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Rye Cover Crop Effects on Soil Quality in No-Till Corn Silage–Soybean Cropping Systems

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Corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] farmers in the upper Midwest are showing increasing interest in winter cover crops. The effects of winter cover crops on soil quality in this region, however, have not been investigated extensively. The objective of this experiment was to determine the effects of a cereal rye (*Secale cereale* L.) winter cover crop after more than 9 yr in a corn silage–soybean rotation. Four cereal rye winter cover crop treatments were established in 2001: no cover crop, rye after soybean, rye after silage, and rye after both. Soil organic matter (SOM), particulate organic matter (POM), and potentially mineralizable N (PMN) were measured in 2010 and 2011 for two depth layers (0–5 and 5–10 cm) in both the corn silage and soybean phases of the rotation. In the 0- to 5-cm depth layer, a rye cover crop grown after both main crops had 15% greater SOM, 44% greater POM, and 38% greater PMN than the treatment with no cover crops. In general, the treatments that had a rye cover crop after both crops or after corn silage had a positive effect on the soil quality indicators relative to treatments without a cover crop or a cover crop only after soybean. Apparently, a rye cover crop grown only after soybean did not add enough residues to the soil to cause measureable changes in SOM, POM, or PMN. In general, rye cover crop effects were most pronounced in the top 5 cm of soil.

Abbreviations: LOI, loss-on-ignition; PMN, potentially mineralizable N; POC, particulate organic C; POM, particulate organic matter; SOC, soil organic C; SOM, soil organic matter.

The corn–soybean cropping systems that dominate the upper Midwest are among the most productive in the world and contribute significantly to making the United States the world's largest producer of corn and soybeans (U.S. Department of Agriculture, 2012). However, the success of corn–soybean cropping systems in this region has not come without costs to soil resources. Agricultural land in the upper Midwest has lost substantial amounts of SOM over the past century (Paustian et al., 1997), resulting in an overall decline in soil quality. The continued degradation of soil in this region will undoubtedly have negative long-term consequences on agricultural productivity, and new management practices must be implemented to reverse the decline in soil quality.

Increasing annual C inputs to the soil in cropping systems through reductions in fallow periods is a viable strategy for enhancing soil quality (Wienhold et al., 2006). In corn–soybean cropping systems in the upper Midwest, one way to increase annual C inputs is to use winter cover crops. Cover crops comprise a broad range of plant species and can perform a wide range of ecosystem services (Kaspar and Singer, 2011) including erosion prevention (Kaspar et al., 2001; Wilhelm et al., 2010), N fixation (Reicosky and Forcella, 1998), nutrient scavenging (Kaspar et al., 2007), weed suppression (Liebman and Davis, 2000), and provision of habitat for beneficial insects (Tillman et al., 2004). Cereal rye is the most winter-hardy of all the small grains (Geiger and Miedaner, 2009) and is the most widely-used

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winter cover crop in Illinois and Iowa (Singer et al., 2007). As a result, it is a good choice for an overwintering cover crop in corn–soybean cropping systems in the upper Midwest.

In contrast to management practices that increase inputs of organic matter to the soil, harvesting corn stover for either silage or energy biomass can have profound negative consequences on soil quality. Silage production has a higher potential for soil degradation than most other intensive cropping systems currently in practice due to its drastic reduction of biomass and nutrients that are recycled back into the soil (Jokela et al., 2009). Stalk removal during corn silage harvest can remove as much as twice the N, three times the P, and 10 times the amount of K removed by corn harvested only for grain (Wheaton et al., 1993). Corn silage harvest also greatly reduces the amount of soil residue cover, leaving soil more vulnerable to erosion processes (Wilhelm et al., 2010). Wilhelm et al. (2010) suggested that the reductions in soil C inputs and soil quality resulting from the removal of corn stover might be partly offset by winter cover crops.

Soil quality of cropping systems can be evaluated through the use of soil quality indicators, which are usually chosen based on the soil processes that are most sensitive to the management differences of the cropping systems being compared (Larson and Pierce, 1991; Doran and Parkin, 1994; Karlen et al., 2006). Soil organic matter and POM are routinely measured in many studies and are well-suited to detect changes in soil quality due to an increase in C inputs from a management practice like cover crops. Additionally, because a cereal rye cover crop scavenges N during the winter fallow periods between main crops and recycles N back to SOM, measurements of PMN may reveal positive changes in soil N cycling.

Soil organic matter is often considered the single most important factor contributing to overall soil quality (Larson and Pierce, 1991; Doran and Parkin, 1994; Sikora et al., 1996). One way that SOM improves soil quality is through the enhancement of soil aggregate formation (Tate, 1987). Soil organic matter also serves as the primary source of plant-available N released through mineralization (Drinkwater et al., 1996) and can contain up to 99% of the total N in soil (Sikora et al., 1996). Additionally, SOM can hold up to 20 times its weight in water (Stevenson, 1994), significantly improving soil water holding capacity. The Mollisols that are typical of the upper Midwest normally contain a relatively large amount of SOM, and this can make it difficult to detect relatively small changes in SOM that result from crop management practices (Kaspar et al., 2006). The measurement of SOM in agricultural fields can also be further complicated by the spatial and temporal variability that is endemic to virtually all agricultural landscapes (Janzen et al., 2002). Thus, although SOM is an important indicator of soil quality, it is difficult to measure management-induced changes in SOM over short time periods.

