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Examining Changes in Soil Organic Carbon with Oat and Rye Cover Crops Using Terrain Covariates

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ABSTRACT

Winter cover crops have the potential to increase soil organic C in the corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation in the upper Midwest. Management effects on soil C, however, are often difficult to measure because of the spatial variation of soil C across the landscape. The objective of this study was to determine the effect of oat (*Avena sativa* L.), rye (*Secale cereale* L.), and a mixture of oat and rye used as winter cover crops following soybean on soil C levels over 3 yr and both phases of a corn–soybean rotation using terrain attributes as covariates to account for the spatial variability in soil C. A field experiment was initiated in 1996 with cover crop treatments, both phases of a corn–soybean rotation, and a controlled-traffic no-till system. Oat, rye, and oat–rye mixture cover crop treatments were overseeded into the soybean phase of the rotation in late August each year. Cover crop treatments were not planted into or after the corn phase of the rotation. Soil C concentration was measured on 450 samples taken across both rotation phases in a 7.62-m grid pattern in the late spring of 2000, 2001, and 2002. Slope, relative elevation, and wetness index (WI) were used as covariates in the analysis of variance to remove 77% of the variation of soil C caused by landscape driven patterns of soil C. Soil C concentrations were 0.0023 g C g soil^{-1} higher in 2001 and 0.0016 g C g soil^{-1} higher in 2002 than in 2000. The main effects of cover crops were not significant, but the interaction of cover crops and rotation phase was significant. The rye cover crop treatment had 0.0010 g C g soil^{-1} higher soil C concentration than the no-cover-crop control in the soybean phase of the rotation, which included cover crops, but had 0.0016 g C g soil^{-1} lower C concentrations than the control in the corn phase of the rotation, which did not have cover crops. Using terrain covariates allowed us to remove most of the spatial variability of soil C, but oat and rye cover crops planted every other year after soybean did not increase soil C concentrations averaged over years and rotation phases.

One approach for offsetting emissions of greenhouse gases from agricultural systems is to employ management practices that increase soil C. Winter cover crops have the potential to increase soil organic C in agricultural soils (Karlen and Cambardella, 1996; Lal et al., 1998; Jarecki and Lal, 2003). In general, soil C storage increases when inputs of plant biomass to the soil are greater than C losses through decomposition, erosion, and leaching (Paustian et al., 1997; Huggins et al., 1998). Winter cover crops have been used successfully to increase soil C in parts of the USA with mild winters (Beale et al., 1955; Patrick et al., 1957; Utomo et al., 1987; Utomo et al., 1990; Kuo et al., 1997; Nyakatawa et al., 2001; Sainju et al., 2002). In some of these studies, the cover crop residues were incorporated with tillage (Beale et al., 1955; Patrick et al., 1957; Kuo et al., 1997; Sainju et al., 2002). Eckert (1991) in Ohio, however, was not able to detect an increase in soil C with a rye cover crop in no-till. Similarly, Utomo et al. (1990) observed no change in soil C with a rye cover crop in either no-till or conventional tillage, but measured an increase with a hairy vetch (*Vicia villosa* Roth) cover crop in no-till. Mendes et al. (1999) found that red clover (*Trifolium pratense* L.) or triticale (× *Triticosecale* Wittmack) winter cover crops did not increase soil C in a tilled vegetable production system.

Although not often used in a no-till corn–soybean rotation, winter cover crops would increase inputs of plant biomass to the soil and would have the potential to increase soil C in this rotation. In the upper Midwest, however, the cover-crop growing season between harvest and planting in a corn–soybean rotation is cold and short. To address this problem, Johnson et al. (1998) successfully established oat and rye cover crops by overseeding into soybean in late August before leaf drop and were able to produce substantial biomass in a no-till corn–soybean rotation in Iowa. Similar, attempts to overseed oat and rye cover crops into corn were not successful (T.C. Kaspar, unpublished data, 1998). Thus, the ability of small grain winter cover crops to increase or maintain soil C levels in corn–soybean rotations in the upper Midwest needs to be evaluated.

Progress in understanding soil C dynamics and in developing management practices, like cover crops, to increase or maintain soil C has been limited by the long time-frame required to observe changes in soil C content. Part of the difficulty in measuring changes in soil C is caused by the temporal and spatial variability of soil C levels in agricultural fields (Ellert et al., 2001; Janzen et al., 2002). Soil C varies from year-to-year as a result of weather-affected changes in crop residue inputs or decomposition of residues and organic matter (Campbell et al., 2000; Janzen et al., 2002). Campbell et al. (2005) showed the soil C in a long-term wheat–fallow rotation varied by up to 13% over a 22-yr period because of weather-affected changes. Additionally, differences in soil C across a field are often greater than the expected response of soil C to management practices (Ellert et al., 2001; Janzen et al., 2002). For example, soil C varies with topography (Schimel et al., 1985; Moor-

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Abbreviations: A_s, specific upslope contributing area; CC, organic carbon concentration; DEM, digital elevation model; GIS, geographic information system; GPS, global positioning system; LSF, length-slope factor; SPI, stream power index; UTM, Universal Transverse Mercator; WI, wetness index; WLOI, weight-loss-on-ignition.

man et al., 2004) and total soil C content along a hillslope can be three times greater at the footslope than at the summit (Schimel et al., 1985). Several studies have demonstrated a strong relationship between soil C and terrain parameters (Moore et al., 1993; Mueller and Pierce, 2003; Moorman et al., 2004). Therefore, for individual fields in which a strong relationship exists between terrain and soil C, terrain parameters could be used as covariates (Steel and Torrie, 1960) in the analysis of variance to partly remove the variation in soil C due to topography.

Winter cover crop growth, C inputs, and decomposition rates vary substantially with cover crop species, soils, climate, and cropping systems (Power and Biederbeck, 1991; Wagger et al., 1998). Furthermore, variation in soil C across fields makes it difficult to detect possible increases in soil C resulting from inclusion of small grain winter cover crops in a cropping system. The objective of this study was to determine the effect of oat, rye, and a mixture of oat and rye used as winter cover crops following soybean on soil C levels over 3 yr and both phases of a corn–soybean rotation using terrain attributes as covariates to account for the spatial variability in soil C.

