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Landscape position and age of reconstructed prairies effect on soil organic carbon sequestration rate and aggregate associated carbon

Jose G. Guzman and Mahdi Al-Kaisi

Abstract: Changes in agricultural land use such as the establishment of prairies on previously cultivated cropland provide an opportunity for greater soil organic carbon (SOC) sequestration rates. In this study, a topo- and chrono-sequence approach was used to investigate relationships between SOC and soil aggregate formation. Our hypothesis was that the greatest increases in SOC sequestration rates are associated with most recently established prairies on cultivated land, where SOC was the most depleted, due to the destruction of soil aggregate. The study was conducted in Jasper and Warren counties in Iowa, from 2005 to 2008. Soils in both counties were formed in loess under native vegetation of tallgrass prairie. There were three reconstructed prairie sites varying in establishment year—1993, 1998, 2003; a row crop production site under no-tillage; and a prairie remnant site. All soil and plant sampling plots were located on summit, midslope, and toe-slope positions. Results show that time since establishment and slope position had a significant impact on SOC sequestration rates in the top 15 cm (6 in) soil depth only. In the summit position, the greatest SOC sequestration rates were observed in the youngest prairie at 2.15 Mg ha^{-1} y^{-1} (0.96 tn ac^{-1} yr^{-1}), and decreased to near equilibrium after approximately eight years. Additionally, SOC was shown to increase linearly at a rate of 0.73 Mg ha^{-1} y^{-1} (0.33 tn ac^{-1} yr^{-1}) since prairie establishment during the 14-year period. In the toe-slope position, SOC sequestration rates were substantially lower at 0.59 Mg ha^{-1} y^{-1} (0.26 tn ac^{-1} yr^{-1}). Furthermore, increases in SOC sequestration rates coincided with increases in water stable aggregate–associated carbon (C) in 0.25 to 2 mm (0.01 to 0.08 in) size fractions. This occurred in the youngest reconstructed prairie (2003) in the summit and in the midslope positions on prairies reconstructed in 1998 and 1993. This suggests that the mechanisms of soil aggregate formation aid in stabilizing SOC, which is significantly affected by slope position and years since prairie establishment.

Key words: chrono-sequence—soil organic carbon—tallgrass prairie—topo-sequence

Changes in land use and alteration of the ecosystem can significantly affect soil organic carbon (SOC) dynamics. Under similar conditions, permanent grasslands tend to have greater SOC content in the surface than cultivated cropland due to slowly decomposing plant residues. Conversely, tillage that disturbs the soil surface increases decomposition of soil organic matter by breaking down aggregates and exposing silt-clay complexes to microbial activities (Oades 1984; Elliott 1986; Paustin et al. 1997). Nonetheless, this reduction in SOC gives rise for the potential of greater SOC sequestration rates when reversing the effects of cultivation (Post and Kwon 2000). However, little is known on interrelationships between soil aggregate formation and SOC sequestration after tillage has ceased (Jastrow 1987; Jastrow et al. 1998).

Interactions between plant residues and soil organic matter with the soil are important factors in the formation of stable soil aggregates for SOC sequestration (Haynes and Beare 1996; Blanco-Canqui and Lal 2004). These factors include (1) above- and below-ground input of organic materials, (2) the decomposability of the organic materials, (3) soil depth at which the organic material is placed, and (4) physical protection either by aggregate formation or by adsorption to silt-clay minerals (Jones and Donnelly 2004). Newly added organic material such as root exudates, fungal and mycorrhizal hyphae, and microbial debris are credited for formation and stabilization of macro-aggregates (Tisdall and Oades 1982). In return, soil aggregates protect organic carbon (C) from microbial decomposition activities. However, the C sequestered to stabilize macroaggregates is considered only short-term (a few weeks) due to relative ease of decomposition by microorganisms and is greatly affected by tillage practices (Cambardella and Elliot 1993). Highly decomposed organic materials such as humic compounds and polymers that resist further breakdown are closely associated with microaggregates (Six et al. 1999). This is due to the physical protection by microaggregates reducing microbial effects, therefore enhancing long-term SOC sequestration. Additionally, these biotic activities are heavily influenced by topography (Hook and Burke 2000; Brye and Kucharik 2003), climate (Brye et al. 2004; Raich and Potter 1995) and soil texture (Feller and Beare 1997; Hassink 1997) over time (Richter et al. 1999; Akla and Lal 2001). Thus, topo- and chrono-sequence approaches provide a gradient of topography and time needed to give insights into the relationships between SOC sequestration and soil aggregate formation. Changes in land use, such as reconstruction of prairies on previously cultivated land, provide opportunities to evaluate potential improvement in SOC, plant biomass, and physical soil properties and how these have been influenced by landscape position within a reestablished prairie system (Baer et al. 2002). In particular, the greatest changes in SOC sequestration rates are expected in the early years of establishment, and sequestration rates may cease to change significantly in long-established systems (Jastrow 1987; McLauchlan et al. 2006; and Kucharik 2007). Information on landscape position effects on SOC sequestration rates is also needed. Studies have shown significant decreases in SOC content in high-risk erosion soils, such as the midslope position, and consequently,

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SOC is then deposited in the toe-slope position, leading to greater SOC content (Gregorich et al. 1998).

Our hypothesis is that changes in soil C dynamics in newly established prairie systems on previously cultivated row crop production land will be highly affected by slope position and temporal variability, where the greatest SOC sequestration rates will be in the most recently established prairie systems. This study was conducted to investigate the effects of landscape position and prairie age since conversion from cultivated cropland on SOC and soil aggregate formation dynamics. In particular, this research can provide answers to questions related to changes in SOC and associated soil properties, such as soil aggregate stability in newly established prairie systems.

Materials and Methods

Site Description and Experimental Design. This study was conducted in Jasper and Warren counties in Iowa from May 2005 to May 2008. During this period, annual precipitation averaged 904 mm (35.6 in), and annual mean temperature was 10.3°C (50.5°F). Soils in both Jasper and Warren counties formed in loess under native vegetation of tallgrass prairie (Bryant and Woster 1978; Nestrud and Woster 1979). All of the reconstructed prairie sites were located in the Neal Smith National Wildlife Refuge (41°35'N, 93°14'W). The remnant prairie was located approximately 95 km (59 mi) southwest in Rolling Thunder Prairie (41°10'N, 93°43'W). Historical backgrounds on the conversion of row crop production to reconstructed prairie in the Neal Smith National Wildlife Refuge sites as well as present vegetative conditions on all sites are summarized in tables 1 to 3. The three reconstructed prairie sites varied in establishment year of 1993, 1998, and 2003, which were categorized as P-1993, P-1998, and P-2003, respectively. These sites were then compared to an adjacent cropland production site that was categorized as a no-till site established in 2003 (NT-2003). A prairie remnant (P-Remnant) site was included to identify the upper limits for SOC and total nitrogen (TN) of prairie ecosystem before conversion to cultivated cropland. To measure the effects of slope position, time since establishment, and soil depth of all sites on SOC, TN, microbial biomass C, and water stable aggregates, each plot was treated as an experimental unit for a total of 45 observations and treatment means for comparisons (three replicated plots × three slope positions × five sites). Due to restrictions in manageable workload (i.e., limited available sites and time constraints on sampling), treatment comparisons were unavoidably based on pseudo-replication. Detailed assessments of soil texture, bulk density, vegetation growth, and other related properties were determined to characterize site variability between sites and to incorporate differences into the analyses and interpretations.

All sampling plots were located on summit, midslope, and toe-slope positions and were chosen by year of establishment and the presence of relatively similar soils (tables 1 to 3). The experiment was designed so that the year of establishment of the site was the main treatment, replicated three times along each slope position in plots of approximately 4 m^2 (43 ft^2) and 30 m (98 ft) apart.