Particulate organic matter has properties that make it useful as a soil quality indicator. Particulate organic matter is defined as the organic fraction of soil that is less than 2 mm and greater than 53 μm in size (Cambardella and Elliot, 1992). In general, POM is highly heterogeneous, containing both labile and recalcitrant elements, which can range from root fragments to charcoal. Cambardella et al. (2001) describes the POM fraction of soil as SOM, which is in the intermediate stages of transition between fresh plant residues and stable organic matter and represents a substantial, yet variable, component of SOM. A study in Nebraska by Cambardella and Elliot (1992) discovered that as much as 39% of the soil organic C (SOC) is associated with the POM fraction in native grassland whereas only 18% of the SOC was found in the POM fraction in a plowed, fallow–wheat cropping system. Additionally, Carter et al. (2003) found that in continuous corn systems in eastern Canada from 18 to 29% of SOC was found in the POM fraction depending on management of manure. These two studies and several others suggest that the percentage of SOC that is found in the POM fraction can vary markedly depending on management and, therefore, could be a useful indicator of management effects and long-term changes in SOM (Cambardella and Elliot, 1992; Bremer et al., 1994; Gregorich et al., 1995; Magdoff, 1996; Sikora et al., 1996; Liebig et al., 2004; Coulter et al., 2009).

Potentially mineralizable N is a relative measure of the ability of the soil to supply N to plants and is commonly used in soil quality assessments (Sainju et al., 2003; Liebig et al., 2004; Andraski and Bundy, 2008). Nitrogen mineralization plays a crucial role in crop production because even in heavily fertilized soils more than half of the N taken up by corn plants can come from mineralization of SOM (Blackmer and Sanchez, 1988). Potentially mineralizable N is determined by measuring the change in soil inorganic N in laboratory incubations over a specified period of time under optimal conditions for microbial activity (Drinkwater et al., 1996). Despite the utility of this measurement, several drawbacks limit its scope of inference. For example, short-term aerobic soil incubation under optimal conditions may not provide an accurate representation or prediction of actual N mineralization that will occur in the field under suboptimal conditions. Additionally, sieving, air-drying, and mixing soil in preparation for this test, which is essential for uniform and consistent handling of multiple samples over time, can cause changes in microbial populations and mineralization of SOM encased within aggregates that would not have occurred if the soil were left undisturbed (Tate, 1987; Drinkwater et al., 1996). Despite these limitations, short-term aerobic incubation offers a consistent and repeatable method for comparing relative differences among management practices on the soil's capacity to supply inorganic N.

Few, if any, long-term studies have investigated whether a cereal rye cover crop can be used to enhance soil quality in the corn–soybean cropping systems of the upper Midwest. In this region, the period between harvest and planting of corn and soybean crops is short and unfavorable for plant growth, and it is not known whether cover crops could increase annual biomass inputs enough to improve soil quality. We hypothesized that it would be easier to measure the positive benefits of a rye winter cover crop after 9 yr of a corn silage–soybean rotation because of reduced main crop residue inputs and greater growth potential of a rye cover crop following corn silage. The objective of this experiment was to measure three indicators of soil quality in a no-till corn silage–soybean cropping system managed with and without a rye cover crop. The soil quality indicators measured were SOM, POM, and PMN. Data from this experiment will provide information about the potential for cereal rye cover crops to positively influence soil quality in this region.

MATERIALS AND METHODS

This experiment was conducted at Iowa State University's Boyd Farm, located in Boone County, IA (42°00′26″ N lat; −93°47′31″ W long), from 2001 to 2011. The two adjacent fields used in this experiment were established in 2001 and represent a combined area of approximately two hectares. The fields have a 2% slope with two predominant soil series: Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludoll) and Nicollet clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludoll) (Andrews and Diderikson, 1981). Average monthly air temperatures and precipitation were calculated using information collected at the Iowa State University research farm located approximately 2 km from the experiment field site and are listed in Table 1 (Iowa State University of Science and Technology, 2012).

Table 1. Average monthly air temperature and total precipitation 2009 to 2011.

Month	Average air temperature (°C)				Total precipitation (mm)			
	2009	2010	2011	1951–2011 Avg.	2009	2010	2011	1951–2011 avg.
Jan.	−10.0	−10.0	−8.9	−7.4	25	28	18	19
Feb.	−2.2	−8.9	−4.4	−4.2	7	19	33	22
Mar.	3.3	3.3	2.8	2.1	103	55	20	53
Apr.	8.9	13.3	8.9	10.0	116	93	101	90
May	15.6	16.7	15.6	16.2	102	92	142	115
June	21.1	22.2	21.1	21.3	104	284	160	128
July	20.6	23.9	25.6	23.3	70	173	75	105
Aug.	21.1	24.4	22.2	22.0	123	285	76	111
Sept.	17.8	18.9	15.6	17.8	24	167	43	82
Oct.	7.8	13.3	12.2	11.4	186	12	25	62
Nov.	6.7	3.3	4.4	2.9	34	60	78	43
Dec.	−6.7	−6.7	−1.1	−4.4	50	18	54	26
Jan.–Dec.†	8.9	9.4	9.4	9.3	945	1287	826	856

† Values for the January through December periods are averages for the period for air temperature and totals for the period for precipitation.