MATERIALS AND METHODS

A field study was initiated in fall 1996 in a 2.6-ha field 9.4 km northwest of Ames, IA with three predominate soils (Andrews and Diderikson, 1981): Canisteo (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls), Clarion (fine-loamy, mixed, superactive, mesic Typic Hapludolls), and Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludolls). No-till corn and soybean had been grown in rotation on the site since 1988 and were continued throughout this experiment. All machinery and foot traffic were restricted to the same interrows each year and row location was maintained from year-to-year. The field was split in half with five contiguous blocks on the north half of the field and five blocks on the south half of the field. To maintain the corn–soybean rotation half the field (five blocks) was planted with corn and the other half was planted with soybean each year. In each subsequent year the main crops were switched from one half of the field to the other. Each cover crop treatment plot was replicated five times within each half of the field. Treatment plots were 7.6-m wide and 65.7-m long and consisted of 10 rows 0.76-m apart (Fig. 1).

Cover crops were planted only in the soybean phase of the corn–soybean rotation. Cover crop treatments, a control (no cover crop), oat (‘Ogle’), rye (‘Rymin’), and an oat–rye mixture (total seed number same as other treatments, half rye and half oat), were initiated in the fall of 1996. All treatments were overseeded into soybean in mid- to late-August at 3.8 million seeds ha^{-1} with a tractor-mounted, 3.8-m wide, drop spreader. The tractor was equipped with wheel shields to minimize damage to the soybean crop.

Cover crop shoot dry matter was collected by positioning a 0.76-m wide by 0.50-m long rectangular frame over the center row of each plot. All cover crop plants within the frame were cut off at the soil surface and dried at 60°C. Two samples per plot were collected in the fall in late October or early November after a hard freeze had caused significant damage to the oat cover crop. In the spring, rye shoot dry matter (in both rye and oat–rye treatments) was collected just before herbicide burndown and corn planting. Although cover crop biomass samples were collected in both fall and spring, it was difficult to estimate the biomass produced by the oat–rye treatment because of the oat component. The oat portion of the oat–rye treatment winter kills, thus biomass collected in the fall contains both oat and rye biomass, whereas biomass collected in the spring contains only rye biomass. Because most of the rye biomass overwinters, simply adding the fall and spring measurements would overestimate biomass production of the rye component. We assumed that oat biomass production in the oat–rye treatment was equivalent to 50% of the oat treatment biomass. Therefore, one-half of the biomass produced by the oat treatment measured in the fall was added to the biomass measured in the spring for the oat–rye treatment. Shoot biomass production of the rye treatment was assumed to be equal to the biomass measured in the spring.

Soybean and corn were slot planted with a five-row, 0.76-m row width, John Deere[1] 7100 planter (Deere and Co., Moline, IL) with bubble coulters. The soybean cultivars, ‘Northrup King S19–90’ (Northrup King Co., Minneapolis, MN) and ‘Stine 2250’ and ‘Stine 2289–4’ (Stine Seed Co., Adel, IA), were planted at 387 000 seeds ha^{-1} in early- to mid-May. The corn hybrid, ‘Pioneer 3563,’ (Pioneer Hybrid International Inc., Johnston, IA) was planted at 84 000 seeds ha^{-1} in early May. All plots received fertilizer and herbicide applications typical for this region and soil type. Corn plots received 213 kg ha^{-1} of N as liquid urea-ammonium nitrate shortly after planting with a spoke-wheel fertilizer injector (Baker et al., 1989). Dry P and K fertilizers were surface applied in the fall after harvest before the corn phase at rates of 49 and 93 kg ha^{-1} of P and K, respectively, when soil tests indicated that levels were low. A burndown application of glyphosate [*N*-(phosphonomethyl) glycine] at 1.12 kg a.i. ha^{-1} was made 1 to 2 d before corn planting to kill the rye. Each fall, soybean and corn grain yields were determined using a modified combine with a weigh tank and moisture meter mounted inside the combine grain storage tank (Colvin, 1990) by harvesting an area 65.7 m long by 2.8 m wide in each plot. The remaining area was bulk harvested and all corn and soybean shoot residues were left on the soil surface. Yields were adjusted to 0.155 g g^{-1} grain moisture.

Monthly precipitation totals and average monthly air temperatures were calculated from daily values collected at the Iowa State University research farm located 4.8 km southwest of the study area (Table 1; Herzmann, 2004).

Four hundred and fifty soil C samples were collected across both rotation phases (i.e., across both halves of the field) in late May or early June in each of 3 yr (2000, 2001, and 2002). Sample collection occurred after planting of the main crop, but before the crop would have affected soil C. Thus, soil samples were identified as coming from the rotation phase that had been growing the previous year. Samples were collected in a grid pattern with 7.62 m between sampling points, except along the separation between the north and south halves of the field (Fig. 1). This resulted in nine subsamples per cover crop treatment plot, which was 360 (nine subsamples × four treatments × five reps × two rotation phases) of the 450 samples. Additionally, 90 of the 450 samples were collected from plots without treatments or in border plots to complete the grid pattern. Coordinates of each sampling point were determined with a global positioning system (GPS). At each sampling point, one sample was collected using a 0.0318-m diam. soil sampler in the center of an untracked interrow. Before sampling, loose residue on the soil surface was brushed aside and only soil from the 0.00- to 0.05-m depth was retained for

