SITE-SPECIFIC ANALYSIS

Relationship of Corn and Soybean Yield to Soil and Terrain Properties

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ABSTRACT

Farmers will be better able to implement site-specific management practices when they understand the causes of spatial and temporal variability of corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] yield in their fields. Our objectives were to determine if a data set containing 20 soil and terrain variables could explain spatial yield variability better than a subset of seven more easily measured variables and to determine whether the relative importance of factors in explaining yield variability differed between corn and soybean or between wet and dry years. Yield data were collected for 11 yr in a 16-ha field in central Iowa. Soil and terrain variables measured included: A horizon depth, carbonate depth, pH, coarse sand, sand, silt, clay, organic C, N, Fe, K, P, and Zn; and seven easily measured variables: electrical conductivity, soil color, elevation, slope, profile curvature, plan curvature, and depression depth. Factor analysis of the variables followed by regression of yield on the resulting factors showed that the 20-variable set explained more of the spatial variation in yield than the subset of seven variables. Further, the analysis of the 20-variable data set showed that soybean yield was affected more by pH, more by closed depressions in wet years, and less by curvature in dry years than corn yield. Similarly, yield was negatively affected by closed depressions and lower landscape positions in wet years, whereas these factors had either no effect or a positive effect in dry years. Alternately, curvature had a negative effect in dry years and no effect in wet years.

S{ITE-SPECIFIC MANAGEMENT} of agricultural fields has the potential to increase profitability, while minimizing environmental contamination (Vanden Heuvel, 1996). Farmers will be better able to implement site-specific management practices when they understand the causes of spatial and temporal variability of corn and soybean yield in their field. Using geographic information systems (GIS), differential global positioning systems (DGPS), yield monitors, aerial photographs, and soil analyses, a number of researchers have collected spatially linked data sets to examine the relationships between crop yield and a few terrain and soil properties across production fields (Timlin et al., 1998; Khakural et al., 1998; Mallarino et al., 1999; Kravchenko and Bullock, 2000; Kaspar et al., 2003). Although these studies have increased our understanding of yield variability across fields, the relationships obtained between crop yield and terrain and soil properties explained only part of the yield variability and did not identify all of the underlying factors that controlled yield. Presumably,

yield data collected over many years in the same field and a larger set of measured soil and terrain variables would have a better chance of accomplishing this goal. Data collection and analysis, however, are costly and labor-intensive, and questions remain about the kind and amount of data that are needed to adequately understand spatial yield patterns. Additionally, it is unclear whether different variables should be measured for soybean and corn or for wet and dry years.

Growing season precipitation often interacts with terrain attributes and soil properties to influence crop yield (Timlin et al., 1998; Jaynes et al., 2002; Kaspar et al., 2003). In years with below average rainfall, field areas higher on a hillslope with greater slopes and convex curvatures usually have less available water and lower yield than areas lower on the hillslope, with lesser slopes and concave curvatures (Ciha, 1984; Halvorson and Doll, 1991; Afyuni et al., 1993; Timlin et al., 1998; Jaynes et al., 2002; Kaspar et al., 2003). Similarly, eroded soils, which commonly have substantial slopes, convex curvatures, and shallow topsoils (Pennock and de Jong, 1987; Lindstrom et al., 1992), show a greater yield decline relative to noneroded soils in growing seasons with below average rainfall than in those with above average rainfall (Langdale et al., 1979; Swan et al., 1987). Conversely, in years with above average rainfall, field areas with slight slope gradients and closed depressions can have reduced yield (Jaynes et al., 2002).

Soybean and corn differ in many anatomical and physiological characteristics (Gardner et al., 1985) and would be expected to respond differently to soil and terrain properties. Sadras and Calviño (2001) found that under dry conditions corn yield was more depressed by shallow soils than soybean yield. Some soybean cultivars are relatively sensitive to iron chlorosis on calcareous soils in Iowa, whereas corn is generally not limited by iron on most Iowa soils (Voss et al., 1999). Soybean, however, can obtain most of its N through N fixation, whereas corn obtains all of its N from the soil. In spite of these differences, Kravchenko and Bullock (2000) observed similar corn and soybean yield responses to soil properties, terrain variables, and precipitation in Illinois and Indiana. In Minnesota, however, Khakural et al. (1998) reported that soybean yield was related to K concentration, soil profile water storage, slope, and carbonate depth, whereas corn yield was related to topsoil depth and soil pH.

Terrain and soil properties are often highly correlated

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Abbreviations: DEM, digital elevation model; DGPS, differential GPS; EC, soil electrical conductivity; GIS, geographic information system; GPS, global positioning system; ICP, inductively coupled plasma-atomic emission spectrometer; UTM, Universal Transverse Mercator.

with each other because of the processes of soil development, erosion, and sedimentation (Gerrard, 1981; Pennock and de Jong, 1987; Moore et al., 1993). As a result, one of the problems encountered when using regression analysis to examine the relationships between a large number of soil and terrain variables and crop yield is multicollinearity. Multicollinearity occurs when two or more independent variables in a regression model are correlated with each other and provide redundant information to the regression model (Bowerman and O'Connell, 1990). When multicollinearity exists among variables, the estimates of variable coefficients are dependent on which variables are included in the final regression model. Furthermore, the variables selected for the final regression model are also influenced by which variables are included in the selection pool. Thus, when using regression analysis to examine the relationship between yield and a large number of correlated terrain and soil variables, it may be difficult to determine the relative importance and validity of the variables included in the final model. Additionally, variables may be selected for the model even when there is not an obvious mechanistic basis for their inclusion because they are strongly correlated with a variable that does have a mechanistic relationship with yield. Multivariate analysis techniques, such as factor analysis (Hair et al., 1987), can be used to avoid the problems of multicollinearity by grouping variables that are strongly correlated and then using these groups as independent variables for regression analysis.