A corn silage–soybean rotation and the experimental treatments were established at the site in 2001. The corn silage and soybean phases of the rotation were grown alternately in the two adjacent fields. As a result, the main crop present in a plot in the year before soil sampling, referred to as previous crop, depended on the year and the field being sampled. For each field, the two factors, previous crop and year, are synonymous, but for the combined analysis across fields and years, the effect of previous crop was of primary interest. The experimental layout for each of the two adjacent fields was a randomized complete block design with six treatments randomly assigned to the plots in the five blocks in each field. Each plot was 54.9 m long and 3.8 m wide and consisted of five main crop rows spaced 0.76 m apart. Four of the six treatments were examined in this study. The four cover crop treatments compared in this experiment were: (i) rye cover crop after the corn silage phase of the rotation and no cover crop after the soybean phase of the rotation (rye after silage), (ii) rye cover crop after soybean and no cover crop after corn silage (rye after soybean), (iii) rye cover crop after both the corn silage and soybean phases of the rotation (rye after both), and (iv) no cover crop after either corn silage or soybean (no cover crop).

The site was managed with no-tillage. Weeds were suppressed using pre-emergence herbicides in corn and postemergence applications of glyphosate [N-(phosphonomethyl) glycine] in both corn and soybean. Glyphosate-resistant cultivars of soybean (cultivar Pioneer 92M11) and hybrid corn (cultivar Pioneer 36V75) were used throughout this experiment. Both corn and soybeans were planted with a five-row, 0.76-m row width no-till planter. Soybeans were planted at 395,000 seeds ha^{-1} in mid-May and corn was planted at 79,000 seeds ha^{-1} in late April to early May (Table 2). Nitrogen fertilizer was applied for corn in split applications at planting and in late May for a total rate of 208 kg N ha^{-1}. Phosphorus and K fertilizer were applied as a subsurface band at average rates of 117 kg P ha^{-1} and 74 kg K ha^{-1} in the fall before corn silage years as indicated by soil tests and corn silage nutrient removal rates.

Winter-hardy cereal rye (variety not stated) was used for the rye cover crop treatments. Although the cover crop treatments were planted each year beginning in 2001, only the dates for winter cover crop planting and termination for 2009 to 2011 are listed in Table 2. Rye was seeded using a no-till grain drill following soybean harvest in late September to mid-October at a rate of 3.0 ′ 10^{6} seeds ha^{-1}. Rye was drilled at the same seeding rate following corn silage harvest from late August to mid-September. Rye was drilled in the main crop inter-row in three rows spaced 0.19 m apart, leaving the old main crop row in the center of an unplanted 0.19 m gap. The main crop was planted into this gap the following spring. Rye was killed with glyphosate applied at 1.12 kg ha of active ingredient ha^{-1} from 4 to 21 d before planting the main crop (Table 2). The variation in the interval between termination and planting the main crop was in part caused by variable field and weather conditions in the spring.

Corn Silage and Soybean Yields

Corn silage was harvested shortly after reaching the one-half milkline stage (Wiersma et al., 1993). Corn silage yields were determined by harvesting the center three rows of each five-row silage plot with a silage chopper and weighing the silage in a weigh wagon equipped with load cells. At silage harvest, a sample was

Table 2. Management dates.

Years	Field 42			Field 44		
	2009	2010	2011	2009	2010	2011
Main Crop	Soybean	Corn	Soybean	Corn	Soybean	Corn
Main crop planting date	12 May	28 Apr.	19 May	5 May	19 May	4 May
Main crop harvest date	30 Sept.	24 Aug.	7 Oct.	16 Sept.	4 Oct.	31 Aug.
Rye cover crop planting date	1 Oct.	25 Aug.	7 Oct.	17 Sept.	5 Oct.	1 Sept.
Rye cover crop kill date	8 May	19 Apr.	6 May	22 Apr.	28 Apr.	25 Apr.

collected from each plot, weighed wet, and weighed after drying at 60°C to constant weight to determine silage water content. Silage dry matter yield was then calculated based on harvested plot area and silage water content. Soybean grain yields were determined using a modified combine with a weigh tank and moisture meter mounted inside the combine grain storage tank by harvesting the entire plot area. Yields were calculated based on harvested plot area and were adjusted to 0.130 g g^{-1} grain moisture.

Cover Crop Shoot Biomass

Cover crop shoot biomass samples were collected in the spring of each year shortly before or after glyphosate application (Table 1). Two samples were taken from each plot by clipping at the soil surface all the rye plants found within a sampling frame 0.76 m wide and 0.50 m long. For each sample, the frame was centered on an interrow of the previous main crop so that the 0.76-m side of the frame was perpendicular to the row direction. Samples were dried at 60°C to constant weight and weighed. Subsamples from each plot were averaged and cover crop shoot dry weights were calculated on an area basis.

