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Nitrogen fertilization and cropping system impacts on soil properties and their relationship to crop yield in the central Corn Belt, USA

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Abstract

Evaluating the effects of management practices on soil physical and chemical properties would be valuable to explain field-level variability in crop production. A 23-year-old experiment on a Muscatune soil (fine-silty, mixed, superactive, mesic, Aquic Argiudolls) in Illinois with five N rates [0 (N_0), 70 (N_1), 140 (N_2), 210 (N_3) and 280 (N_4) kg N ha^{-1}] and two cropping systems [continuous corn (*Zea mays* L.) (CC), and corn–soybean (*Glycine max* (L.) Merr.) rotation (CS)] was evaluated. Specific objectives were to: (i) evaluate the effects of long-term N fertilization and cropping systems on field level changes in soil physical and chemical properties and crop yield, (ii) identify the most responsive soil physical and chemical properties to N fertilizer and crop management, and (iii) investigate the relationship between the selected soil properties and crop yield. Soil was collected in May 2004 to 30 cm depth and 20 soil physical and chemical properties were measured. The univariate analysis indicated that 14 soil properties were significantly influenced by at least one treatment effect (crops, N or crops × N). Due to multicollinearity among soil properties, principal component analysis (PCA) was used to group correlated properties, resulting in five soil properties such as soil organic carbon stock (OC stock), mean weight diameter (MWD), soil C:N ratio, exchangeable potassium (K^+) and gravimetric moisture content (ω). Finally, the multiple regression analysis performed between PCA derived soil properties and corn and soybean yields retained all the representative soil properties from PCA except ω as yield predictors for corn ($P < 0.001$, $R^2 = 0.39$) from CC system, whereas none of the soil properties were significantly related to corn and soybean yields from CS system. The soil properties most influenced by long-term N fertilization of continuous corn were successfully identified with PCA and multiple regression. The insignificant relationship between corn and soybean yields from CS system and PCA derived soil properties might be due to the lack of response of soybean to N fertilization. This study shows the integrated use of multivariate and regression analyses in identifying yield determining soil properties by eliminating the multicollinearity among soil properties.

Keywords: Nitrogen; Continuous corn; Corn–soybean rotation; Soil physical properties; Soil chemical properties; Crop yield; Principal component analysis; Multiple regression analysis

1. Introduction

Soil is an important component of the earth's biosphere (Glanz, 1995), and is essential to sustaining the production of food and fiber and the maintenance of environmental quality. Inappropriate land use and poor

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soil management exacerbate soil degradation, adversely affect the environment, and jeopardize soil's productivity. However, through the adoption of recommended management practices (RMPs) including N fertilization and cropping sequences, agricultural soils can restore and maintain crop productivity and soil quality. Such maintenance of ecosystem services of soil necessitates quantification of the differences in soil processes and functions among management practices that have been in place for long periods of time (Wienhold et al., 2004).

Although crop productivity can be enhanced by N fertilization and diverse/complex cropping sequences, these practices may strongly interact and impact soil properties differently (Russell et al., 2006). Liebig et al. (2002) demonstrated that long-term N fertilization in the Western U.S. Corn Belt region resulted in a trade-off between its positive effects on biological productivity (as shown by the increased organic carbon (OC), total N (TN), and particulate organic matter) and negative effects on nutrient cycling efficiency (as shown by decreased microbial biomass and soil pH). Furthermore, long-term N fertilization has been found to decrease exchangeable calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^{+}) levels, and cation exchange capacity (CEC) (Barak et al., 1997; Liu et al., 1997). A study conducted by Russell et al. (2006) in two long-term experiments at Nashua and Kanawha, IA indicated that cropping systems had more positive effect on soil quality than N fertilization. Soil OC increased in continuous corn (CC) receiving adequate N fertilizer and decreased in crop rotations including soybean (Varvel, 1994; Studdert and Echeverria, 2000). However, degraded soil physical conditions and reduction in aggregate stability can occur in both monoculture corn and corn–soybean cropping systems (Hussain et al., 1988; Raimbault and Vyn, 1991).