Soil Sampling and Analyses. From 2005 to 2007, soil samples were collected annually in early May, to measure any changes in SOC, TN, and pH. Ten to twelve 1.7 cm (0.67 in) soil cores were randomly collected from each of the following depths of 0 to 15, 15 to 30, 30 to 45, and 45 to 60 cm (0 to 6, 6 to 12, 12 to 18, and 18 to 24 in) in each plot. Soil cores for each depth were combined into a single homogeneous sample. Soil samples were 2 mm (0.08 in) sieved and then air dried before being analyzed for pH (1:1; soil to water) using an AR15 pH meter (Accumet Research, Fisher Scientific International Inc.). SOC and TN were determined by dry combustion using a LECO CN analyzer (LECO Corporation, St. Joseph, Michigan). At the same time, three bulk density samples were collected randomly from each plot, using a 1.7 cm (0.67 in) diameter soil probe for each soil depth. Soil cores were taken at the same soil depths and were then oven dried at 105°C (221°F) for 24 hours and weighed. Bulk density (ρ_b [g cm^{-3}]) was calculated as the dried soil mass divided by the soil core volume (Blake and Hartge 1986). The SOC and TN concentrations (mg g^{-1} dry soil) were multiplied by mean ρ_b values and soil depth of 15 cm (6 in) to convert SOC concentration to mass per area basis (Mg ha^{-1}) for all sites. Measurments of SOC, microbial biomass carbon (MBC) and TN measurements were done in the first year (2005) and are shown in (table 4). Initial SOC, microbial biomass carbon (MBC) and TN in 2005 are shown in table 4.

Microbial Biomass Carbon. Samples were collected using a 7.6 cm (3 in) diameter golf course hole cutter to a 15 cm (6 in) depth in mid-August in 2005 and 2007. Microbial biomass was determined by performing the fumigation extraction method (Horwath and Paul 1994). Soil samples were fumigated with ethanol-free chloroform ($CHCl_3$) for 24 hours in a vacuum desiccator. The soil samples were extracted for 30 minutes with 100 mL (0.2 pt) of 0.5M potassium sulfate (K_2SO_4) and then were filtered through Whatman No. 42 filter paper. A similar extraction was performed on the non-fumigated soil samples while the others were being set up for fumigation. The extractant (K_2SO_4) alone was also filtered to determine the background level of C in the filter paper and extractant. Carbon recovered in the extract was measured with an Elementar liquiTOC carbon analyzer (Americas Inc., Mt. Laurel, New Jersey). The MBC was calculated on an oven dry weight basis.

Aggregate Stability and Associated Carbon and Nitrogen. Soil samples were taken using a 7.6 cm (3 in) diameter golf course hole-cutter to a soil depth of 15 cm (6 in) in three replications for each plot in mid-May in 2005 and 2008. Soil samples were then gently sieved through an 8 mm (0.3 in) sieve to remove any undesirable plant residues and rocks. Soil samples were then air dried and stored for analysis. The water stable aggregates (WSA) size distribution was determined following the procedure by Kemper and Rosenau (1986), with some modifications. One hundred grams (3.5 oz) of soil sample was used for wet sieving for five minutes in deionized water at 21°C (70°F), by lowering and then raising the sieves with a stroke length of 20 mm (0.8 in) and a frequency of 90 strokes per minute, using a custom-made sieving machine where 20 cm (7.9 in) diameter sieves could fit. Seven aggregate-size fractions were collected. Aggregates that passed through all sieves, including the 0.053 mm (0.002 in) sieve were categorized as <0.053 mm. The other six fractions were 0.053 to 0.25, 0.25 to 0.5, 0.5 to 1, 1 to 2, 2 to 4, and >4 mm (0.002 to 0.01, 0.01 to 0.02, 0.02 to 0.04, 0.04 to 0.08, 0.08 to 0.16, and >0.16 in). Each soil sample was first misted and then submerged in water in the top sieve for at least five minutes before wet sieving began to

Table 1
Summit parameters: Establishment year, current plant species, physiography, and selected soil properties for each site at the top 15 cm soil depth.

	Site description				
Characteristic	**NT-2003**	**P-2003**	**P-1998**	**P-1993**	**P-Remnant**
Ecosystem	Row crop	Prairie	Prairie	Prairie	Prairie
Establishment year	1870s No-till since 2003	2003	1998	1993	Native remnant
Dominant plant species	2005 and 2007—*Zea mays* L. 2006—*Glycine max* L. Merr.	*Andropogon gerardii* *Schizachyrium scoparium* *Elymus canadensis*	*Andropogon gerardii*	*Andropogon gerardii* *Schizachyrium scoparium* *Solidago canadensis* *Trifolium pratense*	*Andropogon gerardii* *Schizachyrium scoparium* *Sorghastrum nutans* *Solidago canadensis* *Chamaecrista fasciculata*
Root biomass (Mg ha^{-1})	1.2	2.1	16.0	8.2	17.1
Above-biomass (Mg ha^{-1})	11.5	7.7	10.4	12.9	8.2
Physiography					
Slope (%)	0 to 1	0 to 2	0 to 6	3 to 4	2 to 4
Soil properties					
Soil association	Otley-Mahaska	Otley-Mahaska	Otley-Mahaska	Otley-Mahaska	Ladoga-Gara-Armstrong
Soil type	Mahaska	Mahaska	Tama	Mahaska	Sharpsburg
Sand (%)	5	2	2	2	2
Silt (%)	67	69	70	71	69
Clay (%)	28	29	28	27	29
pH	7.1	6.4	7.2	6.8	6.7

Table 2
Midslope parameters: Establishment year, current plant species, physiography, and selected soil properties for each site at the top 15 cm soil depth.

	Site description				
Characteristic	**NT-2003**	**P-2003**	**P-1998**	**P-1993**	**P-Remnant**
Ecosystem	Row crop	Prairie	Prairie	Prairie	Prairie
Establishment year	1870s No-till since 2003	2003	1998	1993	Native remnant
Dominant plant species	2005 and 2007—*Zea mays* L. 2006—*Glycine max* L. Merr.	*Schizachyrium scoparium* *Sorghastrum nutans*	*Andropogon gerardii*	*Andropogon gerardii* *Schizachyrium scoparium* *Sorghastrum nutans*	*Schizachyrium scoparium* *Solidago canadensis* *Bouteloua curtipendula* Shrubs
Root biomass (Mg ha^{-1})	2.5	3.7	10.7	7.4	20.7
Above-biomass (Mg ha^{-1})	12.4	13.0	14.3	11.3	12.2
Physiography					
Slope (%)	10 to 16	5 to 8	6 to 9	4 to 10	10 to 14
Soil properties					
Soil association	Otley-Mahaska	Otley-Mahaska	Otley-Mahaska	Otley-Mahaska	Ladoga-Gara-Armstrong
Soil type	Otley	Otley	Otley	Otley	Adair-Sharpsburg
Sand (%)	2	2	2	3	21
Silt (%)	71	68	68	70	56
Clay (%)	26	30	30	27	23
pH	6.8	6.8	6.7	7.1	6.6

Table 3

Toe-slope parameters: Establishment year, current plant species, physiography, and selected soil properties for each site at the top 15 cm soil depth.

	Site description				
Characteristic	**NT-2003**	**P-2003**	**P-1998**	**P-1993**	**P-Remnant**
Ecosystem	Row crop	Prairie	Prairie	Prairie	Prairie
Establishment year	1870s No-till since 2003	2003	1998	1993	Native remnant
Dominant plant species	2005 and 2007—*Zea mays* L. 2006—*Glycine max* L. Merr.	*Silphium laciniatum* Various other forbs	*Spartina pectinata*	*Spartina pectinata* Various other forbs	*Helianthus grosserratus*
Root biomass (Mg ha^{-1})	1.7	3.6	11.9	10.6	19.9
Above-biomass (Mg ha^{-1})	16.2	12.1	24.2	8.8	13.3
Physiography					
Slope (%)	0 to 1	1 to 5	0 to 1	4 to 5	1 to 4
Soil properties					
Soil association	Otley-Mahaska	Otley-Mahaska	Otley-Mahaska	Otley-Mahaska	Ladoga-Gara-Armstrong
Soil type	Shelby	Shelby	Shelby	Shelby	Colo-Ely
Sand (%)	11	3	3	2	28
Silt (%)	63	68	68	71	49
Clay (%)	26	29	29	27	23
pH	7.0	6.6	6.9	6.8	6.0

Table 4

Effects of slope position and time since prairie establishment on selected soil properties of different soil depths since 2005.