Soil Sampling and Analysis

Soil sampling took place on 9 June 2010 and 13 June 2011. All soil samples were taken from untrafficked interrows at five separate locations starting 9.14 m from the end of each plot and then sampling every 9.14 m. Three soil cores were taken at each of the five locations within the plot: one in the middle rye cover crop row (located near the center of the interrow) and the other two between rye rows at 4.8 cm and 9.5 cm from the middle rye row. A total of 15 soil cores were taken per plot to a depth of 10 cm using a 3.2-cm diameter soil probe. After each sample extraction, soil cores were immediately measured and divided into 0- to 5-cm and 5- to 10-cm depth layer samples. The samples taken in each plot were combined based on depth, yielding two plastic storage bags of soil per plot.

After the samples were collected, they were transported to the laboratory in insulated coolers and then refrigerated at 4°C until processing. When removed from refrigerated storage, the bags were weighed and the soil was pushed through sieves with 8-mm and 4-mm openings and mixed. Two subsamples of approximately 50 g of wet soil were taken from each sample bag and oven-dried at 105°C for 48 h to determine soil water content. Soil water content, along with the original soil weights and volumes of the soil samples, was used to calculate bulk density. Bulk density data will be expressed as g soil cm^{-3}. The remainder of the original soil sample was partially air-dried and then pushed through a 2-mm mesh sieve and thoroughly mixed. Samples were then completely air-dried and returned to refrigerated storage until analysis for PMN and POM.

To determine SOM, two approximately 40-g subsamples of the oven-dried soil used to determine soil water content were analyzed for loss-on-ignition (LOI) by weighing samples before and after burning in a programmable muffle furnace (Fisher-Scientific Isotemp 650-126) at 460°C for 16 h. The LOI procedure requires that soil samples be burned for a predetermined period of time at temperatures high enough to ensure the complete oxidation of SOC yet low enough (<500°C) to avoid oxidation of inorganic C (Schulte and Hopkins, 1996). Studies conducted by Cambardella et al. (2001) and Kaspar et al. (2006) provide an overview of the LOI procedure as it relates to SOM measurements. The SOM content of soil was considered to be the ash-free change in weight after burning and was expressed as g SOM kg dry $soil^{-1}$.

The POM fraction of soil was isolated by adding 240 mL of 5 g L^{-1} sodium hexametaphosphate to two air-dry approximately 80-g soil subsamples, shaking for no less than 18 h, and then wet sieving the soil slurry through a 53-μm sieve (Cambardella and Elliot, 1992; Cambardella et al., 2001). Sand particles and POM remaining on the sieve were then oven-dried at 105°C for 48 h, weighed, burned in a muffle furnace at 460°C for 16 h, and weighed again in a manner consistent with the aforementioned LOI procedure. Particulate organic matter was considered to be the ash-free change in weight after burning and was expressed as g POM kg air-dry $soil^{-1}$.

Potentially mineralizable N was determined by rehydrating two approximately 40-g subsamples of air-dried soil with 14.95 g of water, which was calculated to provide 60% water-filled pore space, and aerobically incubating at 30°C for 28 d, which is similar to the procedure described by Drinkwater et al. (1996). After incubation, 200 mL of 2 M KCl solution was added to each subsample. Subsamples were shaken for 30 min and then filtered using ashless filter paper. Two additional subsamples of 40 g of air-dried soil, which were not incubated, were also extracted with 2 M KCl on Day 0 of the incubation period. The filtered solution from each subsample was then frozen until analysis. After thawing, the filtrate was immediately analyzed for nitrate ($NO_3 + NO_2$) and NH_3 using a colorimetric method (Keeney and Nelson, 1982) and flow injection technology (Zellweger Analytics, Lachat Instrument Division, Milwaukee, WI). Potentially mineralizable N is calculated as difference in total inorganic N between the Day 0 and Day 28 samples and was expressed as mg N kg $soil^{-1}$.

Statistical Analysis

Data sets for individual combinations of field, previous crop, and depth were initially analyzed separately for block and treatment effects as a randomized complete block design using the PROC GLM procedure (SAS Institute Inc., 2010). The two subsamples from each plot for each measurement and sampling year (previous crop) were averaged before any statistical analyses. For the combined analysis, data from both fields and years were combined; however, depths were kept separate to determine soil quality for each depth. Year determined which main crop was planted in each field, and because main crops alternated between fields from year to year, previous crop effects were confounded with year. Therefore, the combined year and previous crop effect will be referred to as previous crop. Because soil samples were taken early in the growing season, it was assumed that effect of the previous crop was more important than the current crop, and that any year effects would be affected by the previous crop. Additionally, because soil samples were taken at the same locations in each plot in both years, the previous crop effect is treated as a repeated measure. For the combined analysis, the experiment could be considered a split plot treatment structure arranged in a completely randomized complete block design combined over fields (McIntosh, 1983). The cover crop treatments and fields were the main-plot factors and previous crop was the repeated-measure split-plot factor. The combined data were analyzed as a mixed model ANOVA with repeated measures using PROC MIXED (SAS Institute Inc., 2010). When the analysis of variance indicated significant effects at the 0.05 probability level, the LSD test at the 0.05 probability level was used to compare treatment means.

