Spatial and Temporal Variability of Corn Grain Yield on a Hillslope

D. J. Timlin*, Ya. Pachepsky, V. A. Snyder, and R. B. Bryant

ABSTRACT

The purpose of this study was to relate the temporal and spatial variability of corn (*Zea mays* L.) grain yield on a Typic Fragiochrept soil on a hillslope to soil properties and topographic features. Corn grain yields were sampled from a field that measured 280 by 150 m using a grid and five transects. One-hundred forty yield measurements were taken on the grid (1983–1985) and 190 measurements on the transects (1984 and 1985) from plots 5.3 m long and two corn rows wide. Measurements of soil surface elevation, soil organic matter (OM), P, and K contents were also taken at the grid plot locations. These data were analyzed using the methods of spectral analysis. Yield spatial and temporal variability was strongly related to surface undulations and the value of surface curvature was found to be a useful parameter to quantify variations in topography. The intra-annual differences in weather had the largest effect on grain yield at locations where the magnitude of curvature was large. Where the magnitude of curvature was small, the correlations of yield for the wet (1984) and dry (1985) years were highly significant. Yields correlated with soil P, K, and OM only in the dry year, 1985. Yields in the relatively dry years (1983 and 1985) correlated with depth to fragipan. Elevation data helped us interpret the spatial and temporal variability of grain yield by separation of areas with convex curvature from areas with concave curvature.

Information on the spatial variability and distribution of crop yield can be used to tailor management practices for specific locations. Yields can now be mapped in detail, and techniques are needed to interpret yield maps in terms of soil variability and to develop site-specific management practices based on that variability (Mulla, 1991).

The variability of soil properties is large in complex hills (Miller et al., 1988). Soil physical properties such as clay content and distribution with depth, sand content, and pH have been shown to be highly correlated with landscape position (Ovalles and Collins, 1986). Sinai et al. (1981) showed that, in an arid region, moisture contents were highly correlated with the curvature of the soil surface. Organic matter (Miller et al., 1988; Bhatti et al., 1991) as well as water-holding capacity (Hanna et al., 1982) have also been shown to vary by slope position. The depth of the Ap horizon, which is an important soil fertility factor, is often greater in swales than on knolls (Miller et al., 1988).

Crop yields on hillslopes are affected by topography and the attendant differences in soil properties. Stone et al. (1985) reported correlations of crop yield with landscape position to be higher than with erosion class. It is difficult, however, to make generalizations about the relationships between topography and crop yield. Graveel et al. (1989) observed that corn yields were more variable on steep slopes but found no significant differences for degree of slope in a study of 24 yr of corn yields in Tennessee. Miller et al. (1988) found no correlations between slope percentage and wheat (*Triticum aestivum* L.) yields. Moulin et al. (1993) found that wheat yields were lowest on more highly elevated knolls where soil erosion losses were greatest. The effect, however, was modified by surface shape, whether convex or concave.

Many soil properties are spatially correlated (Gajem et al., 1981; Burrough, 1993), i.e., close locations are more likely to have similar soil parameters than remote locations. Spatial correlation of crop yields has also been reported. Early work demonstrated this correlation under irrigated conditions (Bressler et al., 1981, 1982; Morkoc et al., 1985). In later work, Miller et al. (1988) reported a range of spatial correlation for wheat yield of about 80 m in California. This value was similar for several soil properties, which included surface soil thickness and sand content. Boyer et al. (1991) observed a strong spatial correlation between biomass production and soil pH on a hillslope. Bhatti et al. (1991) found that the spatial correlation of wheat yields was related to organic matter distributions that resulted from erosion.

Because soil properties and associated crop yields are often spatially correlated, spatial analysis should be used when quantifying their variability. Miller et al. (1988) found that classical statistical techniques that did not account for spatial correlations were inadequate for showing the effects of soil erosion on dryland wheat yields. Methods adapted from time series analysis, mining geostatistics, and studies of turbulence have been applied as statistical tools to describe the interdependence and structural arrangement of soil properties (Burgess and Webster, 1980; Kachanoski et al., 1985a,b). These methods have also been applied to a description of the dependence of crop yields on soil properties (Bresler et al., 1981, 1982; Boyer, et al., 1991). Bhatti et al. (1991) suggested that easily measured covariates could be used to divide fields into management units. Soil properties such as A horizon thickness or topographic properties such as curvature have been shown to have a periodic component in their spatial distribution (Kachanoski et al., 1985a,b; Folorunso and Rolston, 1985). Spectral analysis was used in these studies to quantify the periodic distribution of variance.

Weather interacts in a complex way with topography to affect crop yields because of the relationships among soil relief, root growth, and hydrologic regime. Ciha (1984) demonstrated that winter wheat yields were most closely related to slope position. The relationship was especially noticeable during dry years and appeared to be related to the depth of the surface layer. In this context, surface curvature can be an informative characteristic of topographic relief. Kachanoski et al. (1985a)

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has shown that curvature is related to the accumulation or loss of soil from an area.

The purpose of this study was to investigate the spatial dependence of corn grain yields as related to topography, soil depth, levels of nutrients, and weather.

MATERIALS AND METHODS

Site and Sampling

The study site is on the Cornell agronomy research farm at Mt. Pleasant, NY. The dominant soil at the Mt. Pleasant site is a Mardin silt loam — a coarse loamy, mixed, mesic Typic Fragiochrept. This is a moderately well-drained soil that formed in uniform noncalcareous glacial till. The Mardin soil is not characterized by frequent occurrences of outwash lenses. Depth to the fragipan generally varies from 0.35 to 0.66 m, though some eroded areas have depths as shallow as 0.2 m and some depositional areas are as deep as 1 m. The slope varies from 6 to 15% and the soil surface undulates transverse to the slope.

Soil depth was defined as depth to the leached, elluviated horizon above the fragipan and was measured with a hand auger. Daily precipitation and Class A pan evaporation data were collected from a weather station located at the farm office, <1 km from the field. Elevations were measured using a surveying transit on a rectangular grid. The measurement intervals were 20 m in the *x* direction and 17 m in the *y* direction. The elevations were interpolated by kriging with Surfer (Golden Software, Golden, CO) using the default settings of a linear semivariogram. A contour elevation map was constructed from these measurements (Fig. 1).