	Summit soil depth (cm)				Midslope soil depth (cm)				Toe-slope soil depth (cm)			
Site	**0 to 15**	**15 to 30**	**30 to 45**	**45 to 60**	**0 to 15**	**15 to 30**	**30 to 45**	**45 to 60**	**0 to 15**	**15 to 30**	**30 to 45**	**45 to 60**
	SOC (Mg ha^{-1})											
NT-2003	38.65b	33.10ab	24.85a	15.42a	33.88c	27.54b	21.80b	20.54ab	44.68a	40.62a	48.23a	36.62a
P-2003	30.76c	31.21ab	25.93a	18.49a	40.39b	45.24a	46.66a	34.28a	38.20a	39.26a	42.49a	36.00a
P-1998	36.69b	23.73b	12.37b	8.40b	34.37c	24.25b	13.75b	8.76b	40.90a	38.80a	36.14a	36.71a
P-1993	41.35b	34.72a	24.23a	17.38a	25.23d	22.25b	15.93b	8.72b	44.65a	34.91a	36.57a	37.62a
P-Remnant	55.90a	34.09a	23.26a	10.32a	51.63a	31.34b	25.24b	6.75b	40.75a	44.80a	39.77a	34.45a
	TN (Mg ha^{-1})											
NT-2003	2.34c	2.02ab	1.69b	0.96b	2.97bc	2.17a	1.70a	0.95a	3.96a	3.28a	3.44a	3.61a
P-2003	1.81c	1.55b	1.76b	1.26b	3.76ab	2.25a	2.25a	0.82a	3.57ab	3.18a	3.09ab	3.55a
P-1998	3.21b	3.12a	1.65b	1.19b	3.06bc	2.25a	1.51a	1.23a	3.27b	2.81a	2.84ab	2.43ab
P-1993	3.35b	3.00a	2.30a	1.78a	2.28c	2.09a	1.31a	0.71a	3.55ab	3.04a	2.44b	2.02b
P-Remnant	4.38a	2.79a	1.99ab	1.07b	4.03a	2.66a	2.28a	0.90a	3.55ab	2.80a	2.36b	1.63b
	C/N											
NT-2003	16.52	16.39	14.70	16.06	11.41	12.69	12.82	21.62	11.28	12.38	14.02	10.14
P-2003	16.99	20.14	14.73	14.67	10.74	20.11	20.74	41.80	10.70	12.35	13.75	10.14
P-1998	11.43	7.61	7.50	7.06	11.23	10.78	9.11	7.12	12.51	13.81	12.73	15.11
P-1993	12.34	11.57	10.53	9.76	11.07	10.65	12.16	12.28	12.58	11.48	14.99	18.62
P-Remnant	12.76	12.22	11.69	9.64	12.81	11.78	11.07	7.50	11.48	16.00	16.85	21.13
	MBC (g m^{-2})											
NT-2003	58.36c				56.14b				16.27d			
P-2003	32.28d				40.37b				36.11cd			
P-1998	74.14b				99.39a				48.49c			
P-1993	54.09c				47.97b				76.07b			
P-Remnant	116.01a				115.66a				118.10a			

Notes: SOC = soil organic carbon. TN = total nitrogen. C/N = carbon/nitrogen ratio. MBC = microbial biomass carbon. Numbers followed by different lower case letter within same column and slope position are significantly different at $p \leq 0.1$.

slake off air-dried soil. Following wet sieving, the soil samples were immediately poured into tubs and oven dried at 65°C (150°F) until all water was completely evaporated, and dry weight was recorded for each size fraction. In addition, WSA dry weights were adjusted to soil moisture corrections from air-dried subsamples of WSA.

The WSA–associated carbon (C) and TN concentrations were determined by dry combustion using a LECO CN analyzer (LECO Corporation, St. Joseph, Michigan) for each size fraction after aggregates were ground to a fine powder using a mortar and pestle. Organic C and TN concentrations were then adjusted for sand-free fraction WSA. Sand-free fraction WSA was determined by wet sieving a second set of soil samples, using the same WSA procedure mentioned earlier. Soil aggregate factions from each sieve were collected, dried, and the weights were recorded. The soil aggregate fractions were then placed into a 250 mL (0.5 pt) Nalgene bottle, and sodium hexametaphosphate solution equivalent to 5:1 (milliliter of solution to gram of soil) was added and left overnight in a mechanical shaker at 350 rpm. The solution was then passed through a 0.053 mm (0.002 in) sieve, where sand was collected, washed with deionized water, and oven dried at 65°C (150°F).

Statistical Analysis. Data were analyzed using Proc Mixed procedure (SAS Institute Inc. 2002). Means were separated using ANOVA F-test when treatment effects were significant. Statistical significance was evaluated at $p \leq 0.10$.

Results and Discussion

Effects of Landscape Position and Prairie Age on Soil Carbon Sequestration Rates. Soil depth showed no significant effect on SOC sequestration rates; thus, the differences between sites across slope positions are presented for the top 60 cm (24 in) soil depth (figure 1a). Differences among sites were only observed in the summit position where NT-2003 and P-1998 sites had the greatest SOC sequestration rates and the P-2003, P-1993, and P-Remnant sites were at or near zero rates. Comparisons between sites' SOC sequestration rates for each slope position in the top 15 cm (6 in) soil depth show the effects of prairie age or cessation of tillage on SOC change (figure 1b). In the summit position, the most recently established sites (NT-2003 and P-2003 sites) had the great-

Figure 1

Change in soil organic carbon (SOC) stock for each site from 2005 to 2007 in the (a) top 60 cm and (b) 15 cm soil depths as influenced by slope position. Treatments within the same slope position with the same letter are not significantly different according to the least-squares means test at $p \leq 0.1$. Error bars indicate standard error.