Yield variability can be partly explained by management-induced changes in soil properties. Wright et al. (1990) reported that soil properties such as texture, fertility, organic matter and available water can have a significant effect on corn yield. In a study conducted to assess the short-term stover management impacts on no-till monoculture corn system, Blanco-Canqui et al. (2006) reported that soil temperature, water holding capacity and stability of aggregates were the principal determinants of grain yield. Similar conclusions have been drawn from data generated in other studies (Huang et al., 2004; Jiang and Thelen, 2004; Kaspar et al., 2004). Simple correlation and multiple regression analyses have been used to model the relationship between crop yield and soil properties. Apart from the correlation with crop yield, soil properties have often been correlated with each other. Using intercorrelated soil properties in multiple regression analysis to identify the yield determining soil properties can create the problem of multicollinearity (Bowerman and O'Connell, 1990). Consequently, use of appropriate statistical tools can play a significant role. Multivariate analysis techniques are useful to avoid the problems of multicollinearity by grouping properties that are strongly correlated. Principal component analysis (PCA), one of several multivariate methods, is aimed at data reduction through linear combinations of the original variables to a few independent variables that explain most of the variance from the large original data set (Martens and Naes, 1989). This multivariate tool has been used by many researchers to identify the most sensitive soil and/or topographic properties influencing crop production (Mallarino et al., 1999; Jiang and Thelen, 2004; Kaspar et al., 2004; Blanco-Canqui et al., 2006; Cox et al., 2006).

The use of PCA to identify the yield determining soil properties is particularly relevant in cropland soils of United States, where the increase in crop productivity from 1950 to 2005 was 287% for corn and 100% for soybean (USDA-NASS, 2006). This drastic increase in productivity warrants the identification of more site and management specific data on the influence of soil properties on crop yields. A better understanding of these relationships could lead to more efficient implementation of strategies to improve crop productivity. Thus, the objectives of this study were to (i) evaluate the effects of long-term N fertilization and cropping systems on field-level changes in soil physical and chemical properties and crop yield, (ii) identify the most responsive soil physical and chemical properties to N fertilizer and crop management, and (iii) determine the relationship between the selected soil properties and crop yield.

2. Materials and methods

2.1. Site descriptions

Detailed descriptions of the experimental site, treatments, and the cultural practices were reported previously (Jagadamma et al., 2007). This study was conducted on a 23-year-old N rate and cropping system experiment at the Northwestern Illinois Agricultural Research and Demonstration Center in Monmouth, IL. The experiment is located at 40°90′N latitude and 90°73′W longitude, and sited at the northwest quarter of section 22, Warren County, Illinois. The average elevation of the site was 230 m with <0.6 m elevation change across the site. The soils of this site belong to Muscatune series (fine-silty, mixed, superactive, mesic, Aquic Argiudolls). Treatments included: (i) two cropping systems [continuous corn (*Zea mays* L.) (CC), and corn–soybean (*Glycine max* (L.) Merr.) rotation (CS)], (ii) five N rates [0 (N_0), 70 (N_1), 140 (N_2), 210 (N_3) and 280 (N_4) kg N ha^{-1}] applied only to corn every year, and (iii) presence (C_1) or absence (C_0) of oat (*Avena sativa* L.) as a cover crop. The cover crop treatment was started in 2001. The treatments were allocated in split–split plot arrangement in a randomized complete block experimental design with cropping systems as the main plot, N rate as the split plot, and presence or absence of cover crop as split–split plot. The treatments were replicated three times and the sub plots were 9 m × 6 m in size. The oat cover crop was drilled in the designated plots following the harvest of previous corn or soybean. The field was chisel plowed during fall to 25–30 cm depth, generally within a day or two prior to sowing the cover crop. In the spring, the cover crop was incorporated with spring tillage, which involved a single pass of field cultivator to 10 cm depth, prior to sowing corn and 70–80% of the crop residue cover was maintained. The N fertilizer was injected at 10–15 cm depth before planting corn as urea (46% N) until 1996, and urea ammonium nitrate solution (28% N) thereafter. Neither P nor K fertilizer was applied to either corn or soybean because the soil test results showed these to be adequate. Additionally, no lime was applied as the soil pH was $\geq$6.0 during the entire period of this experiment. Weed control was achieved by using recommended rates and timing of appropriate herbicides along with hand weeding if necessary. Plots were essentially weed free during the study period. Corn and soybean were planted at 76 cm row spacing and at a rate of 80,000 and 375,000 seeds ha^{-1}, respectively, using a four-row, tractor drawn planter. The corn ears from the center two rows of each plot were hand harvested and weighed in October 2004 to quantify grain yields. Upon air-drying, corn ears were shelled, and kernels and cobs weighed separately. Subsamples of kernel and cob were oven dried at 60 °C for 48 h to determine the water content. Grain yield was reported at water content of 15.5%.