The site had been in an alfalfa–timothy (*Medico sativa* L.–*Phleum pretense* L.) mix for the previous 3 yr (1980–1983). In the spring of 1983 the field was moldboard plowed to 0.15 m and treated with atrazine (2-chloro-4-ethylamino-6-isopropylamino-s-triazine) to control weeds before planting. The field was fertilized with 30 kg N ha^{-1}, 60 kg P ha^{-1}, and 30 kg K ha^{-1}. In 1983 to 1985, an early season variety of corn was planted in 0.76-m rows parallel to the slope and N was side dressed at the rate of 70 kg N ha^{-1} as anhydrous NH_3.

In 1983, corn grain yields were recorded from 140 plots spaced at 20-m intervals from east to west and at 17-m intervals north and south (Fig. 1). The choice of the grid spacing was based on the desire to place plots on all the major terrain features. Each harvested plot was four rows wide by 5.3 m long. The origin of the grid system (0,0) was set at the lower left-hand corner of the grid shown in Fig. 1. Columns harvested parallel to the *y* axis were labeled X1 to X14 (Fig. 1).

In 1984 and 1985, grain yields were measured for the same 140 plots but only two rows were harvested. Yields were also measured along five transects. Two vertical transects were laid out perpendicular to the slope at either end of the field (T1 and T2), and three horizontal transects were laid out parallel to the slope (T3, T4, and T5) (Fig. 1). Corn grain yields were harvested from two rows, 5.3 m long, and the plots were placed continuously along the transect. A total of 21 plots were harvested from each of the vertical transects (T1 and T2) and 51 plots from each of the horizontal transects (T3, T4, and T5).

Soil samples were taken for chemical analysis at the nodes of the grid. Half the grid was sampled in 1984 (68 samples) and the full grid was sampled in 1985. The samples were taken in the fall, shortly before harvest. Approximately 100 g of soil were collected with a 2.5-cm-diam. soil probe from the 0- to 15-cm layer at three locations in a plot. The bulked samples were analyzed for pH, OM, K, and P using standard methods

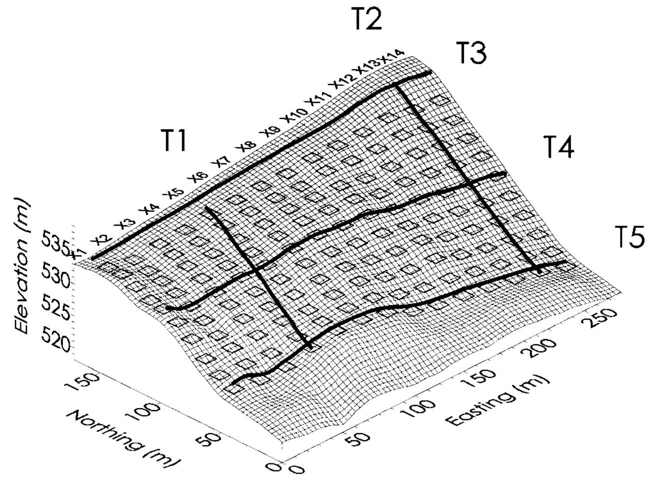

Fig. 1. Three-dimensional representation of surface elevations and plot locations at the Mt. Pleasant site. The grid plots are represented by squares. The columns of grid plots are identified as X1 through X14 labeled from the upper left side of the plot. The transects are labeled T1 through T5. The vertical scale is exaggerated by a factor of four.

at the Cornell University Soil Analysis Laboratory. The soil was ashed for P and K analysis. Phosphorus was analyzed by the vanadomolybdophosphoric acid method (Greweling, 1976) and K was analyzed by treating the soil with HCl and measured using atomic adsorption.

Spectral Analysis

A function known as the *autocorrelation function* provides information about the relative sequencing and clustering of events in a temporal or spatial sequence (Panofsky and Dutton, 1984). To compress information on spatial dependence of soil parameters and crop yield, we used power spectrum transforms of the covariance or autocorrelation function from a space domain to a frequency domain. The power spectrum shows how variance is distributed as a function of the sampling interval, hence the variance is described as a function of the frequency of samples (i.e., cycles per meter). The inverse of frequency is the period or sampling interval. An advantage of a power spectrum over autocorrelation functions is that estimates of variance at neighboring frequencies are approximately independent, which makes interpretation of a power spectrum easier (Jenkins and Watts, 1968). The nonstationary low-frequency components can also be easily filtered.

The power spectrum of a one-dimensional series, *x*, is calculated as

$$S_{xx}(f) = 2\Delta\left\{\mathrm{Cov}_{xx}(0) + 2\sum_{k=1}^{L-1}\mathrm{Cov}_{xx}(k)\,W(k)\,\mathrm{Cos}(2\,\pi f k\Delta)\right\} \quad [1]$$

where k is the lag; $\mathrm{Cov}_{xx}(0)$ and $\mathrm{Cov}_{xx}(k)$ are the sample covariances at lags 0 and k; $W(k)$ is a weighting function (window) that smooths the spectrum; Δ is the sampling interval; f is the frequency, calculated as $f = i/2\Delta N$, with $i = 1, 2, ..., N$, where N is the total number of observations in the series; and L is the truncation point, i.e., the maximum number of lags used to calculate the spectrum. Usually L is 30 to 40% of the total number of lags in the series. The $\mathrm{Cov}_{xx}(0)$ is equivalent to the overall variance of the series and is estimated as

$$\mathrm{Cov}_{xx}(0) = \frac{1}{N}\sum_{i=1}^{N}(X_i - \overline{X})^2 \quad [2]$$

where $\overline{X}$ is the mean of X in the series, the $\mathrm{Cov}_{xx}(k)$ in Eq. [1] is the covariance function at lag k, the estimate of which is given as

$$\mathrm{Cov}_{xx}(k) = \frac{1}{N}\sum_{i=1}^{N-k}(X_i - \overline{X})(X_{i+k} - \overline{X})$$
$$0 \leq k \leq L + 1 \quad [3]$$

The use of N rather than $N - 1$ as a divisor in Eq. [2] and [3] was suggested by Jenkins and Watts (1968). The Tukey window is used to calculate weights $[W(k)]$ for smoothing (Jenkins and Watts, 1968):

$$W(k) = \begin{cases} 0.5\left[1 + \mathrm{Cos}\left(\frac{\pi K}{L}\right)\right] & k < L \\ 0 & k \geq L \end{cases} \quad [4]$$

The number of lags (L) necessary to give an estimate of the peak with acceptably low bias depends on the widths of the peaks in the spectrum. The choice of bandwidth to distinguish the peaks for the transects was based on a compromise between the amount of detail required and the number of degrees of freedom desired for the estimate. The number of lags (L) is related to the bandwidth (b) for a Tukey window as $b = 1.333/L\Delta$, and the degrees of freedom as $2 \times 1.333 - L_t/L$. Here, 1.333 is the coefficient for the Tukey window, and L_t is the total number of lags in the transect. Maximum lag numbers of 5 and 10 were used to smooth the spectra for the vertical and horizontal transects, respectively. These values provided bandwidths of 0.055 and 0.023 (cycles m^{-1}) and 11 and 14 degrees of freedom (Jenkins and Watts, 1968) for the vertical and horizontal transects, respectively. These bandwidths correspond to smoothing windows of about 40 m for the horizontal transects and 18 m for the vertical.

