Multivariate Analysis and Visualization of Soil Quality Data for No-Till Systems

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To evidence the multidimensionality of the soil quality concept, we propose the use of data visualization as a tool for exploratory data analyses, model building, and diagnostics. Our objective was to establish the best edaphic indicators for assessing soil quality in four no-till systems with regard to functioning as a medium for crop production and nutrient cycling across two Illinois locations. The compared situations were no-till corn–soybean rotations including either winter fallowing (C/S) or cover crops of rye (*Secale cereale*; C-R/S-R), hairy vetch (*Vicia villosa*; C-R/S-V), or their mixture (C-R/S-VR). The dataset included the variables bulk density (BD), penetration resistance (PR), water aggregate stability (WAS), soil reaction (pH), and the contents of soil organic matter (SOM), total nitrogen (TN), soil nitrates (NO_3–N), and available phosphorus (P). Interactive data visualization along with canonical discriminant analysis (CDA) allowed us to show that WAS, BD, and the contents of P, TN, and SOM have the greatest potential as soil quality indicators in no-till systems in Illinois. It was more difficult to discriminate among WCC rotations than to separate these from C/S, considerably inflating the error rate associated with CDA. We predict that observations of no-till C/S will be classified correctly 51% of the time, while observations of no-till WCC rotations will be classified correctly 74% of the time. High error rates in CDA underscore the complexity of no-till systems and the need in this area for more long-term studies with larger datasets to increase accuracy to acceptable levels.

Traditional conservation programs in the United States have emphasized the retirement from production of environmentally sensitive land, while current conservation efforts and funds are aiming at improving stewardship on land used for crop production and grazing (Wiebe and Gollehon, 2006). Most of the 80% increase in conservation funding outlined by the 2002 Farm Act goes toward conservation efforts under two programs, the Environmental Quality Incentives Program (EQIP) and the Conservation Security Program (CSP), that pay farmers to address resource concerns such as soil quality, water quality, or wildlife habitat on working lands. Unlike EQIP, CSP requires a substantial level of environmental stewardship before producers become eligible for enrollment, meaning soil and water quality must be addressed before land can be enrolled in CSP (Wiebe and Gollehon, 2006). No-till and/or the use of cover crops are two of the few management practices that allow CSP eligibility (USDA/NRCS, 2005), encouraging producers to go beyond basic conservation efforts encouraged by more traditional programs like EQIP.

Research on dynamic soil quality in cropland has traditionally compared highly contrasting situations such as no-tilled systems against their conventionally tilled counterparts and/or "pristine" situations (Campbell et al., 1998; Wander and Bollero, 1999; Liebig et al., 2004; Giuffre et al., 2006). Soil-quality studies on less contrasting management situations that reflect enhancements to a current conservation effort, such as the introduction of winter cover crops in no-till systems, are rare in the literature, yet they offer producers feasible options to improve stewardship in their operations.

Villamil et al. (2006) investigated the effects on soil properties when WCC are included in no-till corn (*Zea mays* L.) soybean [*Glycine max* (L.) Merr.] cropping systems, yet soil quality, per se, was not discussed in their work. Although the U.S. Midwest was considered marginal for the use of WCC (Reeves, 1994), Villamil et al. (2006) found that, compared to winter fallowing, crop sequences that included vetch or a mixture of vetch and rye increased SOM content down to 30 cm in depth. Increases in C sequestration in the soil might represent additional income for farmers now that C markets are underway (Ribaudo et al., 2007). Villamil et al. (2006) also showed that WCC provided

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Abbreviations: C/S, corn–soybean rotation with winter fallow; C-R/S-R, C-R/S-V, and C-R/S-VR, corn–soybean rotation with rye, vetch, or their mixture, respectively, as winter cover crops; WCC, winter cover crop; BD, bulk density; SOM, soil organic matter content; PR, penetration resistance; TN, total nitrogen content; NO_3–N, nitrate N content; P, soil available phosphorus; WAS, water aggregate stability; CDA, canonical discriminant analysis; LD, linear discriminant function.

additional benefits for crop production such as lowered BD and PR of the surface soil, while decreasing environmental risks by improving WAS and trapping nutrients in their biomass (i.e., NO_3–N and P).

