied treatments in either 2000 or 2001, both years with wet springs and early summers. The CV values were also substantially lower in these 2 yr than in any other studied years. During these 2 yr, higher-elevation sites probably had sufficient water supply, which ensured somewhat higher yields than those during years with average/low precipitation, resulting in overall more uniform yields from the plots.

Although in 1999 the total spring–early-summer precipitation was much lower than in 2000–2001, the CV value of ChiselNoChem-T4 was not higher than that of other treatments. A possible explanation could be a number of very high precipitation events that occurred at the end of April before planting and at the end of June just before the critical corn-yield-determining period of anthesis. These events probably prevented water stress at higher-elevation areas. Furthermore, in 1999, the no-till treatment, NoTillConv-T2, had the highest CV value. This increase in variability may be due to no-till corn grain yield antagonism from previous wheat crop similar to that reported by Beuerlein and Houdashelt (1997). Yield data (Table 1) indicated that the no-till treatment had the lowest corn grain yields relative to the other treatments in 1999. Additionally, in 1996, the other study year with corn following wheat, the no-till treatment also tended to have a higher yield CV value relative to the other treatments. The occurrence of higher corn grain yield CV values in the presence of stress from an antagonistic effect of the previous wheat crop in the no-till system is consistent with the finding of higher overall CV values during moisture stress years as reported above.

The effect of topography on the CV values was also different in different treatments. Table 2 shows statistically significant ($p < 0.1$) correlation coefficients between CV values and maximum terrain slope values for the studied treatments in the 6 yr. Significant positive correlation was observed for ChiselNoChem-T4 in 1996, 1997, and 1999 and for ChiselConv-T1 and NoTillConv-T2 in 1998. There was no significant correlation between CV and terrain slope in 2000 and 2001. Initially, we hypothesized that higher topographical diversity would result in higher yield variability in all studied treatments and that the relationship between them would be particularly strong in years with limiting precipitation. However, the linear trend in CV–terrain slope relationship was pronounced only in ChiselNoChem-T4. This implies that although water availability was an important factor

Table 2. Correlation coefficients between the yield coefficients of variation and maximum terrain slope. Only correlation coefficients significant at $p < 0.1$ are shown in the table.

	Years					
Treatment	1996	1997	1998	1999	2000	2001
ChiselConv-T1	–	–	0.90	–	–	–
NoTillConv-T2	–	–	0.97	–	–	–
ChiselLow-T3	–	–	–	–	–	–
ChiselNoChem-T4	0.96	0.99	–	0.97	–	–

affecting yield variability in this study, nutrient availability also had a major effect on yield variability within the plots. For example, the main difference between ChiselNoChem-T4 and ChiselLow-T3 is that ChiselLow-T3 received additional N inputs. The CV values of ChiselNoChem-T4 were correlated with terrain slope while those of ChiselLow-T3 were not related to terrain slopes. This indicates that spatial distribution of plant available N along topographical gradients in the experimental plots was the main driving force of differences in yield variability between these two treatments.

Correlation coefficients reported in Table 2 characterize the linear component of the relationship between CV and terrain slope. Higher-order components of these relationships in different treatments and at different weather conditions were quantified using multiple regression models (Fig. 4). The relationship between CV and terrain slope was quadratic in ChiselConv-T1 and linear in ChiselNoChem-T4, but the effect of slope was not significant in NoTillConv-T2 and ChiselLow-T3. The quadratic relationship with slope of ChiselConv-T1 can be explained by considering that in this study, the flat plots with low slopes as well as plots with high slopes from backslope areas had the most uniform growth conditions. The plots with medium slopes often were from toeslope and footslope positions and included depressions as well as sloped areas, which resulted in more diversity of growth conditions. Hence, our lower variability at high slopes observed in this study may to some extent have resulted from small size of the experimental plots. It is likely that in large fields, a more diverse set of topographical conditions will be present; hence, higher maximum terrain slopes per field are likely to be associated with higher yield CV values, resulting in a linear or continuously increasing relationship between the maximum terrain slope and yield CV values.