2.2. Soil sampling and analyses

Soil samples were obtained on 22 May 2004 at the third mature leaf (V3) stage of corn and the unifoliate stage of soybean. Three core samples per plot were collected to 30 cm depth using a 2.86 cm diameter hydraulic soil probe mounted on a tractor. After determining the bulk density (ρ_b), the three soil cores per plot were pooled, air dried for a week at 22–25 °C, gently ground with a wooden roller and sieved through a nest of sieves consisting of 8, 5, and 2 mm sizes. The natural aggregates retained on the 5 mm sieve were used for soil structural stability analysis and soil passing through the 2 mm sieve was used for analyses of various physical and chemical properties.

Soil ρ_b and particle density (ρ_s) were measured by the core method (Grossman and Reinsch, 2002) and the pycnometer method (Flint and Flint, 2002a), respectively. Total porosity was calculated empirically from ρ_b and ρ_s and expressed on percent basis (Flint and Flint, 2002b). Gravimetric moisture content (ω) was determined by oven drying a representative fraction of field moist soil at 105 °C. Soil structural stability was estimated by the wet sieving method (Nimmo and Perkins, 2002) and expressed as mean weight diameter (MWD) and water stable aggregates (WSA). Soil texture was determined by the hydrometer method (Gee and Or, 2002).

Soil chemical properties considered were soil pH, organic carbon concentration (OC), total nitrogen concentration (TN), soil C:N ratio, OC and TN stocks, CEC and exchangeable Ca^{2+}, Mg^{2+}, K^{+}, and sodium (Na^{+}). Soil pH was determined in 1:2 soil water suspension using pH meter (Thomas, 1996). A part of the representative soil samples (2 mm) was further ground using a ball mill and sieved through a 0.125 mm sieve for the determination of OC and TN by the dry combustion method (Nelson and Sommers, 1996) using a NC 2100 soil analyzer (ThermoQuest CE Instruments, Milan, Italy). The OC was assumed to be equal to total C since soil pH was <7.1 (Al-Kaisi et al., 2005). Stocks of OC and TN were calculated as the product of OC (or TN) concentrations, ρ_b, and soil depth (30 cm) (Lal et al., 1998). The soil C:N ratio was computed as the quotient of OC and TN concentrations. The exchangeable Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} were measured by the ammonium acetate extraction method at pH 7.0 (Sumner and Miller, 1996), and the exchangeable acidity using $BaCl_2$-triethanolamine solution buffered at pH 8.2 and back-titrated with HCl. The CEC was calculated by adding both the exchangeable bases and the acidity.

2.3. Statistical analyses

Analysis of variance (ANOVA) was conducted using PROC GLM of SAS (SAS Institute, 1994) on 20 soil properties (ρ_b, ρ_s, porosity, ω, sand, silt, clay, MWD, WSA, pH, OC, TN, C:N ratio, OC and TN stocks, CEC, Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}), to test the null hypothesis of no overall treatment effect on individual soil properties. Data analysis showed that growing 3 years of oat cover crop had no effect on any of the parameters measured. Hence final ANOVA was conducted without the cover crop term in the model. Only 14 properties that showed significant difference ($P \leq 0.05$) between different levels of at least one treatment (crops, N or crop × N) were retained for further study. All retained physical and chemical soil properties were subjected to correlation analysis using PROC CORR procedure of SAS (SAS Institute, 1994) to identifying associations between soil properties and crop yield and correlations among soil properties. The PCA was conducted further using PROC FACTOR procedure of SAS (SAS Institute, 1994).

Groups of soil properties or factors derived from PCA are considered mutually orthogonal, uncorrelated, and successively explain the maximum residual variation (Sena et al., 2002). A factor, as an array variable, may hold contribution from all 14 soil properties. Total variance of each factor was defined as eigenvalue (Swan and Sandilands, 1995). Factors with eigenvalues ≥ 1 (Brejda et al., 2000) and those that explained at least 5% of the variation in the data (Wander and Bollero, 1999) were retained. Soil properties from each factor were selected based on the correlation coefficients or factor loadings between soil properties and each factor (Sharma, 1996; Johnson and Wichern, 1992). Generally, soil properties with higher loading coefficients were included in each factor because they could be expected to have greater effect on yield variability. However, there are no established or clear rules to help decide what a 'large' factor loading is (Mallarino et al., 1999). Soil properties with factor loadings >0.50 were selected to be included in each factor. If the loading coefficient of a soil property was >0.50 in more than one factor, it was included in the factor having the highest coefficient value for that property. The retained factors were subjected to varimax rotation to redistribute the variance of significant factors and thereby maximize the relationships between interdependent soil properties (SAS Institute, 1994).