Winter cover crops are recognized as one of the most cost-effective and environmentally sound ways to control soil erosion, nutrient leaching, and runoff from farmland (Lal et al., 1991; Reicosky and Forcella, 1998), and some new programs are acknowledging those benefits. Adoption of WCC is being promoted in Maryland through its "WCC Program for a Cleaner Chesapeake Bay," which incorporates $8.3 million of funding to offer farmers grants of up to $50 per acre to help pay for the cost of establishing WCC (Maryland Department of Agriculture, 2007). The use of WCC with no-till practices might also be an important community resource for water-quality trading programs that are simply a market-based tool that enables some industrial and municipal facilities to meet regulatory requirements more cost-effectively (Conservation Technology Information Center, 2006).

Attributes that are most sensitive to management are the most desirable as indicators for soil quality assessments (Arshad and Martin, 2002). A sensitive soil indicator will display a statistically significant change in magnitude and/or direction, the latter being a function of the goal we wish to achieve. Yet soil quality is a multidimensional concept, and, as such, many variables should be considered together, as opposed to individually, to get a better understanding of the true dynamics of the system.

Multidimensional data visualization is used in several disciplines, including the natural sciences, geography, computer sciences, and statistics (Swayne et al., 2006), but, to our knowledge, no research in the agronomical field has yet made use of it. The use of interactive data visualization aids in model development and diagnoses and can become an invaluable tool for soil quality assessment. Several authors (Wander and Bollero, 1999; Brejda et al., 2000a,b; Giuffre et al., 2006; Shukla et al., 2006; Xu et al., 2006) have used multivariate analysis techniques such as Principal Component Analysis (PCA), Factor Analysis (FA), or a combination of PCA or FA with Discriminant Analysis (DA) to aid in soil quality assessment by identifying those components or factors that were most discriminating between land or management categories. Yet a need exists to further the use of multivariate statistical methods in conjunction with multidimensional data visualization for a more comprehensive evaluation of cropping systems.

Our objective was to establish the most sensitive edaphic indicators for assessing soil quality in four no-till systems with regard to functioning as a medium for crop production and nutrient cycling across sites. The compared situations were no-till corn–soybean rotations including either winter fallowing (C/S) or cover crops of rye (C-R/S-R), hairy vetch (C-R/S-V), or their mixture (C-R/S-VR).

Materials and Methods

Study Area

The research was conducted at Urbana (40°5′ N, 88°13′ W) and Brownstown (38°58′ N, 89°10′ W), in central and southern Illinois, respectively. Average annual precipitation is 1040mm in Urbana and 930 mm in Brownstown. Average annual temperature is 11°C at both sites. The experimental area at the Urbana site is on Flanagan (Fine, smectitic, mesic, Aquic Argiudolls) silt loam soils with a slope of about 2% as described by Villamil et al. (2006). Flanagan series consists of dark colored, somewhat poorly drained soils, developed in 100 to 150 cm of loess over loam till under prairie vegetation. Permeability is moderate, and surface runoff is slow to medium (Soil Survey Staff, 2007). At Brownstown, the plots are on Cisne (Fine, smectitic, mesic Mollic Albaqualfs) silt loam soils in nearly flat surface. Cisne series consists of very deep, poorly drained soils on till plains. Cisne soils formed in 76 to 140 cm loess and the underlying gritty loess under forest vegetation. Permeability is slow or very slow, and surface runoff is negligible to medium. Both soils occupy extensive areas in Illinois (Soil Survey Staff, 2007).

Experimental Design

Data were collected in 2002 and 2003 at Urbana and in 2002 at Brownstown. Four crop rotations, C/S, C-R/S-R, C-R/S-V, and C-R/S-VR, were evaluated in no-till systems. Experimental plots were established in 1998 at both locations, and two adjacent fields were used to have the corn and soybean phase of the rotation represented each year. Both fields at each location had previously been in a no-till corn–soybean rotation for at least 5 yr. The experimental layout for crop rotation factor was a randomized complete block design with four replications in each field (Villamil et al., 2006).

Each year, a rye-WCC was drilled into corn stubble while rye-WCC, vetch-WCC, and the mixture rye-vetch-WCC were drilled into soybean stubble. Winter cover crops were killed with glyphosate (N–[phosphonomythyl] glycine) at 1.1 kg ha^{-1} a.i. in the spring before planting the main crops. Nitrogen fertilizer was applied each year to corn as ammonium sulfate at an average rate of 135 kg ha^{-1} N at planting. Neither phosphorus nor potassium fertilizer were applied. Detailed information on WCC management is available in Villamil et al. (2006).