The coherence is a measure of the correlation between two series (here denoted as x and z) as a function of frequency (Jenkins and Watts, 1968) and measures the influence of noise in the system. A large noise spectrum relative to the signal will result in a low coherency. The squared coherency, $K(f)^2_{xz}$, is calculated as (Jenkins and Watts, 1968)

$$K(f)^2_{xz} = \frac{A(f)^2_{xz}}{S(f)_{xx}\, S(f)_{zz}}$$

$$A(f)^2_{xz} = \sqrt{L(f)^2_{xz} + Q(f)^2_{xz}}$$

$$L(f)_{xz} = 2\Delta\left\{l_{xz}(0) + 2\sum_{k=1}^{L-1} l_{xz}(k)\, W(k)\, \mathrm{Cos}(2\pi fk\Delta)\right\}$$

$$Q(f)_{xz} = 4\Delta\sum_{k=1}^{L-1} q_{xz}(k)\, W(k)\, \mathrm{Sin}(2\,\pi\, fk\Delta) \quad [5]$$

Here $S(f)_{xx}$ and $S(f)_{zz}$ are the power spectra for series x and z, respectively, calculated using Eq. [1], and f is calculated here as it is for Eq. [1]; $L(f)_{xz}$ is the cospectrum between series x and z. The sample cospectrum gives the decomposition of the zero lag cross covariances with frequency. The even and odd cross covariance estimates $[l(k)_{xz}$ and $q(k)_{xz}]$ used in Eq. [5] are calculated as

$$l(k)_{xz} = \frac{1}{2}\{\mathrm{Cov}(k)_{xz} + \mathrm{Cov}(-k)_{xz}\}$$

$$q(k)_{xz} = \frac{1}{2}\{\mathrm{Cov}(k)_{xz} - \mathrm{Cov}(-k)_{xz}\} \quad 0 \leq k \leq L - 1 \quad [6]$$

Here $q(0)_{xz}$ and $q(F)_{xz} = 0$ and F is the highest frequency $[F = 1/(\Delta N)]$. The cross covariances $\mathrm{Cov}(k)_{xz}$ and $\mathrm{Cov}(-k)_{xz}$ are calculated as

$$\mathrm{Cov}_{xz}(k) = \frac{1}{N}\sum_{i=1}^{N-k}(X_{1i} - \overline{X}_1)(X_{2i+k} - \overline{X}_2)$$

$$\mathrm{Cov}_{xz}(-k) = \frac{1}{N}\sum_{i=1}^{N-k}(X_{1i+k} - \overline{X}_1)(X_{2i} - \overline{X}_2)$$
$$0 \leq k \leq L + 1 \quad [7]$$

Confidence limits for the spectral densities were calculated by the method given in Jenkins and Watts (1968, p. 254). A threshold limit for the coherency above which the coherency was significantly different from zero was calculated by a method given in Koopmans (1974, p. 284).

Integral scales or correlation distances can also be obtained from smoothed power spectra (Panofsky and Dutton, 1984). Correlation distances from spectral densities are determined by plotting the product of frequency and spectral density $[fS(f)]$ against the $\log_{10}$ of frequency. The correlation distance will be $1/f_{max}$, where f_{max} is the frequency at the maximum of $fS(f)$ (Panofsky and Dutton, 1984).

The covariance was normalized by dividing the covariances in Eq. [1] by $\mathrm{Cov}_{xx}(0)$, therefore the spectral density as used here is unitless. Trends were removed by fitting a quadratic or cubic function to the transect yield data. Trend was removed from the yield data if the fit to a polynomial function was significant ($P < 0.01$). Higher order polynomials were fit until the change in R^2 obtained by fitting the next highest order polynomial was judged to be negligible. The predicted values were subtracted from the measured value and the residuals were used in subsequent calculations.

Auxiliary Calculations

Means, standard deviations, correlations, and probability density distributions were calculated using SAS (SAS Institute, 1995). Tests for normal probability distributions were done with the Shapiro–Wilk test. Topographic curvature was calculated from the elevations interpolated to obtain elevations on a grid 3.58 m in the x direction and 2.94 m in the y direction. Curvature (M) was calculated from the elevations using the following approximation (Sinai et al., 1981):

$$M \approx \frac{\partial^2 Z}{\partial X^2} + \frac{\partial^2 Z}{\partial Y^2} = \nabla^2 Z \quad [8]$$

The derivatives in Eq. [8] were approximated as

$$\nabla^2 Z = \frac{(Z_{i+1,j} + Z_{i-1,j} - 2Z_{i,j})}{\Delta X^2} + \frac{(Z_{i,j+1} + Z_{i,j-1} - 2Z_{i,j})}{\Delta Y^2} \quad [9]$$

where Z is elevation, i represents the indices for the x coordinates and j for the y coordinates. Sinai et al. (1981) reported that the $\nabla^2 Z$ better correlated with soil moisture than the curvature M. The equation for calculating M is given in Sinai et al. (1981). In concave regions, the curvature will be positive and in convex regions it will be negative.

Only locations that had more than ± 0.0006 curvature were included into the analysis. This cutoff was determined as a function of the error in interpolating elevations.