When more than one property was selected within a factor, their linear correlations were calculated using PROC CORR procedure of SAS (SAS Institute, 1994) to determine whether the properties could be considered redundant (Andrews et al., 2002). Among the correlated soil properties at $P \leq 0.05$, the soil property with the highest factor loading was selected for further consideration. If the highly weighted variables within a factor were not correlated, each soil property was considered important and was retained in the data set. Finally, to study the relationship between the selected soil properties and grain yield, multiple regression analysis was performed with the help of PROC REG (SAS Institute, 1994) using the PCA derived soil properties as independent variables and long-term average corn and soybean yield as dependent variables at $P \leq 0.10$.

3. Results and discussion

3.1. Crop yield

Yield data for corn from both CC (22-year average from 1983 to 2004) and CS systems (11-year average in alternate years from 1983 to 2003), and for soybean from CS system (11-year average in alternate years from 1984 to 2004) were obtained from the Northwestern Illinois Agricultural Research and Demonstration Center, Monmouth, IL. Averaged across N rates, CS resulted in higher average corn grain yield (10.54 Mg ha^{-1}) than CC (8.08 Mg ha^{-1}) ($P \leq 0.05$). Baldock et al. (1981) found that the increase in corn yield following legumes could be attributed to N supply, but also to other unknown factors unrelated to N limitation. Increasing rate of N application resulted in increasing corn grain yield for both CC and CS systems (Fig. 1) with values ranging from 4.82 (N_0) to 9.53 (N_4) Mg ha^{-1} for CC and 8.72 (N_0) to 11.23 (N_3) Mg ha^{-1} for CS ($P \leq 0.05$). As compared to the N_0 treatment, mean corn grain yield in treatments N_1 through N_4 was 61–98% higher in CC system and 21–29% higher in CS system indicating a greater response to N fertilizer in the CC system. The long-term average corn grain yield from northeast and northcentral Iowa also showed a strong response to N fertilization for the CC system and moderate response for the CS system (Mallarino and Pecinovsky, 1999; Mallarino and Rueber, 1999). Conversely, mean soybean yield was not affected by N applied to the preceding corn crop, with values ranging from 4.46 to 4.62 Mg ha^{-1}.

3.2. Effect of treatments on soil properties

Descriptive statistics from univariate ANOVA of all 20 soil properties are summarized in Table 1. Properties that showed significance ($P \leq 0.05$) in at least one treatment effect (crops, N or crops × N) were the 14 soil properties of ρ_b, ω, MWD, WSA, clay, pH, OC, TN, C:N ratio, OC and TN stocks, Mg^{2+}, K^{+} and Na^{+}. The

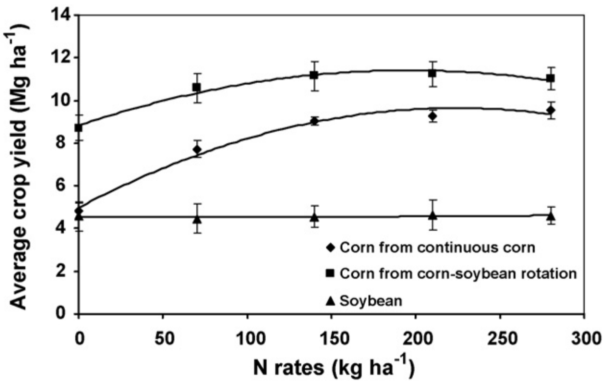

Fig. 1. The effect N fertilization on long-term average grain yield of corn and soybean.

remaining six properties (ρ_s, porosity, sand, silt, Ca^{2+} and CEC) were excluded because they failed to meet the screening criteria. A similar screening approach was used by Sharma et al. (2005).

Soil ρ_b was lower (1.25 Mg m^{-3}) for N_4 than for N_0 and N_1 (Table 2). Lower ρ_b with increased fertilizer N rate may have been due to greater biomass production and return of crop residues to the soil. However, among the cropping systems treatments (CC and CS), ρ_b did not change significantly. The ω was significantly higher and clay content lower for CC than CS system. Both OC and TN concentrations showed significant differences due to long-term N fertilization and cropping systems treatments (Jagadamma et al., 2007). Among the N treatments, the concentrations for OC and TN were: $N_0 < N_1 = N_2 = N_3 < N_4$. The OC and TN stocks also followed similar trends with the highest values for N_4 and the lowest for N_0 treatments. These results were in

Table 1
Analysis of variance (ANOVA) summary for measured physical and chemical soil properties