Soil Sampling and Analysis

We selected the measurements of BD, PR, WAS, pH, and the contents of SOM, TN, NO_3–N, and available P, as representative measurements found in the soil quality literature also suggested by Doran et al. (1994). Each soil sampling was made after a rain event to ensure soil water content at sampling close to field capacity. Soil BD was determined following procedure 3B6a of the Soil Survey Laboratory Methods Manual (USDA/NRCS, 2004), which determines the BD value of a moist soil core of known volume. For BD and soil chemical analyses, two soil subsamples per plot to 30-cm depth were taken with a Giddings sampler (40.8-mm diam.,; Giddings Machine Co., Fort Collins, CO). The cores were then cut to obtain 0 to 5, 5 to 10, and 10 to 15-cm subsamples and stored in plastic bags. After weighing the subsamples and measuring the water content gravimetrically, BD values were obtained and the results averaged for each plot and depth. The same samples were composited, air-dried, sieved through 2-mm, and analyzed for SOM content (loss on ignition [LOI]) following Davies (1974) procedure. Determinations of pH (1:1 soil:water), TN (dry combustion), NO_3–N (colorimetry), and available P (Bray-1) were made following the procedures in the Soil Survey Laboratory Methods Manual (USDA/NRCS, 2004). Profile soil PR (kPa) was recorded with a Rimik CP-20 cone penetrometer (Agridry Rimik, Queensland, Australia) with a cone basal area of 1.2 cm^2 and cone angle of 30°. Five subsamples, each consisting of three sub-subsamples, were recorded at each plot and the results averaged at the selected depths of 0 to 5, 5 to 10, and 10 to 15 cm to get one measurement per plot per depth considered. One sample from the center of each plot was taken with a shovel down to a depth of 15 cm for the determination of WAS (g g^{-1}). The sample was divided into three incremental subsamples (0–5, 5–10, and 10–15 cm). Two 25-g subsamples of each depth were used to determine WAS on the 1- to 2-mm aggregate-size fraction following the standard procedure developed by Kemper and Rosenau (1986).

Statistical Analysis

The dataset included the variables pH, SOM, TN, NO_3–N, P, WAS, BD, and PR. The multivariate normal distribution plays an important role in many multivariate procedures (Johnson and Wichern, 2002), thus departures from normality in our dataset were explored with the summary statistics and histograms for each of the studied variables in R (R Development Core Team, 2007). In addition, we used the SAS 9.1 macro *%multinormal* (SAS Institute, 2002) to explore the multivariate distribution with the χ^2–Q-Q plot. Consequently, TN and NO_3–N contents were log-transformed to improve normality. The statistical model considered location, year, blocks (nested within location), rotation, and depth as a split arrangement within rotation. A multivariate analysis of variance (MANOVA) was performed in SAS 9.1 (SAS Institute, 2002) to assess the effect of location, year, depth, and crop rotation (Table 1). Since depth is considered a split within rotation, the error term used to test rotation was rotation × block (location). The most important outcome from Table 1 is the lack of a significant rotation × depth interaction that allowed us to focus on the effect of the crop rotations across years, locations, and depths. Observations taken in different years, locations, and depths are handled as replicates when applying the various multivariate methods. Thus, 72 observations ($n = 72$) were available to assess the effect of each crop rotation on soil quality — samples were taken at three depths from four blocks in two adjacent fields and collected 2 yr at Urbana and 1 yr at Brownstown ($3 \times 4 \times 2 \times 3 = 72$). A total of 288 observations were therefore available for the multivariate analysis. Table 2 shows descriptive univariate summaries (mean value and standard error) for each soil attribute under each management practice.

Next, data visualization of standardized data was performed using GGobi 2.0 (Swayne et al., 2007). Standardized variables of the measured soil properties have a zero mean and a unit variance and eliminate the effect of different units of measurement on the relative importance of the variables to distinguish among crop rotations. Data visualization also allowed us to check the assumptions of multivariate normality and homogeneity of the variance–covariance matrices of the treatment groups (here, rotations) required for CDA (Johnson and Wichern, 2002; Swayne et al., 2006). Different multidimensional projections and rotations were visually investigated with the "2D tours" (motion graphics) in GGobi 2.0 and later validated with CDA.