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

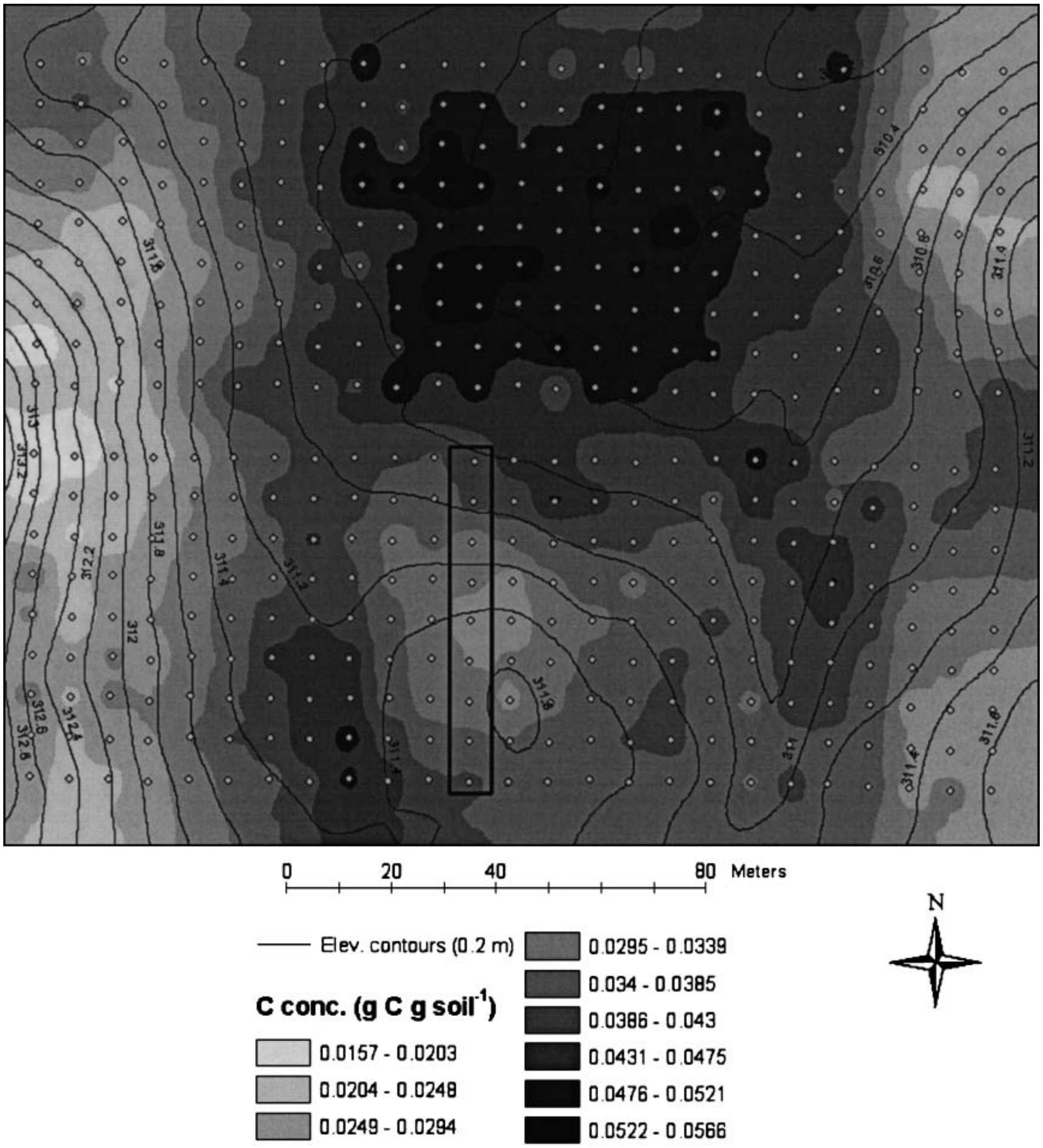

Fig. 1. Site map showing 0.2-m elevation contours, sampling points, one of the treatment plots (rectangle), and inverse-distance weighted estimates of soil carbon concentrations (g C g soil^{-1}) derived from weight-loss-on-ignition measurements at the sampling points averaged over 3 yr.

analysis. Each sample was pushed through a 2-mm sieve, dried at 105°C for at least 24 h, and weighed to determine bulk density using the field-moist sample volume. No attempt was made to remove particulate organic matter or root debris from the sample. The organic C content of each sample was determined using the weight-loss-on-ignition (WLOI) method (Schulte et al., 1991; Schulte and Hopkins, 1996; Cambardella et al., 2001). Dried samples were weighed to ± 0.0001 g and then heated for 16 h at 360°C in a programmable muffle furnace with preset ramp-up and ramp-down periods. Samples were then reweighed after cooling in a desiccator to determine weight loss. The WLOI method was calibrated for the soils in this field using an additional 200 samples. For calibration, one hundred cores were taken throughout the field with a 0.0318 m in diam. soil sampler to a depth of 0.10 m. Each core was then split into two samples, one from the 0.00- to 0.05-m soil layer and the other from the 0.05- to 0.10-m soil layer. The calibration samples were passed through a 2-mm sieve, dried at 105°C, weighed, and ground. Two subsamples from each sample were treated with a 1 *M* H_2SO_4 solution to remove carbonates, and analyzed for total C using the dry combustion method (Nelson and Sommers, 1982) on a Carlo-Erba NA1500 NCS elemental analyzer (Haake Buchler Instruments, Paterson, NJ). The remaining soil from each calibration sample was then analyzed using the WLOI method. Using the regression of C concentration measured by dry combustion on weight-loss-on-ignition, the C concentrations of experimental grid samples were then calculated using the formula:

$$\mathrm{CC} = 0.6413 \times \mathrm{WLOI} - 0.0006; r^2 = 0.86$$

where CC = organic carbon concentration (g C g soil^{-1}) and WLOI = weight loss on ignition (g g soil^{-1}).

Elevation and position measurements were made for the field on 6 June 2000 with a kinematic, differential GPS receiver (Ashtech Z Surveyor, Magellan Corp., Santa Clara, CA) mounted on an all terrain vehicle. Readings were logged every

Table 1. Average monthly air temperature and total precipitation 1999-2002.

	Avg. Air Temperature, °C					Total Precipitation, mm				
Month	**1999**	**2000**	**2001**	**2002**	**1951-2004 Avg.**	**1999**	**2000**	**2001**	**2002**	**1951-2004 Avg.**
Jan.	**−8.3**	**−4.4**	**−5.6**	**−1.1**	**−7.4**	**21.6**	**14.2**	**28.2**	**6.6**	**18.4**
Feb.	**1.1**	**1.1**	**−7.8**	**−1.1**	**−4.1**	**16.0**	**41.4**	**32.5**	**26.2**	**22.2**
Mar.	**3.3**	**6.7**	**−1.1**	**0.6**	**1.9**	**24.6**	**11.2**	**27.9**	**10.2**	**51.5**
Apr.	**10.0**	**11.1**	**13.3**	**10.6**	**9.9**	**207.0**	**20.8**	**96.0**	**94.7**	**87.7**
May	**16.7**	**17.8**	**16.7**	**15.0**	**16.2**	**149.9**	**120.4**	**190.2**	**129.8**	**114.5**
June	**21.1**	**20.0**	**21.1**	**23.3**	**21.2**	**185.2**	**103.6**	**49.8**	**80.5**	**126.8**
July	**25.6**	**22.2**	**24.4**	**24.4**	**23.3**	**161.5**	**72.1**	**48.3**	**149.9**	**101.8**
Aug.	**21.1**	**22.8**	**23.3**	**21.7**	**22.0**	**151.4**	**33.8**	**73.9**	**208.5**	**104.5**
Sep.	**16.7**	**20.0**	**16.7**	**19.4**	**17.7**	**61.0**	**25.7**	**149.1**	**37.6**	**79.6**
Oct.	**12.2**	**13.3**	**11.1**	**8.3**	**11.4**	**8.6**	**49.5**	**65.0**	**79.2**	**60.1**
Nov.	**7.8**	**0.6**	**9.4**	**2.2**	**2.7**	**23.6**	**60.5**	**36.3**	**5.6**	**43.2**
Dec.	**−2.2**	**−12.8**	**−0.6**	**−1.1**	**−4.3**	**13.2**	**40.4**	**9.7**	**0.0**	**23.5**
Jan.–Dec.†	**10.4**	**9.9**	**10.1**	**10.2**	**9.2**	**1023.6**	**593.6**	**806.9**	**828.8**	**833.7**
Oct.–May†	**—**	**6.3**	**2.1**	**5.5**	**3.0**	**—**	**253.4**	**525.2**	**378.5**	**421.1**