RESULTS AND DISCUSSION

Weather

Average monthly air temperatures and total monthly precipitation for 2009 to 2011 are shown in Table 1. Weather data for 2009 are included because the rye winter cover crop treatments that were sampled in summer 2010 were planted in fall 2009. Air temperatures during the fall 2009 cover crop establishment season varied from the 60-yr average, with temperatures 3.6°C cooler in October and 3.8°C warmer in November. Total precipitation in 2009 was 89 mm higher than the 60-yr average; however, it is worth noting that the fall cover crop establishment season also varied from the average with September being drier than normal (58 mm below average) and October being wetter than normal (124 mm above average). Average air temperatures in 2010 did not show much variation from the 60-yr average; however, total precipitation was significantly higher than normal. Total precipitation for 2010 was 431 mm higher than the long-term average, with precipitation from June to August being 68 to 174 mm higher than average for each month during that time. Average air temperatures in 2011 did not show much variation from the long-term average with the exception of a cooler than average (−3.3°C) December. Total precipitation in 2011 was 30 mm lower than the 60-yr average, with the monthly totals in the period between July and October being 30 to 39 mm less than average.

Rye Cover Crop Shoot Biomass

In 2010 and 2011, rye biomass was consistently lower after soybean compared with after corn silage (Table 3). There was an approximate five-fold increase in rye shoot growth when rye followed corn silage compared with rye after soybean. This difference most likely is due to a longer rye fall growing season when following corn silage. Silage was harvested earlier than soybean, giving the rye after corn silage an extra 14 to 43 d of fall growth when compared to rye after soybean (Table 2). Average rye shoot biomass after soybean was similar to rye biomass data presented by Johnson et al. (1998), who reported an average rye biomass of 0.41 Mg ha^{-1}. In contrast, another study in central Iowa by Kaspar et al. (2007) recorded an average rye biomass of 1.26 Mg ha^{-1} for a rye cover crop planted after soybean harvest and 1.66 Mg ha^{-1} for rye planted after corn grain harvest, which is normally later than soybean harvest, indicating that weather in individual years also can greatly affect cover crop shoot biomass.

Table 3. Cover crop shoot dry weight for treatments with a rye cover crop in a corn silage–soybean rotation over 2 yr and two adjacent fields.

Field	Field 42		Field 44		Avg. both fields	
Previous crop†	Soybean	Corn	Corn	Soybean	Corn	Soybean
Sampling year	2010	2011	2010	2011	Avg.	Avg.
Treatment						
Rye after silage	—	3.40a	1.99a	—	2.69 a	—
Rye after both	0.69a‡	3.23a	2.50a	0.21 a	2.86 a	0.45 a
No cover crop	—	—	—	—	—	—
Rye after soybean	0.87a	—	—	0.28 a	—	0.57 a
Previous crop avg.					2.78	0.51

† Previous crop refers to main crop that was present in a field the year before cover crop samples were taken.

‡ Numbers within a column followed by the same lowercase letter are not significantly different as indicated by LSD test at the 0.05 probability level.

Corn Silage and Soybean Yields

Corn silage and soybean grain yields are shown in Table 4. Corn silage is reported as dry weight of silage and soybean is reported as grain yield at 130 g kg^{-1} water content. Yields in 2010 for both main crops were lower than those in the other 2 yr of this experiment and may be attributable to abnormally wet conditions during summer 2010 (Table 1). Soybean yields for rye after silage treatment were slightly higher than the yield of the rye after soybean treatment in 2009. In 2010, soybean yield for the rye after both treatment was greater than that of the no cover crop treatment. Corn silage yields were statistically higher in 2010 and 2011 for the rye after both treatment where corn silage was planted after terminating a rye cover in the spring than for the rye after silage treatment in which there was no cover crop immediately preceding corn. In all 3 yr, corn silage yield was not significantly reduced when following a rye cover crop (rye after both and rye after soybean treatments) compared with when there was no rye cover crop immediately preceding corn planting (rye after silage and no cover crop treatments). In Ontario, Raimbault et al. (1990) observed up to a 16% corn silage yield reduction in no-till when corn silage followed a rye cover crop. Later studies by

Table 4. Corn silage and soybean yields for treatments with and without a rye cover crop in a corn silage–soybean rotation over 3 yr and two adjacent fields.