RESULTS

Weather

The weather during the 3-yr period varied from very wet and cool to dry and warm. Generally 1983 and 1985

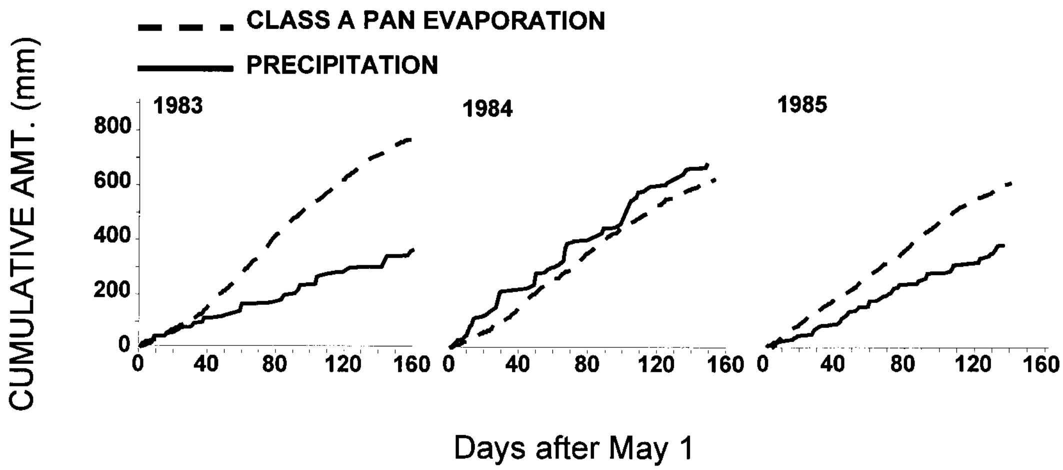

Fig. 2. Cumulative rainfall and Class A pan evaporation at Mt. Pleasant during the growing seasons of 1983 to 1985.

had warm and moderately dry summers. The summer of 1984 was cool and wet. Cumulative potential evapotranspiration (Class A pan) and rainfall are plotted in Fig. 2. Based on visual observations, there did not appear to be significant moisture stress on the corn crop in 1983. We observed considerable wilting of the plants in 1985 in many parts of the field.

Grain Yield Temporal Variability

Mean grain yields decreased during the 3-yr period and the grain yields were much more variable in 1984 than they were in 1983 or 1985 (Table 1). The coefficients of variation for yield over the field were highest in the wet year 1984 (28%), compared with the drier years, 1983 (13%) and 1985 (19%). In the wet year, 1984, average yields were generally higher for the east side of the field (Table 1), possibly reflecting the more uniform topography and better drainage. Contour maps of cumulative probabilities of grain yield superimposed on topography are shown in Fig. 3 for each of the 3 yr. The yield maps show little temporal stability in yields among the 3 yr except for a few locations. The highest yielding areas in 1983 and 1985 were in similar locations, about 50 m east of the origin and 75 m north as well as in the upper right-hand section of the field. Yields in the upper right-hand portion of the field (200–250 m east of the origin and 100–150 m north) as well as east of 150 m were higher than the mean for both 1983 and 1985. Visual inspection of Fig. 3 suggests that yields were usually lower in depressional areas in 1984 than in the other 2 yr. Yields sampled in the grid locations in 1985 were significantly correlated with 1983 and 1984 yields at the same location, but 1984 and 1983 yields were not correlated (Table 2).

Summary statistics for the transect data are given in Table 3. Yields as functions of position for the five transects are shown in Fig. 4 and 5. The yields from the transects had higher variability in 1984 than in 1985, the same as those from the grid. The relative variabilities among the transects were similar between years, however. The variability of yields in T1 was significantly higher than the variability in T2 for both years ($P < 0.01$ for 1984 and $P < 0.1$ for 1985). The variability of yields along T3 was also significantly higher than in T4 for both years ($P < 0.01$).

The temporal variability of grain yields varied by transect and hence location in the field. There were no significant correlations between the 1984 and 1985 yields for the vertical transects T1 and T2. Yields harvested

Table 1. Tabulated statistics of grain yields from the grid for 1983 to 1985.

	1983			1984			1985		
Source†	N	Mean	SD	N	Mean	SD	N	Mean	SD
		Mg ha^{-1}			Mg ha^{-1}			Mg ha^{-1}	
X1	10	5.06	0.597	9	4.36	1.408	10	3.72	0.662
X2	10	5.21	0.923	7	3.82	1.673	9	4.10	0.898
X3	10	5.33	0.403	9	4.23	1.236	10	4.64	0.729
X4	10	5.40	0.500	10	4.95	0.881	10	5.28	0.646
X5	10	5.30	0.713	8	3.96	1.352	10	4.80	0.820
X6	10	5.17	0.409	8	4.32	1.571	10	4.48	1.175
X7	10	4.93	0.424	9	4.45	1.323	10	4.32	0.486
X8	10	5.13	0.838	10	3.89	1.487	10	4.34	0.434
X9	10	4.83	0.446	10	5.28	1.281	10	4.16	0.641
X10	10	5.22	0.712	10	5.50	0.760	10	5.02	0.498
X11	10	4.87	0.670	8	5.07	1.141	10	3.95	0.913
X12	10	5.07	0.394	10	4.87	1.380	10	4.11	0.803
X13	10	5.23	1.100	10	5.31	0.969	10	4.53	0.881
X14	10	5.22	0.918	10	5.12	1.111	10	4.11	0.821
Grid	140	5.14	0.671	128	4.69	1.316	139	4.40	0.840

† Grid column number.

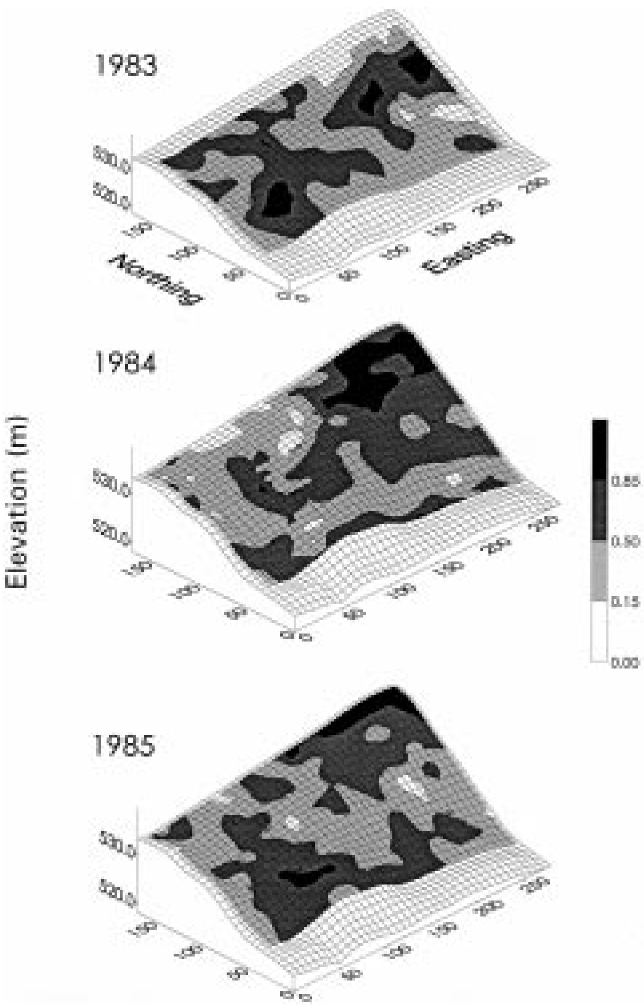

Fig. 3. Contour maps of cumulative probabilities of corn grain yields for 1983 to 1985 overlaid on topography. Yields above the 0.5 level are above the mean.

