

Management and Crop Residue Influence Soil Aggregate Stability

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ABSTRACT

Soil management is one of the most important factors influencing the structure of soils. The interaction of management (including tillage and crop rotation history) with soil biochemistry, soil aggregation, and soil humus composition was determined in a native prairie and a producer field situation in 1997. A comparison of a native prairie and an adjacent conventional corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation on the same soil type found that the Webster soil (fine-loamy, mixed, superactive, mesic Typic Endoaquoll) after soybean (C₃ plant) was lower in monosaccharide content and protein content as determined by ion chromatography, and lower in phenolic acid content than the Webster soil after corn (C₄ plant) or in native prairie as determined by gas chromatography. A wet, nested sieve aggregate stability measurement determined that the prairie soil had a higher mean aggregate size (1.85 mm) when compared with the soil in the presence of decomposing corn (1.0 mm) or soybean (0.34 mm) residues. Mean aggregate size was found to be correlated with soil monosaccharide content ($r = 0.75$), total soil protein content ($r = 0.995^{***}$), total soil phenolic acid content ($r = 0.997^{***}$), and alkaline extractable humic substance content ($r = 0.98^{**}$). Alkaline extractable humic substances were correlated with the phenolic acid content of the humic substances ($r = 0.996^{***}$). The results suggest that the decrease in soil stability after soybean growth was due to a decrease in the content of soil humic substances caused by the substantially lower phenolic acids content (humic acid precursors) in the soybean residue.

THE MECHANISM involved in the binding of soil particles into stable aggregates varies with a variety of factors related to soil parent material, climate, vegetation, and management practices (Martin et al., 1955; Harris et al., 1966; Kay, 1990). Soil aggregates are pro-

posed to be the basic units of soil structure (Lynch and Bragg, 1985) and organic residues applied to soil with different management systems have been shown to improve structure (Waksman, 1936; Kononova, 1961). Soil structure improvement with organic addition or crop growth is not solely dependent on the total amount of organic C present, but is a function of a number of factors including the chemical composition of the organic matter and employed management system (Strickling, 1950; Martin, 1971; Dormarr, 1983).

The use of tillage in crop production decreases the stability of soil and the decomposition of different crop residues have also been shown to degrade soil structure. Under identical management and soil situations, corn following soybean results in greater erosion than continuous corn or soybean following corn (Lafren and Moldenhauer, 1979). The soil instability following soybean production has been reported to be caused by a decrease in soil aggregate strength resulting in decreased aggregate size and an increased surface crusting (Kidder et al., 1943; Fahad et al., 1982). McCracken (1984) found that equal amounts of soybean and corn residue, allowed to decompose in soil for 4 mo, did not produce the same level of stable soil aggregates, suggesting that amount of decomposing soybean residue may not be the major factor reducing the soil structure in soil following soybean growth.

The study was conducted to investigate management factors such as crop rotation on soil structure in a producer-managed corn–soybean rotation and an adjacent native prairie setting, holding soil type and climatic variables the same. The effects of the plant residue chemistry (prairie vegetation, corn, and soybean residues) was also investigated on the resulting soil biochemistry.

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Abbreviations: *, **, ***, Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

Table 1. Properties of soils sampled April 1997.

Soil	pH [†]	Organic C [‡]	Inorganic C [§]	Total N	Texture [#]		
					Sand	Silt	Clay
g kg ⁻¹ soil							
Webster, corn ^{††}	7.38	30.50	2.15	2.64	395	387	218
Webster, soybean	7.28	28.82	1.44	1.86	409	396	195
Webster, prairie	7.03	43.96	1.12	3.84	380	373	247

[†] Values for pH were obtained in 1:2.5 soil to 0.01 M CaCl₂.

[‡] Organic C was determined by dry combustion analysis after treatment with HCl.

[§] Inorganic C was determined by subtraction of organic C from total C after dry combustion analysis.

^{||} Total N was determined by dry combustion analysis.

[#] Texture was determined by dispersion and the pipette method of Gee and Bauder (1986).