Field	Field 42			Field 44		
Main crop†	Soybean	Corn	Soybean	Corn	Soybean	Corn
Year	2009	2010	2011	2009	2010	2011
	Mg ha^{-1}					
Treatment						
Rye after silage	4.00a‡	16.72b	3.51a	19.21a	2.92ab	18.21b
Rye after both	3.95ab	19.58a	3.51a	19.60a	2.99 a	19.30 a
No cover crop	3.90ab	18.57ab	3.41a	19.21a	2.66b	18.87ab
Rye after soybean	3.77b	17.26ab	3.29a	19.61 a	2.81ab	18.50ab
Avg.	3.91	18.03	3.43	19.40	2.84	18.72

† Main crop that was present in a field in the year indicated. Corn silage is reported as dry weight of silage and soybean is reported as grain yield at 130 g kg^{-1} water content.

‡ Numbers within a column and year followed by the same lowercase letter are not significantly different as indicated by LSD test at the 0.05 probability level.

Table 5. Probabilities of a greater F value for main effects and interactions from the analysis of variance for bulk density, soil organic matter, particulate organic matter, and potentially mineralizable N for the 0- to 5-cm and 5- to 10-cm soil layers.

Soil Layer		0- to 5-cm soil layer				5- to 10-cm soil layer			
Measurement		Bulk density	Total soil organic matter	Particulate organic matter	Potentially mineralizable N	Bulk density	Total Soil organic matter	Particulate organic matter	Potentially mineralizable N
ANOVA effect	df	Pr > F							
Field (F)	1	0.257	0.226	0.960	0.235	0.312	0.390	0.105	0.328
Treatment (T)	3	0.303	0.001	0.001	0.001	0.454	0.044	0.068	0.141
T × F	3	0.515	0.388	0.743	0.705	0.180	0.614	0.220	0.061
Previous crop (P)	1	0.178	0.045	0.949	0.008	0.039	0.001	0.571	0.054
F × P	1	0.814	0.001	0.002	0.001	0.280	0.001	0.934	0.386
T × P	3	0.095	0.088	0.107	0.025	0.719	0.191	0.380	0.722
T × F × P	3	0.697	0.164	0.330	0.290	0.149	0.553	0.378	0.567

this same group (Raimbault et al., 1991) showed that killing the rye cover crop 14 d before corn planting reduced or eliminated the yield decrease. Similarly, Faé et al. (2009) observed no significant silage yield decrease when silage was planted 6 to 10 d after a cereal rye termination. Although Johnson et al. (1998) observed that a cereal rye cover crop reduced corn grain yield, Miguez and Bollero (2005), using meta-analysis of data from a large number of studies, concluded that there was a neutral corn grain yield response to grass cover crops. Thus, although in our study a rye cover crop terminated before planting corn silage did not reduce yields, the effect of cereal rye cover crops on corn grain or silage yield is variable and not well understood.

Bulk Density

Bulk density showed no significant differences among cover crop treatments in the 0- to 5-cm or 5- to 10-cm depth layers, and the only significant effects were for previous crop for the 5- to 10-cm soil layer (Table 5). Jokela et al. (2009) also did not observe a significant effect of a rye cover crop on bulk density in the 0- to 5-cm or 5- to 15-cm depth layers. Bulk density means were on average 1.26 and 1.45 g cm^{-3} for the 0- to 5-cm and 5- to 10-cm layers, respectively (data not shown). When the previous crop was corn, the average bulk density of the 5- to 10-cm soil layer (1.47 g cm^{-3}) was greater than when the previous crop was soybean (1.43 g cm^{-3}). This is a relatively small difference, and because samples were taken from an untracked interrow, we have no explanation for why this occurred. Because cover crop treatments did not affect bulk density, values for SOM and POM were expressed on a concentration basis.

Table 6. Soil organic matter (SOM) in the 0- to 5-cm and 5- to 10-cm depth layers determined by weight loss on ignition for treatments with and without a rye cover crop in a corn silage–soybean rotation averaged over 2 yr and two adjacent fields.

Depth Layer	0- to 5-cm depth			5- to 10-cm depth		
Previous crop†	Corn	Soybean	Avg.	Corn	Soybean	Avg.
	g SOM kg soil^{-1}					
Treatment						
Rye after silage	54.5b‡	54.4b	54.4a	47.9ab	49.1b	48.5ab
Rye after both	56.3a	56.7a	56.5a	48.7a	51.6a	50.2a
No cover crop	49.2c	49.4c	49.3b	46.6b	48.6b	47.6b
Rye after soybean	48.7c	50.4c	49.5b	46.6b	48.0b	47.3b
Previous crop avg.	52.2B	52.7A		47.4B	49.3A	

† Previous crop refers to main crop that was present in a field the year before soil samples were taken.

‡ Numbers within a column followed by the same lowercase letter and numbers within a row and depth layer followed by the same uppercase letter are not significantly different as indicated by LSD test at the 0.05 probability level.