† Values for the Jan. through Dec. and Oct. through May periods are averages for the period for air temperature and totals for the period for precipitation. Values for the Oct. through May period are shown in the column for the year in which May occurred.

1 s as the vehicle moved across the field at approximately 3.7 m s^{-1}. North to south transects were driven approximately 7.6 m apart across the field. A base-station GPS receiver, located at a benchmark on the edge of the field, was used to differentially correct the roving GPS receiver. The ground control locations were referenced to a Universal Transverse Mercator (UTM) projection (Zone 15, North American Datum 1983). Elevation values were estimated in height above the ellipsoid (m). Position measurements are reliably within ± 0.03 m laterally and ± 0.06 m vertically for this equipment.

The elevation data produced a digital terrain model comprising 3722 points, which was used to generate a digital elevation model (DEM) for the field on a 2-m regularized grid using the surface mapping program SURFER (Golden Software, Golden CO). A gaussian distribution semivariogram model provided the best visual fit for the elevation data and was used to generate the DEM at a 2-m resolution. The primary terrain attributes: relative elevation (m), slope (the rate of maximum change in elevation to surrounding grid cells, °), plan curvature (curvature of the surface perpendicular to the direction of slope, km^{-1}; values are negative for curvatures that are concave upward), and profile curvature (curvature of the surface in the direction of the slope, km^{-1}; values are negative for curvatures that are concave upward), were then calculated for each 2-m grid cell of the DEM using the Arc/Info geographical information system (GIS) software CURVATURE command (Arc/Info, 1998; Environmental Systems Research Institute, Redlands, CA USA). Specific upslope contributing area (A_s), which is total upslope contributing area divided by the 2-m cell width ($m^2\ m^{-1}$) was calculated from elevation data using an infinite direction method (Tarboton, 1997) incorporated in the Taudem software (Tarboton, 2002). Three compound terrain indices (Wilson and Gallant, 2000), wetness index (WI), stream power index (SPI), and length-slope factor (LSF) were also calculated by

$$\mathrm{WI} = \ln[\mathrm{A_s}/\tan(\mathrm{slope})]$$

$$\mathrm{SPI} = \mathrm{A_s} \times \tan(\mathrm{slope})$$

$$\mathrm{LSF} = 1.4 \times (\mathrm{A_s}/22.3)^{0.4} \times [\sin(\mathrm{slope})/0.0896]^{1.3}$$

where A_s = specific upslope contributing area.

A stepwise regression procedure (PROC REG; SAS Institute, 1999) was used to regress soil C concentration and bulk density on terrain parameters using all 450 grid sampling points. Selection of terrain parameters for use as covariates was based on a probability of less than or equal to 0.05 (Freund and Littell, 2000; SAS Institute, 1999) and partial R^2 greater than or equal to 0.01. The stepwise regression analysis of soil C concentration returned five parameters (slope, WI, elevation, $(\mathrm{elevation})^2$, and a slope × elevation interaction term; combined $R^2 = 0.77$). The regression analysis of soil bulk density returned four parameters (elevation, slope, $[\mathrm{slope}]^2$, and LSF; combined $R^2 = 0.40$). After the preliminary stepwise regression procedure, an initial analyses of variance for soil C concentration and bulk density were conducted using PROC MIXED (SAS, 1999), the appropriate covariates for each variable, and the 360-grid sampling points that occurred within the treatment plots. The experiment was analyzed as a split-plot design (Gomez and Gomez, 1984) with five replications, six combinations of years and rotation phases as the main plots, and cover crop treatments as the split plots. The residuals from this analysis were examined using PROC VARIOGRAM (SAS Institute, 1999) with a lag distance of 7.62 m and a maximum lag of 10 to examine the spatial covariance of the residuals. In both cases, spatial covariance was minimal and the omnidirectional variogram was not different from the unidirectional variograms. PROC NLIN (SAS Institute, 1999) using a weighted least square procedure (Gotway, 1991) was then used to fit and compare spherical, gaussian, and exponential models to the empirical variograms. In both cases, the spherical models converged to a solution and were selected because each had reasonable values for the nugget, sill, and range (Meek, 2002). The nuggets were very small, sills were equal to or slightly less than the variance of the residuals, and the ranges fell between 20 and 29 m. For the final analyses, the spherical models were then used in PROC MIXED (SAS Institute, 1999) following the examples of Littell et al. (1996) to account for the spatial covariance among the errors, to adjust the error estimates, and to calculate the least squares means for treatments and year by rotation phase combinations. Tukey's test at the 0.10 probability level and single degree of freedom comparisons were used to compare treatment means when the analysis of variance indicated significant treatment effects at the 0.10 probability level (SAS Institute, 1999).

RESULTS AND DISCUSSION

Average monthly temperatures and total monthly precipitation for 1999 to 2002 are presented in Table 1. Averages for the 8 mo (October–May) preceding soil C sampling each year were also calculated. This period was selected because it roughly approximates the time from grain harvest to sampling during which the C inputs to the soil of the previous grain crop and cover crop decompose. The period from October 2000 through May 2001 was on average colder and wetter than the other

Table 2. Cover crop shoot dry matter 1996-2001.