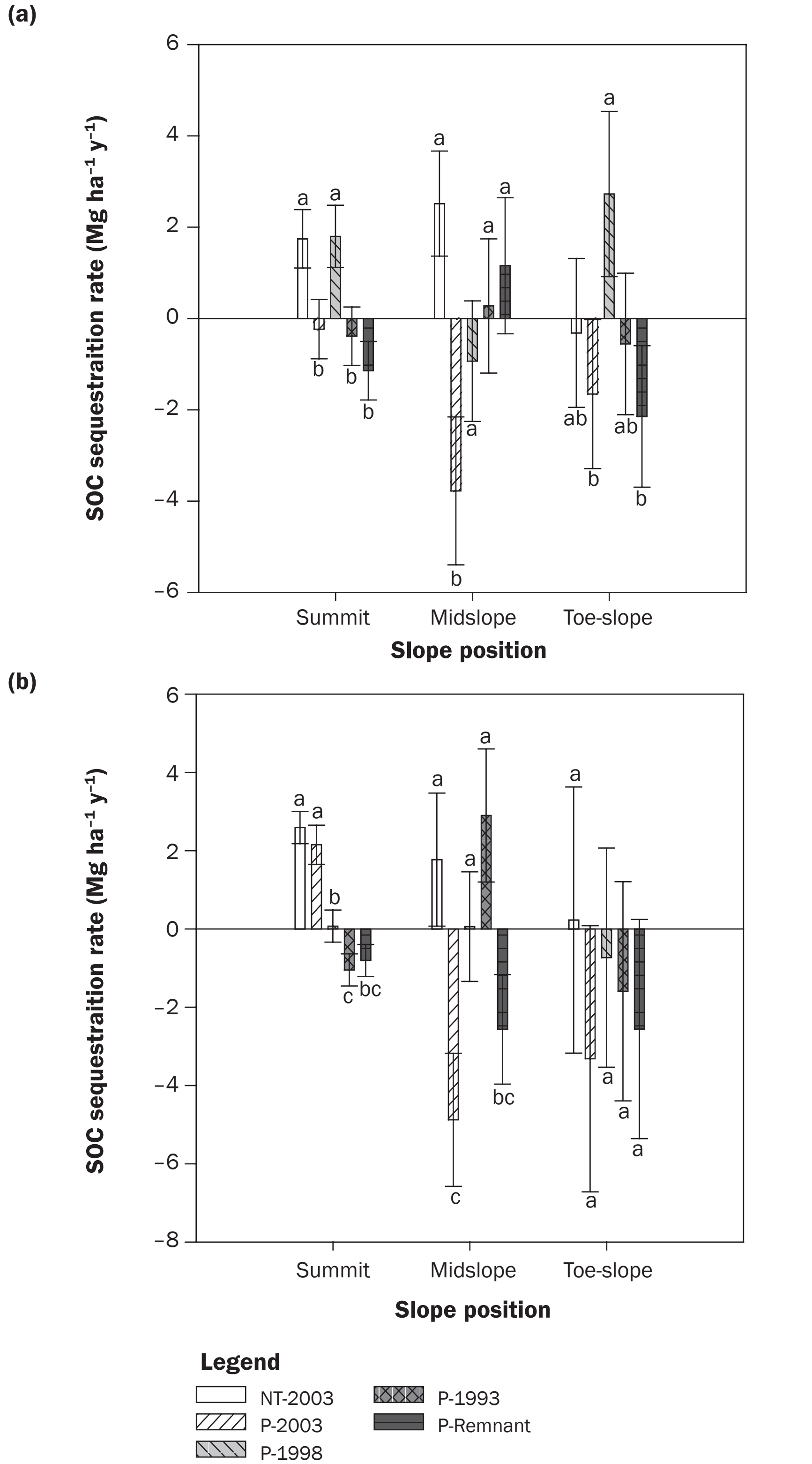
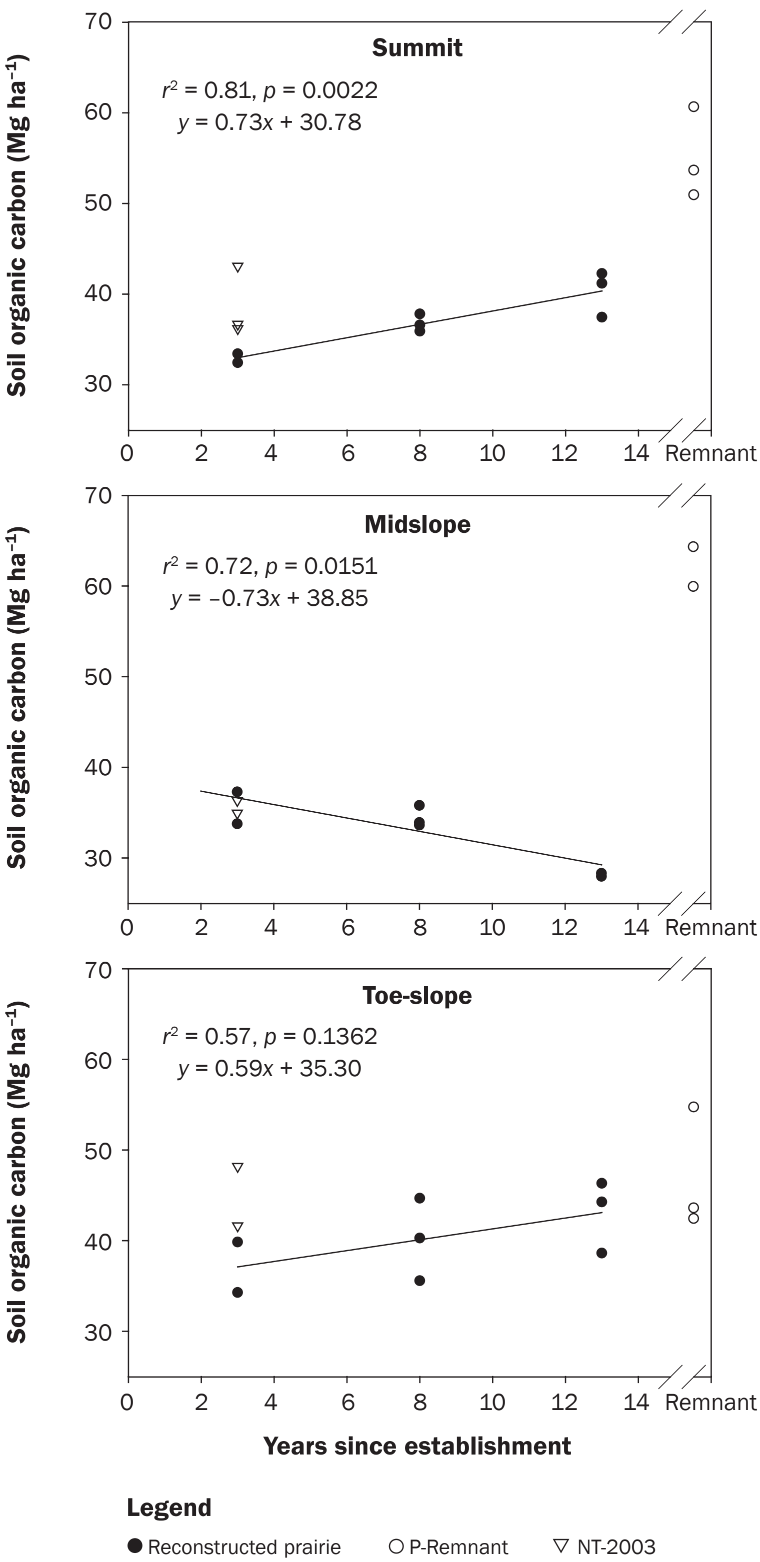


Figure 2
Soil organic carbon content over a 2- to 14-year period of reconstructed prairies of a soil depth of 15 cm. A no-till site and remnant prairie were included for comparison with reconstructed prairies but were not included in the linear best fit. Each point represents one plot that was averaged from 2005 to 2007.



est SOC sequestration rates (2.59 and 2.15 Mg SOC ha^{-1} y^{-1} [1.15 and 0.95 tn ac^{-1} yr^{-1}], respectively) followed by the P-1998 site, the P-Remnant, and P-1993 site, respectively, which were at or near zero rates. Similar findings by Kucharik (2007) have shown SOC sequestration rates of 1.3 Mg C ha^{-1} y^{-1} (0.58 tn ac^{-1} yr^{-1}) during the first four to five years, 2.1 Mg C ha^{-1} y^{-1} (0.94 tn C ac^{-1} yr^{-1}) during 6 to 10 years, and near zero change in SOC rate at 25 cm (10 in) soil depth in 11 to 16 years since establishment of reconstructed prairies on previously cultivated Mollisols in Wisconsin.

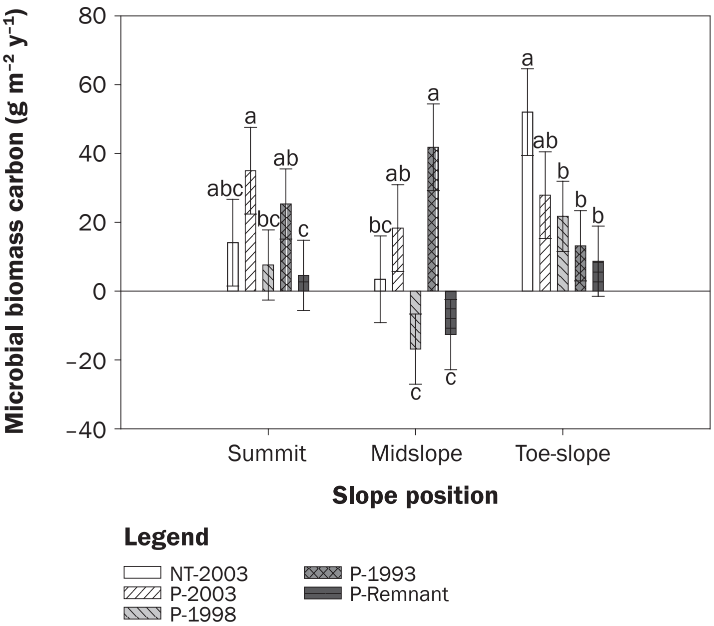
In the midslope and toe-slope positions, variability in SOC sequestration rates increased dramatically compared to the summit positions. In the midslope position, the largest SOC sequestration rate occurred in the P-1993 site at 2.90 Mg SOC ha^{-1} y^{-1} (1.29 tn SOC ac^{-1} yr^{-1}), although it was not significantly different from the P-1998 and NT-2003 sites, 0.07 and 1.77 Mg SOC ha^{-1} y^{-1} (0.03 and 0.79 tn SOC ac^{-1} yr^{-1}), respectively. In the toe-slope position, there were significant declines in SOC sequestration rates observed in the most recently established prairie site (P-2003) at –4.88 Mg SOC ha^{-1} y^{-1} (–2.17 tn SOC ac^{-1} yr^{-1}) and the P-Remnant site at –2.57 Mg SOC ha^{-1} y^{-1} (–1.14 tn SOC ac^{-1} yr^{-1}). However, differences in SOC sequestration rates within each site at the toe-slope position were not significant due to the high variability within each site.

The rate of SOC increase in the top 15 cm (6 in) soil depth in the summit at 0.73 Mg SOC ha^{-1} y^{-1} (0.32 tn SOC ac^{-1} yr^{-1}) and toe-slope position at 0.59 Mg SOC ha^{-1} y^{-1} (0.26 tn SOC ac^{-1} yr^{-1}) positions showed a linear relationship over time during the 2- to 14-year period (figure 2). Comparable rates of increase in SOC sequestration rates have been reported of 0.62 Mg SOC ha^{-1} y^{-1} (0.27 tn SOC ac^{-1} yr^{-1}) in Minnesota (McLauchlan et al. 2006) and 0.45 Mg SOC ha^{-1} y^{-1} (0.20 tn SOC ac^{-1} yr^{-1}) in Texas (Potter et al. 1999). Lower SOC sequestration rates in the toe-slope position compared to the summit position might be attributed to less drastic differences in SOC content between reconstructed prairies and the P-Remnant site, which is hypothesized to be near saturation.