Table 1. Multivariate analysis of variance (MANOVA) table to assess the effect of location, year, depth, crop rotation, and the interaction term depth × rotation on the studied variables.

Factors	Wilks's λ	F value	num Df	den Df	Pr (> F)
location	0.34	57.63	8	240	< 0.0001***
year	0.33	62.40	8	240	< 0.0001***
depth	0.14	50.40	16	41	< 0.0001***
rotation	0.08	2.34	24	480	0.008***
depth × rotation	0.88	0.65	48	1185	0.968

Canonical discriminant analysis was performed to construct new variables called linear discriminants (LD), which allowed for reduction of the dimension of the data, and to determine which of the original variables were mainly responsible for the mean differences between management practices, as suggested by Johnson and Wichern (2002). Finally, when we perform a discriminant analysis, we need to be able to estimate the probabilities of correct classification of new observations using methods such as resubstitution or cross-validation. The resubstitution method is simple yet inherently biased since it uses the same data used to build the discriminant rule to later test it, thus overestimating the probabilities of correct classification. On the other hand, in cross-validation, the sample of data is partitioned into subsets such that the analysis is initially performed on a single subset (training set), while the other subset(s) (testing set) are retained for subsequent use in confirming and validating the initial analysis. Thus, cross-

Table 2. Descriptive univariate summary of soil reaction (pH), available phosphorus (P), soil organic matter (SOM) content, bulk density (BD), water aggregate stability (WAS), total nitrogen (TN), nitrate N (NO_3-N) content, and penetration resistance (PR) for each crop rotation. Mean values and standard errors (in parentheses) based on 72 observations. Crop rotations: corn-fallow/soybean-fallow (C/S), corn-rye/soybean-rye (C-R/S-R), corn-rye/soybean-vetch (C-R/S-V), and corn-rye/soybean-vetch+rye (C-R/S-VR).

Attribute	C/S	C-R/S-R	C-R/S-V	C-R/S-VR
pH, 1:1 soil:H_2O	5.75	5.82	5.75	5.88
	(0.06)	(0.07)	(0.06)	(0.07)
P, mg Kg^{-1}	41.33	35.07	37.10	36.50
	(1.61)	(1.70)	(1.44)	(1.41)
SOM content, kg Mg^{-1}	33.00	33.70	35.17	36.07
	(0.88)	(0.95)	(1.03)	(1.07)
BD, Mg m^{-3}	1.41	1.37	1.37	1.37
	(0.01)	(0.02)	(0.02)	(0.02)
WAS, g g^{-1}	38.64	42.93	42.08	44.11
	(1.33)	(1.31)	(1.21)	(1.27)
TN, mg Kg^{-1}	0.26	0.28	0.29	0.21
	(0.04)	(0.05)	(0.05)	(0.04)
N-NO_3, mg Kg^{-1}	13.69	15.23	11.67	14.17
	(2.88)	(3.04)	(2.63)	(3.26)
PR, kPa	1408.65	1330.97	1491.26	1459.01
	(55.1)	(62.21)	(79.41)	(73.95)