A unique data set was collected in a commercial field in central Iowa, which included 11 yr of weigh-tank yield data and 20 soil and terrain variables. Our first objective for this study was to determine if factor analysis of 20 soil and terrain variables, followed by stepwise regression analysis of the resulting factors would provide a better understanding of the causes of spatial variability of corn and soybean yield than factor and regression analysis of a subset of seven more easily measured terrain, EC, and soil color variables. Our second objective was to determine whether the relative importance of the resulting factors in explaining yield variability differed between corn and soybean or between wet and dry years.

MATERIALS AND METHODS

Site Description and Crop Management

Data used in this study were collected on a 16-ha field in central Iowa composed of soils in the Clarion (fine-loamy, mixed, mesic Typic Hapludolls)–Nicollet (fine-loamy, mixed, mesic Aquic Hapludolls)–Webster (fine-loamy, mixed, mesic Typic Haplaquolls) soil association, which formed in calcareous glacial till (Andrews and Dideriksen, 1981). The field is characterized by low relief swell and swale topography representative of the Des Moines lobe of the Cary substage of glaciation (Fig. 1). The field was tile drained, but there were no surface inlets and surface water frequently accumulates and remains in closed depressions for several days after high intensity and/or high volume precipitation events. Detailed information on the soils can be found in Steinwand and Fenton (1995) and Steinwand et al. (1996). Field management is con-
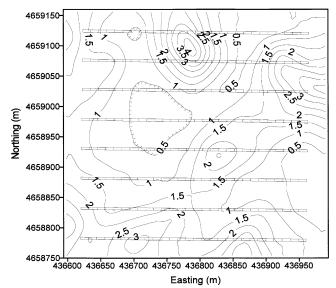

Fig. 1. Site map showing 0.5 m elevation contours and yield transects.

sidered typical for Iowa and is described in detail in Karlen and Colvin (1992) and Colvin et al. (1997). The field has been in a 2-yr corn–soybean rotation since 1957 with corn planted in odd numbered years. From 1932 to 1981, the primary tillage was fall moldboard plowing followed by disking and harrowing. Since 1981, the primary tillage has been fall chisel plowing or disking followed by harrowing before soybean planting. In recent years, only one or two passes with a field cultivator have occurred before corn planting. Considered typical, fertilizer management has consisted of at least 168–38–93 kg (N–P–K) ha^{-1} applied in the fall after soybean since 1980. Rainfall during the May through August growing season was used as an indicator of plant-available water (Kaspar et al., 2003). Daily precipitation totals were obtained from an Iowa State University research farm located 7 km south of the study area (Todey, 2000) and cumulative precipitation for the period May through August was calculated (Table 1).

Yield Measurements

Crop yield was measured for 11 consecutive years, starting with corn in 1989. Details of the harvest method used and a further description of the yield data can be found in Colvin et al. (1997). Grain yield was measured using a modified combine with a weigh tank mounted inside the combine grain storage tank (Colvin, 1990). The weigh tank was mounted on strain

Table 1. Cumulative precipitation from May through August for each year from 1989 to 1999.

Year	May–August cumulative precipitation
	mm
1989	**300**
1990	**732**
1991	**376**
1992	**357**
1993	**1060**
1994	**358**
1995	**378**
1996	**555**
1997	**384**
1998	**528**
1999	**595**
Avg. 1951–2000	**443†**

† Avg. May–August cumulative precipitation for 1951 to 2000 at Ames 8 WSW weather recording station (Todey, 2000).

gauges to measure grain weight and an electronic capacitance moisture meter, mounted in the weigh tank, was used to determine moisture content. Strips, three rows wide (2.28 m) for corn and five rows wide (3.80 m) for soybean, were harvested along eight east–west transects (338.8 m long) spaced 48.8 m apart within the field (Fig. 1). Transects were relocated each year from buried permanent benchmarks and 28 yield plots (12.1 m long) within each transect were located and marked. Thus, each year resulted in 224 transect plot yield measurements. The individual yield plots were 12.1 by 2.28 m for corn and 12.1 by 3.80 m for soybean.

Terrain Attributes

Elevation and position measurements were made for the 16-ha field in the spring of 1999 before corn planting with a kinematic DGPS receiver (Ashtech Z Surveyor, Magellan Corp., Santa Clara, CA)[1] mounted on an all terrain vehicle. Readings were logged every 1 s as the vehicle moved across the field at approximately 4 m s^{-1}, providing measurements about every 4 m. North to south transects were driven approximately 4.5 m apart across the field. These data were supplemented by collecting additional elevation data by driving along ridges and swales to minimize interpolation errors in the subsequent terrain model. A base-station global positioning system (GPS) receiver, located at a benchmark on the eastern edge of the field, was used to differentially correct the roving GPS receiver. The ground control locations were referenced to a Universal Transverse Mercator (UTM) projection (Zone 15, North American Datum 1983). Elevation values were estimated in height above the ellipsoid (m). Position measurements are reliably within ±0.03 m laterally and ±0.06 m vertically for this equipment.