The average daily April–June precipitation was found to be the best yield CV predictor among the weather variables. The regression for ChiselLow-T3 was not significant (at $P < 0.05$). In the other three treatments, the relationship with precipitation was best described by a quadratic curve, reflecting low CV values in the 2 yr with wet springs (2000 and 2001).

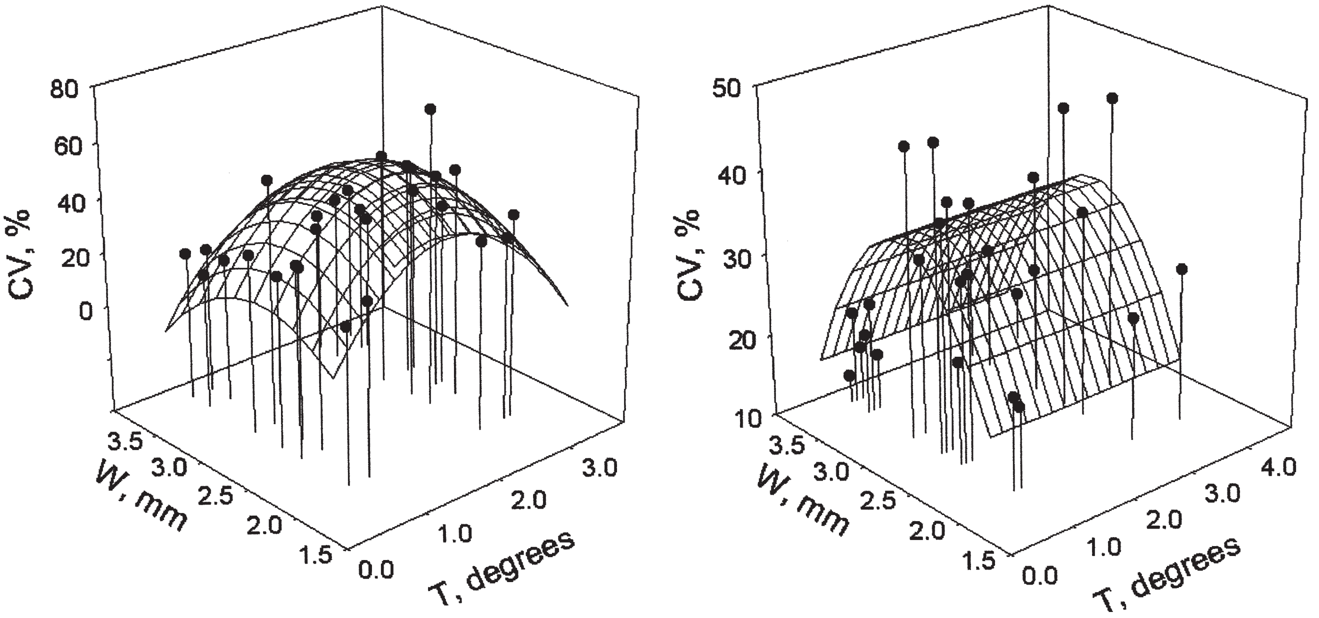
Spatial Variability: Variograms

As an example of typical yield variograms encountered in this study, we present general relative variograms for 1998 wheat yields from the five available replications of the ChiselConv-T1 and six replications of ChiselNoChem-T4 treatments (Fig. 5). Treatment effect on the Var1.5 was similar to that observed for the CV (Table 3). In 1996 and 1998, the Var1.5 values were significantly higher in ChiselNoChem-T4 that in the other treatments. In 1999, the Var1.5 values in NoTillConv-T2 were significantly higher than the Var1.5 values for ChiselLow-T3 and ChiselNoChem-T4. Also, in 1999, the variogram slope near the origin was greater in NoTillConv-T2 than that in any other treatment. This result lends further support to the occurrence of greater corn grain yield variability from the apparent antagonism of the previous wheat crop in the no-till system. Additionally, the integral scale values for the no-till treatment (NoTillConv-T2) during the corn grain years (1996 and 1999) tended to be higher than those of ChiselConv-T1 and ChiselLow-T3 and relatively higher than the integral scale values for the soybean and wheat crop years within the no-till system treatment (NoTillConv-T2). The trend for higher values of spatial variability characteristics suggests the observed antagonistic effect of wheat crop on no-till corn may be manifested both on a small scale, as expressed by the Var1.5 and the variogram slope near origin values, and on a large scale, as reflected in higher integral scale values. Note, that in this study, the small-scale variability is only considered in the direction of combine harvester path while small-scale variations in perpendicular direction are smoothed.