^{††} The vegetation following the soil is the vegetation that was grown in 1996 and decomposed during the 1997 growing season.

MATERIALS AND METHODS

Soil and Plant Samples

The Webster silty-clay loam soils used in this study were obtained from a native prairie (Kelso Prairie, Pocahontas County, IA) and two different fields located directly across the county road on private lands. It was assumed that the same soil type was sampled due to proximity of the sites, location on Pocahontas County soil map (1984 survey), and the properties listed in Table 1. The soil described as the corn soil was planted to corn in 1996 and the soybean soil was planted to soybean in 1996 and duplicate samples (within 1 m² grid) of the respective soils were sampled (0–15 cm) during 1997 when the alternate crop in the rotation was grown. The properties of the overwintered corn, soybean, and prairie vegetation sampled (April 1997) are listed in Table 2. The plant samples analyzed were a mix of both leaf and stem portions and prairie grass species sampled were not identified. The soils were sampled in April and September 1997. The pH was measured in 0.01 M CaCl₂ and texture by a pipette method described by Gee and Bauder (1986). Total C, organic C (total C after acid neutralization), and total N were determined by dry combustion with a Perkin Elmer (Wellesley, MA) 2400 C/H/N analyzer and inorganic C was determined by the difference between total C and organic C.

Analyses

Total carbohydrate content was measured by acid extraction and ion chromatography with pulsed amperometric detection of individual monosaccharides as described by Martens and Frankenberger (1990). Briefly, 500 mg soil or 100 mg plant residue were treated with 12 M H₂SO₄ for 2 h, then refluxed with 2 M H₂SO₄ at 80°C for 16 h, titrated to pH 5 with 5 M KOH, centrifuged to remove precipitate. An aliquot was diluted for analysis.

Total protein content was measured by acid extraction and ion chromatography with pulsed amperometric analysis of the

Table 2. Properties of plant residues (dry weight basis) used in this study.[†]

Vegetation	Organic C	Total N	Total carbohydrates	Total protein	Total phenolic acid
Corn	445.0	4.3 (103) [‡]	106.5	2.3	27.1
Soybean	396.8	10.7 (37)	73.2	4.6	1.9
Prairie	452.8	3.7 (122)	110.2	3.0	8.5

[†] Organic C and total N were determined as listed in Table 1. Total carbohydrate content, total protein content, and total phenolic acid content were determined as listed in the Materials and Methods section.

[‡] The value in parentheses indicate C to N ratio.

individual amino acids and sugars as described by Martens and Frankenberger (1992). Briefly, 500 mg soil or 100 mg plant residue were autoclaved for 16 h with 4 M methane sulfonic acid (2 mg tryptamine mL⁻¹), titrated to pH 5 with 5 M KOH, centrifuged to remove precipitate. An aliquot was diluted for analysis. The monosaccharides and amino acids were separated on a Dionex (Sunnyvale, CA) DX-500 ion chromatograph equipped with a Dionex CarboPac PA10 (2 mm i.d.) for monosaccharide analysis and a Dionex AminoPac PA1 (2 mm i.d.) for amino acid analysis. Separation was achieved with a NaOH gradient (5–80 mM) for monosaccharides and a NaOH–Na acetate gradient (30–80 mM NaOH; 0–500 mM Na acetate) for amino acids.

Plant (50 mg) and soil (2 g) phenolic acids were extracted with 5 mL 1 M NaOH for 16 h in a reciprocal shaker at 30°C as described by Provan et al. (1994). After extraction, the sample was centrifuged and the supernatant was placed in a glass disposable test tube and heated at 90°C for 2 h to release the conjugated phenolic acid (Whitehead et al., 1983). The heated extract was then cooled, titrated with 4 M HCl to <pH 2.0, diluted to 10 mL, and centrifuged to remove precipitate. An aliquot was passed through a Varian (Harbor City, CA) Bond Elut PPL solid phase extraction tube. The tubes were dried under a stream of air and the phenolic compounds were eluted into gas chromatography autosampler vials with 1 mL of ethyl acetate. The phenolic compounds (1 µL injection, 10:1 split ratio) were then analyzed for composition with a Hewlett-Packard (Palo Alto, CA) 6890 gas chromatograph equipped with a HP-5 (5% crosslinked phenylmethyl siloxane) capillary column (30 m length, 0.32 mm column i.d., 0.25 µm film thickness) and were detected with a flame ionization detector. The following conditions were employed for phenolic acid separation: injector temperature, 250°C; temperature ramp, 70°C for 2 min then ramped to 250°C at 10°C min⁻¹; and detector temperature, 250°C. This extraction procedure releases both possible free and conjugated phenolic acids, although analysis of the nonheated extracts found very low levels of free phenolics in plant or soil samples.