The elevation data produced a digital terrain model comprising 15 592 points, which was used to generate a digital elevation model (DEM) for the field on a 2-m regularized grid using the Arc/Info KRIGING command (Arc/Info, 1998; Environmental Systems Research Inst., Redlands, CA). A gaussian distribution semivariogram model provided the best visual fit for the elevation data and was used to generate the DEM at a 2-m resolution. The primary terrain attributes— elevation (m), slope (the rate of maximum change in elevation to surrounding grid cells,°), plan curvature (curvature of the surface perpendicular to the direction of slope, km^{-1}; values are negative for curvatures that are concave upwards), and profile curvature (curvature of the surface in the direction of the slope, km^{-1}; values are negative for curvatures that are concave upwards)—were then calculated for each 2-m grid cell of the DEM using the Arc/Info GIS software CURVATURE command (Arc/Info, 1998). Within the field there were several closed depressions (potholes) characteristic of the poor drainage of this young landscape (Andrews and Dideriksen, 1981). A depression depth attribute was calculated to quantify the effect the closed depressions could have on yield. The DEMfill script associated with the Spatial Analyst extension of ARC/View (Environmental Systems Research Inst., Redlands, CA) was used to numerically fill in the internal depressions within the DEM surface. This new surface was then subtracted from the original DEM surface to give the depression depth. The depression depth surface was 0.00 m for most of the field and

positive in areas of closed depressions with a maximum value of 0.30 m.

Soil Variables

Apparent soil electrical conductivity (EC) was measured at the same time elevation measurements were made using an EM-38 electrical conductivity induction meter (Geonics, Ltd., Mississauga, ON, Canada). The EM-38 was attached to a fiberglass boom in the vertical dipole position and pulled across the field with an all terrain vehicle (Jaynes et al., 1995a). The meter was set at a height of 0.08 m above the ground. Electrical conductivity was measured and recorded with the position data giving >4250 spatially registered EC measurements. A 2-m grid cell coverage of EC for the field was created from the survey data using the Arc/Info GIS software TOPOGRID command (Arc/Info, 1998) and an isotropic, gaussian variogram model.

A color photograph of the field was taken from an airplane at an altitude of 1500 m on 16 May 2001 using ASA 100 film. The bare-soil photograph was acquired after corn planting, when most of the soybean residue was no longer visible because of decomposition and incorporation, and before plants were visible in the photo. A 0-255 gray scale digital image of the photograph was created using a desktop scanner (Scan-Maker III, Microtek, Redondo Beach, CA) with a resulting resolution of 0.029 m^2 per pixel. The digital image was georeferenced using the Georeference tool in TNTmips (Micro-Images, Lincoln, NE) and control targets of known location that were set around the perimeter of the field. The resulting georeferenced image was then rectified to the UTM projection using the Plane Projective Model in TNTmips. The digital image was resampled to create a 2-m grid cell coverage of the field.

The 224 yield plots were digitized as polygons (12.1 by 2.28 m for corn; 12.1 by 3.80 m for soybean) and overlain on the EC, soil color, and terrain 2-m grid cell coverages. The area within each of the 224 yield plot polygons was converted to a raster format with a 0.0625-m^2 resolution. The values of the field attributes for each 0.0625-m^2 yield polygon raster were taken from the underlying 2-m grid cells of the appropriate coverage. The mean value for each attribute within each of the 224 yield plots was calculated by arithmetic averaging of the values for all 0.0625-m^2 rasters that fell within the specific yield plot polygon.

In May 1997, 10 soil cores (16 mm diam. by 150 mm deep) were collected randomly within each transect yield plot and composited. Each sample was passed through a 2-mm sieve and air-dried. Soil samples were extracted using Mehlich III solution (Mehlich, 1984) and analyzed for P, K, Fe, and Zn using a simultaneous inductively coupled plasma–atomic emission spectrometer (ICP) (Soltanpour et al., 1996; Thermo Jarrell Ash, ICAP 61E, Franklin, MA).

A soil core was collected from the approximate center of each transect plot and georeferenced using GPS in April 1999. A truck-mounted hydraulic soil sampler was used for the extraction. The soil sampling tube was 1.20 m long and 3.2 cm internal diameter. Thickness of A horizon was defined as the depth below the surface of the first change of soil color or texture, and is similar to the requirements for a mollic epipedon (chroma and value ≤3). Carbonate depth was determined by dropping a 10% hydrochloric acid solution on the sides of the core and by measuring the distance from the soil surface to where effervescence occurred. From each core sampled, the upper 150 mm of soil was removed from the core, air-dried, mixed, and subsampled for pH, texture, total organic C, and N. An Orion pH meter was used to measure

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[1] Equipment and company names are necessary to report factually on available data; however, the USDA nor Iowa State University neither guarantees nor warrants the standard of the product or company, and the use of the name by USDA and Iowa State University implies no approval of the product or company to the exclusion of others that may also be suitable.

the pH of each soil sample using a 1:1 (vol/vol) soil–water solution (McLean, 1982). Particle size distribution of the <2-mm fraction was determined by the pipette method after pretreatment to remove organic matter with 30% H_2O_2, dispersion with sodium hexametaphosphate, and shaking on a reciprocating shaker overnight (Walter et al., 1978). Sand fractionation was performed by mechanical dry sieving. A subsample was ground, treated with 1 M H_2SO_4, and total organic C and total N were measured using the dry combustion method on a Carla–Erba NA1500 NCS elemental analyzer (Nelson and Sommers, 1982; Haake Buchler Instruments, Paterson, NJ).

Statistical Analysis

Principal component analysis was used to group the 20 soil and terrain variables into factors based on the correlation matrix of the variables using PROC FACTOR and the principal component analysis method of factor extraction (Hair et al., 1987; Brejda et al., 2000; SAS Inst., 2000). Principal component analysis was used as the method of factor extraction because it requires no prior estimates of the amount of variation of each soil and terrain variable that will be explained by the factors. Its purpose is to derive linear combinations of a set of variables or factors that retain most of the information and variation contained in the variable data set (SAS Inst., 2000). The maximum number of factors possible is 20, which is equal to the number of variables. Only factors with eigenvalues >1 were retained (Hair et al., 1987; Brejda et al., 2000) and were rotated orthogonally with the varimax option (SAS Inst., 2000). Rotation of factors is essentially the application of linear transformation to obtain a more meaningful and discriminating patterning of variable factor loadings within and between factors (Hair et al., 1987). Factor loadings are the correlations between the soil and terrain variables and each factor. Factor scores for the retained factors, which ranged from negative to positive values, were calculated from factor loadings for each variable and variable values for each of the 224 yield transect plots using PROC FACTOR (SAS Inst., 2000).