None of the topographical variables were significantly correlated with Var1.5 values. This result was expected since crop variability characterized by Var1.5 occurs at a range of distances and scales much smaller than those of topographical measurements in this study. However, Var1.5 values were affected by weather conditions. The Var1.5 values were significantly lower in the 2 yr of high spring precipitation (2000 and 2001). This indicates not only an overall reduction of variability in yields as reflected in lower CV values in these two wet years, but also that the crop yields at very short distances (1.5 m) were much more uniform than in 1996–1999.

The slope of the line fitted to the first three variogram lag distances captured variogram behavior near the origin, hence variability at a scale 1.5 to 10 m. In four of the six studied years, the slopes of ChiselNoChem-T4 were greater than those of either some (1996, 1997) or all (1998, 2001) other treatments. That is, the yield variability in ChiselNoChem-T4 increased with distance much more rapidly than that in the other treatments as distance increased from 1.5 to 10 m. It indicates that crop yields of the no-input system (ChiselNoChem-T4) were more sensitive to small-scale variations in nutrient availability and water availability conditions of the field, resulting in spatial continuity decreasing faster with distance compared with that of other treatments. The small-scale pattern of yields in ChiselNoChem-T4 was, thus, more heterogeneous than that of the other treatments with the areas of similar yields being smaller in this treatment than in the others.

The maximum terrain slope and average daily April–June precipitation were significantly related to the variogram slopes near the origin (Table 4). Similar to CV, in ChiselConv-T1, the quadratic terms for terrain slope and precipitation were statistically significant. The high-



a) ChiselConv-T1:
$y_{ijk} = -192.9 + 60.1T_{ik} - 14.9T_{ik}^2 + 135.2W_j - 24.8W_j^2, \quad adjR^2 = 0.62$

b) NoTillConv-T2: $y_{ijk} = -154.39 + 132.8W_j - 23.1W_j^2, \quad adjR^2 = 0.52$

c) ChiselNoChem-T4: $y_{ijk} = -74.0 + 10.0T_{ik} + 79.0W_j - 15.5W_j^2, \quad adjR^2 = 0.64$

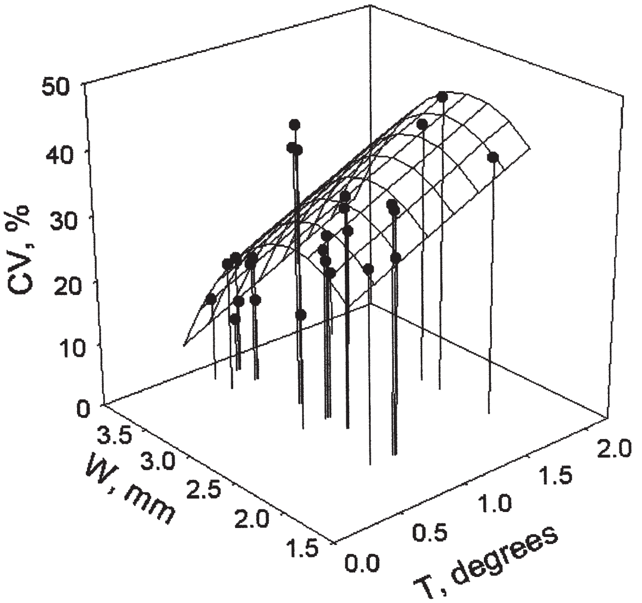


Fig. 4. Coefficient of variation for crop yields (y_{ijk}) as a function of terrain slope (T) and average daily precipitation in April–June (W) in (a) ChiselConv-T1, (b) NoTillConv-T2, and (c) ChiselNoChem-T4. The results were not significant for ChiselLow-T3 (not shown). Effect of terrain slope (T) was not significant for NoTillConv-T2 and hence is not included.