Soil Organic Matter

For SOM in both depth layers, the cover crop treatments and previous crop main effects and the field by previous crop interaction were significant (Table 5). Average SOM was significantly higher in the rye after silage and the rye after both treatments than in the no cover crop and rye after soybean treatments at the 0- to 5-cm soil depth (Table 6). Average SOM was 15% greater in the rye after both treatment than the no cover crop treatment at the 0- to 5-cm soil depth. Even though the rye after soybean treatment had a cover crop every other year, it was not significantly different than the no cover crop treatment. Apparently, the cover crop in the rye after soybean, which produced less than 20% of the shoot biomass of the rye after silage treatment, did not contribute enough organic matter to the soil to produce a measureable change in SOM. For the 5- to 10-cm depth, the average SOM in the rye after both treatment was about 5% higher than that in the no cover crop and rye after soybean treatments (Table 6). Because cover crop residues on the surface were not incorporated into the 5- to 10-cm soil layer by tillage, we expected that changes in SOM in this soil layer would take place more slowly and would be more dependent on root residues than the surface soil layer (Gale and Cambardella, 2000). For the 5- to 10-cm depth, neither the rye after soybean nor the rye after silage treatments were significantly different from the no cover crop treatment and apparently had not contributed enough organic matter to cause a measureable change in SOM. The previous crop also had a very small, but significant, effect on SOM for both depth layers. Average SOM in both depth layers was significantly higher when the previous crop was soybean (Table 6). In part, this may have occurred because soybean residue was returned to the soil surface, whereas almost all of the corn stover was removed from the fields during silage harvest. There was also a significant field by previous crop interaction for both depth layers (data not shown). In Field 42 SOM was increased in both depth layers when soybean was the previous crop, and in Field

44 SOM did not differ with the previous crop. Year determined which main crop was planted in each field, and because main crops alternated between fields from year to year, previous crop effects were confounded with year. We suspect that the field by previous crop interaction was largely due to higher main crop yields and most likely greater shoot and root growth of the previous crop in 2009 than 2010 (Table 4). Because most of the corn stover is removed with silage harvest, the larger corn crop in 2009 in Field 44 did not have as large of an influence as the large soybean crop in Field 42.

In general, measuring changes in SOM resulting after implementation of cover crops can be difficult. Faé et al. (2009) found no differences in SOC in a corn silage system with or without cover crops after 2 yr. Similarly, Jokela et al. (2009) were not able to detect a cover crop induced change in SOM after 4 yr even though they were able to detect a change in active C measured using $KMNO_4$ oxidation. After 4 to 6 yr, Kaspar et al. (2006) were also unable to detect a change in SOM resulting from the addition of a rye cover crop following only the soybean phase in a corn grain–soybean rotation. One possible reason that our experiment was able to detect changes in SOM was the length of time our treatments have been in place, which was 10 yr in 2011. Even so, our experiment was not designed to quantify changes in net SOM over time. Thus, even though the rye after both treatment had greater SOM than the no cover crop treatment, it is possible that SOM did not increase over time but rather that the rye after both treatment lost less SOM than the no cover crop treatment did over 10 yr.

Particulate Organic Matter

Significant differences for POM were only observed for the cover crop treatment main effect and the field by previous crop interaction for the 0- to 5-cm depth layer (Table 5). Particulate organic matter was significantly higher in the rye after silage and the rye after both treatments compared to the no cover crop and rye after soybean treatments at the 0- to 5-cm soil depth (Table 7). Particulate organic matter averaged over both years and fields was 44% greater in the rye after both treatment than the no cover crop treatment. Similar to the results for SOM, the rye after soybean treatment was not significantly different from the no cover crop treatment probably because of the low cover crop biomass production of this treatment. A significant field by previous crop interaction (data not shown) was also measured for the 0- to 5-cm depth. This interaction was identical to that observed for SOM and was probably caused by the larger soybean crop in one of the two fields (Table 4). There was no significant difference among treatments at the 5- to10-cm depth (Table 7), although the probability of a greater F value from the ANOVA came close to being significant ($Pr > F = 0.07$; Table 5). We assume that the relatively low contribution of organic matter to that soil layer by cover crop roots was not enough to cause a significant change in POM. To the best of our knowledge, there have been no published studies that have examined the effect of cover crops on POM in corn silage systems. Faé et al. (2009) and Sequeira and Alley (2011), however,

Table 7. Particulate organic matter (POM) in the 0- to 5-cm and 5- to 10-cm depth layers for treatments with and without a rye cover crop in a corn silage–soybean rotation averaged over 2 yr and two adjacent fields.

Depth Layer	0- to 5-cm depth			5- to 10-cm depth		
Previous crop†	Corn	Soybean	Avg.	Corn	Soybean	Avg.
	g POM kg soil^{-1}					
Treatment						
Rye after silage	8.8a‡	8.1ab	8.4a	3.7a	3.4 a	3.5 a
Rye after both	8.8a	8.9a	8.8a	3.8a	4.3 a	4.0 a
No cover crop	6.3b	5.9c	6.1b	3.0a	3.3 a	3.2 a
Rye after soybean	5.8b	6.7ab	6.3b	3.4a	3.2 a	3.3 a
Previous crop avg.	7.4A	7.4A		3.5A	3.6A	

† Previous crop refers to main crop that was present in a field the year before soil samples were taken.