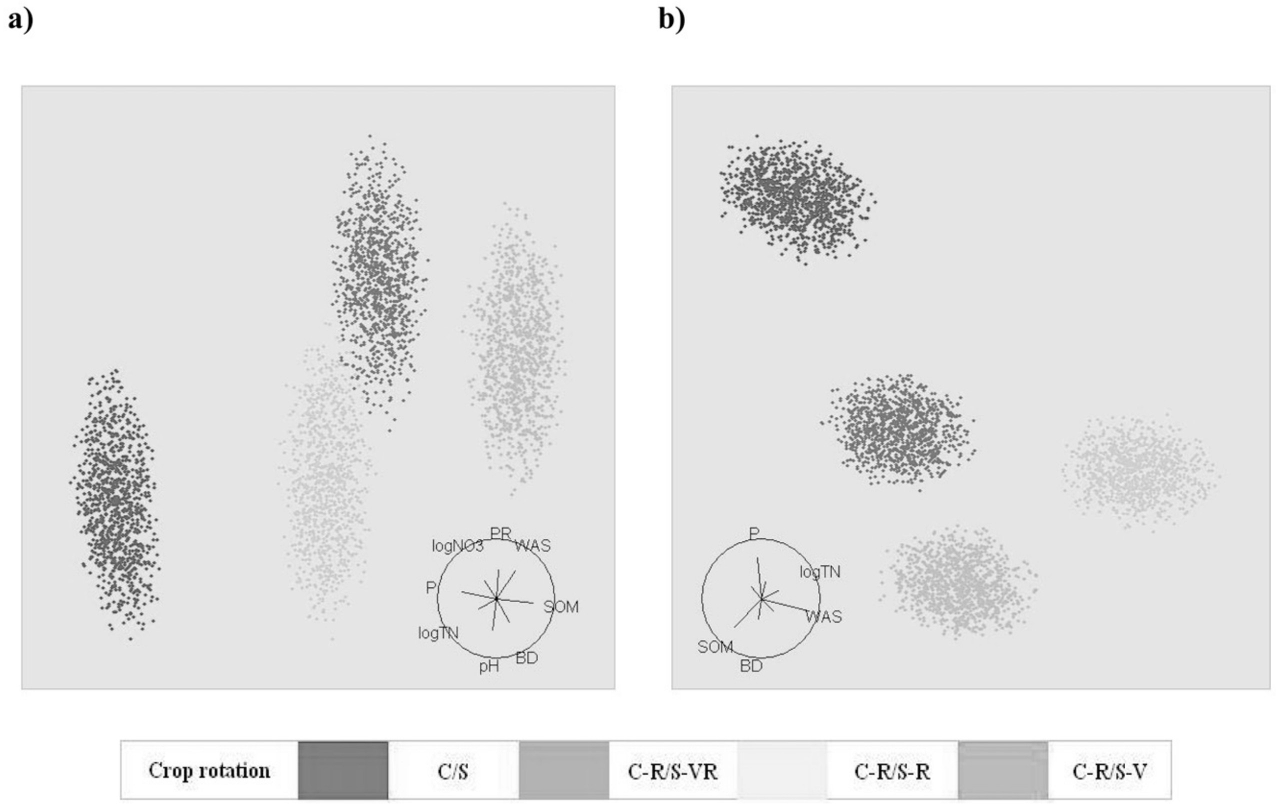

Fig. 1. Two examples of multidimensional projections of the 95% confidence ellipses for four crop rotations in the GGobi environment showing the group separation in this 8D data space where: (a) all 8 orthonormal axes are evident; or (b) just 5 axes are clearly shown, while the remaining 3 are perpendicular (orthogonal) to the projection. Crop rotations: corn-fallow/soybean-fallow (C/S), corn-rye/soybean-rye (C-R/S-R), corn-rye/soybean-vetch (C-R/S-V), and corn-rye/soybean-vetch+rye (C-R/S-VR). Soil variables: water aggregate stability (WAS), available phosphorus (P), soil organic matter content (SOM), bulk density (BD), penetration resistance (PR), natural logarithm of total nitrogen content (logTN) and of nitrate N content (logNO$_3$), soil reaction (pH).

validation renders nearly unbiased estimates of correct and incorrect classifications (Johnson and Wichern, 2002).

All statistical analysis was done with R 2.6.2 (R Development Core Team, 2007) except for the MANOVA that was run in SAS 9.1 (SAS Institute, 2002). The latter allows for specifying an error term in a MANOVA analysis, not yet feasible in R. The "rggobi" and "DescribeDisplay" packages in R account for efficient communication between R and GGobi and the possibility of plotting GGobi projections in the R environment. The "MASS" package available with the base R software contains the functions to carry out CDA and cross-validation and to create the parallel coordinates plot of the CDA means. A parallel coordinate plot is useful to see the relative difference for a variable among treatments. This plot scales all variables from 0 to 1 and displays the means for each treatment connected by a line.

Results and Discussion

Table 1 shows the results from the MANOVA. The factors year, block, and location were modeled as random effects because our intent was not to compare soil quality for specific years or locations but rather to study the effects of different no-till crop rotations on dynamic soil quality. The significant effect of depth reflects the stratification of nutrients within the soil profile that occurs under no-till practices (Kladivko, 1994) along with the effects on soil physical properties resulting from the continuous surface addition of plant residues (Schomberg et al., 1994). More importantly, the lack of a significant rotation × depth interaction ($p < 0.97$) implies that the four crop rotations caused similar nutrient stratification and residue effects within the soil profile.