est variogram slopes near the origin were observed at average terrain slope values and average precipitations, indicating that these were the conditions with the highest small-scale diversity of plant growth conditions producing small-sized patterns in yield distributions. Wet conditions of 2000 and 2001 probably provided more uniform water availability conditions, resulting in stronger spatial continuity of yields at distances up to 10 m, that is, in larger patterns of similar yields at this scale. Terrain slope was not related to the variogram slopes near the origin in NoTillConv-T2, suggesting that, in general, the presence of crop residue on the soil surface might have helped buffer the small-scale yield variability associated with terrain slope (e.g., by reducing runoff). In ChiselNoChem-T4, variogram slopes near the origin were linearly increasing with terrain slope and linearly decreasing with higher precipitation (Table 4).

Range was significantly ($P < 0.1$) lower in NoTill-

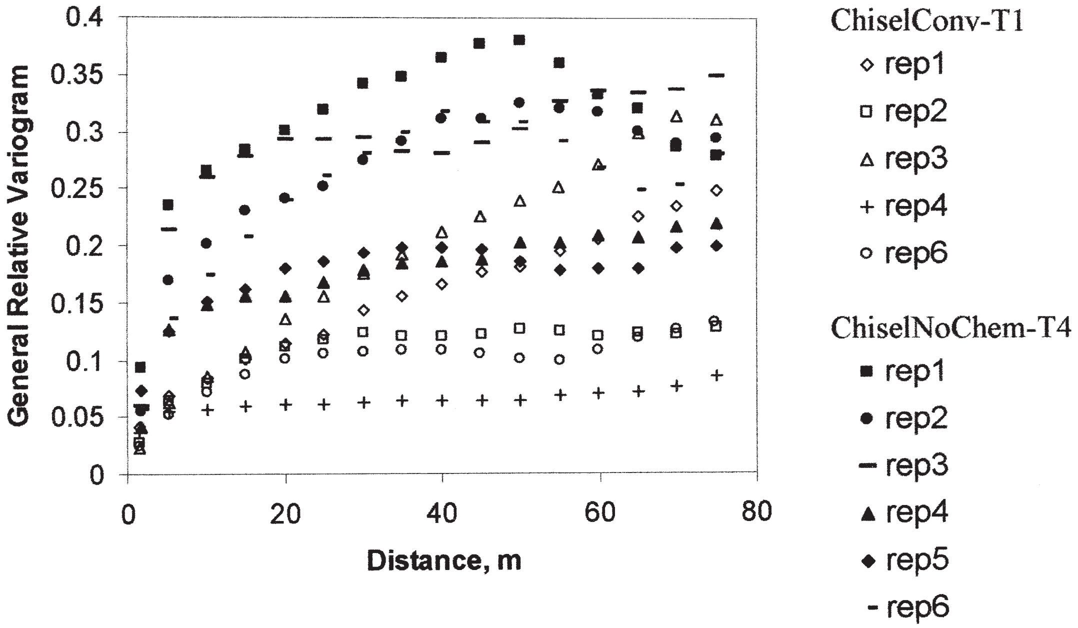


Fig. 5. General relative variograms for 1998 wheat yield from the five experimental plots of ChiselConv-T1 treatment and six experimental plots of the ChiselNoChem-T4 treatment.