Soil aggregate stability was determined with a nested sieve arrangement (4, 2, 1, 0.5, and 0.25 mm) wet sieved in degassed, distilled water for 5 min as described by Kemper and Rosenau (1986). All soils were passed field moist through an 8-mm sieve, wet sieved in the moist condition (180–250 g water kg⁻¹ soil) and corrected for sand content by dispersion in sodium metaphosphate. The mean weight diameter (MWD) was calculated with the following equation.

$$\text{MWD} = (\sum X_i S_i) / W$$

Where X_i = sand corrected weight of soil remaining on sieve size, S_i , and W is the total weight of soil (minus sand) used for the analysis (Haynes and Beare, 1997). The upper and lower limits of the mean weight diameter in this study were 4 and 0.25 mm, respectively.

Table 3. Mean aggregate size in a prairie and a cultivated corn-soybean rotation as measured in April (Spring) and September (Fall) 1997.[†]

Soil	Spring, mean aggregate size	Fall, mean aggregate size	Spring	Fall
			>1.0 mm [‡]	>1.0 mm
mm				
Webster, corn	0.72 ± 0.09	0.99 ± 0.10	23.7	34.0
Webster, soybean	0.24 ± 0.02	0.34 ± 0.05	7.3	11.2
Webster, prairie	1.83 ± 0.05	1.85 ± 0.09	73.6	76.0

[†] The vegetation following the soil is the vegetation that was grown in 1996 and decomposed during the 1997 growing season.

[‡] The percentages are weight of aggregates remaining on the sieves >1.0 mm size.

RESULTS AND DISCUSSION

The properties of the Webster soils used are given in Table 1. The soils were chosen to determine the effect of decomposing corn and soybean residue on soil structure and soil biochemistry in a producer-managed system for comparison of vegetation and management to the soil structure and biochemical profiles of an original native prairie. Table 2 shows that although the organic residues had a similar organic C content, plant residues vary in total N (C to N ratio of 37:122), total carbohydrates (73.2–110.2 g kg⁻¹ dry weight [DW]), total protein (2.3–4.6 g kg⁻¹ DW), and total phenolic acid content (1.9–27.1 g kg⁻¹ DW). The results support the findings of Kononova (1961), who reported that organic residues from different genus are different in their biochemistry.

Unlike the corn and soybean tilled soils, the native prairie soil was significantly more water stable (5.5 and 2.2× greater stability than the average soybean and corn soil values, respectively, Table 3), although the organic C difference between the agroecosystems was only ≈15 g kg⁻¹ soil (30.6–34% difference) after about 90 yr of tillage (Table 1). The prairie soil aggregates remained stable through the growing season, but the corn and soybean soil showed changes in aggregate stability during the growing season (Table 3), suggesting that decomposing corn and soybean residue can affect soil structure during the next growing season.