from the horizontal transects (T3 and T4), however, did display similar patterns within a transect for both years even though weather conditions were dissimilar (Fig. 5). Only the correlation between 1984 and 1985 yields for T3 was high and significant ($R^2 = 0.867$, $P < 0.001$). The correlation for the 1984 and 1985 yields in T4 was not significant ($P > 0.1$) although the trends were similar for the 2 yr (Fig. 5b). The relative ranking of mean yields from the transects were not the same for both years. Transect 3 had the highest yield in 1984 but not in 1985.

Table 2. Correlation coefficients (*r*) for grain yields and depth to fragipan from grid samples.

Source	1984	1985	Depth to fragipan
1983	0.061 (0.50)†	0.287 (0.0006)	0.086 (0.349)
1984		0.229 (0.0097)	0.239 (0.0126)
1985			0.38212 (0.0001)

† Probability level in parentheses.

Table 3. Statistics for transect yields before and after removing trend.

Year	Transect	*N*	Mean	SD
			Mg ha^{-1}	
		Raw data		
1984	1	23	4.05	1.37
	2	24	5.22	0.69
	3†	51	4.23	1.77
	4†	51	4.37	1.47
	5	50	4.55	0.93
1985	1†	23	4.55	1.24
	2	24	4.26	0.85
	3†	51	5.03	1.35
	4†	51	4.10	0.73
		Residuals after removing trend		
1984	3	51	0	0.89
	4	51	0	1.10
1985	1	23	0	0.89
	3	51	0	0.66
	4	51	0	0.63

† With trend.

Grain Yields and Topography

There were no strong trends in grain yield up- and downslope for T1 or T2 (Fig. 4). The 1985 yields along T1 tended to be lowest at the top of the field, where we observed the soil to be dense and shallow. The plots of grain yield vs. distance from the horizontal transects (T3, T4, and T5) show cyclic trends in the data (Fig. 5a, 5b, and 5c). Semivariograms for the grid data did not show any significant spatial structure to the variance of grain yield or significant cross covariances with the other properties measured. Semivariograms of the transect data (not shown) revealed periodic structures that were analyzed using spectral analysis as reported below.

The elevations for the transects are plotted with yield against distance in Fig. 4, 5a, 5b, and 5c. Surface undulations are seen most clearly in T1, T2, and T4, and to a smaller extent in T5. Visual observation suggests that there is a tendency for larger changes in yield in the horizontal transects where there are undulations or the slope changes markedly. While the 1984 and 1985 yields at any one location were different for the 2 yr on T4, the clustering of yields along the transect and the periodic variation do appear similar based on visual observation of Fig. 5b. Yields on T5 in 1984 appear to vary in a similar manner to the 1984 yields on T4. Transect 3 1984 and 1985 yields are very similar. The topography of T3 is much different than the topography of T4 as measured by the degree of curvature. The magnitude of curvature was larger in the areas where T4 and T5 were located than in the area where T3 was located (Fig. 5).

Spectral analysis was used to investigate the periodic components of the grain yield and curvature for the transect data. Smoothed power spectra and squared coherencies were calculated using Eq. [1] to [8]. Trends were removed from T3 and T4 for 1984 and T1, T3, and T4 for 1985 using quadratic functions (Table 3).

Plots of power spectra for grain yield in T1 and T2 do not reveal a dominant component of variance of grain yield at any particular frequency (Fig. 6). The variability appears to be randomly distributed among

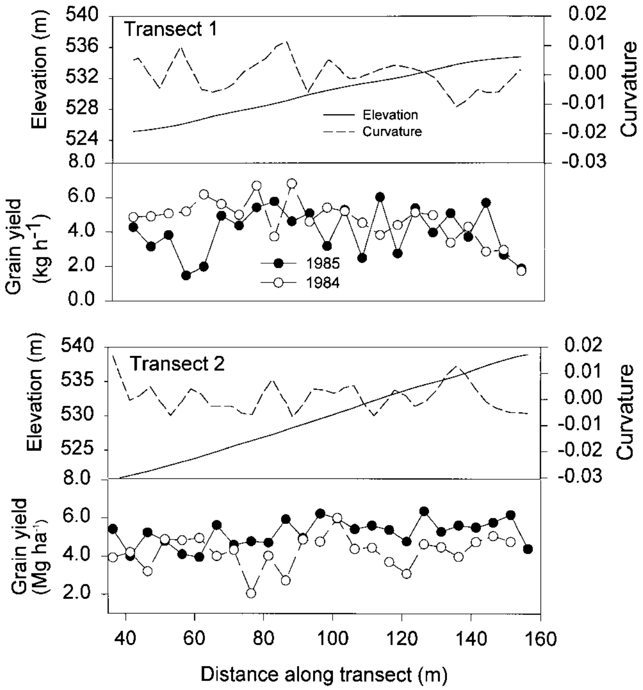

Fig. 4. Corn grain yields, curvature, and elevations along transects T1 and T2.

the frequencies. This is in accordance with the data shown in Fig. 4, where little evidence of periodic variation of grain yield can be seen. Transects T1 and T2 curvature power spectra also appear to be evenly distributed over all frequencies and do not exhibit evidence of any significant periodicity.

Power spectra for grain yield along T3, T4, and T5 show larger components of variance for grain yield at certain frequencies. The distributions of variance of grain yield with frequency for each of these transects are also similar for the 2 yr, especially for the low-frequency variance component. All the horizontal transects show significant components of grain yield variance at periods greater than ≈33 m ($f < 0.03$) and a smaller peak centered at a period of 12 m ($f = 0.08$). Some of this variance at the higher frequency, however, may be leakage from the larger peak at 33 m. This cycling of grain yield at a period of approximately 33 m can be seen in Fig. 5a, 5b, and 5c. The power spectra for curvature depend on frequency in the same fashion as the power spectra for grain yield, especially for T4 and T5. The peaks in the power spectrum for curvature in T3 are slightly shifted, compared with the power spectrum for grain yield. The power spectra for curvature are similar for both T4 and T5.