Conv-T2 than in all the other treatments in 1997, and range was significantly higher in ChiselConv-T1 than in NoTillConv-T2 and ChiselLow-T3 in 1998. There was no significant relationship between range and topographical variables. Range was significantly positively correlated with the average daily April–May precipitation in NoTillConv-T2 and ChiselNoChem-T4 ($P <$ 0.01). However there was no significant correlation between range and weather variables in ChiselConv-T1 and ChiselLow-T3. These observations are consistent with other indications of more spatially correlated pattern of yields in the wet years of 2000 and 2001 as observed from the lower Var1.5 and lower variogram slope near the origin values. Similar results were reported by Jaynes and Colvin (1997), who observed positive correlation between range and growing season precipitation in a 6-yr study with corn and soybean yields. Schepers et al. (2004) in a 5-yr study on an irrigated field observed lowest spatial correlation ranges in the driest and the wettest years of their study.

The integral scales were not significantly different among the treatments in four of the six studied years. In 1997, the integral scales in NoTillConv-T2 were lower than those in the other treatments while in 2001, the integral scales in NoTillConv-T2 were higher than those in the other treatments (Table 3). For individual treatments, there was no statistically significant relationship between topographical and weather variables with the integral scales ($P < 0.05$).

For the combined data from all the treatments, there was a significant interaction between terrain slope and average daily April–June precipitation effects on the integral scales (Fig. 6). For plots with low slopes, the integral scales were increasing with higher precipitation. In plots with high slopes, the integral scales were much larger in dry than in wet springs and changed substantially during the 6 yr studied. In these plots, there were substantial areas of yield affected by water distribution during dry springs. However, during wet springs, the yield spatial patterns were probably mainly affected not by the overall lack of water, but by smaller-scale variations in water contents and soil properties, hence resulting in smaller integral scale values.

SUMMARY

The overall variability (CV) and the spatial variability of crop yields were affected by management practice and related to spring–early-summer weather conditions and field topography. Stressful conditions, regardless of the stress's origin, were associated with increase in both the overall yield variability and the small-scale yield variability, making yields more sensitive to the small-scale variations in growth conditions due to soil and microtopographical differences. Increase in variability was observed in crops under lack of water stress and lack of N stress as well as in corn stressed by antagonism from previous wheat crop in no-till management. The results support the notion that in well-managed fields of North-Central region, weather-related stresses are one of the major sources of influence on yield variability. The effects of these water stresses are either enhanced or relieved within the field, e.g., higher or lower water availability at sites with corresponding topography. Water stresses and yield variability associated with them are also enhanced or relived by management features, e.g., enhanced by shortage of N in organic systems, enhanced by corn/wheat antagonism in no-till, and somewhat relieved by no-till management in soybean and wheat.

Specifically, higher coefficients of variation, higher variogram values at 1.5-m distance, and higher variogram slopes near the origin were observed in the years with low or average precipitations than in the 2 yr with

Table 3. Spatial variability characteristics for crop yields by year and treatment averaged from the available plots.

Year	Crop	ChiselConv-T1	NoTillConv-T2	ChiselLow-T3	ChiselNoChem-T4	ChiselConv-T1	NoTillConv-T2	ChiselLow-T3	ChiselNoChem-T4
		Variogram value at 1.5-m lag distance				Variogram slope near origin			
1996	Corn	0.07a†	0.07a	0.05a	0.12b	0.013ab	0.011ab	0.008a	0.020b
1997	Soybean	0.06b	0.04a	0.04a	0.04a	0.020ab	0.012a	0.011a	0.024b
1998	Wheat	0.03a	0.03a	0.03a	0.06b	0.006a	0.005a	0.008a	0.016b
1999	Corn	0.04ab	0.05b	0.02a	0.03a	0.007a	0.015b	0.004a	0.005a
2000	Soybean	0.01a	0.02a	0.01a	0.01a	0.003a	0.004a	0.005a	0.002a
2001	Wheat	0.02a	0.02a	0.04a	0.02a	0.001a	0.004a	0.003a	0.005b
		Range				Integral scale			
		m							
1996	Corn	18a	20a	27a	25a	6.6a	9.2a	8.0a	6.0a
1997	Soybean	23b	13a	27b	17b	8.3b	4.4a	8.1b	6.1ab
1998	Wheat	31b	20a	21a	27ab	8.7a	6.5a	7.6a	7.2a
1999	Corn	30a	27a	30a	31a	10.0a	11.1a	10.0a	11.8a
2000	Soybean	25a	30a	31a	34a	6.6a	5.5a	7.4a	7.3a
2001	Wheat	27a	27a	22a	29a	3.9a	7.7b	4.3a	5.8ab

† Values within the same row for each spatial variability characteristic are not significantly different from each other ($p < 0.1$).