A stepwise regression procedure (PROC REG; SAS Inst., 2000) was used to regress corn and soybean yield on the factor scores. Selection of factors for inclusion in the model was based on probability ≤0.05 (Freund and Littell, 2000; SAS Inst., 2000). These same procedures were repeated using a subset of seven "easily measured" variables: EC, soil color, elevation, slope, plan curvature, profile curvature, and depression depth. Corn and soybean yield measurements were standardized before analysis by dividing yield by the maximum yield attained by the specific crop in any transect plot over all the years (13.78 Mg ha^{-1} for corn; 4.28 Mg ha^{-1} for soybean; Table 2). Additionally, corn and soybean yields were averaged over years with either above average or below average cumulative precipitation in the period May through August (443 mm is 50-yr average May–August precipitation; Todey, 2000; Tables 1 and 2).

Table 3. Mean, maximum and minimum values, and standard deviation of 20 soil and terrain variables for 224 transect yield plots.

	Mean	Maximum	Minimum	SD
A horizon depth, m	0.61	1.25	0.06	0.28
Carbonate depth, m	0.91	1.40	0.00	0.42
Coarse sand >2 mm, g kg^{-1}	11	134	0	17
Sand, g kg^{-1}	440	765	90	157
Silt, g kg^{-1}	325	545	146	85
Clay, g kg^{-1}	235	219	441	78
C, g kg^{-1}	24.4	66.4	3.4	12
N, g kg^{-1}	1.8	4.0	0.4	1
pH	6.05	7.65	4.62	0.90
EC†, mS m^{-1}	36	64	12	12
Soil color, gray scale	108	165	65	24
Elevation, m	1.13	3.41	0.00	0.77
Slope, °	1.42	4.70	0.05	0.90
Profile curvature, km^{-1}	−0.33	2.87	−5.37	0.99
Plan curvature, km^{-1}	0.27	5.83	−2.42	1.03
Depression depth, m	0.01	0.30	0.00	0.05
Fe, mg kg^{-1}	163	332	20	61
K, mg kg^{-1}	109	363	33	52
P, mg kg^{-1}	31	114	4	21
Zn, mg kg^{-1}	1.8	4.6	0.0	1.0

† EC, electrical conductivity.

After the preliminary stepwise regression procedure the residuals were examined using PROC VARIOGRAM (SAS Inst., 2000) with a lag distance of 12 m and up to a maximum lag of 14 (0.5 of transect length) to determine whether spatial covariance exists among the residuals. In all cases spatial covariance was present and the omnidirectional variogram was not different from the east–west variogram (direction of the transects). PROC NLIN (SAS Inst., 2000) using a weighted least square procedure (Gotway, 1991) was then used to fit and compare spherical, gaussian, and exponential models to the empirical variograms. In all cases, the spherical models converged to a solution and were selected because each had reasonable values for the nugget, sill, and range, and had the best or near best multiple performance criteria (Meek, 2002). The nuggets were very small or equal to zero, sills were equal to or slightly less than the variance of the residuals, and the ranges fell between 39 and 77 m for factors based on 20 variables and between 51 and 118 m for factors based on seven variables. The spherical models were then used in PROC MIXED (SAS Inst., 2000) following the examples of Littell et al. (1996) to account for the spatial covariance among the errors and to adjust the intercept and coefficients of the regression models.

RESULTS AND DISCUSSION

Complete Variable Set

Means, maximum and minimum values, and standard deviations for the 20 measured soil and terrain variables are presented in Table 3. Of note is the wide range in

Table 2. Corn and soybean transect plot yields averaged over years with above and below average growing season precipitation.

	Mean†	Max.	Min.	SD	Standardized mean‡	SD of standardized yield	Mean May–August precip.§
	Mg ha^{-1}						mm
Corn 4 dry yr avg.	9.33	11.39	3.73	1.14	0.68	0.08	360
Corn 2 wet yr avg.	7.25	9.62	0.00	1.97	0.53	0.14	828
Soybean 2 dry yr avg.	3.10	3.70	1.53	0.43	0.72	0.10	358
Soybean 3 wet yr avg.	2.95	3.89	0.00	0.90	0.69	0.21	605

† Yields of individual transect plots were averaged over wet or dry years before means.
‡ Corn and soybean yield of individual transect plots were divided by the maximum yield that was recorded during the 11 yr in the 228 transect yield plots. The maximum corn and soybean yields were 13.78 and 4.28 Mg ha^{-1}, respectively.
§ The 50-yr average (1951–2000) May–August precipitation is 443 mm.

Table 4. Rotated factor loadings and communalities of measured variables for the four factors with eigenvalues >1.0.