In the midslope position, SOC content generally decreased since year of establishment at –0.73 Mg SOC ha^{-1} y^{-1} (–0.32 tn SOC ac^{-1} yr^{-1}). However, in the P-1993 and

Figure 3

Change in microbial biomass carbon as influenced by slope position and site from 2005 to 2007. Treatments within the same slope position with the same letter are not significantly different according to least-squares means test at $p \leq 0.1$. Error bars indicate standard error.



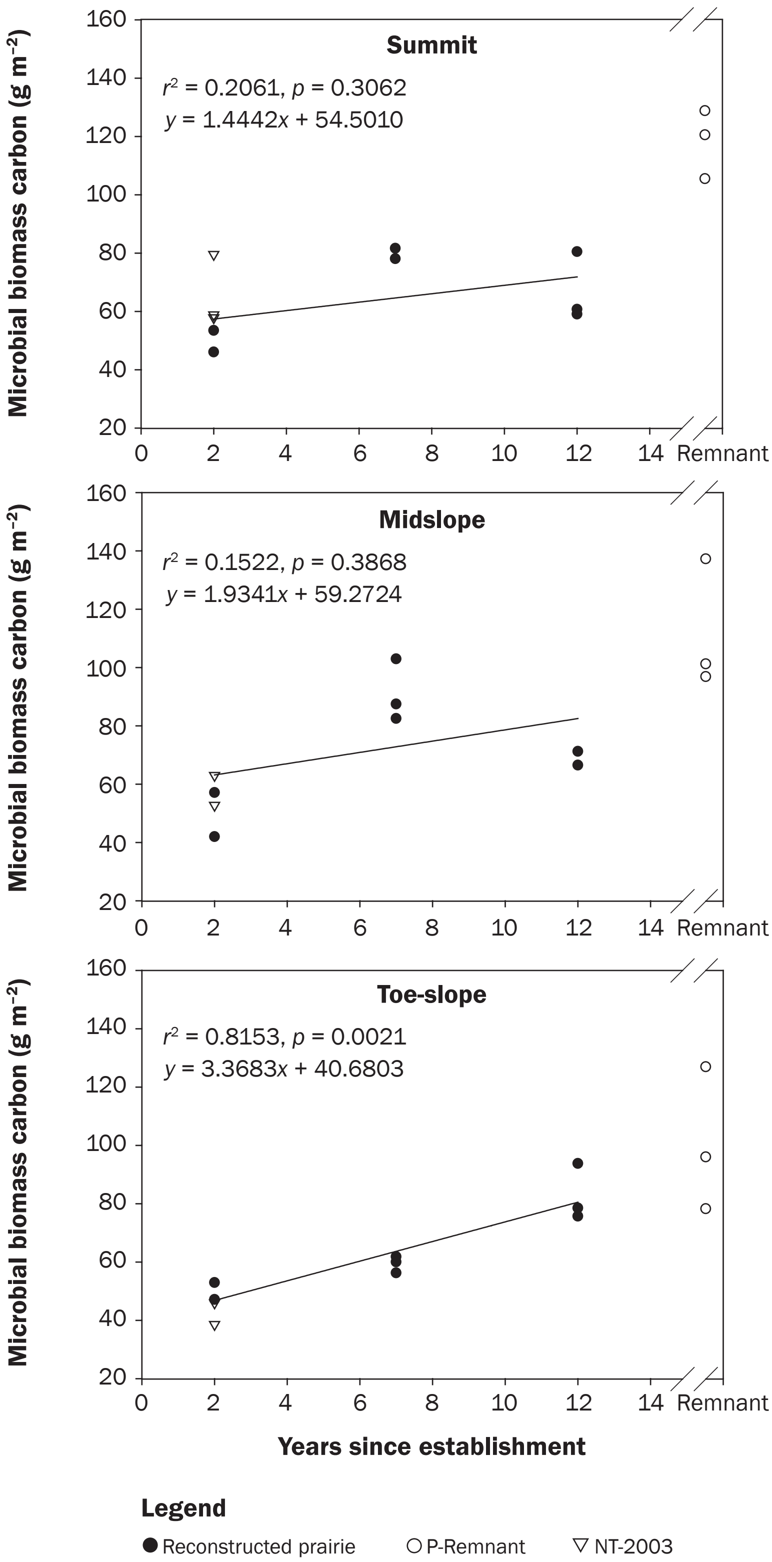
P-1998 sites, SOC content did increase from the 2005 to 2007 period in the midslope position. This suggests that the midslope position has lower SOC sequestration rates compared to the summit and toe-slope positions, at least in the first four years of prairie establishment before an increase of SOC content can be observed. This was likely due to lower contributions of organic matter from root biomass in the P-2003 midslope position compared to the midslope positions on older established prairies (table 2). In addition, it is well known that in the midslope position, there is a greater potential of C loss due to soil erosion compared to the summit and toe-slope positions (Hook and Burke 2000). This might explain why there is an initial loss of SOC content in the early years of prairie establishment in the midslope position.

Generally in this study, vegetation (above- and below-ground plant biomass) and biogeochemical properties (SOC, TN) were greatly reduced in the midslope position and were enhanced in the toe-slope position as described in tables 1 to 3. The greatest potential mechanism for soil erosion in these sites was water runoff detaching soil particles and depositing them on the toe-slope position. In the NT-2003 site, significant increases in SOC content were observed over two years in the summit and midslope positions but not in the toe-slope position (figure 1b). These results varied from the P-2003 site, where decreases in SOC content were observed in the midslope position, even though tillage operations had ceased at both sites in the same year. This might be attributed to the conservation practices in the NT-2003 site, such as contour planting and leaving crop residue on the surface, reducing soil erosion. The P-Remnant site on average had greater SOC content in the summit and midslope positions than did the other sites, although SOC in the toe-slope position was similar to that of the reconstructed prairies and NT-2003 sites (figure 2).

Rate of change in MBC varied by site and slope position (figure 3). The rate of change or increase in MBC of the P-Remnant site was significantly lower than the newly reconstructed prairies at all slope positions and the NT-2003 at the toe-slope position (figure 3). Microbial biomass C is an indicator of positive or negative changes in the soil C pool as influenced by changes in land use, landscape position, and management. The results suggest that the higher rate of MBC change is associated with the newly established prairie system. This supports the idea that the P-Remnant site is in a stable condition, while the reconstructed prairies and NT-2003 site are undergoing postmanagement effects. In general, years after cessation of tillage and establishment of prairie grasses, positive trends are observed in MBC content (figure 4) across all slope positions of reconstructed prairies and the NT-2003 site. However, the slope of these lines is much greater at the toe-slope position, which is a reflection of greater organic C accumulation at that position, due to being wetter and colder compared to summit and midslope positions. Other studies reported increases in MBC content as age of reconstructed prairies and grasslands increased as well (Knops and Tilman 2000; McLauchlan et al. 2006; Kucharik 2007).

Site had a significant effect on soil TN accumulation in the top 60 cm (24 in) soil depth at different slope positions (figure 5a). Changes in TN content since prairie sites' establishment were not well described by a linear regression function at all slope positions as observed with SOC content. Increases or no change in soil TN content occurred in every site with the exception of the P-2003 site in the toe-slope position (figure 5a). Knops and Tilman (2000) showed that vegetation composition can significantly affect TN and SOC pools. In their study, prairies with high legume populations increased SOC and TN accumulation rates, C3 grasses and forbs decreased SOC, and C4 grasses increased SOC only (due to high carbon to nitrogen ratio). This may explain why in the top 60 cm soil depth (figure 5a), increase in TN sequestration rates were observed in sites where a high population of legumes occurred in this study. These sites include P-1993 and P-Remnant as described in site description tables 1 to 3. In addition, significant increases in TN sequestration rates were observed in the P-2003 and NT-2003 sites in the top 15 cm (6 in) soil depth (figure 5b). This may be attributed to the cessation of tillage practices under row cropping systems such as no-till and grass systems, which have been well documented in increasing SOC and TN in the soil surface (Al-Kaisi et al. 2005). In the top 15 cm soil depth, similar results in TN content were observed as in the top 60 cm (figure 5a). Other studies reported increases in TN sequestration rates in the top 5 to 30 cm (2 to 12 in) soil depth only (Gebhart et al. 1994; Franzluebbers and Stuedemann 2005; Kucharik 2007), but changes in SOC and TN content were highly variable as soil depth increased, leading to undetectable changes.