Figure 1 shows two multidimensional projections of the 95% confidence ellipses for the multivariate mean value of each crop rotation group. Points in Fig. 1 are not observed values but rather simulated points that would fall in the ellipse region which aid in the visualization of the means. The circle in the bottom left of each plot in Fig. 1 displays the axis of the data space. The data space is 8D, defined by 8 orthonormal axes. All of the axes are evident in Fig. 1a, whereas just five of the axes are shown in Fig. 1b, the other three being orthogonal to the projection. The length of the axes inside the circle indicates the loadings or relative importance of each variable in separating among the four groups of crop rotation data in a particular projection.

Figure 1b shows that C/S is in the upper part of the graph. According to the axes drawn in the lower left corner, the major variables represented (higher loadings) are P content, WAS, and SOM content. Based on the ellipses and axes in Fig. 1b, C/S has low values of SOM content and WAS and higher values of P compared with the rotations including WCC. In addition, crop rotations with vetch-WCC (C-R/S-VR and C-R/S-V) have higher SOM content than C/S and C-R/S-R because this would be the "rank" of the ellipses in the direction of the SOM content axis. Likewise, the rotations including rye-WCC (C-R/S-VR and C-R/S-R) have higher WAS than C-R/S-V and C/S, since this would be the rank of the ellipses in the direction of the WAS axis. Figure 1b also suggests that the variable that separates C/S from the rest most effectively is P because the C/S ellipse is the highest in the direction of the P axis.

After investigating multiple projections with the 2D tours, the variables P, SOM, WAS, logTN, and BD were identified as the most important soil attributes to differentiate among crop rotations in no-till systems. In addition, motion graphics allowed us to realize that the separation among WCC rotations was more difficult to attain than the separation of these rotations from winter fallowing (C/S rotation).

The projections are consistent with the CDA on measured soil attributes. Discriminant analysis indicated that the first two LD account for 91.2% of the total variance among rotations. Each LD is a linear combination of the independently measured soil attributes and is orthogonal to the others. Table 3 shows the loadings of the soil attributes on the first two LDs and the variables that most contributed to each LD function. Soil attributes with a high relative weight in the discriminant function contribute more to the discriminant power of the function, thus they are the most desirable as indicators of soil quality. The first LD (LD1) explained 78% of the variance and was dominated by high negative loadings from P, NO_3–N contents, and BD and high positive loadings from SOM content and WAS. Although the loading signs are artifacts resulting from the analysis, LD1 implies a contrast among variables that might have negative environmental influences (P, NO_3–N, and BD) vs. variables with positive effects on crop production and the environment (WAS and SOM). The second LD (LD2) explains an additional 13% of the total variance and showed the combined role of SOM, BD, PR, and logTN (negative values due to transformation) in sorting out crop rotations.

Table 3. Coefficients of linear discriminant functions, LD1 and LD2. Variables: soil reaction (pH), available phosphorus (P), soil organic matter content (SOM), bulk density (BD), water aggregate stability (WAS), penetration resistance (PR), natural logarithm of total nitrogen content (logTN) and of soil nitrate N content (logNO$_3$).

Variable	LD1	LD2
pH	−0.12	0.10
P	−1.18	0.27
SOM	0.57	0.86
BD	−0.43	0.56
WAS	0.45	0.02
PR	−0.19	0.36
logTN	−0.04	−0.47
logNO$_3$	−0.38	−0.01

The parallel-coordinates plot of the CDA means for each no-till crop rotation is shown in Fig. 2. In this plot, variables are scaled from 0 to 1 and CDA means are joined for the same crop rotation. The plot allowed for easy characterization of crop rotations and identification of those soil attributes that better discriminate among them. As a result, Fig. 2 shows that no-till C/S had less WAS and higher BD and available P than the WCC rotations. In addition, a negative correlation between WAS and P seems to be present in these no-till systems. The enhancement of soil structure with cover crops was also reported by McVay et al. (1989), Latif et al. (1992), Hermawan and Bomke (1997), Dapaah and Vyn (1998), Sainju et al. (2003), and Villamil et al. (2006). Nevertheless, only a few of these studies (McVay et al., 1989; Villamil et al., 2006) were conducted using WCC chemically suppressed in combination with no-till. Yet only the research of Villamil et al. (2006) compared WCC rotations within no-till systems.