Properties	Units	R^2	CV	Mean	ANOVA P value		
					Crop	Nitrogen	Crop × N
Physical							
ρ_b	Mg m^{-3}	0.44	5.4	1.30	0.12	0.05	0.70
ρ_s	Mg m^{-3}	0.45	6.1	2.56	0.22	0.80	0.16
Porosity	%	0.44	8.4	49.0	0.07	0.14	0.22
ω	g g^{-1}	0.72	4.9	0.25	0.0002	0.44	0.25
MWD	mm	0.72	25.7	0.57	0.0006	0.0002	0.005
WSA	g kg^{-1}	0.71	11.4	505.4	0.05	0.005	0.006
Sand	g kg^{-1}	0.40	10.7	148.1	0.87	0.20	0.71
Silt	g kg^{-1}	0.47	2.6	590.2	0.13	0.57	0.77
Clay	g kg^{-1}	0.48	4.4	261.7	0.03	0.27	0.29
Chemical							
pH		0.88	3.8	6.5	<0.0001	<0.0001	0.0009
OC	g kg^{-1}	0.74	6.6	19.4	0.0002	<0.0001	0.44
TN	g kg^{-1}	0.76	7.9	1.58	0.0006	<0.0001	0.49
C:N ratio		0.64	4.5	12.3	0.53	0.02	0.25
OC stock	Mg ha^{-1}	0.47	9.2	75.5	0.05	0.04	0.71
TN stock	Mg ha^{-1}	0.59	9.5	6.16	0.03	0.0.001	0.80
Ca^{2+}	cmol$_c$ kg^{-1}	0.67	5.6	17.1	0.20	0.14	0.37
Mg^{2+}	cmol$_c$ kg^{-1}	0.69	5.1	3.11	0.0002	0.0017	0.11
K^+	cmol$_c$ kg^{-1}	0.65	25.0	0.13	0.001	0.01	0.19
Na^+	cmol$_c$ kg^{-1}	0.59	11.9	0.09	0.005	0.13	0.69
CEC	cmol$_c$ kg^{-1}	0.70	4.4	26.7	0.08	0.47	0.11

ρ_b, bulk density; ρ_s, particle density; ω, gravimetric moisture content; MWD, mean weight diameter; WSA, water stable aggregates; OC, organic carbon concentration; TN, total nitrogen concentration; OC stock, organic carbon stock; TN stock, total nitrogen stock; Ca^{2+}, exchangeable calcium; Mg^{2+}, exchangeable magnesium; K^+, exchangeable potassium; Na^+, exchangeable sodium; CEC, cation exchange capacity.

Table 2
Main effects of treatments on selected physical and chemical soil properties

Soil properties	Units	Cropping systems		Nitrogen rates				
		CC[a]	CS	N_0[b]	N_1	N_2	N_3	N_4
ρ_b[c]	Mg m^{-3}	1.29 a[d]	1.29 a	1.34 a	1.31 a	1.31 ab	1.30 ab	1.25 b
ω	g g^{-1}	0.25 a	0.24 b	0.246 a	0.246 a	0.243 a	0.252 a	0.248 a
Clay	g kg^{-1}	258.3 a	265.1 b	258.4 a	268.3 a	261.5 a	260 a	260.3 a
OC	g kg^{-1}	20.1 a	18.7 b	17.5 a	19.2 b	19.1 b	20.1 b	20.9 c
TN	g kg^{-1}	1.64 a	1.52 b	1.38 a	1.54 b	1.59 b	1.65 b	1.76 c
C:N ratio		12.2 a	12.3 a	12.7 a	12.5 ab	12.1 ab	12.3 ab	11.9 b
OC stock	Mg ha^{-1}	77.2 a	73.7 b	70.1 a	75.6 ab	75.2 ab	78.1 b	78.4 b
TN stock	Mg ha^{-1}	6.33 a	5.99 b	5.52 a	6.07 b	6.22 bc	6.39 bc	6.61 c
Mg^{2+}	$cmol_c$ kg^{-1}	3.03 a	3.20 b	3.25 a	3.14 ab	3.11 b	3.11 b	2.95 c
K^+	$cmol_c$ kg^{-1}	0.15 a	0.12 b	0.16 a	0.14 ab	0.11 c	0.12 bc	0.12 bc
Na^+	$cmol_c$ kg^{-1}	0.08 a	0.09 b	0.09 a	0.089 a	0.091 a	0.089 a	0.088 a

[a] CC = continuous corn; CS = corn–soybean rotation (corn in sampling year 2004).
[b] $N_0 = 0$, $N_1 = 70$, $N_2 = 140$, $N_3 = 210$, $N_4 = 280$ kg N ha^{-1} applied in corn phase only.
[c] ρ_b, bulk density; ω, gravimetric moisture content; OC, organic carbon concentration; TN, total nitrogen concentration; OC stock, organic carbon stock; TN stock, total nitrogen stock; Mg^{2+}, exchangeable magnesium; K^+, exchangeable potassium; Na^+, exchangeable sodium.
[d] Values in a row within a treatment type followed by the same letters are not significantly different at $P \leq 0.05$ using Fisher's protected LSD.