Oct.-May period	Shoot dry matter			
	Oat-rye †	Oat	Rye	Avg.
	Mg ha^{-1}			
1996-1997	1.30 A	0.10 B	1.55 A	0.98 c‡
1997-1998	2.43 A	0.38 B	2.30 A	1.70 b
1998-1999	1.77 A	1.16 B	1.59 A	1.51 b
1999-2000	4.06 A	0.67 B	4.03 A	2.92 a
2000-2001	1.53 A	0.59 B	1.38 A	1.17 c
2001-2002	2.56 A	0.60 C	1.74 B	1.63 b
Avg.	2.28 A	0.58 C	2.10 B	

† Estimated shoot dry matter oat-rye treatment by adding half of oat dry matter from fall measurement to spring shoot dry matter measurement.
‡ Numbers within a row followed by the same uppercase letter and numbers within a column followed by the same lowercase letter are not significantly different as indicated by the LSD test at the 0.10 probability level. Columns or rows without uppercase or lowercase letters indicate that main effects or interaction effects were not significant in the analysis of variance.

two periods. This period had twice as much precipitation and was 4.2°C colder than the same period in 1999–2000. The 2000–2001 period also had 39% more precipitation and was 3.4°C colder than the 2001–2002 period. We would hypothesize that the colder and wetter conditions during the 2000–2001 period would result in less decomposition of crop residues, cover crop residues, and soil C than during the same periods in 1999–2000 and 2001–2002 (Linn and Doran, 1984; Skopp et al., 1990; Vigil and Kissel, 1995; Ruffo and Bollero, 2003).

Cover crop shoot biomass produced by the oat, rye, and oat–rye cover crop treatments are presented in Table 2 for the winters of 1996–1997 through 2001–2002. Averaged over the six winters the oat–rye mixture produced slightly more shoot biomass than the rye treatment, mainly because of significant year × cover crop interaction for the 2001–2002 winter. The biomass produced by the oat cover crop treatment was <28% of the other two treatments because the oat cover crop did not overwinter. These biomass measurements are slightly higher than the average shoot biomass production of oat, rye, and oat–rye cover crops (0.46, 1.87, and 1.69 Mg ha^{-1}, respectively) reported by Johnson et al. (1998) in central Iowa. The greater average production in this study probably was the result of the significantly higher biomass production of the cover crop treatments in the winter of 1999–2000, which was relatively warm.

Table 3. Average corn grain yields 1997-2002 for cover crop treatments.

Year	Corn grain yields				
	No cover crop	Oat-rye	Oat	Rye	Avg.
	Mg ha^{-1}				
1997	9.48 A†	8.39 B	9.44 A	8.20 B	8.88 e
1998	10.56 A	9.41 B	11.00 A	9.05 B	10.01 cd
1999	9.94	10.26	10.87	10.04	10.28 bc
2000	10.33 A	8.94 B	10.33 A	8.70 B	9.58 d
2001	11.68 A	10.59 B	11.40 A	10.53 B	11.05 a
2002	11.21 A	10.52 BC	11.10 AB	10.33 C	10.79 ab
Avg.	10.53 A	9.69 B	10.69 A	9.48 B	10.10

† Numbers within a row followed by the same uppercase letter and numbers within a column followed by the same lowercase letter are not significantly different as indicated by the LSD test at the 0.10 probability level. Columns or rows without uppercase or lowercase letters indicate that main effects or interaction effects were not significant in the analysis of variance.

Corn grain yields for the years 1997–2002 are presented in Table 3 and are comparable with the county average for the same period of 9.87 mg ha^{-1} (National Agricultural Statistics Service, 2006). Corn yields are presented as an indication of the relative amounts of crop biomass that were produced in the various treatments and over the years preceding soil C sampling. We assume that in general, root and shoot biomass is proportional to the grain yield produced in a given year and that lower yield indicates lower biomass relative to other treatments or years (Buyanovsky and Wagner, 1986; Huggins and Fuchs, 1997). Averaged over 6 yr, corn yields of the no-cover crop control and the oat treatment were greater than those of the rye and oat–rye treatments. Johnson et al. (1998) also observed that corn grain yield was reduced following a rye or oat-rye cover crop. In 1999, however, there did not seem to be a negative effect of the rye or oat–rye cover crop treatments on corn yield. We assume that in years when corn grain yield was reduced following a rye or oat–rye cover crop that biomass C added to the soil was also reduced.

Soybean yields for 1997–2002 are shown in Table 4 and are comparable with the county average for the same period of 3.04 Mg ha^{-1} (National Agricultural Statistics Service, 2006). Cover crop treatments and the interaction of cover crops and years did not have a significant effect on soybean yields. Cover crops were overseeded into soybean in late August at about the time that soybean plants usually began losing leaves and had almost finished seed fill. Thus, we did not expect soybean yield to be affected by the cover crops. It was possible that the wheel traffic and disturbance caused by passage of the tractor during overseeding could have damaged the soybean plants and reduced yields, but this did not seem to be the case. We assumed that because yields were similar that biomass C added by the soybean crop to the soil did not differ among treatments.

Bulk density corrected for landscape variation using terrain covariates was significantly affected only by year (Table 5) and not by rotation phase, cover crop treatments, or interactions. Bulk density was significantly greater in 2001 than in 2000 (Table 5). We assume that the year-to-year changes in bulk density were due to weather-related soil consolidation or settling resulting from precipitation, snow cover, and freeze–thaw cycles (Unger, 1991).

Table 4. Average soybean grain yields 1997-2002 for cover crop treatments.

Year	Soybean grain yields				
	No cover crop	Oat-rye	Oat	Rye	Avg.
	Mg ha^{-1}				
1997	3.02	2.67	2.90	2.79	2.85 bc†
1998	3.54	3.35	3.57	3.18	3.41 a
1999	2.76	2.25	2.49	2.48	2.50 c
2000	2.94	3.08	3.13	3.12	3.07 ab
2001	2.71	2.65	2.59	2.63	2.65 bc
2002	3.04	3.09	3.25	3.24	3.16 ab
Avg.	3.00	2.85	2.99	2.91	

† Numbers within a column followed by the same lowercase letter are not significantly different as indicated by the LSD test at the 0.10 probability level. Columns or rows without uppercase or lowercase letters indicate that main effects or interaction effects were not significant in the analysis of variance.