‡ Numbers within a column followed by the same lowercase letter and numbers within a row and depth layer followed by the same uppercase letter are not significantly different as indicated by LSD test at the 0.05 probability level.

observed greater particulate organic matter C (POC) measured with dry combustion in corn silage systems containing cover crops than in those without cover crops. Although POC and POM measurements are related, they measure different components of SOM using different methodology (Cambardella et al., 2001). Cambardella et al. (2001), however, found that both measurements were equally sensitive to changes in cropping management and soil quality across a range of soil types and locations.

Potentially Mineralizable Nitrogen

Both the cover crop treatment and previous crop main effects and the cover crop by field and the field by previous crop interactions significantly affected PMN in the 0- to 5-cm soil layer (Table 5). The previous crop effect was also significant for the 5- to 10-cm layer, but the cover crop treatment effect and the interactions were not. Treatment average PMN was significantly higher in the rye after silage and the rye after both treatments compared to the no cover crop and rye after soybean treatments for the 0- to 5-cm soil depth (Table 8). In the 0- to 5-cm soil layer, the no cover crop treatment had 38% less PMN than the

Table 8. Potentially mineralizable N (PMN) in the 0- to 5-cm and 5- to 10-cm depth layers for treatments with and without a rye cover crop in a corn silage–soybean rotation averaged over 2 yr and two adjacent fields.

Depth layer	0- to 5-cm depth			5- to 10-cm depth		
Previous crop†	Corn	Soybean	Avg.	Corn	Soybean	Avg.
	mg N kg soil^{-1}					
Treatment						
Rye after silage	44.6a‡	46.8ab	45.7a	21.5a	21.6a	21.5a
Rye after both	49.9a	49.2a	49.6a	21.9a	27.2a	24.6a
No cover crop	34.2b	37.4b	35.8b	16.2a	20.8a	18.5a
Rye after soybean	31.2b	44.3ab	37.8b	19.7a	26.2a	22.9a
Previous crop avg.	40.0B	44.2A		19.8B	24.0A	

† Previous crop refers to main crop that was present in a field the year before soil samples were taken.

‡ Numbers within a column followed by the same lowercase letter and numbers within a row and depth layer followed by the same uppercase letter are not significantly different as indicated by LSD test at the 0.05 probability level.

rye after both treatment. On average, the rye after both and the rye after silage treatments apparently added enough organic matter and N to the 0- to 5-cm layer to cause a measureable increase in PMN whereas the rye after soybean treatment did not. In both depth layers, PMN was higher when the previous crop was soybean. The previous crop effect was likely due in part to relatively more soybean residues left in the field compared to corn silage and the higher mineralization rates of soybean residues. Soybean shoot residues on the soil surface, however, do not completely explain the higher PMN following soybean in the 5- to 10-cm soil layer. Soybean root residues would be expected to have a greater impact on the 5- to 10-cm layer than surface residues (Gale and Cambardella, 2000), and it is possible that soybean root residues would also have had a greater mineralization potential than corn root residues. The interaction effect of field by previous crop was also significant at the 0- to 5-cm depth layer as it was for SOM and POM (data not shown). As discussed previously, the significant interaction may have been caused by the differences observed between 2009 and 2010 main crop yields and growth (Table 4). Interestingly, the cover crop treatment by previous crop interaction was also significant for the 0- to 5-cm layer possibly because of a greater PMN for the rye after soybean treatment when the previous crop was soybean. It is possible that a rye cover crop following a soybean crop may take up some of the N rapidly mineralized from soybean residues and then make that N available for mineralization after the cover crop is terminated. In general, we would assume that over the long-term, increasing inputs of cover crop residues and the N contained in those residues to soil would increase PMN over time. Research by Biederbeck et al. (1994) suggests there is a positive correlation between POM and PMN. While our experiment did not investigate this correlation, our data did show a roughly similar treatment effect pattern for both POM and PMN at both depth layers. The greater PMN observed when a rye cover crop was planted in both years or only following corn silage could mean that cover crops have the potential to increase long-term N availability (Drinkwater et al., 1996) in corn silage–soybean cropping systems, which could help reduce the need for synthetic N fertilizers.

CONCLUSION

Farmers are faced with a number of challenges, including demands to increase production to meet the needs of a growing population, adapting to an increasingly variable climate, and the rising costs of energy and inputs. One way to meet these challenges is through maintaining and improving soil quality. Adding a rye winter cover crop to no-till corn silage–soybean cropping systems can, at the very least, slow decline in soil quality and could possibly even maintain or improve soil quality. Our data show that in general, treatments with rye cover crops after both main crops or only after corn silage had higher SOM, POM, and N mineralization relative to treatments without a rye cover crop or a rye cover crop following only soybean. Our data also indicate that the positive effects of a rye cover crop were more pronounced in the top 5 cm of the soil profile. Although our experiment has demonstrated better soil quality with cover crops, it is likely that these changes take place slowly and farmers would probably not observe any changes in soil quality in the first few years after adoption. Other obstacles to farmer adoption of cover crops include lack of knowledge about successful cover crop management, input costs associated with cover crops, and challenges associated with poor cover crop establishment due to unfavorable weather conditions. To some extent, these obstacles should diminish over time as cover crops are more widely used, farmers gain more management experience, and cover crop seeds and related services become more readily available.

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