The enhancement of WAS with WCC rotations is likely related to increases in SOM content in the C-R/S-V and C-R/S-VR rotations and to root mass in the C-R/S-R rotation (Haynes and Beare, 1997). The lack of SOM content improvement with C-R/S-R reflected not only the difference in residue quality and quantity between grasses and legumes as WCC but also the need for a N source by soil microorganisms and fauna for breakdown and incorporation of residues into SOM (Villamil et al., 2006). All WCC rotations lowered

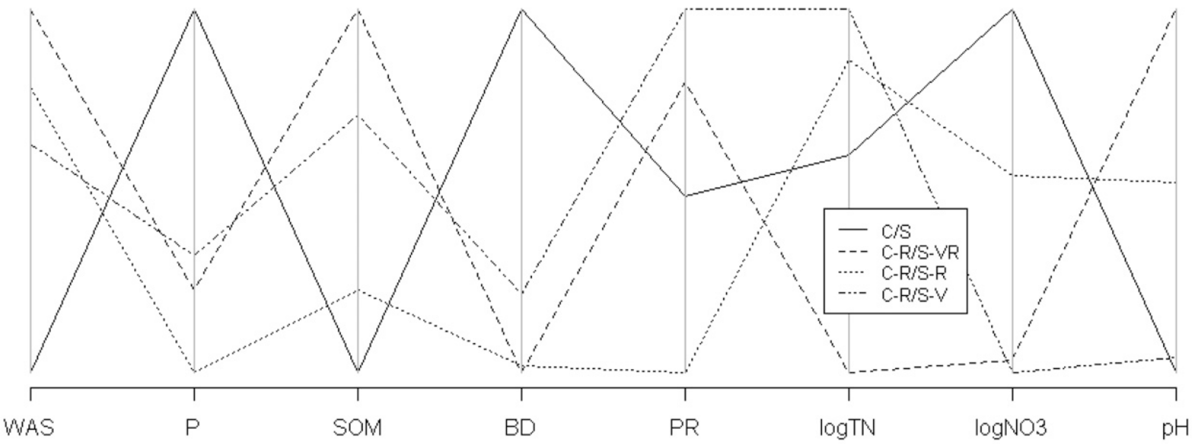

Fig. 2. Parallel coordinates plot for the crop rotation means of the canonical discriminant analysis (CDA) functions. Crop rotations: corn-fallow/soybean-fallow (C/S), corn-rye/soybean-rye (C-R/S-R), corn-rye/soybean-vetch (C-R/S-V), and corn-rye/soybean-vetch+rye (C-R/S-VR). Soil variables: water aggregate stability (WAS), available phosphorus (P), soil organic matter content (SOM), bulk density (BD), penetration resistance (PR), natural logarithm of total nitrogen content (logTN) and of nitrate N content (logNO3), soil reaction (pH).

Table 4. Cross-validation of the discrimination results obtained with canonical discriminant analysis (CDA). Crop rotations: corn-fallow/soybean-fallow (C/S), corn-rye/soybean-rye (C-R/S-R), corn-rye/soybean-vetch (C-R/S-V), and corn-rye/soybean-vetch+rye (C-R/S-VR).

Crop rotation	Predicted			
TRUE	C/S	C-R/S-R	C-R/S-V	C-R/S-VR
C/S	37	15	8	12
C-R/S-R	18	23	12	19
C-R/S-V	19	21	11	21
C-R/S-VR	19	21	14	18

BD compared to C/S, yet the C-R/S-R also caused an important reduction on soil PR. Continuous residue addition and the greater activities of soil microorganisms, fauna, and roots in WCC rotations might account for these differences. The reduction of BD that can be achieved with the use of any WCC rotation and of PR with C-R/S-R is a highly desirable condition for improving aeration, water infiltration, seed establishment, and root development, as well as for preventing environmental problems related to surface compaction (Kladivko, 1994; Soane and van Ouwerkek, 1995).

Regarding soil chemical attributes, lower P levels with WCC rotations indicated immobilization of this nutrient in the WCC biomass, which is important from an environmental point of view to reduce P runoff losses to waterways. Agronomically, the amounts of P lost per annum in runoff are generally inconsequential, but from a water-quality perspective, very small concentrations of P may cause a body of water to become eutrophic (Hart et al., 2004). All rotations showed mean values greater than the maximum P test levels (32 mg kg^{-1}) recommended for corn and soybean production in Illinois, yet our study shows the potential of WCC rotations to reduce soil P test levels below the agronomical optimum. Reductions on available soil P with the use of legume WCC have also been found by Groffman et al. (1987), and McVay et al. (1989), while the same effect with grass WCC was reported by Eckert (1991).