accordance with those by Russell et al. (2006), Liebig et al. (2002) and Salinas-Garcia et al. (1997). The effect of cropping systems on OC and TN concentrations and stocks were also significant (CC > CS). The higher OC stock in CC than CS has been credited to greater crop residue production by corn than soybean (Studdert and Echeverria, 2000; Paustian et al., 1997; Varvel, 1994). However, average crop residue production estimated in a previous study at this experiment was similar (7.17 Mg ha^{-1}) for both CC and CS systems (Jagadamma et al., 2007). The higher OC stock in CC than in CS system even with the same residue production may have been due to increased resistance to microbial degradation of corn residue than soybean residue (Hao et al., 2002). The C:N ratio was not affected by cropping systems, but did decline with N fertilization from 12.7 (N_0) to 11.9 (N_4). Exchangeable Mg^{2+} also varied significantly among N rates and cropping systems, with mean values increased by $N_4 < N_3 = N_2 \leq N_1 \leq N_0$ for N rates and CC < CS for cropping systems. Exchangeable K^+ was significantly affected by N rates, with the highest mean value at the N_0 level. Across N levels, K^+ was significantly higher for CC than for CS. This effect can be attributed to lower uptake of K by corn grain relative to other crops (Russell et al., 2006) and the overall lower grain yield from the CC than CS system. Exchangeable Na^+ was significantly lower for CC than CS system, but not affected by N rates.

Significant interactions between cropping systems and N rates were observed for MWD, WSA and soil pH (Fig. 2). The MWD in CC ranged from 0.47 mm (N_0) to 0.93 mm (N_4), indicating a strong effect of N fertilization (Fig. 2A). In contrast, MWD was not affected by N rates in the CS system. Similarly, WSA increased with increasing N rate in CC with significantly higher mean values for N_3 and N_4 treatments as compared to lower N levels (Fig. 2B). However, the effect of N rate on WSA was not consistent in the CS system. Soil pH declined linearly with increasing N rate from 6.97 (N_0) to 5.58 (N_4) in the CC system, while the magnitude of pH variation with N rates was smaller (6.96 for N_0 to 6.45 for N_4) in the CS system (Fig. 2C). Soil acidification through nitrification of ammoniacal fertilizers has been well documented (Gajda et al., 2000; Liebig and Doran, 1999). Since there was no N application in the soybean phase of the CS system, the cumulative amount of N added to the CS system was half that for the CC system and was likely the reason for less soil acidification due to N fertilization in CS than in CC system.

3.3. Correlation analysis

Following univariate analysis, the retained soil properties were subjected to correlation analysis. Significant correlations were observed between soil properties and grain yield, as well as between soil properties (Table 3). Corn grain yield was positively correlated to MWD, WSA, OC, TN, OC stock and TN stock and negatively correlated to soil pH, Mg^{2+} and K^+. Among soil physical and chemical properties, 56 significant correlations were observed. Strong positive correlations were observed among OC and TN concentrations and stocks ($r = 0.65$–0.89, $P < 0.0001$).