The coherence between curvature and yield for T3 in 1984 is only significant at periods of about 12 m (Fig. 7). The increased correlation at this high frequency is there in 1985 but it is not significant. The coherences for T4 are similar for both years and are significant for the period centered on about 33 m. Correlation distances from the spectral densities are given in Table 4. The spectral density plots contained two peaks, so two correlation distances were calculated.

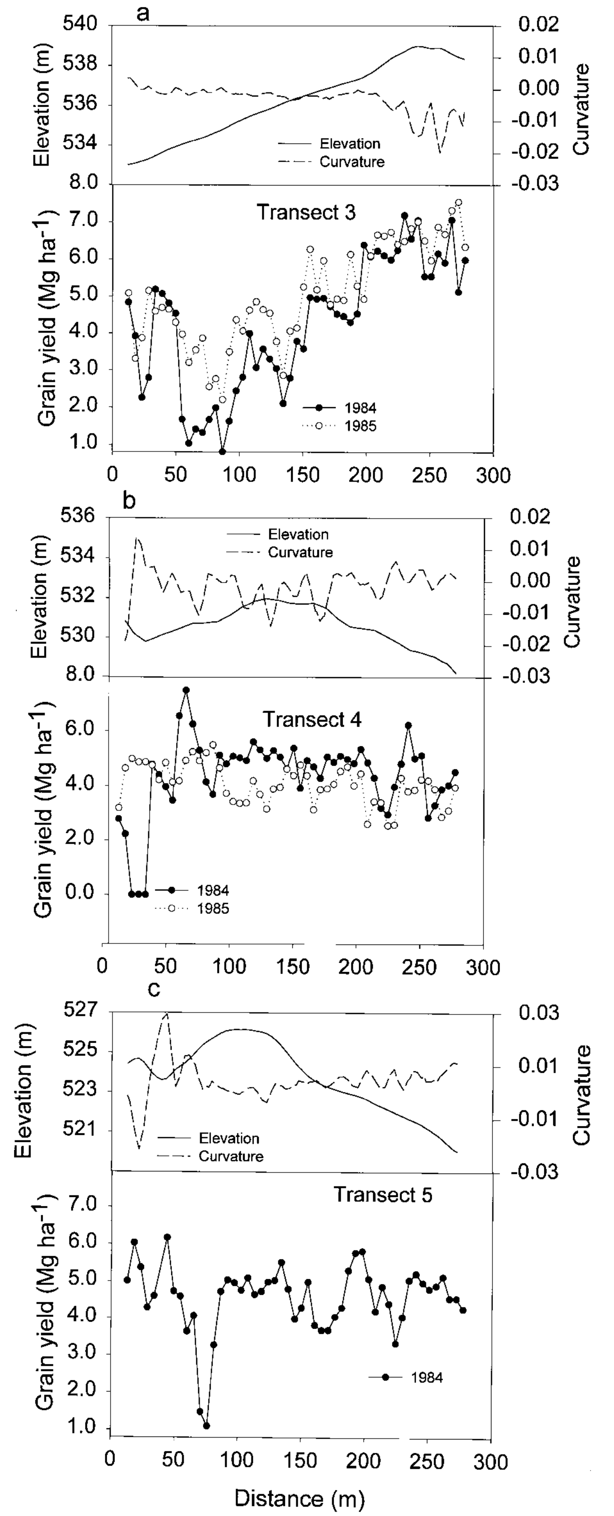

Fig. 5. Corn grain yields, curvature, and elevations along transects T3, T4, and T5.

Statistics for grain yield means, depth to fragipan, and OM contents for the grid plots as a function of curvature are given in Table 5. The calculated curvatures for the grid were evenly distributed about a mean of 0.0 (data not shown). The yields in locations with concave curvature were significantly higher than yields in convex sec-

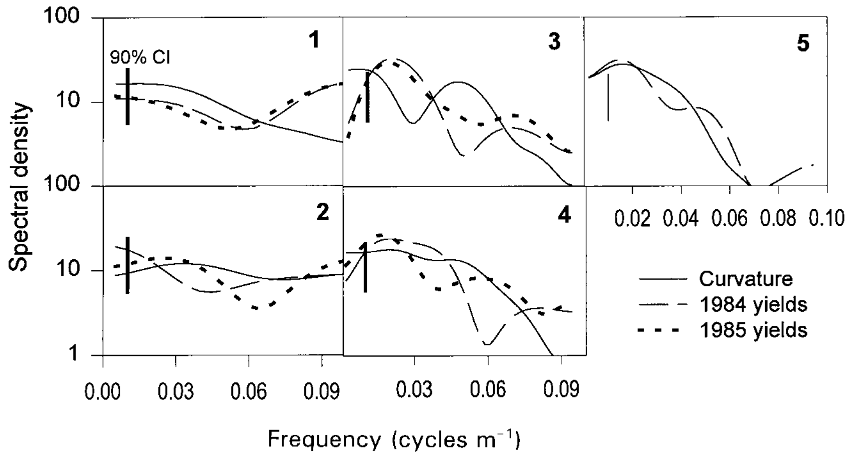

Fig. 6. Power spectra for grain yields and curvature for transect data.

tions in 1983 and 1985 ($P \leq 0.10$). The difference in mean yields between the convex and concave sections was not significant in 1984. This is partly due to the high variance in grain yield that year. Depth to fragipan was slightly greater at concave than convex locations but the difference was not statistically significant (Table 5). There was also no statistically significant relationship between surface curvature and OM for the 1985 samples.

Grain Yield and Soil Properties

Correlations for grain yield and depth to the fragipan are given in Table 2. Only yields in 1984 and 1985 were significantly correlated with soil depth.

The distributions of P and K were lognormal, and OM was normally distributed. Summary statistics are given in Table 6. The correlations were therefore carried out using ranks, and the Spearman correlation coefficients are reported. Grain yields in 1985 were significantly ($P < 0.01$) correlated with OM, P, and K. The correlation coefficients (r) with grain yield were 0.269 for OM, 0.252 for P, and 0.267 for K. No significant correlations were found for the 1984 yield data.