Table 5. Least squares means for soil bulk density for year by cover crop treatment combinations.

Year	Soil bulk density: No cover crop	Oat-rye	Oat	Rye	Avg.
	Mg m^{-3}				
2000	0.99	0.99	1.01	1.02	1.00 b†
2001	1.10	1.07	1.11	1.06	1.09 a
2002	1.05	1.02	1.01	1.04	1.03 ab
Avg.	1.05	1.03	1.04	1.04	

† Numbers within a column followed by the same lowercase letter are not significantly different as indicated by Tukey's test at the 0.10 probability level. Columns or rows without uppercase or lowercase letters indicate that main effects or interaction effects were not significant in the analysis of variance.

Changes in bulk density can cause changes in C concentration because of changes in the equivalent depth of sampling (Ellert et al., 2001). Bulk density, however, was not affected by rotation phase or cover crop treatments. As a result, any differences among these treatments in C concentration were accompanied by corresponding differences in C mass on an area basis. We will continue to discuss the C data in terms of C concentration rather than C mass because it was the more direct measurement of C in this study.

Figure 1 is a map of the soil C concentration of the upper 0.05 m averaged over the 3 yr. Carbon concentration varied by a factor of 3.8 across the field. The lowest soil C concentrations (min. = 0.015 g C g soil^{-1}) were found along the west edge of the field in an area where the greatest elevations and slopes occurred. The highest soil C concentrations (max. = 0.057 g C g soil^{-1}) were found in the north-central part of the field, which had relatively low elevations and gradual slopes. In general, the north half of the field, which has a large relatively flat area, had higher soil C concentrations than the south half of the field. On a field scale, soil C concentration decreased as slope and relative elevation increased (Fig. 2 and 3) and increased as wetness index increased. The stepwise regression of soil C concentration on terrain parameters produced the following relationship with an $R^2 = 0.77$:

$$\begin{aligned} CC = 0.045 &- (0.013 \times \text{slope}) \\ &+ (0.001 \times \text{WI}) - (0.005 \times \text{elevation}) \\ &+ [0.006 \times (\text{elevation} \times \text{slope})] \\ &- [0.004 \times (\text{elevation})^2] \end{aligned}$$

where CC = organic carbon concentration (g C g soil^{-1}), slope = slope (deg), WI = wetness index, elevation = elevation relative to lowest elevation in field (m), and elevation × slope = slope and elevation interaction term (deg m). We speculated that there were several reasons for this relationship. First, over the long term, erosional processes probably have moved topsoil and soil C from higher landscape positions to lower positions (Li and Lindstrom, 2001; Ritchie et al., 2004). Second, the eroded soils found at the summit and shoulder landscape positions in this geologic region of Iowa are more coarse textured than soils in lower landscape positions (Kemmis et al., 1981; Kaspar et al., 2004). Crop production on these soils is often limited by water and nutrients and this results in lower C inputs (Kaspar et al., 2004). Third, soil respiration measurements in this field have indicated a faster rate of C loss during the spring from the drier, coarse-textured soils at backslope landscape positions than from wetter, colder, finer-textured soils at footslope positions (Parkin and Kaspar, 2003).

Analyzing the C concentration data without removing the large spatial variation resulting from landscape and

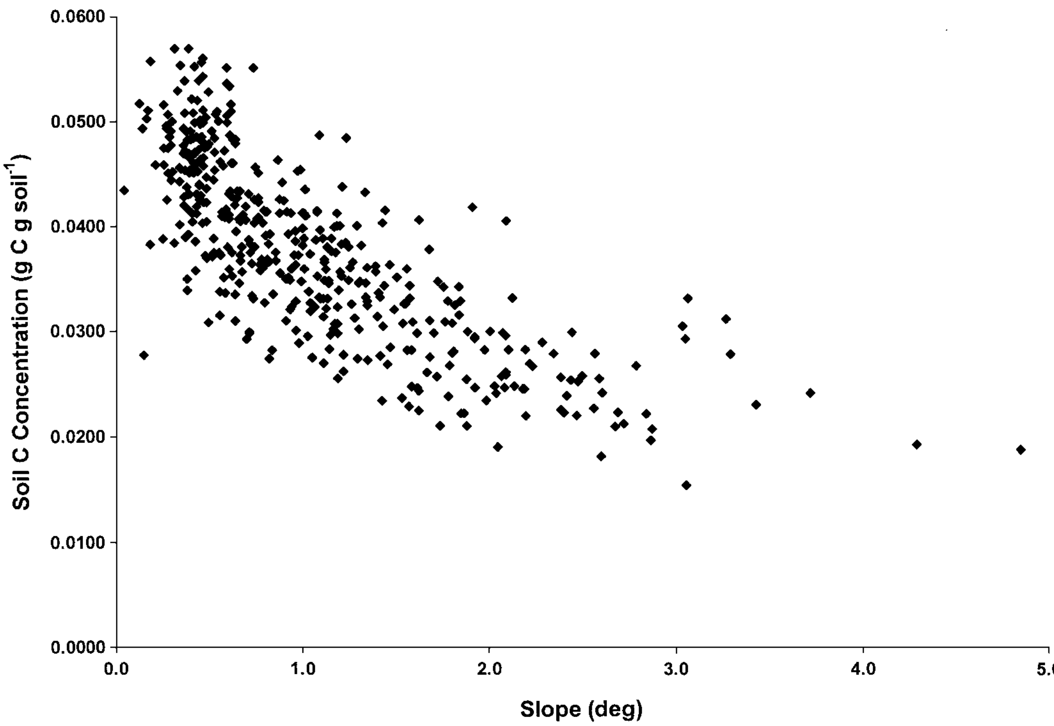

Fig. 2. Relationship between C concentrations at each sampling location averaged over 3 yr and slope.