Figure 4
Microbial biomass carbon content over a 2- to 14-year period of reconstructed prairies of a soil depth of 15 cm. A no-till site and remnant prairie were included for comparison with reconstructed prairies but were not included in the linear best fit. Each point represents one plot that was averaged from 2005 to 2007.



Effects of Landscape Position and Prairie Age on Carbon and Nitrogen Sequestration Associated with Water-Stable Aggregates. Initial WSA distributions by mass in 2005 are shown in figure 6. Age of prairie site played a major role in the formation of WSA. In general, the two youngest (less than three years) established sites (P-2003 and NT-2003 sites) had the lowest percentage of WSA greater than 1 mm (0.04 in) compared to the older (greater than three years) established prairies and P-Remnant site (figure 6). Conversely, these two sites had a greater percentage of WSA less than 1 mm. This suggests these two sites have the greatest potential for increases in soil aggregation. It is likely the WSA > 1 mm distribution of these two sites can potentially be similar to those of other reconstructed prairies and P-Remnant sites within ten years. These results agree with the findings of Jastrow et al. (1996) that soil aggregates in reconstructed prairies can reach aggregate size distributions comparable to remnant prairies in approximately 10 years after cessation of tillage.

Years after cessation of tillage and slope position as of 2005 also had an effect on WSA–associated C distribution by size fractions (figure 7). The P-Remnant site had its greatest WSA–associated C concentrations typically in the 1 to 4 mm (0.04 to 0.16 in) size fractions, while the lowest concentration occurred in the silt and clay fraction (<0.053 mm [<0.002]), followed by the >4 mm (0.16 in) and <0.5 mm (<0.02 in) size fractions. In the summit and toe-slope positions, the two older reconstructed prairie sites (P-2003 and NT-2003 sites) had similar WSA–associated C distribution as the P-Remnant site with lower C concentrations. However, the P-2003 and NT-2003 sites and two older reconstructed prairie sites in the midslope position had their greatest WSA–associated C concentration in the 0.5 to 2 mm (0.02 to 0.08 in) size fraction. Over time these reconstructed prairies will eventually develop similar WSA–associated C distributions as the remnant prairie. Also, these progressive changes in WSA can result in potential increases in aggregate-associated C concentration for WSA greater than 0.053 mm (0.002 in). This may suggest that there is a shift of WSA–associated C from 0.5 to 2 mm aggregates to larger aggregates (2 to 4 mm). Many studies have shown that when soil is left undisturbed and there is sufficient C input, macroaggregate formation is increased as well as microaggregates within macroaggregates (Six et al. 1999), which can be a major determinate in long-term SOC sequestration.

Significant increases of WSA–associated C concentration between 2005 and 2008 were observed only in the 0.25 to 2 mm (0.01 to 0.08 in) size fractions and varied with site and slope position (figure 8). In general, the NT-2003 and P-2003 sites had the greatest increases in WSA–associated C concentration in the summit position. However, in the midslope position, the two older established prairies, P-1998 and P-1993, had the greatest increases in WSA–associated C concentration. This was expected, since the midslope position had lower SOC concentration in 2005 than the summit and toe-slope positions, which resulted in higher potential for SOC sequestration rate. Lower C input and greater erosion during the first few years of prairie establishment might explain the low WSA–associated C concentration in the P-2003 midslope position. In addition, the P-Remnant site was consistently among the lowest in WSA–associated C sequestration rates, suggesting this site might have reached equilibrium (Guzman and Al-Kaisi 2009). Only small changes in WSA–associated C concentration were observed in the toe-slope position, which may be attributed to greater SOC concentration compared to the summit and midslope positions (table 4). Substantial increases in SOC were not expected since differences between remnant prairie and reconstructed prairies were not significant.

Increases in WSA–associated C concentration in 0.25 to 2 mm (0.01 to 0.08 in) size fractions (figure 8) seemed to coincide with increases in SOC sequestration (figure 1b) providing a linkage between the two. Although one conceivably might think that large macroaggregates (>2 mm) should have greater SOC sequestration rates than intermediate macroaggregates (0.25 to 2 mm) and microaggregates (0.053 to 0.25 mm [0.002 to 0.01 in]), in part due to large macroaggregates being comprised of many microaggregates bound with freshly added organic materials (Oades 1984; Six et al. 2002), the freshly added C that binds microaggregates into larger macroaggregates is considered to be soil C unprotected from decomposition by microorganisms and more susceptible to a disruptive process such as water movement. This implies that recently

Figure 5

Soil total nitrogen (TN) sequestration rates for each site from 2005 to 2007 in the (a) top 60 cm and (b) 15 cm depths as influenced by slope position. Treatments within the slope position with the same letter are not significantly different according to the least-squares means test at *p* ≤ 0.1. Error bars indicate standard error.