Evaluation of TN content in soils is deemed essential for assessing chemical aspects of soil quality under the soil quality framework (Doran et al., 1994,) and TN has been identified, along with SOM content, as the most powerful indicator of soil quality under contrasting land uses in many areas of the United States (Brejda et al., 2000a,b). In our study of no-till systems, TN was lower with C-R/S-VR, while lower soil NO_3–N content levels were also achieved with C-R/S-V. Environmental concerns regarding water quality have led to many investigations, recently reviewed by Thorup-Kristensen et al. (2003), on the use of WCC as NO_3–N content catch crops. In addition, soil pH values seemed to separate C-R/S-V and C/S from the rotations that included rye in both periods (C-R/S-R and C-R/S-VR); still, consistent with the literature (Schomberg et al., 1994), the effect of residues on soil pH was negligible.

Overall, differences in WAS, BD, and P clearly discriminated between C/S and WCC rotations. However, further separation among WCC rotations was not as clear. The high relative loading of SOM content in both LD and of logTN in LD2 also points out the usefulness of these two soil attributes as soil quality indicators to monitor changes in no-till systems. The selection of these soil attributes as indicators of dynamic soil quality is consistent with sensible indicators reported for other regions and cropping systems by Wander and Bollero (1999), Brejda et al. (2000a,b), Giuffre et al. (2006), Shukla et al. (2006), and Xu et al. (2006).

When performing discriminant analysis it is necessary to estimate the probabilities of correct classifications of new observations (Johnson and Wichern, 2002). Though a measure of accuracy is of primary importance when dealing with classification procedures, the presentation of error rates obtained by cross-validation, or even by resubstitution methods, is generally absent in the soil-quality literature. Table 4 shows the confusion matrix (Venables and Ripley, 2002) which gives the number of cases with true class I (True crop rotation) classified as of class j (Predicted crop rotation) by the cross-validation procedure on our CDA results. These estimates are likely to be unbiased estimates of the true probabilities of successful classification and, as a consequence, are better estimates than those we could have obtained by the resubstitution method (Johnson and Wichern, 2002). It was determined that 51.4, 31.9, 15.3, and 25.0% of the observations in C/S, C-R/S-R, C-R/S-V, and C-R/S-VR, respectively, were correctly classified by the discriminant rule (Table 4). As it can be observed in the tours and the parallel coordinates plot, it was more difficult to discriminate among rotations with WCC, considerably inflating the error rate. If it is considered that C-R/S-R and C-R/S-V rotations resemble C-R/S-VR (the latter including both WCC), it can be observed that many of the errors entailed classifying WCC rotations as opposed to separating these from winter fallowing (C/S). Then, C-R/S-R was classified into the correct rotation 58.3% (32.0 + 26.3) of the time, C-R/S-V was classified correctly 44.4%, and C-R/S-V was correctly classified 73.6% of the time. By considering two groups instead, 51% of the observations of no-till C/S and 74% of the observations of no-till WCC rotations would be correctly classified, for an overall error rate of 37.5%.

Conclusions

Management practices that represent steps forward in land stewardship are often more difficult to evaluate (i.e., distinguish among treatments) from a soil-quality standpoint than those involving sharply conflicting practices. However, indicators sensitive enough to reflect subtle changes are needed to support the adoption of these practices, as well as to increase the public recognition of both these practices and the farmers who adopt them. For example, the use of WCC in no-till systems is an interesting option available to producers to improve land stewardship in their farms and become eligible for CSP programs. The introduction of WCC accrue the benefits from no-till practices by providing additional residue accumulation and root activity in the soil at periods of the year that are not suitable for commercial crop production. Using visualization systems along with a multivariate approach to reflect the multidimensionality of soil quality, our research shows that WAS, BD, P, TN, and SOM content have the greatest potential as soil-quality indicators in no-till systems in Illinois. High error rates in our discriminant analysis underscore the complexity of no-till systems and the need in this area for more long-term studies with larger datasets to increase accuracy to acceptable levels. We expect the results of our study will contribute to the development of conservation policies and programs that favor and further reward farmers who incorporate cover crops along with their no-till operations. Our results show that their cropping systems are likely to provide environmental benefits beyond those provided by no-till farming.

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