Conflicting results have been reported on effects of soybean residue on soil physical properties. Browning (1949) and Calland (1949) reported that soybean in rotation with other crops leaves heavy, dark colored soils in better tilth than corn or small grains. Siemens and Oschwald (1978) measured less penetrometer resistance after soybean than after corn. In a 6-yr study of different rotations on a 6.3% sloped Grundy silt loam (fine, smectitic, mesic Aquertic Argiudolls), Laflen and Moldenhauer (1979) reported that soybean after corn and continuous corn had 35% less soil loss than corn after

soybean. The increased loss was attributed to the smaller mean aggregate size that results following soybean than following other agronomic crops (Armbrust et al., 1982; Fahad et al., 1982). Figure 1 shows that the majority of the stable aggregates in the soil after soybean (92.7%) were 0.25 mm or smaller and were less stable than the Webster soil following corn (76.3%), even though the two soils had little difference in organic C content (Table 1). In contrast, only 26.4% of the soil aggregates in the prairie soil were <0.25 mm in size.

At present, researchers are not positive why soybean effects a decrease in measurable soil physical properties (McCracken et al., 1985). Browning et al. (1943) suggested that several factors may be responsible for a reduction in soil physical properties following soybean. An extreme fluctuation in soil moisture surrounding the shallow root system (Allmaras et al., 1975) and the decomposition products of soybean roots and shoots may work together to result in less stable aggregates. Although less residue is generated in a soybean cropping system (3.86–4.84 Mg ha⁻¹) compared with corn (4.66–6.44 Mg ha⁻¹) or other small grains (Huggins et al., 1998), quantity of residue may not be the only factor resulting in less aggregation. McCracken (1984) reported that decomposition of soybean residues can promote water-stable aggregates, but to a smaller degree than corn residue. After 4 mo incubation, McCracken (1984) found that soil amended with 1% soybean root and shoot residue produced fewer water-stable aggregates than soil treated with 1% corn residue when incubated under optimal conditions. Understanding the chemistry of the soybean residue in contrast to the corn and prairie residues may help explain why equal amounts of each residue result in different degrees of soil stability.

Corn and prairie vegetation are greater in carbohydrate content (1.45× and 1.51×, respectively) and phenolic acid content (14.3× and 4.5×, respectively) when

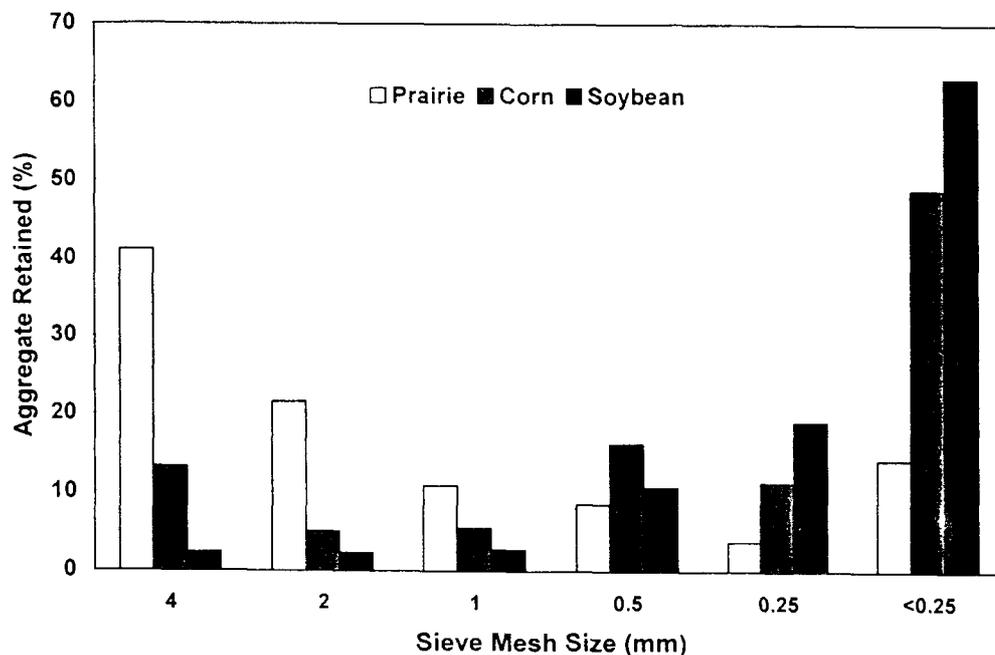


Fig. 1. Size distribution of soil aggregates in the native prairie and the comparison corn-soybean rotation.