DISCUSSION

The value of curvature can be a useful indicator of small-scale variations in topography that affect crop yield (Sinai et al., 1981; Boyer et al., 1990). The power spectra for curvature and grain yield showed similar distributions with frequency. Grain yields in the normal to dry years 1983 and 1985 were significantly higher where curvature was positive (concave). There was no correlation with curvature for the wet-year (1984) grid yields. The significant correlations in 1983 and 1985 may have been due to the type of plant–water relations and hydrologic conditions that occur when water is limiting as opposed to when there is too much water. Water availability, either too much or too little is probably the most important source of grain yield variability in a landscape. Mean water-holding capacity by landscape position has been shown to be a good predictor of corn silage yield (Wright et al., 1990). Higher wheat yields have been reported for areas where soil has accumulated and lower yields for areas where soil has eroded (Moulin et al., 1993). It is reasonable to expect that high curvature (either positive or negative) marks locations where soil has accumulated or eroded, and higher or lower yields would be associated with these locations in a dry season. Kachanoski et al. (1985a) showed that concave curvature in their study was associated with a larger A horizon thickness than was convex curvature.

Overall, the significance levels in Table 5 for the differences in mean yield with curvature for the grid data were not high. Because of the wide grid spacing, we may have encountered some loss of small-scale features.

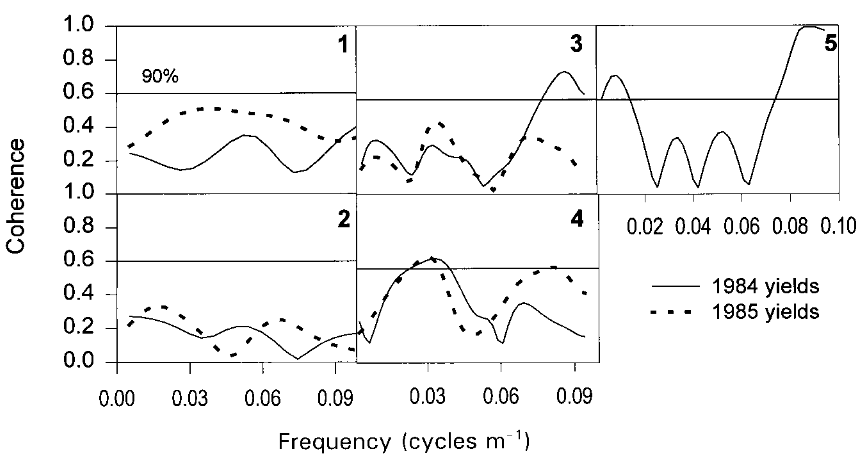

Fig. 7. Coherence between curvature and corn yield for transect data.

Table 4. Correlation distances for the yield data collected along transects.

Year	Transect	$1/f_{max}$† 1st peak	$1/f_{max}$† 2nd peak
		m	
1984	T3	34	13
1984	T4	39	14
1984	T5	59	20
1985	T3	47	14
1985	T4	46	16

† There were two peaks in the spectral density function (Fig. 6); f_{max} is the frequency at the maximum product of frequency and spectral density.

Table 6. Summary statistics for organic matter (OM), P, and K contents in the experimental field.

Source	Mean†	SD‡	N	Shapiro–Wilk statistic§
		1984		
OM, %	4.2	0.4	68	0.970
P, mg kg^{-1}	3.4	1.6	68	0.751***
K, mg kg^{-1}	43.5	1.3	68	0.914***
		1985		
OM, %	3.9	0.4	139	0.965
P, mg kg^{-1}	3.3	1.7	139	0.739***
K, mg kg^{-1}	40.7	1.2	139	0.928***

*** Significant at the $P = 0.001$ probability level.
† Geometric mean for variables with lognormal distributions (P and K).
‡ 10^x for log-transformed values where x is the standard deviation of log-transformed values.
§ Significance indicates that the null hypothesis of a normal distribution is rejected.

Boyer et al. (1990) found that the grid spacings used to calculate curvature can affect cross correlations with volumetric water content. The values of curvature in this study were in the range ±0.04. Sinai et al. (1981) observed larger curvature in the range ±0.10 and reported strong correlation of wheat yield with curvature in an arid environment.

The relationship between curvature and grain yield varied by location within the field and with magnitude of curvature. Comparing T3 and T4, the larger the values of curvature along a transect were, the more temporal difference there was in grain yield between 1984 and 1985. The grain yield trends were very similar along most of T3 for both years (Fig. 5a). Trends in yield along T4 were generally dissimilar for 1984 and 1985 except for a distance from 200 to 300 m (Fig. 5b) where the curvature was smaller. Curvature along most of T3 was negligible and no significant coherence between yields and curvature was found for T3 for any frequency. There was a significant coherence of curvature with grain yield in T4 for both years at a period of about 33 m ($f = 0.03$ cycles m^{-1}). A source of this correlation can be seen in Fig. 5b where yields and curvature both show a cycling variation with a period of about 30 m. The reason for the differences between T3 and T4 may lie in their relative locations. Transect T4 was downslope from T3 and had higher values of surface curvature and smaller changes in elevation. Transect T3 was located toward the top of the hillslope and had a relatively large change in elevation from west to east. It is possible that run-on and runoff processes as well as local soil profile characteristics were different, resulting in a much different hydrologic regime in the area of T4 in 1984 compared with 1985.

The curvature spectrum for 1984 T5 yields was similar to the T4 spectrum. The comparability reflects the similar topography and similar relative locations within the hillslope for the two transects. The coherence between T5 curvature and yield was different from the coherence for T4, however. Transect T5 coherence was significant at both low and high frequencies. The periodic structure of curvature appeared to cycle at two frequencies (Fig. 5c). The high-frequency cycling had a period of about 15 to 20 m. The low-frequency cycle corresponded to the plateau seen in Fig. 5c. Curvature was highly positive at the start of the transect, became slightly negative, and finally positive again at the end of the transect. The correspondence between curvature and yield was strongest for the high-frequency (short-period) cycling. These results suggest two scales of structure for yield and curvature.

Note that there were no significant differences for grain yield between convex and concave curvature in 1984. Kachanoski et al. (1985a) discussed the possibility where positive and negative correlations can cancel out any significant relationships between two variables if the variables are positively correlated at one frequency and negatively correlated at another. The cospectrum (Fig. 8) for yield and curvature on T4 in 1984 is negative for the larger periods (30–50 m) with only a smaller positive component at higher frequencies (<20 m). The cospectrum for T4 in 1985 is positive for all periods. The cospectra do show that the effect of curvature on yield was different for the 2 yr, but there is only weak evidence of both positive and negative correlations of yield with curvature in 1984. It is possible that during the wet year (1984) concave and convex areas in some parts received and transmitted water differently than in other parts. A concave area that is present as a gully running downslope from north to south would have different hydrologic relations than an isolated depressional area that occupies only a small part of the field. In the dry years (1983 and 1985) the hydrology of the concave areas was probably similar for most of the field.