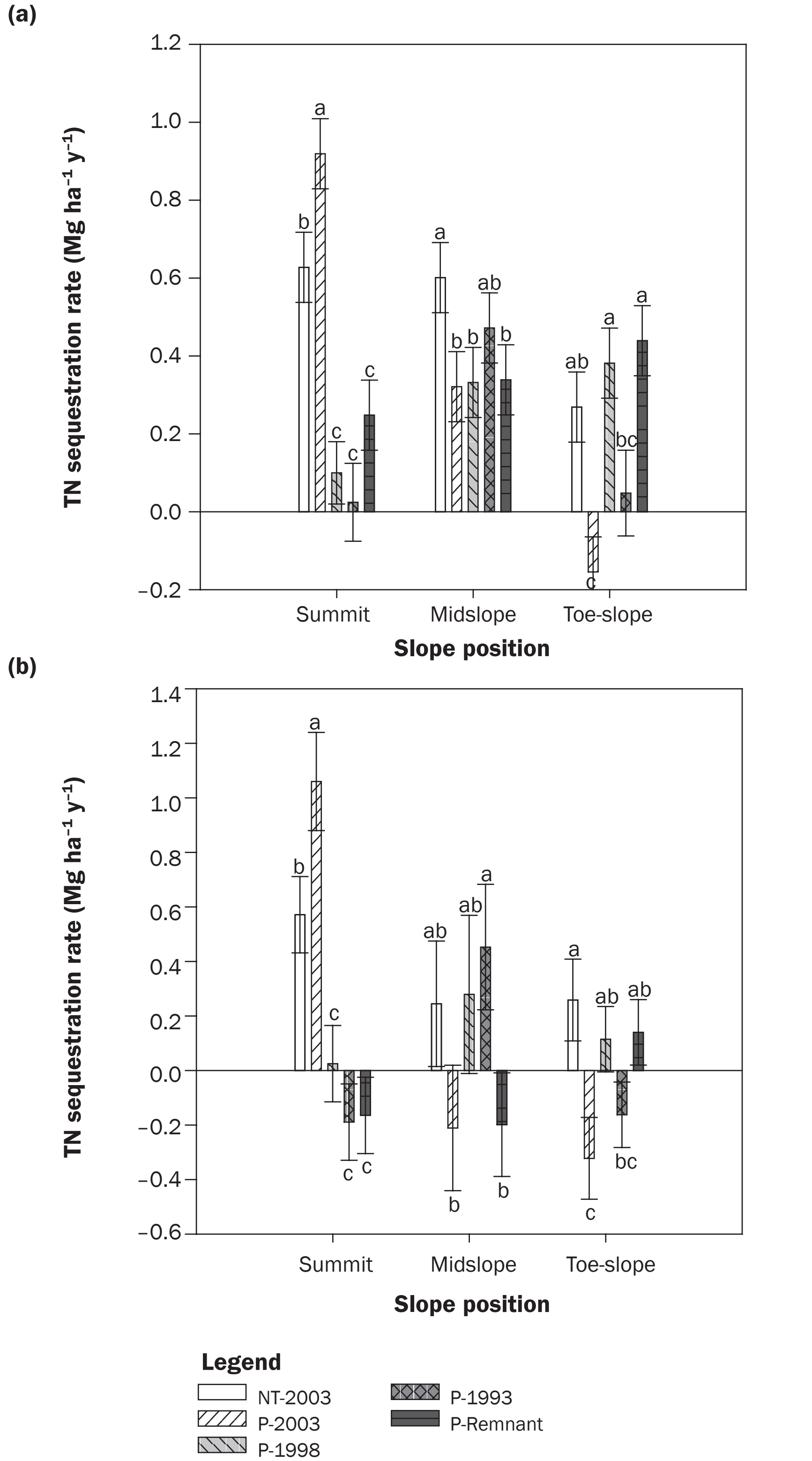
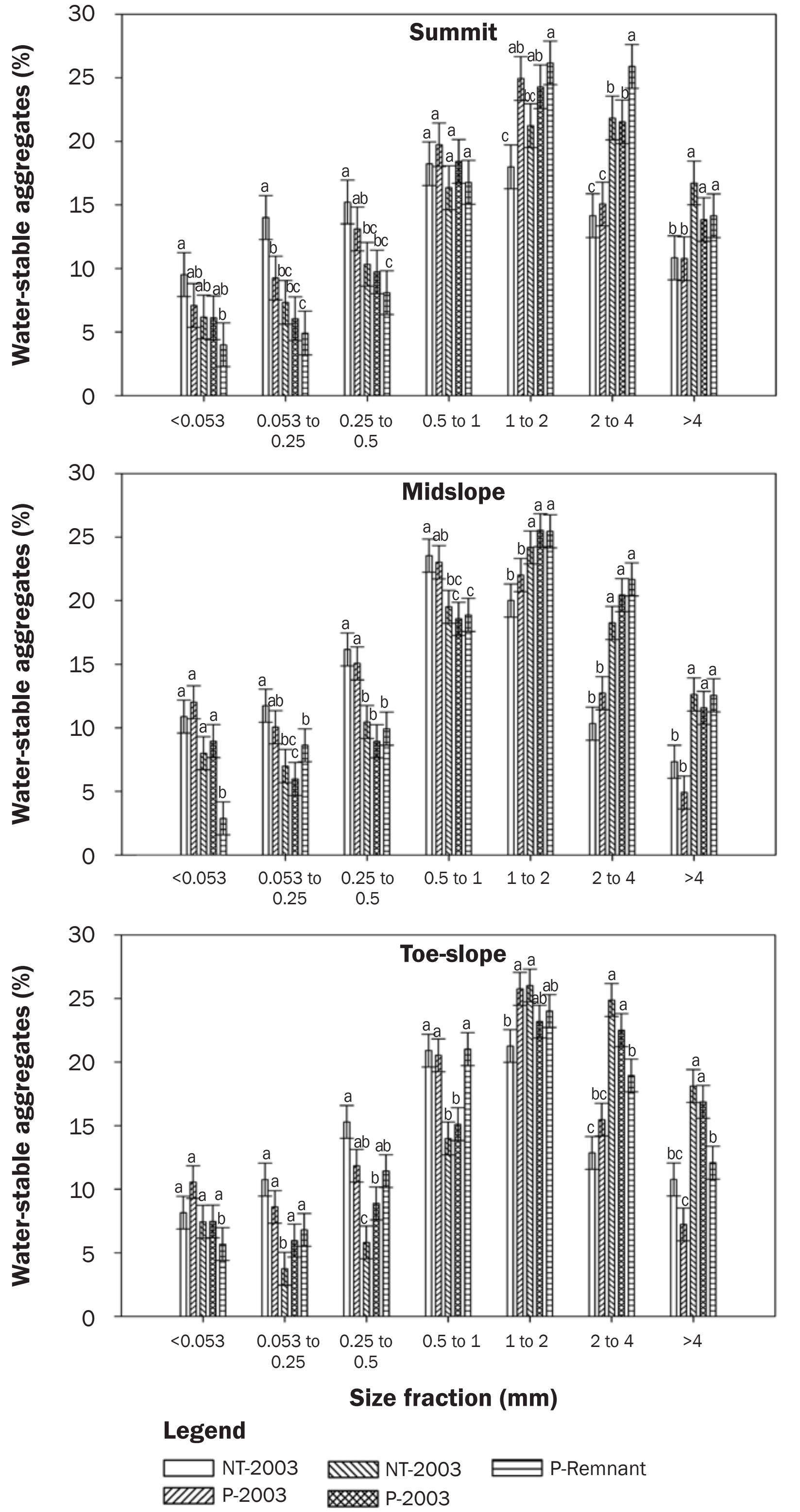


Figure 6

Distribution of water-stable aggregates fractions as influenced by site and slope position in 2005 for each site. Treatments within the same size fraction with the same letter are not significantly different according to the least-squares means test at $p \leq 0.1$. Error bars indicate standard error.



added C input from plant materials is less important for long-term SOC sequestration than physically protected C in microaggregates (Monreal and Kodama 1997) and intermediate macroaggregates (0.25 to 2 mm) as suggested in this study. However, inputs of plant residues can lead to greater accumulation of C binding agents that further stabilize microaggregates and intermediate-macroaggregates within larger macroaggregates over time, which provides further protection for freshly added C from microbial decomposition activities (Six et al. 1999) and increases WSA formation (Six et al. 2000; Mikha and Rice 2004).

Differences in WSA–associated TN concentration between sites across all slope positions were not observed (data not shown). Once again, although site had a significant effect on WSA–associated TN content, type of vegetation (forbs, legume, and C3 or C4 grasses) and its C/N ratio and lignin content seem to be the determining factors, in addition to age of prairie site and slope position effects. The WSA–associated TN sequestration rates were greatest in sites and slope positions where high populations of legumes occurred, such as the P-1993 and P-Remnant in the summit and P-2003 in the toe-slope position as described in tables 1 to 3. In the NT-2003 site, plant vegetation varied by year, since it was in a corn–soybean rotation (2005 and 2007 in corn), and N fertilizer was applied when corn was planted, resulting in much different N dynamics when compared to the prairies. In addition, size of the fraction was not a significant factor in WSA–associated TN sequestration rates, suggesting that soil TN was not a significant factor in aggregate formation.

Summary and Conclusions

Slope position and age since establishment had a significant impact on SOC sequestration rates in the top 15 cm (6 in) soil depth only. At the summit position, the youngest established prairie (P-2003) had the greatest SOC sequestration rate at 2.15 Mg SOC ha^{-1} y^{-1} (0.96 tn SOC ac^{-1} yr^{-1}), although rates sharply decreased as age increased over a 14-year period. Another interesting finding of this study was that SOC increased linearly over the 14-year period at a rate of 0.73 Mg SOC ha^{-1} y^{-1} (0.33 tn SOC ac^{-1} yr^{-1}). However, there was greater variability in SOC sequestration rates at the midslope and toe-slope positions compared to the summit position. For the most part, this could be explained by losses of SOC and productivity of soil in the midslope position when soil erosion was high and deposition of SOC accumulated in the toe-slope position. As a result, SOC sequestration rates in reconstructed prairies in the midslope position were negative, especially during the first five years before increases were observed. At the toe-slope position, an average sequestration rate of 0.59 Mg SOC ha^{-1} y^{-1} (0.26 tn SOC ac^{-1} yr^{-1}) was determined over the first 14 years since prairie establishment. For soil TN sequestration rates, slope position and age since establishment were not significant determinants. Instead, vegetation type for each site and slope position was determined to be the main factor in TN pools in these reconstructed prairies. In the NT-2003 cropland site, SOC content increased similarly to that of the P-2003 site in the summit and toe-slope positions. However, in the midslope position of the NT-2003 site, increases in SOC content were similar to that of the summit position, due to residue and contour planting practices reducing soil erosion compared to the P-2003 site. The P-Remnant site, which typically had the greatest SOC content across all slope positions, had no significant change in SOC rate.

Slope position and age of prairie or time since cessation of tillage also had a significant impact on WSA formation. In general, the two most recently established sites (P-2003 and NT-2003) had the lowest percentages of WSA greater than the 2 mm (0.08 in) fraction across all slope positions. However, formation of macroaggregates of newly established sites occurred rapidly and could potentially reach similar WSA percentage distributions to that of older reconstructed and remnant prairies within approximately 10 years. Furthermore, the greatest increases in WSA–associated C concentration were observed in the 1 to 2 mm (0.04 to 0.08 in) fraction, and the least were in the <0.053, 0.053 to 0.25, and >4 (<0.002, 0.002 to 0.01, and >0.16 in) fractions. In summary, this study provides evidence for the existence of feedback between the formation and stabilization of WSA aggregates and SOC sequestration as affected by time since establishment (or cessation of tillage) and slope position effects. The findings of this research showed that the greatest potential for SOC sequestration was associated with the newly established prairie sites, where SOC content was most significantly

Figure 7

Water-stable aggregates' associated carbon distribution by size fractions as influenced by site and slope position in 2005. Treatments within the same site with the same letter are not significantly different according to the least-squares means test at $p \leq 0.1$. Error bars indicate standard error.