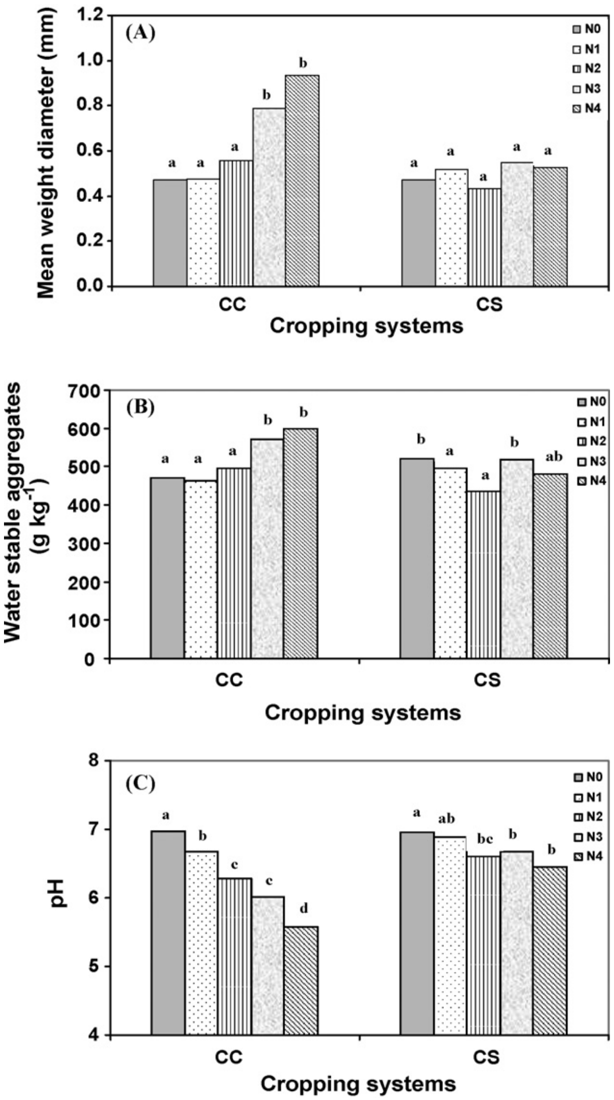

Fig. 2. Interaction effect of cropping systems and N rates on (A) mean weight diameter, (B) water stable aggregates, and (C) soil pH. Similar letters on top of the histogram of each figure indicates statistically equal values at $P \leq 0.05$ using Fisher's protected LSD. CC, continuous corn; CS, corn–soybean rotation.

Similarly, correlations between MWD and WSA, MWD and OC, pH and C:N ratio, and pH and Mg^{2+} were also positive and highly significant ($P < 0.0001$). Among the negative correlations, those that were highly significant ($P < 0.0001$) were between pH and MWD, pH and OC, pH and TN, pH and TN stock, TN and C:N ratio, TN and Mg^{2+}, TN stock and C:N ratio, and K^+ and Na^+. These correlations reflected multicollinearity among soil physical and chemical properties, which makes the interpretation of multiple regression equations between yield and soil properties unreliable (Cox et al., 2006; Mallarino et al., 1999; Bowerman and O'Connell, 1990).

3.4. Principal component analysis

In order to group the correlated soil properties to the smallest possible subsets representing the majority of variation, PCA was performed using the 14 soil properties selected from the univariate screening procedure. Each of the first five groups or factors had eigenvalues >1 and were retained for interpretation (Table 4). These five factors explained cumulative sample variance of 80%. The first and the most important factor, which explained 36% of the variation, had high factor loading (>0.50) for properties such as OC stock, TN stock, OC and TN. Factor 2 had high

Table 3
Pearson's correlation coefficients for soil properties and corn grain yield

Properties	ρ_b	ω	MWD	WSA	Clay	pH	OC	TN	C:N ratio	OC stock	TN stock	Mg^{2+}	K^+	Na^+	Yield
ρ_b	–														
ω	**−0.31**	–													
MWD	**−0.37**	**0.28**	–												
WSA	**−0.28**	0.24	**0.81**	–											
Clay	0.06	−0.12	−0.04	−0.07	–										
pH	**0.38**	−0.24	**−0.54**	**−0.28**	**0.28**	–									
OC	**−0.31**	**0.42**	**0.53**	**0.38**	−0.11	**−0.49**	–								
TN	**−0.38**	0.19	**0.47**	**0.31**	−0.16	**−0.64**	**0.85**	–							
C:N ratio	**0.26**	**0.27**	−0.08	0.01	0.11	**0.48**	−0.08	**−0.59**	–						
OC stock	0.25	0.23	**0.31**	0.22	−0.07	**−0.28**	**0.84**	**0.65**	0.06	–					
TN stock	0.07	0.04	**0.32**	0.19	−0.14	**−0.50**	**0.76**	**0.89**	**−0.51**	**0.82**	–				
Mg^{2+}	0.2	−0.14	**−0.45**	−0.17	0.09	**0.60**	**−0.47**	**−0.53**	**0.29**	**−0.35**	**−0.46**	–			
K^+	−0.09	0.21	0.00	−0.05	0.00	0.14	0.03	−0.04	0.11	−0.03	−0.09	−0.04	–		
Na^+	0.02	0.09	−0.24	−0.05	−0.12	0.09	−0.04	−0.04	0.04	−0.02	−0.03	**0.35**	**−0.59**	–	
Yield	−0.14	−0.08	**0.38**	**0.26**	0.05	**−0.50**	**0.41**	**0.44**	−0.24	**0.35**	**0.41**	**−0.33**	**−0.39**	0.12	–

ρ_b, bulk density; ω, gravimetric moisture content; MWD, mean weight diameter; WSA, water stable aggregates; OC, organic carbon concentration; TN, total nitrogen concentration; OC stock, organic carbon stock; TN stock, total nitrogen stock; Mg^{2+}, exchangeable magnesium; K^+, exchangeable potassium; Na^+, exchangeable sodium. Correlation coefficients in bold are significant at $P \leq 0.05$.

loading from C:N ratio, ρ_b and soil pH and collectively explained 13% of the sample variance. The highly weighted variables under Factor 3 were MWD and WSA. Similarly K^+ and Na^+ from Factor 4 and ω from Factor 5 were selected as highly weighted variables.