Variable	Factor 1 landscape position	Factor 2 closed depressions	Factor 3 pH	Factor 4 curvature	Communalities
A horizon depth	0.44	0.46	0.02	−0.61	0.78
Carbonate depth	−0.10	0.09	0.61	−0.42	0.58
pH	0.31	0.18	−0.83†	−0.19	0.86
Coarse sand (>2 mm)	−0.67	0.17	−0.42	0.17	0.68
Sand	−0.92†	−0.25	0.12	0.03	0.92
Silt	0.89†	0.21	−0.01	−0.07	0.84
Clay	0.88†	0.26	−0.22	0.01	0.90
C	0.86†	0.30	−0.25	−0.14	0.91
N	0.88†	0.34	−0.19	−0.13	0.94
EC‡	0.83†	0.19	−0.23	−0.35	0.90
Soil color	−0.92†	−0.13	0.01	0.07	0.88
Elevation	−0.62	−0.22	0.04	0.55	0.74
Slope	−0.86†	−0.14	−0.18	0.03	0.79
Profile curvature	0.04	0.00	−0.02	0.88†	0.78
Plan curvature	−0.46	−0.01	−0.39	0.56	0.68
Depression depth	0.28	0.79†	−0.07	0.05	0.72
Fe	0.00	0.20	0.87†	−0.06	0.80
K	0.30	0.86†	0.13	−0.03	0.85
P	0.16	0.90†	0.08	−0.24	0.90
Zn	0.74†	0.46	−0.09	−0.17	0.79
Eigenvalues	8.27	3.21	2.45	2.27	

† Variable factor loadings >0.70.
‡ EC, electrical conductivity.

organic C content, ranging from 0.0034 to 0.0664 kg kg^{-1}. Furthermore, the minimum values reported for pH, K, P, and Zn fall below the minimum recommended levels for corn of 6.0 for pH and of 91 mg K kg^{-1}, 16 mg P kg^{-1}, and 0.8 mg Zn kg^{-1} (Voss et al., 1999).

Factor analysis is the name of a class of multivariate statistical methods that can be used to summarize and describe large groups of variables (Hair et al., 1987; Brejda et al., 2000). It can be used to identify relationships among groups of variables, which when examined may suggest an underlying common factor that explains why these variables are correlated. Of 20 possible factors, only the first four had eigenvalues >1.0 (Table 4). Communalities of the 20 variables measured in this field indicated that these four factors explained a large part of the variation of most of the measured variables (Table 4). More than 80% of the variation in sand, silt, clay, C, N, pH, EC, soil color, slope, P, and Zn were explained by the four factors. Measured variables with relatively high factor loadings (>0.70) within each factor are indicated in Table 4. Factor loadings indicate the correlation between a variable and an underlying common factor. These highly loaded variables were then used to propose a possible common underlying factor that linked variables together within each factor. Additionally, by examining factor loadings and communalities we might have been able to identify variables that could be eliminated because they are not highly correlated with any of the factors or they provide redundant information. For the purposes of this paper, however, we have retained all of the measured variables in the analyses.

Factor 1 had the largest eigenvalue by far and also had the most variables with large positive or negative loadings. It had high positive loadings (>0.70) for silt, clay, organic C, N, Zn, and EC and high negative loadings for sand, soil color, and slope. It was termed the *landscape position factor* because soil development and

properties along a hillslope are determined by slope, position on the hillslope, surface water flow, drainage, and soil transport (Ruhe, 1969; Gerrard, 1981; Pennock and de Jong, 1987; Moore et al., 1993). Slope is negatively related to silt, clay, and organic matter content because of the processes of erosion and sedimentation (Malo et al., 1974; Pachepsky et al., 2001), especially at sites such as this one where the topsoil contains more silt, clay, and organic matter than the underlying soils (Steinwand and Fenton, 1995). Furthermore, organic C is strongly correlated with clay content because the capacity of a soil to retain organic matter is favored by fine texture and poor drainage (Baddock and Nelson, 2000). Soil color is an indicator of soil organic matter and has a negative loading because low values are indicative of dark, high organic matter soils and high values indicate light colored, low organic matter soils. Soil electrical conductivity (EC) has been shown to be highly correlated with soil properties such as clay content (Williams and Hoey, 1987), water content (Kachanoski et al., 1988), soil salinity (Rhoades and Corwin, 1981), soil organic matter content (Jaynes et al., 1995b), and cation exchange capacity (McBride et al., 1990). Nitrogen and Zn also have high loadings for Factor 1 and these two nutrients are strongly correlated with C and clay content (Moraghan and Mascagni, 1991; Baddock and Nelson, 2000; Blackmer, 2000).

Factor 2 was termed the *closed depression factor* because of a high positive loading for depression depth. Only two other variables, P and K were highly loaded for this factor. Both of these variables were highly correlated to each other and to depression depth. We hypothesize that high P and K levels occurred in the closed depressions in this field because over the years erosional processes have deposited sediments carrying P and K in these locations. The farmer's normal practice is to surface apply P and K fertilizer in late fall or winter in years before corn and to incorporate with shallow tillage

Table 5. Coefficients, multiple coefficient of determination (R^2), and root mean squared error (RMSE) for regression of standardized corn and soybean yield averaged over wet and dry years on factors of 20 soil and terrain variables.

Avg. standardized grain yield	Intercept	Factor 1 landscape position	Factor 2 closed depressions	Factor 3 pH	Factor 4 curvature	R^2	RMSE
Corn dry years	0.678	0.042	ns	0.021	−0.038	0.71	0.045
Corn wet years	0.529	−0.054	−0.077	0.050	ns	0.70	0.079
Soybean dry years	0.727	0.056	ns	0.024	−0.028	0.67	0.058
Soybean wet years	0.703	−0.034	−0.100	0.067	ns	0.68	0.119

in the spring. As a result, the P and K fertilizer has the potential to move with sediments when water flows across the surface during winter or early spring and to be deposited into the closed depressions. High P and K levels did occur in other areas of the field resulting in moderately high Factor 2 scores. In one area of the field close to the northern edge, the high P and K levels may have resulted from overlapping of fertilizer applied to the neighboring field to the north, which is not separated from the study field by a fence or buffer area.