The temporal variation in grain yield in this field was strongly related to location within the landscape and therefore to the topographic features at that location.

Table 5. Statistics for relationships between curvature and yield, depth to fragipan, and organic matter content (OM).

Source	Concave N	Concave Mean	Concave Sd	Convex N	Convex Mean	Convex SD	t†	P
1983 yield, Mg ha^{-1}	67	5.235	0.749	61	5.033	0.571	1.7	0.09
1984 yield, Mg ha^{-1}	61	4.673	1.407	55	4.663	1.227	0	0.96
1985 yield, Mg ha^{-1}	66	4.507	0.865	61	4.229	0.788	1.89	0.06
Depth, cm	61	51.2	18.7	50	46.3	12.1	1.65	0.10
1985 OM, kg kg^{-1}	67	0.039	0.005	61	0.039	0.003	0.11	0.99

† The t-statistic tests for the difference between yields in concave and convex positions. The null hypothesis is that there is no difference.

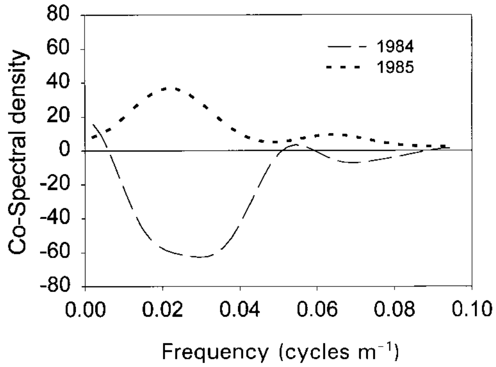

Fig. 8. Cross spectra for 1984 and 1985 yields and curvature along transect T4.

Furthermore, topographic properties such as slope and curvature were present at different scales within the field and the impact of these on crop yield was affected by weather. Based on the strong correlation for 1984 and 1985 yields in T3 and the lack of correlation in the other transects, we deduced that the interaction of weather with landscape had a greater effect on the variability of grain yields in T1, T2, and T4 than in T3. Along T3, the yields in both years increased in the direction of increasing elevation, with highest yields at the summit (Fig. 5c). This trend may be related to erosion processes. Boyer et al. (1990) found the summit and shoulder slopes to be less eroded than the backslope position, based on clay content.

The weak spatial structure in grain yields from plots along T1 and T2 (Fig. 4) suggests that large-scale variability such as the rapidly increasing elevation in the northing direction (Fig. 1) may overcome the effects of small-scale topographic features such as curvature. The relatively small number of data points (21) may have also made it difficult to distinguish spatial structure.

Soil depth correlated with yields in the wet and dry years 1984 and 1985. A possible explanation for the absence of correlation in the dry year 1983 may lie in the timing of the rain or the field history. The difference between evapotranspiration and rainfall (Fig. 1) was not as great in 1983 as it was in 1985. The field had also been in a pasture mix 3 yr before the experiment and possibly had better retention of rainfall and less runoff. Meek et al. (1990) reported infiltration rates in soil seeded with cotton (*Gossypium hirsutum* L.) were four to nine times higher than normally measured when cotton was preceded by a 3-yr alfalfa rotation.

Soil levels of P, K, and OM correlated with yields in 1985 but did not correlate in 1984. The reason for the lack of correlation for OM in 1984 may have been similar to the reason for the lack of correlation with curvature, i.e., negative and positive correlations canceled each other. A contributory reason for the lack of correlation in 1984 for P and K may have been related to the poor growing conditions that year, so that nutrients were not limiting.

All correlation coefficients for P, K, and OM with yield in this study were relatively low. Wright et al. (1990) reported that Bray 1 extractable P and exchangeable Ca and Mg did not contribute to corn-silage yield differences. Pierce et al. (1995) also reported little relationship between corn grain yields and soil fertility, mainly due to high levels of measured nutrients. The field in our study was also fertilized at relatively high rates of P and K. The relationship between grain yield and fertility factors is not linear and often the increase in yield diminishes as the nutrient levels increase toward a limiting amount. The ranges of yields and the dependent nutrient variables in this study were relatively narrow and were probably within the limiting range. It is likely that these factors contributed to the low correlations found.

Spatial variability of corn grain yields was anisotropic in this field. Power spectra of vertical transects showed less spatial structure than the power spectra for the horizontal transects. The power spectra for the horizontal transects indicated periodicity and high autocorrelation at high frequencies (close spacing of samples). Two correlation distances were calculated from the transect data using the spectral density functions. The larger distance (30–60 m) corresponded roughly to the distance between two locations with similar curvature. The smaller distance (10–20 m) probably corresponded to an average distance in which curvature did not change significantly.

CONCLUSIONS

The results of this study suggest that topography and related factors such as soil depth and drainage have a large effect on the variation of corn yields. Grain yields in this field were most strongly related to soil properties that are related to water-holding capacity and drainage. These include topographic location, surface curvature, OM content, and soil depth. Where the curvature was small, the patterns of the yield variation along transects were similar for the 2 yr. In general, the yield maps did not always suggest clear temporal relationships of grain yield with major topographic positions within the field. In the absence of strong relationships, the yield maps together with the topography maps still appear to be useful in understanding yield variability within a field. Areas with low curvature generally had the same positions of low and high yields both in dry and in wet years. Elevation maps appear to be useful to interpret yield maps from complex hillslopes by separation of areas with low curvature from areas with high curvature. Closely spaced data taken along the transects provided more information on the spatial structure of grain yield than did data from the more coarsely spaced grid. These results suggest that transects placed in representative parts of a field and covering a range of topographic positions may be a better source of spatial information than a grid with uniform but wider spacing.

Yield maps collected during several years provide an estimate of the temporal stability of crop yield. The intrayear correlation between yields in zones of negative and positive curvature can be thought of as a persistence in productivity in these zones. Researchers have quantified the in-season persistence in soil water contents under a developing crop (Vachaud et al., 1985; van Wesenbeeck et al., 1988). It may be promising to apply these techniques to intrayear variations of yields in zones defined by the surface curvature when long time series of yields are available. Since the spatial distribution of yields is affected by variations in topography at different scales, an interesting development of this work will be to find a minimum set of topographic parameters sufficient to explain an acceptable level of variation in yields.

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