Table 4. Total carbohydrate, total protein, and total phenolic acid content determined for the Webster soils in April (Spring) and September (Fall) 1997.†

Soil	Season	g kg ⁻¹ soil		
		Carbohydrate	Protein	Phenolic acids
Webster, corn	Spring	8.72 ± 0.11	4.21 ± 0.04	0.71 ± 0.01
	Fall	9.50 ± 0.30	3.92 ± 0.20	0.45 ± 0.05
Webster, soybean	Spring	4.13 ± 0.56	3.20 ± 0.31	0.47 ± 0.02
	Fall	3.81 ± 0.23	3.62 ± 0.01	0.20 ± 0.01
Webster, prairie	Spring	9.22 ± 0.36	6.11 ± 0.09	1.14 ± 0.06
	Fall	8.91 ± 0.30	5.89 ± 0.12	1.33 ± 0.08

† The vegetation following the soil is the vegetation that was grown in 1996 and decomposed during the 1997 growing season.

compared with soybean, but soybean contained more protein than the corn (2×) and prairie residues (1.5×) (Table 2). In general, after residue decomposition in the soils, the prairie soil contained higher concentrations of carbohydrates, proteins, and phenolic acids when compared with the corn and soybean soils (Table 4). Mean aggregate size of soils under corn, soybean, and prairie (Table 3) was correlated with total soil monosaccharide content ($r = 0.75$), total soil amino acid content ($r = 0.995^{***}$), and total soil phenolic acid content ($r = 0.997^{***}$) for the average values measured in 1997. It is of interest that the chemistry of soybean, corn, or prairie residues measured as C content ($r = 0.89$), total N content ($r = -0.86$), C to N ratio ($r = 0.93^*$), and total monosaccharide content ($r = 0.87$) were related with soil stability as measured via wet-sieving for the Fall 1997 samples, but protein content ($r = -0.54$) and total phenolic acid content ($r = 0.08$) were not as predictive for aggregate size. These relationships suggest that the biochemistry of the residues added to soil directly influences soil properties.

Humic acids have been reported to be important for controlling soil properties including soil structure. Utilizing an alkaline extraction and purification procedure (Schnitzer, 1982), different levels of humic acids were extracted from the corn (3.53 g Spring 1997 and 5.76 g kg⁻¹ soil, Fall 1997), soybean (1.30 g, Spring 1997 and 1.60 g kg⁻¹ soil, Fall 1997) and prairie soils (19.00 g, Spring 1997 and 20.04 g kg⁻¹ soil, Fall 1997). Figure 2 shows a close relationship between humus content and mean weight aggregates ($r = 0.985^{**}$). Employing the phenolic acid analysis described in the Methods section to analyze the total phenolic acid content of the humic substances determined that the humic phenolic acids were also closely related to alkaline extractable humus content ($r = 0.996^{***}$), suggesting that the level of humus in soil and water stable aggregation are related to the soil phenolic acid content (data not given). Agro-management of the soil under corn and soybean has resulted in only a 30 to 34% loss of organic C during approximately 90 yr of tillage, but the same management has resulted in a loss of nearly 77% and 93% of the humic-like substances from the corn and soybean soil, respectively, when compared with the native prairie soil. Stevenson (1994) reported that polyphenols from plant lignin or microbial synthesis were important precursors of soil humic substances. Monreal et al. (1995) also reported that lignin dimers (polyphenols) determined by pyrolysis-mass spectrometry were highly correlated ($r = 0.98^{**}$) with the proportion of stable aggregates in