Table 4. Regression models for the variogram slope near origin for crop yields (y_{ijl}) as a function of terrain slope (T) and average daily precipitation in April–June (W).

Treatment	Regression equation	Adjusted R^2
ChiselConv-T1	$y_{ijl} = -0.12 + 0.04T_{il} - 0.01T_{il}^2 + 0.08W_j - 0.01W_j^2$	0.39
NoTillConv-T2	$y_{ijl} = -0.09 + 0.07W_j - 0.01W_j^2$	0.46
ChiselLow-T3	NS	
ChiselNoChem-T4	$y_{ijl} = 0.02 + 0.01T_{il} - 0.01W_j$	0.38

high spring–early-summer precipitations. Both the coefficients of variation and the small-scale variability were even higher in the zero chemical input (organic) treatment (ChiselNoChem-T4) than in the treatments that received any fertilizer inputs. However, in years with above-average spring–early-summer precipitation, there was no noticeable difference in coefficients of variation or spatial variability patterns of the studied management treatments.

Terrain slope was the topographical variable most

$$y_{ijk} = -17.4 + 7.5T_{ik} - 0.7T_{ik}^2 + 14.1W_j - 2.3W_j^2 - 1.2TW_{ijk}, \quad R^2 = 0.24$$

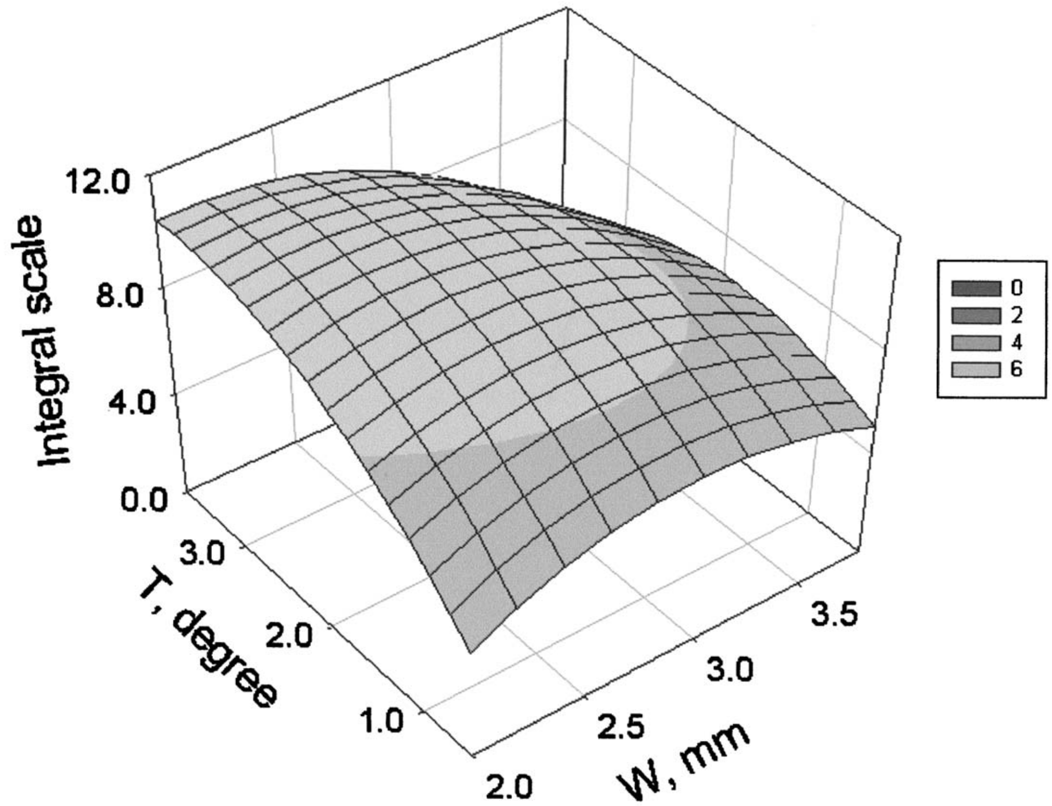


Fig. 6. Integral scale(y_{ijk}) as a function of terrain slope (T) and average daily precipitation in April–June (W).

closely related to yield variability in this study. The coefficients of variation, variogram slopes near origin, and integral scales were related to terrain slope with different quantitative relationships observed in different treatments.

Amount of precipitation obtained from April to June was the weather variable most strongly related to the CV and small-scale variability characteristics, such as variogram value at 1.5-m lag distance and variogram slope near the origin. For the large-scale variability characteristics, such as range and integral scale, the range increased with increasing April–May precipitation while the relationship between precipitation and the integral scale varied with the topographical (terrain slope) characteristics of the plot.

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REFERENCES