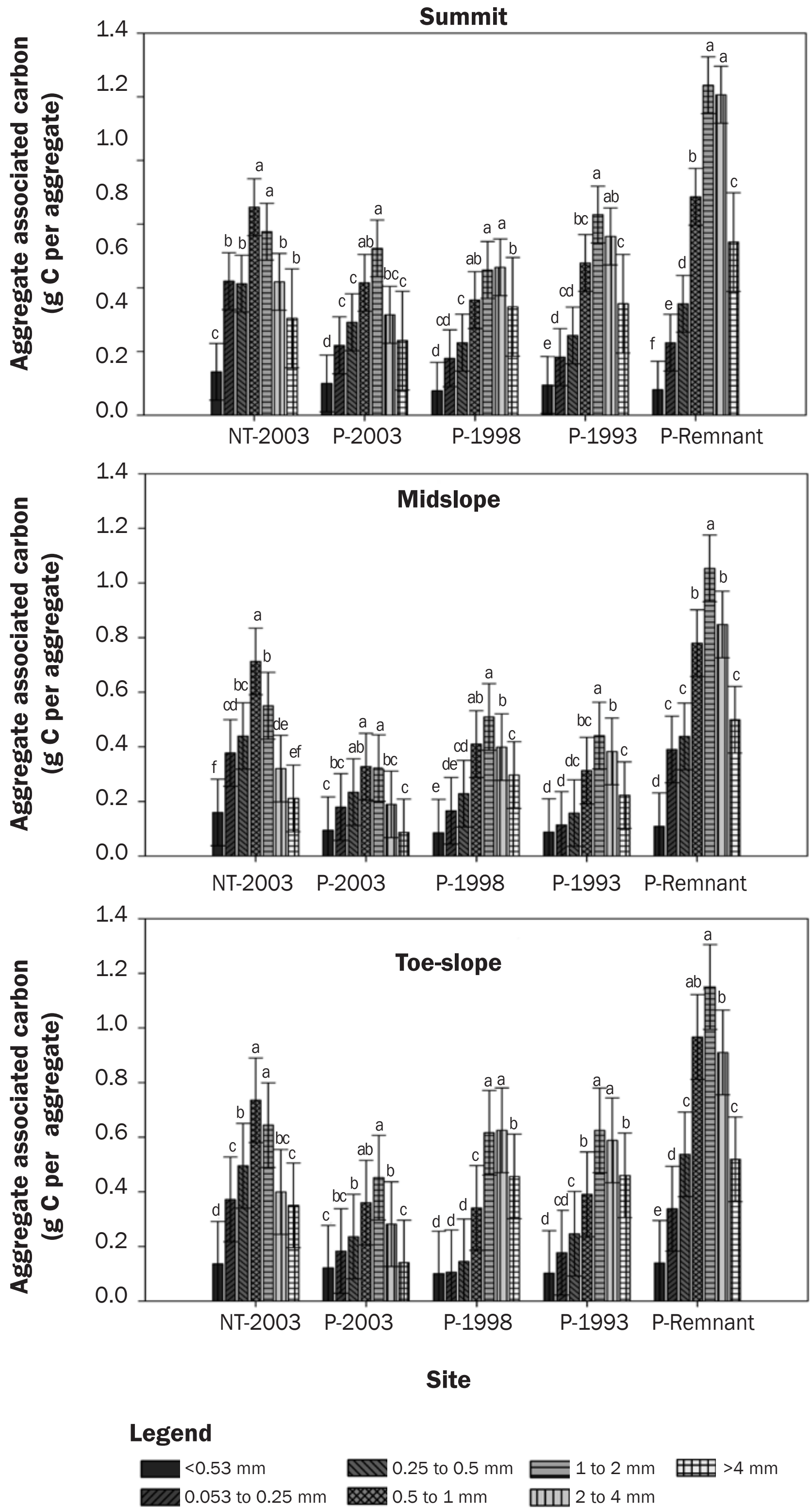
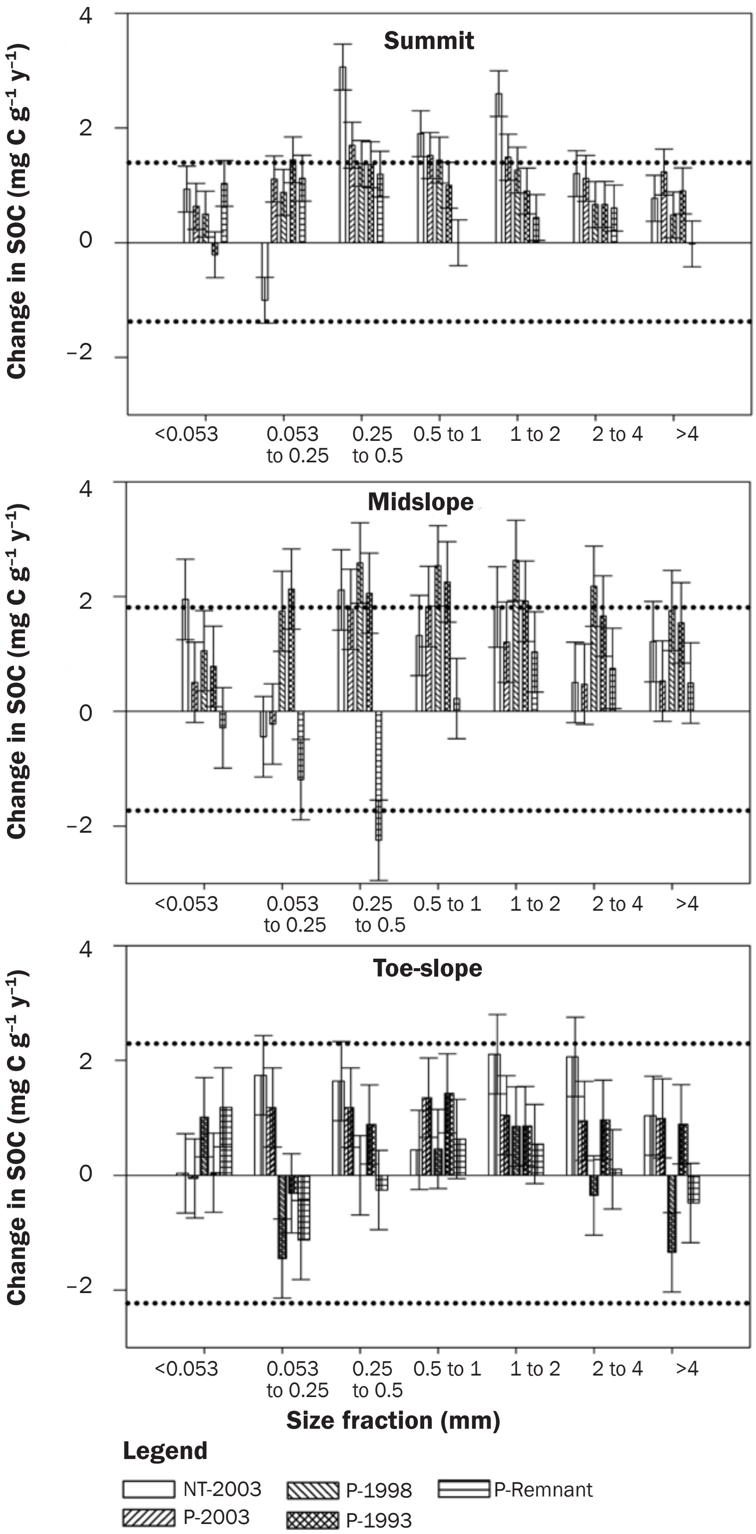


Figure 8

Changes in water-stable aggregates' associated soil organic carbon (SOC) concentration by size fraction as influenced by site and slope position between 2005 and 2008. The dotted lines represent the significant level of change in SOC rate from zero change in SOC for each site within each fraction, according to the least-squares means test at $p \leq 0.1$. Error bars indicate standard error.



depleted compared to a nearby P-Remnant site. This usually occurred in the most recently established prairie sites, and the midslope position, where soil erosion had occurred. In addition, increases in SOC sequestration rates coincided with increases in WSA–associated C concentration in the intermediate macroaggregates and microaggregates (0.25 to 2 mm [0.01 to 0.08 in] size fractions). This provides strong evidence of the relationship between SOC sequestration and the mechanism of soil aggregate formation that aids in protecting microaggregates from microbial decomposition.

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