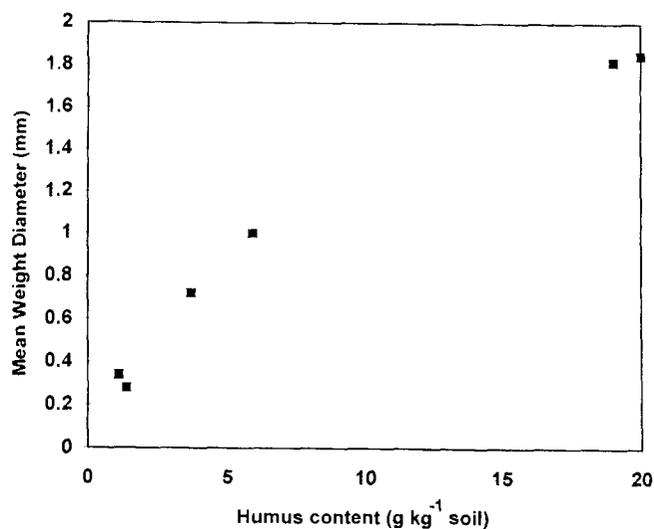


Fig. 2. Relationship between alkaline extractable humus content and mean weight diameter measured in the native prairie and the corn-soybean rotation.

a wheat (*Triticum aestivum* L.)-fallow and a continuous wheat management system. Lignin has been determined in the past to be measured by differential solubility in a strong mineral acid. The phenolic acid extraction and analysis scheme employed in this study measures the lignin content as phenolic acid monomers, but lignin is not the only source of phenolic acids that may be found in soil. In addition to the function of phenolic acids in vascular tissues (Hartley and Harris, 1981), phenolics are found in nature as stress metabolites (Gershenzon, 1984) and seed and root exudates (Kovacs, 1971), and they affect cell and plant growth (Lynn and Chang, 1990). The evidence suggests that the term lignin may not be entirely correct when referring to the all of the possible phenolic acids measured in soil or plant analysis and the data presented here suggest that identification of phenolic acids rather than a gravimetric analysis would be of tremendous importance to understanding the role of phenolics in soil aggregation.

Analysis of the residue biochemistry determined that soybean residue was very low in phenolic acid content compared with the corn and that prairie vegetation and the soybean soil was less resistant to disruption and had less phenolic acids and alkaline-extractable humic compounds than the corn and prairie soils. The results suggest that the decrease in soil stability after soybean growth is due to a decrease in humic substance content caused by the lack of phenolic acids (humic acid precursors) in the soybean residue. Understanding the contribution to soil structure from plant phenolic acid becomes more important, since vegetation is the main source of phenolic compounds in soils (Swift et al., 1979; Stevenson, 1994). The differences in phenolic acid content with C₃ and C₄ plants may be responsible for the reduction of 31% in the humification rate constant for carbon derived from soybean when compared with the humification constant for carbon derived from corn with fall plowing reported after a 10-yr field study (Huggins et al., 1998).

The soybean-corn rotation and the native prairie add different residue biochemistry and also differ in residue

management. Due to a wet fall in 1996, no fall tillage operations were conducted with the corn and soybean soils. The degradation of organic polymers released to soil from decaying vegetation involves depolymerization and oxidation reactions that are catalyzed by soil microbial enzymes. Polysaccharide polymers, such as cellulose and hemicellulose, usually undergo depolymerization reactions and polyphenol compounds are degraded mainly by oxidation reactions (Wershaw, 1993). The nature of the degradation pathway results in polyphenol oxidation releasing oxidized fragments in which much of the chemical structure of the original polymer is preserved (Wershaw, 1993). Kristensen et al. (1995) reported that mineralization of leachable and easily hydrolyzable compounds such as carbohydrates and amino acids from fresh plant detritus was equally fast under aerobic and anaerobic conditions, but under reduced oxygen tensions, mineralization of complex structural macromolecules such as polyphenols and complex lipids was hampered by inefficient and slow bacterial hydrolysis. The data may help explain why soil carbon levels increase in no-till and reduced-tillage management programs (Dick, 1983) due to lower oxygen levels in the micro- and macroaggregates measured with increased surface residue as a result of reduced tillage (Doran, 1980).

Intensity of tillage interacting with the crop residue decomposition greatly influences soil structure. The results of this study suggest that the amount of humic-like substances synthesized from plant residues remaining in soil determines soil aggregate stability. Additional studies are needed to confirm these results in other soils under different tillage systems.

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