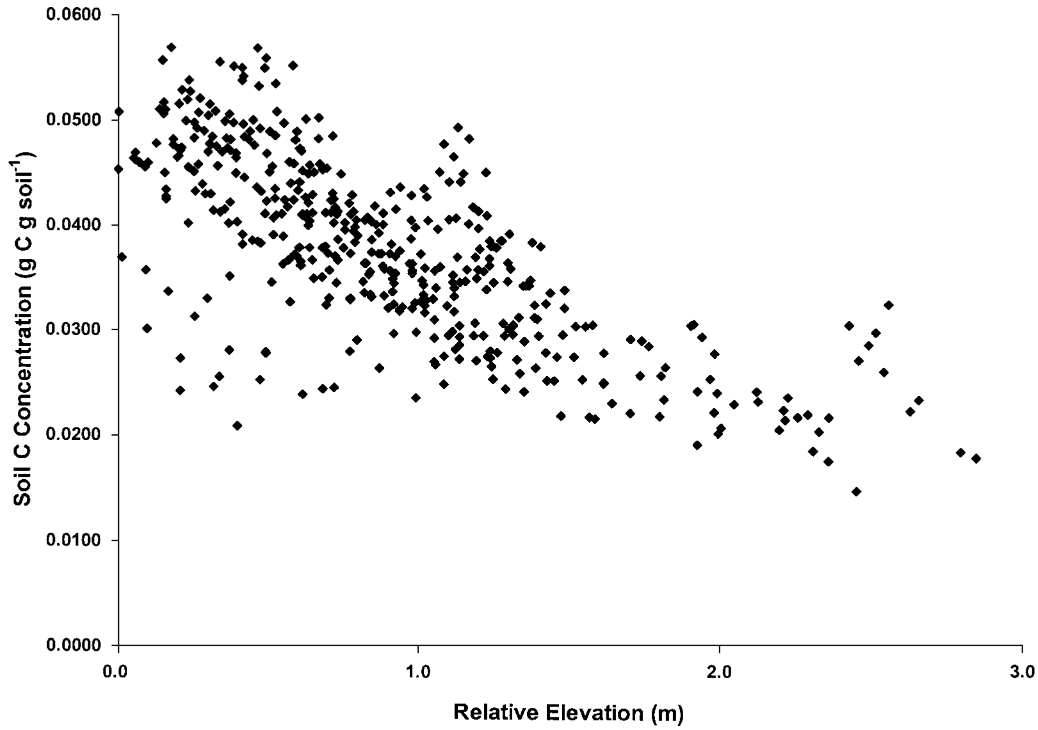

Fig. 3. Relationship between C concentrations at each sampling location averaged over 3 yr and relative elevation.

terrain features resulted in drastically different results than when the data were analyzed with terrain covariates. Table 6 shows the probabilities of a greater F value for main effects, interactions, and single degree of freedom comparisons from the analysis of variance for C concentration with and without terrain covariates. When the data were analyzed without terrain covariates, only the interaction of year and rotation phase was significant at the 0.10 level. When the data were analyzed with terrain covariates, year, and the interactions of year and cover crop treatments, of rotation phase and cover crops, and of year, rotation phase, and cover crops were significant at the 0.10 level. The other two main effects, rotation phase and cover crop treatments, were not significant in either analysis. The significance of the rotation phase and year interaction for the analysis without terrain covariates can probably be explained by the spatial pattern of soil C concentrations in the field (Fig. 1). As mentioned before the corn–soybean rotation was maintained by rotating the two main crops between the north and south halves of the field. Because the north half of the field had a higher average C concentration than the south half, whichever rotation phase was in the north half of the field in the year before sampling would have had a higher soil C concentration in a given year. By using the terrain covariates we removed some of the confounding between field half and rotation phase. Another advantage of using terrain covariates to remove the spatial variability of soil C was that we were able to detect much smaller differences between treatment combination means. For example, for the year by cover crop treatment means differences as small as 0.0011 g C g soil^{-1} were significant at the 0.10 probability level when terrain covariates were used in the analysis as compared with 0.0031 g C g soil^{-1} without covariates. Similarly, differences between rotation phase by cover crop treatment means were significant at the 0.10 level at 0.0010 and 0.0025 g C g soil^{-1}, for the analyses with and without covariates, respectively.

Average soil C concentrations of both 2001 and 2002 were significantly greater than those in 2000 (Table 6 and 7). The higher C concentration in 2001, however, could not be explained by the greater bulk density in 2001 (Table 5). Additional samples collected as part of the calibration data set showed that C concentration of the 0.05- to 0.10-m layer was significantly less than that

Table 6. Probabilities of a greater F value for main effects, interactions, and single degree of freedom comparisons from the analysis of variance for C concentration with and without terrain covariates.

	Pr > F	
Main effects and interactions	Without terrain covariates	With terrain covariates
Year	0.738	0.004
Rotation phase	0.388	0.936
Year × rotation phase	0.094	0.699
Cover crop (CC)	0.141	0.238
Year × CC	0.937	0.003
Rotation phase × CC	0.776	0.001
Year × rotation phase × CC	0.997	0.037
Single degree of freedom comparisons		
2000 vs 2001	0.451	0.001
2000 vs 2002	0.604	0.019
2001 vs 2002	0.812	0.260
Oat-rye vs no CC	0.179	0.269
Rye vs no CC	0.338	0.543
Oat vs no CC	0.819	0.436
(Oat-rye vs control for soybean) vs (oat-rye vs control for corn)	0.945	0.253
(Rye vs control for soybean) vs (rye vs control for corn)	0.359	0.001
(Oat vs control for soybean) vs (oat vs control for corn)	0.930	0.196

Table 7. Least squares means for C concentration for year by cover crop treatment combinations.

Year	Soil C concentration				
	No cover crop	Oat-rye	Oat	Rye	Avg.
	g C g soil $^{-1}$				
2000	**0.0385 A†**	**0.0374 B**	**0.0376 AB**	**0.0371 B**	**0.0376 b**
2001	**0.0395 B**	**0.0413 A**	**0.0392 B**	**0.0395 B**	**0.0399 a**
2002	**0.0387**	**0.0397**	**0.0389**	**0.0394**	**0.0392 a**
Avg.	**0.0389**	**0.0395**	**0.0386**	**0.0386**	

† Numbers within a row followed by the same uppercase letter and numbers within a column followed by the same lowercase letter are not significantly different as indicated by Tukey's test at the 0.10 probability level. Columns or rows without uppercase or lowercase letters indicate that main effects or interaction effects were not significant in the analysis of variance.