Factor 3 was termed the soil *pH factor* because of high positive loadings for pH and high negative loadings for Fe content. Carbonate depth also had moderate negative loading as carbonates near the surface would tend to increase pH. Iron content was negatively correlated with pH and Fe availability is known to decrease as pH increases (Moraghan and Mascagni, 1991). The areas in the field with relatively high pH (>7.5) are found on the edges of closed depressions where relatively high water tables occur seasonally or on shoulders and summits with severely eroded, coarse-textured soils with calcium carbonates near the surface. Zinc availability also decreases with high pH, but the effect is more pronounced on soils with low organic C contents (Moraghan and Mascagni, 1991), and therefore Zn did not correlate as well with pH as did Fe.

Factor 4 was termed the *curvature factor* because of a high positive loading for profile curvature. Plan curvature and elevation also had moderate positive loading and A horizon depth had a moderate negative loading. Relatively large positive or negative curvatures occur in areas of transition on hillslopes and these areas either lose or accumulate soil through erosive processes. Thus, areas with relatively high elevation and convex curvature lose soil and have shallow A horizons and areas with low elevation and concave curvature accumulate soil and have deep A horizons. It is likely that a portion of the erosion that occurs in these field areas is caused by displacement of soil caused by tillage operations over many years (Lindstrom et al., 1992). The shallow topsoils in convex field areas have reduced storage capacity for water and nutrients. Additionally, field areas with convex curvature tend to receive less water from higher elevations by way of surface flow or subsurface lateral flow. The reverse is true of concave footslopes, which receive water from higher elevations and have deeper topsoils.

Using factors as variables for multiple regression analysis avoids the multicollinearity problems that are associated with multiple regression analysis using variables that are correlated with each other. A previous study (Kaspar et al., 2003) had demonstrated that the spatial pattern of yield variability in this field differed between years with below average May–August cumulative precipitation (dry years; Tables 1 and 2) and those with above average precipitation (wet years). Therefore, corn and soybean yields of transect plots were averaged over wet years or dry years before they were regressed on the factor scores for the four factors derived from the factor analysis of the 20 terrain and soil variables (Table 5).

The corn dry years regression equation had an R^2 of 0.71 and a RMSE of 0.045. Three factors contributed significantly to the regression equation. The most important term in the regression equation was the landscape position factor, Factor 1, which had a positive coefficient. In drier growing seasons, the primary effect of this factor on yield was probably related to water availability. In particular, topsoils with high silt, clay, and organic C contents and low sand contents were assumed to be able to hold more water than the coarser-textured soils in this field. In several locations erosion had removed the topsoils and because the underlying subsoils were extremely sandy, these areas had very negative Factor 1 scores and low yields. High Factor 1 scores were also indicative of high total N and Zn content. Total N of soils is related to N availability, and therefore is important for corn growth (Blackmer, 2000). Zinc levels <0.8 mg kg^{-1} (Table 3) can result in Zn deficiencies in corn (Voss et al., 1999), especially on eroded soils with low organic C and high pH (Moraghan and Mascagni, 1991). Because soil Zn concentrations were less than the recommended soil tests levels for corn production in some areas of the field, Zn deficiency may have reduced yield in some areas with very negative Factor 1 scores.

The curvature factor, Factor 4, was the second most important term in the corn dry years regression and had a negative coefficient. In general, yield was low in areas of the field with convex shoulders, high elevations, and shallow topsoils. Conversely, yield was high at concave footslope positions, with low elevations and deep topsoils. In years with below average growing season precipitation, these characteristics are probably related to water storage and infiltration.

The third factor to affect the corn dry years regression equation was the soil pH factor (Factor 3), which had a positive coefficient and a large negative loading for pH and a large positive loading for Fe. Iron generally does not limit corn yield in Iowa (Voss et al., 1999). The minimum pH measured in this field was 4.62 (Table 3) and for the soil types in this field, liming is recommended for corn when the soil pH is <6.0 (Voss et al., 1999). The maximum pH in this field, 7.65

(Table 3), is slightly higher than desirable. The positive coefficient for this factor in the regression equation, the negative factor loading for pH, and the positive loading for Fe, however, indicated that high pH and low Fe were related to low yield rather than low pH as would normally be expected (Tables 4 and 5). Negative Factor 3 scores, high relative pH values, and low Fe concentrations occurred at two landscape positions in this field, along the edges of closed depressions and at coarse-textured shoulder and summit positions. Examining a plot of Factor 3 scores vs. yield (data not shown) illustrated that shoulder and summit positions with negative Factor 3 scores had relatively low corn yields, whereas lowland positions with negative Factor 3 scores had relatively high yields. Thus, we speculate that the association of high pH and low Fe with shoulder and summit positions resulted in the positive relationship of Factor 3 with yield and that the relatively low water availability at these positions or some other unknown factor(s) was (were) the causal factor(s). Factor 2, the closed depression factor, did not have a significant effect on yield.

The regression equation of the average corn yield of the 2 wet years had an R^2 of 0.70 (Table 5), but because yield was usually more variable in wet years in this field (Table 2), the RMSE was 0.079 and was considerably larger than that of the corn dry years. Three of the four factors contributed significantly to the regression equation. The closed depression factor had a negative coefficient and the greatest effect on predicted yield. The depression factor did not have a significant effect on corn yield in the dry years. During the 2 wet years, however, water frequently ponded in the closed depressions resulting in excessive wetness or waterlogging stress on corn plants in or near the closed depressions. Factor 1, the landscape position factor, also had a negative coefficient, which is opposite the sign of the coefficient in the dry years. In wet years, high Factor 1 scores, which were associated with low slopes and finer textured soils, identified areas of the field with poor drainage, excessive wetness stress, and low yield. In contrast, field areas with low or negative Factor 1 scores, moderate slope, and slightly coarser textured soils had moderate to relatively high yields. Factor 3, the pH factor, had a positive coefficient. This factor also had a positive coefficient for the regression on yield in the dry years, but the wet years' coefficient was twice as large, indicating the increased importance of this factor in the wet years. As for corn yield in the dry years, we would not anticipate that Fe would limit corn yield. High pH and low Fe were associated with field areas where yield probably was limited by other factors. For example, Factor 3 scores were negative along the edges of the closed depressions and in the wet years, corn yields were probably reduced in these areas by excessive wetness stress. Factor 4, the curvature factor, had no effect on corn yield in the two wet years. This indicates that the shallow topsoil depth on the convex shoulders was not as much of a disadvantage in years with above average rainfall.