Correlation coefficients among OC, TN, OC stock and TN stock under Factor 1 were strongly correlated (Table 3). The OC stock was selected as a representative from Factor 1 because it had the highest factor loading of 0.95. Under Factor 2, ρ_b, pH and C:N ratio were significantly correlated. Soil C:N ratio with the highest factor loading of 0.85 was selected to represent Factor 2. Similarly, MWD and K^+ were selected as representatives from Factors 3 and 4, respectively. Only ω was

Table 4
Factor analysis results based on 14 soil physical and chemical properties

Factors	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Eigenvalue	5.1	1.9	1.7	1.4	1.2
Percent variance	36.3	13.5	12.0	10.1	8.7
Cumulative variance	36.3	49.7	61.7	71.8	80.5
Eigen vectors					
ρ_b [a]	0.13	***−0.71***	−0.02	0.05	0.52
MWD	0.31	−0.21	***0.93***	0.10	0.08
WSA	0.15	0.05	***0.88***	−0.06	0.05
ω	0.16	0.06	0.23	0.22	***0.79***
Clay	−0.08	0.05	0.04	0.18	−0.46
pH	−0.4	***0.63***	−0.33	0.09	−0.27
OC	***0.87*** [b]	−0.09	0.2	0.03	0.34
TN	***0.80***	−0.50	0.16	0.04	0.14
C:N ratio	−0.10	***0.85***	0.05	−0.05	0.30
OC stock	***0.95*** [c]	0.27	0.15	0.02	0.06
TN stock	***0.93***	−0.17	0.13	0.05	−0.11
Mg^{2+}	−0.31	0.40	−0.23	−0.22	−0.09
K^+	−0.04	0.03	−0.09	***0.91***	0.16
Na^+	−0.22	0.06	−0.13	***−0.83***	0.34

[a] ρ_b, bulk density; MWD, mean weight diameter; WSA, water stable aggregates; ω, gravimetric moisture content; OC, organic carbon concentration; TN, total nitrogen concentration; OC stock, organic carbon stock; TN stock, total nitrogen stock; Ca^{2+}, exchangeable calcium; Mg^{2+}, exchangeable magnesium; K^+, exchangeable potassium; Na^+, exchangeable sodium.
[b] Factor loadings in bold italic are considered highly weighted.
[c] Underlined factor loadings correspond to the indicators included in the MDS

ranked as highly weighted from Factor 5, which was also added to the dataset. The final soil properties selected were OC stock, MWD, C:N ratio, K^+ and ω.

3.5. Multiple regression analysis

Multiple regression analysis using the backward elimination procedure was performed to identify the smallest subset of soil properties for predicting corn and soybean grain yield. The regression equation to predict corn grain yield for CC was highly significant ($P < 0.001$, $R^2 = 0.67$) and retained all the soil properties derived from the PCA except ω:

$$Y = 12.08 + 0.18(\text{SOC stock}) + 3.14(\text{MWD}) - 1.13(\text{C : N ratio}) - 21.94(\text{K}^+)$$

In contrast, both the corn and soybean yield from CS system was not significantly related to the PCA derived soil properties. This might be due to the lack of response of soybean to long-term N fertilization. Soybean can obtain most of its N through N fixation. Kaspar et al. (2004) reported that soybean and corn differ in many anatomical and physiological characteristics (Gardner et al., 1985) and would be expected to respond differently to soil properties and landscape characteristics. In Minnesota, Khakural et al. (1998) studied the yield determining variables for corn and soybean and found that corn yield was related to topsoil depth and soil pH, whereas soybean yield was related to soil profile water storage, percent slope, exchangeable K and depth to carbonate.

4. Conclusion

This study demonstrated how PCA could be effectively used to group correlated soil properties into unique factors for application in regression models to predict grain yield. The PCA identified five soil properties (OC stock, MWD, soil C:N ratio, K^+ and ω) as a representative subset of the original 20 soil properties evaluated in a 23-year N-rate and cropping systems experiment in northwestern Illinois. The multiple regression analysis performed using the PCA-derived soil properties was highly significant ($P < 0.001$) for predicting corn yield from CC system, but not for corn and soybean yield from CS system. We conclude that the soil properties most influenced by long-term N management of continuous corn can be precisely identified by employing PCA coupled with multiple regression analysis.

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