Beuerlein, J., and P. Houdashelt. 1997. Corn and bean yields fall when no-tilled after wheat [Online]. Available at http://www2.agriculture.purdue.edu/agcomm/aganswers/story.asp?storyID=896 (verified 20 Dec. 2004). College of Agric., Purdue Univ., West Lafayette.

Changere, A., and R. Lal. 1997. Slope position and erosional effects on soil properties and corn production on a Miamian soil in Central Ohio. J. Sustainable Agric. 11:5–21.

Deutsch, C.V., and A.G. Journel. 1998. Geostatistical software library and user's guide. Oxford University Press, New York.

Drummond, S., and K. Sudduth. 2003. From sensors to information: Cleaning yield monitor data. Proc. InfoAg 2003 Conf., Indianapolis, IN. 29 July–1 Aug. 2003. Potash and Phosphate Inst., Norcross, GA.

Environmental Systems Research Institute. 1996. ArcView Spatial Analyst. ESRI, Redlands, CA.

Gajem, Y.M., A.W. Warrick, and D.E. Myers. 1981. Spatial dependence of physical properties of a Typic Torrifluvent soil. Soil Sci. Soc. Am. J. 45:709–715.

Isaaks, E.H., and R.M. Srivastava. 1989. An introduction to applied geostatistics. Oxford Univ. Press, New York.

Jaynes, D.B., and T.S. Colvin. 1997. Spatiotemporal variability of corn and soybean yield. Agron. J. 89:30–37.

Jaynes, D.B., T.C. Kaspar, T.S. Colvin, and D.E. James. 2003. Cluster analysis of spatiotemporal corn yield patterns in an Iowa field. Agron. J. 95:574–586.

Jiang, P., and K.D. Thelen. 2004. Effect of soil and topographic properties on crop yield in a North-Central corn–soybean cropping system. Agron. J. 96:252–258.

Kaspar, T.C., T.S. Colvin, D.B. Jaynes, D.L. Karlen, D.E. James, and D.W. Meek. 2003. Relationship between six years of corn yields and terrain attributes. Precis. Agric. 4:87–101.

Kravchenko, A.N., and D.G. Bullock. 2000. Correlation of corn and soybean grain yield with topography and soil properties. Agron. J. 92:75–83.

Lamb, J.A., R.H. Dowby, J.L. Anderson, and G.W. Rehm. 1997. Spatial and temporal stability of corn grain yields. J. Prod. Agric. 10:410–414.

Lark, R.M. 2001. Some tools for parsimonious modeling and interpretation of within-field variation of soil and crop systems. Soil Tillage Res. 58:99–111.