The regression equation for the average soybean yield of the 2 dry years had an R^2 of 0.67 and the RMSE was 0.058 (Table 5). This indicates that the regression for the soybean dry years explained a smaller percentage of the variability and had more residual error than the regression for corn dry years. Three factors contributed significantly to the regression equation for the average yield of soybean in the dry years. Factor 1, the landscape position factor, was the most important factor in the regression equation and had a positive coefficient. In the dry years, field areas with high positive Factor 1 scores had finer textured soils, higher organic C contents, and relatively high yields compared with areas that had low negative Factor 1 scores, coarser textured soils, and lower organic C contents. For soybean, we suspect that high Factor 1 scores in dry years were related to better topsoil water availability and that availability of Zn and N was not as important as it would have been for corn. The next most important factor that affected soybean yield in the dry years was Factor 4, the curvature factor. The curvature factor was somewhat less important in the soybean regression equation than it was in the corn regression equation for the dry years. Similar to the corn regression, Factor 4 had a negative coefficient indicating that negative Factor 4 scores and higher soybean yields were associated with concave terrain features near the base of hills where topsoil depth, water infiltration, water storage, and water supply from higher elevations would be greater than that at convex shoulder positions. The pH factor, Factor 2, had a positive coefficient. In contrast to corn, soybean in Iowa is commonly Fe deficient on high pH, calcareous soils (Voss et al., 1999). Unlike corn, soybean yields at both shoulder and lowland landscape positions with very negative Factor 3 scores were lower than yields at the same landscape positions with higher Factor 3 scores. Thus, soybean yield may have been reduced by high pH and low Fe availability. Soybean yield, like corn, was not affected by the closed depression factor (Factor 2) in the dry years.

The regression equation for the average soybean yield of the three wet years had an R^2 of 0.68 and a RMSE of 0.119 (Table 5). Because soybean yield was more variable in the wet years than in the dry years (Table 2), the RMSE for the wet years was much larger than that of the regression equation for the dry years. Soybean had a more negative coefficient for the closed depression factor than corn in the wet years. This reflected the very low or zero yields often obtained from the closed depressions because of surface ponding and excessive water stress at various times during the growing season. The next most important factor in the regression equation was the pH factor. The positive coefficient for this factor was larger than that of the regressions for the soybean dry years or for corn yield. The relatively large coefficient probably reflects a stronger response of soybean to negative Factor 3 scores, which are associated with high pH and low Fe and with the edges of the closed depressions. Factor 1, the landscape position factor, also had a negative coefficient, but it was less negative than the coefficient for the wet corn years. The negative coefficient reflects the low yield of the fine-textured soils with low slopes and the relatively higher

yield of coarser textured soils on more sloping areas. In the wet years, excessive wetness probably limited yield rather than water storage. Factor 4, the curvature factor, was not significant.

Two of the more interesting results of this analysis were the comparisons between wet and dry years and between corn and soybean. Regression equations for the wet years had negative coefficients for Factor 1, the landscape position factor, whereas those for the dry years had positive coefficients. Furthermore, Factor 1 was one of the two most important factors in the dry years, but was not as important in the wet years. The negative response of yield to Factor 1 in the wet years was dominated by areas of the field with high Factor 1 scores, fine soil texture, low slopes and low yields or no yield because of ponding, high water tables, and excessive wetness stress. Furthermore, the effect on yield of reduced water and nutrient availability on the coarse-textured soils (i.e., very negative Factor 1 scores) was reduced by ample rainfall in wet years. Wet and dry years' regression equations also differed in that Factor 2, closed depressions, had a strong negative effect on yield in the wet years and no effect in the dry years. This was primarily due to the reduction of yield in the closed depressions caused by ponding, high water tables, and excessive water stress in the wet years. In the dry years, ponding and high water tables either did not occur or occurred for very short periods of time. Factor 3, the high pH factor, had a stronger influence in wet years than dry years. Similar to the effects of Factors 1 and 2, this was probably the result of relatively low yields in wet years in the field areas along the edges of the closed depressions, which also tend to have high pH and low Fe contents. Prolonged periods of high water contents in calcareous soils also may intensify Fe deficiency due to a buildup of HCO_3 in the soil solution (Moraghan and Mascagni, 1991). Factor 4, profile curvature, was much more important in the dry years than in the wet years. Here again, greater than average precipitation in the wet years reduced the negative effects on yield of shallow topsoils, less profile water storage, and less infiltration on convex shoulders compared with concave footslope positions.

Differences between the regression equations for corn and soybean involve all four factors. Soybean had slightly larger Factor 3 coefficients, more negative Factor 2 coefficients, and less negative Factor 4 coefficients than corn. Negative Factor 3 scores resulting from high pH and low Fe would logically be more important for soybean than corn because soybean is more susceptible to iron chlorosis than corn. Conversely, Factor 4, the curvature factor, may be more important for corn yield than for soybean yield. The convex shoulders in the field are severely eroded and have shallow topsoils, and thus do not have the water and nutrient storage capacity needed to produce the greater biomass of the corn crop, especially in the dry years. Sadras and Calviño (2001) reported that under dry conditions corn yield was more depressed by shallow soils than soybean yield. The more negative Factor 2 scores for soybean in the wet years may indicate a greater susceptibility to ponding and high water tables in the closed depressions than corn. Lastly, corn responded more strongly to Factor 1 in the wet years and less strongly in the dry years than soybean. In other words, corn responded more favorably and consistently to the improved drainage with coarser-textured soil and greater slopes in the wet years and was not affected as much or as consistently by coarse soils and slope in the dry years as soybean.