of the 0.00- to 0.05-m layer (data not shown). Therefore, the increase in bulk density in 2001 should have resulted in a dilution of C and a lower concentration rather than the higher concentration observed. A possible reason for the differences in C concentration between years may have been differences in the decomposition rates. Because particulate organic matter and root debris were not removed from the samples, years in which less of this organic matter decomposed before sampling would have had higher C concentrations. The 8-mo preceding sampling (October–May) was colder and wetter in 2001 and 2002 than in 2000 (Table 1; Herzmann, 2004). The winter of 2000–2001 also had deep snow cover for over 90 d, which is unusual for central Iowa (Table 1; Herzmann, 2004). The cold and wet conditions probably slowed residue and organic matter decomposition (Linn and Doran, 1984; Skopp et al., 1990; Vigil and Kissel, 1995; Ruffo and Bollero, 2003). Another factor, which may have caused the year-to-year variation in C concentration, was the amount of crop and cover crop biomass input to the soil in the months preceding each year's sampling. The corn crop (2000; Table 3) and cover crop (2000–2001; Table 2) biomass inputs preceding the 2001 C sampling were less than those preceding the 2000 sampling. The soybean yields (2000; Table 4) preceding the 2001 C sampling, however, were 0.57 Mg ha^{-1} greater than the 1999 yields that preceded the 2000 sampling. Thus, even though the soybean crop and presumably its biomass inputs were slightly larger preceding the 2001 C sampling, there does not seem to be strong evidence that greater biomass inputs accounted for higher C concentration in 2001 than in 2000 when averaged over preceding crops and cover crop treatments.

The year by cover crop treatment interaction was significant for C concentration (Table 6). In 2000 the no-cover crop control had the highest C concentration, whereas in 2001 the oat–rye treatment had the highest C concentration (Table 7). In 2002, there were no significant differences among the cover crop treatments. Because the year by cover crop means are averaged over rotation phases, they are difficult to interpret. There were no apparent trends or evidence in the data we collected that explain these results. The year by rotation phase by cover crop treatment interaction was also significant (Table 6). The only obvious interaction apparent in the year by rotation phase by cover crop means (data not shown) was that for the no-cover crop check in the corn phase, the lowest C concentrations were measured in 2001, whereas for the other cover crop treatments the lowest concentrations were measured in 2000. Additionally, for the no-cover crop check in the soybean phase the C concentration for the year 2002 was low relative to the other cover crop treatments. There are no apparent trends or evidence in the corn–soybean yield data that would explain this interaction.

The interaction of rotation phase and cover crop treatments was significant for C concentration. The single degree of freedom comparisons showed that the C concentration response of rye relative to the control was different depending on whether the rotation phase was soybean or corn (Table 6). When the rotation phase was soybean, the rye treatment had a greater C concentration than the control and the oat treatment (Table 8), but was not different from the oat–rye treatment. When the rotation phase was corn, the rye treatment had a lower C concentration than the control and the oat–rye mixture. Even though the main effects of cover crops and rotation phase were not significant, the significant interaction makes some sense. Cover crops were only overseeded into the soybean crop and thus, we would assume that their influence on soil C would be greatest when the rotation phase was soybean. Because the rye was not killed until just before corn planting, most of the rye biomass had decomposed for only a short time before sampling. No particulate organic matter was removed from the soil samples and we would assume that some of the soil C measured was rye root debris. Alternately, the oat biomass in the oat and oat–rye treatments began decomposing soon after the oat cover crop winter-killed in the preceding fall. So it is possible, that the oat residue had less impact on the soil C concentration because more of the oat residue had decomposed by the time the samples were taken. When the rotation phase was corn, no cover crops were seeded into the corn crop. Average corn yields following a rye cover crop were 1.04 Mg ha^{-1} less than corn yields following the no-cover-crop control (Table 3), which would mean that C inputs to the soil would be less for corn following a rye cover crop. Although these explanations make sense for the rye-control comparisons, they do not seem to be completely consistent with the response of the oat–rye treatment. Carbon concentrations of the oat–rye treatment were not different from the rye treatment in the soybean phase and in the corn phase

Table 8. Least squares means for C concentration for cover crop treatment by rotation phase combinations.

Rotation phase	Soil C concentration				
	No cover crop	Oat-rye	Oat	Rye	Avg.
	g C g soil^{-1}				
Soybean	**0.0384 B†**	**0.0393 AB**	**0.0384 B**	**0.0394 A**	**0.0389**
Corn	**0.0395 A**	**0.0396 A**	**0.0387 AB**	**0.0379 B**	**0.0389**
Avg.	**0.0389**	**0.0395**	**0.0386**	**0.0386**	

† Numbers within a row followed by the same uppercase letter are not significantly different as indicated by Tukey's test at the 0.10 probability level. Columns or rows without uppercase or lowercase letters indicate that main effects or interaction effects were not significant in the analysis of variance.

were not different from the control and were greater than the rye treatment. In the soybean phase the oat–rye treatment produced more cover crop biomass than the rye treatment. In the corn phase of the rotation, the average corn grain yield of the oat–rye treatment was 0.21 Mg ha^{-1} greater than that of the rye treatment, but it was still on average 0.84 Mg ha^{-1} less than that of the no-cover-crop control treatment. Thus, it seems that the reduced corn biomass inputs of the oat–rye treatment did not reduce the C concentration relative to the control as much as it did for the rye treatment.

SUMMARY

On a field scale, the spatial pattern of soil C was related to terrain variables. Soil C decreased as slope and elevation increased and as the wetness index decreased. By removing the spatial variability of soil C using terrain covariates we were able to detect differences in soil C concentrations of treatment means as small as 0.0010 g C g soil^{-1} as compared with 0.0025 g C g soil^{-1} when terrain covariates were not used.

A rye cover crop increased soil C relative to the control in the soybean phase, but decreased soil C relative to the control in the corn phase. The oat and oat–rye cover crop treatments did not differ from the control in either the corn or soybean phase. Averaged over both phases of the corn–soybean rotation the small grain winter cover crops overseeded into soybean did not increase soil C relative to the no-cover-crop control. Before small grain winter cover crops can be used to increase soil C in a corn–soybean rotation the upper Midwest, their management needs to be improved so that soil biomass inputs of the cover crops are increased and yield of corn following a rye cover crop is not reduced. One possibility is to find rye cultivars that don't inhibit corn growth. Another approach would be to plant an oat cover crop preceding corn and a rye cover crop preceding soybean. An oat cover crop did not reduce corn yields in this study or in a previous study (Johnson et al., 1998). Strock et al. (2004) found that a rye cover crop planted following corn did not decrease soybean yields. Planting cover crops in both years may increase the rate of biomass inputs to the soil and may eventually increase soil carbon.

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