Machado, S., E.D. Bynum, Jr., T.L. Archer, R.J. Lascano, L.T. Wilson, J. Bordovsky, E. Segarra, K. Bronson, D.M. Nesmith, and W. Xu. 2002. Spatial and temporal variability of corn growth and grain yield implications for site-specific farming. Crop Sci. 42:1564–1576.

McConkey, B.G., D.J. Ulrich, and F.B. Dyck. 1997. Slope position and subsoiling effects on soil water and spring wheat yield. Can. J. Soil Sci. 77:83–90.

Milliken, G.A., and D.E. Johnson. 2002. Analysis of messy data: Analysis of covariance. CRC Press, Boca Raton, FL.

Moore, I.D., P.E. Gessler, G.A. Nielsen, and G.A. Peterson. 1993. Soil attribute prediction using terrain analysis. Soil Sci. Soc. Am. J. 57:443–452.

Perfect, E., and J. Caron. 2002. Spectral analysis of tillage-induced differences in soil spatial variability. Soil Sci. Soc. Am. J. 66:1587–1595.

Porter, P.M., J.G. Lauer, D.R. Huggins, E.S. Oplinger, and R.K. Crookston. 1998. Assessing spatial and temporal variability of corn and soybean yields. J. Prod. Agric. 11:359–363.

Robertson, G.P., J.R. Crum, and B.G. Ellis. 1993. The spatial variability of soil resources following long-term disturbance. Oecologia 96:451–456.

Robertson, G.P., K.M. Klingensmith, M.J. Klug, E.A. Paul, J.C. Crum, and B.G. Ellis. 1997. Soil resources, microbial activity, and primary production across an agricultural ecosystem. Ecol. Appl. 7:158–170.

Rockström, J., J. Barron, J. Brouwer, S. Galle, and A. de Rouw. 1999. On-farm spatial and temporal variability of soil and water in pearl millet cultivation. Soil Sci. Soc. Am. J. 63:1308–1319.

Roel, A., and R.E. Plant. 2004. Spatiotemporal analysis of rice yield variability in two California fields. Agron. J. 96:77–90.

Schepers, A.R., J.F. Shanahan, M.A. Liebig, J.S. Schepers, S.H. Johnson, and A. Luchiari, Jr. 2004. Appropriateness of management zones for characterizing spatial variability of soil properties and irrigated corn yields across years. Agron. J. 96:195–203.

Schmidt, F., and A. Persson. 2003. Comparing of DEM data capture and topographic wetness indices. Precis. Agric. 4:179–192.

Si, B.C., and R.E. Farrell. 2004. Scale-dependent relationship between wheat yield and topographic indices: A wavelet approach. Soil Sci. Soc. Am. J. 68:577–587.

Simmons, F.W., D.K. Cassel, and R.B. Daniels. 1989. Landscape and soil property effects on corn grain yield response to tillage. Soil Sci. Soc. Am. J. 53:534–539.

Tawainga, W.K., W.J. Cox, H.M. Van Es, and M. Glos. 2003. Spatial yield response of two corn hybrids at two nitrogen levels. Agron. J. 95:1012–1022.

Timlin, D.J., Y. Pachepsky, V.A. Snyder, and R.B. Bryant. 1998. Spatial and temporal variability of corn grain yield on a hillslope. Soil Sci. Soc. Am. J. 62:764–773.

Tsegaye, T., and R.L. Hill. 1998. Intensive tillage effects on spatial variability of soil physical properties. Soil Sci. 163:143–154.

Warrick, A.W., D.E. Myers, and D.R. Nielsen. Geostatistical methods applied to soil science. 1986. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron Monogr. 9. ASA and SSSA, Madison, WI.

Whelan, B.M., and A.B. McBratney. 2000. The "null hypothesis" of precision agriculture management. Precis. Agric. 2:265–279.

Yates, S.R., A.W. Warrick, A.D. Matthias, and S. Musil. 1988. Spatial variability of remotely sensed surface temperatures at field scale. Soil Sci. Soc. Am. J. 52:40–45.