Seven-Variable Subset

With the proper equipment, terrain variables (elevation, slope, plan curvature, profile curvature, and depression depth) and EC can be measured on most fields in a few hours. Similarly, soil color can be easily measured from aerial photographs of bare soil. Therefore, it is important to determine if the same information for interpreting crop yield variation can be derived from factor and regression analysis of a subset of seven more easily measured variables as was determined from the 20-variable set. Factor analysis of the seven variables revealed that only the first two factors out of seven possible factors had eigenvalues >1.0 (Table 6). Communalities of the seven variables measured in this field indicated that these two factors explained >70% of the variation in EC, soil color, slope, elevation, plan curvature, and profile curvature. Depression depth was not well represented by either of the two factors and had only a moderate loading on Factor 1. The factor loadings for Factor 1 indicated a strong relationship of light colored soils, low EC readings, and relatively high slopes and elevations with the underlying common factor. This factor was similar to Factor 1 from the 20-variable data set and was also termed the *landscape position factor*. The second factor could be termed the *curvature factor* and had high positive loadings for plan and profile curvature. Relatively large positive or negative curvatures occurred in areas of transition on hillslopes and this factor is similar to Factor 4 from the factor analysis of the 20-variable data set.

The relationships of the average corn and soybean yield in the wet and dry years to the two factors are presented in Table 7. The two-factor models always had lower R^2 and higher RMSE than the corresponding four-factor model (Table 5), especially in the wet years. The four-factor model was more successful at explaining the yield variation for a number of reasons. First, the four-

Table 6. Rotated factor loadings and communalities of seven easily measured variables for the two factors with eigenvalues >1.0.

Variable	Factor 1 landscape position	Factor 2 curvature	Communalities
EC	−0.82†	−0.37	0.81
Soil color	0.92†	0.18	0.87
Elevation	0.71†	0.51	0.77
Slope	0.89†	0.09	0.80
Profile curvature	−0.12	0.90†	0.83
Plan curvature	0.34	0.74†	0.66
Depression depth	−0.58	0.13	0.35
Eigenvalues	3.78	1.33	

† Variable factor loadings >0.70.

Table 7. Coefficients, multiple coefficient of determination (R^2), and root mean squared error (RMSE) for regression of standardized corn and soybean yield averaged over wet and dry years on factors of seven easily measured terrain and soil variables.

Avg. standardized grain yield	Intercept	Factor 1 landscape position	Factor 2 curvature	R^2	RMSE
Corn dry years	0.678	−0.042	−0.035	0.58	0.054
Corn wet years	0.543	0.076	ns	0.36	0.114
Soybean dry years	0.730	−0.051	−0.035	0.53	0.069
Soybean wet years	0.724	0.071	ns	0.18	0.190

factor model has a high factor loading for depression depth in Factor 2 and captures more of the variation in the wet years. Second, the four-factor model has a pH factor, which explains some of the yield variability caused by high pH for soybean. Third, the magnitude of the yield response to the pH, closed depressions, and curvature factors in the four-factor model differs between corn and soybean. Thus, the factor and linear regression analysis based on the 20-variable data set explained more of the variability, provided a better understanding of the factors causing yield variability, and identified the differences in the relative importance of factors between wet and dry years and between soybean and corn.

CONCLUSIONS

This analysis does suggest several general recommendations for improving management of this field. First, drainage of the closed depressions could be improved by increased tiling, adding surface inlets for the tiles, or altering the surface drainage pattern. Second, the water and nutrient availability of the field areas with coarse-textured soils could be improved by increasing the organic matter content through manure applications or cover cropping. Third, loss of topsoil from convex shoulders and adjoining areas should be minimized by reducing tillage, maintaining surface residue cover, and planting off-season cover crops. Fourth, high pH areas in the field could be managed by planting iron chlorosis–tolerant soybean cultivars. While these recommendations would be positive steps to reducing the yield variability in this field, it is surprising that the analysis did not indicate that low pH or low soil P and K levels were possible causes of yield variability. For example, the normal recommendation for these soils for corn and soybean production is to apply lime when soil pH is <6.0. Although some of the transect plots had pH values that were relatively high, 133 out of the 224 plots had pH values <6.0. Similarly, 103 transect plots out of 223 had K values below the recommended optimum level of 91 mg kg^{-1}. It is unclear as to why the analysis did not identify low levels of these variables as being related to low yield.

For this particular field, measuring a larger set of soil and terrain variables provided a better understanding of the underlying causes of spatial variability of corn and soybean yield than five terrain variables, EC, and soil color. Additionally, the 20-variable set was more useful for demonstrating that the relative importance of factors in explaining yield variability differed between corn and soybean and between wet and dry years. In spite of the large number of measured variables and the multiple years of yield data, 29% or more of the spatial variability in yield remains unexplained. Most likely, some of this unexplained variability is due to measurement error for yield, soil, and terrain variables. Weed, disease, nematode, or insect pressure, nonuniform application of herbicides or fertilizers, variation in plant populations, or other unmeasured factors probably also affected yield. While the results of this analysis are only applicable to this field and to other fields in the same area with similar topography, soils, and management, this approach for analyzing the data can be applied to other fields and crops. In the future, we hope to use this approach to examine additional fields and to use the background information as covariates for evaluating the response of corn and soybean yield to inputs such as N, P, K, and lime.

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