Impact of Prairie Age and Soil Order on Carbon and Nitrogen Sequestration

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Conservation Reserve Program (CRP) prairie restorations can sequester soil C and N, but the varied effects of soil order and ecosystem age are uncertain. Soil bulk density (D_b) (0–20 cm) and soil organic C (SOC) and total N at 0 to 5, 5 to 10, and 10 to 25 cm were measured at 39 paired CRP–crop sites in Wisconsin to quantify SOC and N stock changes as a function of prairie age (4–16 yr) and soil order (Alfisols and Mollisols). Several important outcomes were found regarding land conversion to CRP: (i) soil D_b decreased on Alfisols (-0.12 ± 0.11 g cm^{-3}, $P < 0.0001$) but not Mollisols; (ii) SOC sequestration rates were not significantly different between Mollisols (49.7 ± 64 g C m^{-2} yr^{-1}) and Alfisols (43.9 ± 86 g C m^{-2} yr^{-1}), but were only detectable ($P < 0.05$) in the upper 5 cm; (iii) whole SOC and N to a depth of 25 cm did not change significantly; (iv) the annual average SOC sequestration rate declined ($P < 0.05$) as prairie age increased (from 72 ± 105 to 13 ± 25 g C m^{-2} yr^{-1} for youngest to oldest age groupings); and (v) short-term SOC and N increases could be lost with time. These data suggest that there may be a discontinuity between the intensity of continuing management that is needed for sustained, long-term SOC increases in planted prairies and the resources that the CRP has available to achieve this level of ecosystem functioning.

Abbreviations: D_b, bulk density; CRP, conservation reserve program; GPS, global positioning system; SOC, soil organic carbon; TN, total soil nitrogen.

The federal CRP, a land set-aside program that pays landowners to remove highly erodible land from agricultural production, is being viewed as a legitimate large-scale effort that could sequester significant quantities of atmospheric C into soils, helping to mitigate an intensifying greenhouse effect. It is well documented that the transformation of the central U.S. tallgrass prairies to lower productivity agricultural systems during the 1800s led to a rapid release of CO_2 from fertile soils to the atmosphere (Mann, 1986; Post and Kwon, 2000). A search of the literature published during the last decade suggests, however, that deliberate rehabilitation of agricultural land with native prairie and grassland vegetation can greatly enhance soil C accumulation (Gebhart et al., 1994; Post and Kwon, 2000; Follett et al., 2001; Brye and Kucharik, 2003; Post et al., 2004), potentially offering a temporary means to help curtail atmospheric CO_2 buildup during the next several decades. Sequestered C via prairie restoration efforts in degraded agricultural soils is attributable to a higher allocation of photosynthate (>50%) belowground to a dense, fibrous root system, a reduction in organic matter decomposition rates, the cessation of plowing and tillage, and a reduction in wind and water erosion.

The precise amount of soil C and TN sequestered as part of the CRP and the potential for future sequestration remains highly debatable because of the numerous factors that influence the rate of soil C and N accumulation at the microscale and because of varied experimental approaches that have been used to detect small changes over short time periods. Soil formation processes, parent material, and climate (Jenny, 1941; Follett et al., 2001), previous land management, the initial soil conditions at the time of restoration (e.g., N and pH), soil texture (Ihori et al., 1995; Percival et al., 2000), species planted (Knops and Tilman, 2000), ecosystem age (Potter et al., 1999; Brye and Kucharik, 2003; Post et al., 2004), landscape slope and position (Brejda et al., 2001), and post-restoration management intensity (e.g., control of invasive species, burning frequency, and mowing) all affect the capacity of prairie restorations to be a sustained C sink.

Post and Kwon (2000) conducted a meta-analysis of average global C sequestration rates on land converted from agricultural production to grassland and reported the average soil C sequestration rate was 33.2 g C m^{-2} yr^{-1}. Other studies specific to CRP land suggest that the average soil C sequestration rate varies from 11 to 304 g C m^{-2} yr^{-1}. In some cases, detection has only been significant in the top 5 to 10 cm of soil, and in others, down to 20 cm (Gebhart et al., 1994; Burke et al., 1995; Reeder et al., 1998, Potter et al., 1999; Follett et al., 2001; Kucharik et al., 2003). The variation is undoubtedly due to differences in measurement and statistical techniques, site characteristics, ecosystem age, planted species, and climate. Nonetheless, the large range in soil C accumulation rates across large continental to global scales makes it difficult to hypothesize about future C offsets and the role that the 15 Mha of CRP land will play in the global C cycle. Additionally, the development of a C credit trading system will depend on verifiable soil C sequestration amounts (Metting et al., 2001; Post et al., 2001); thus, given the degree of uncertainty in soil C accumulation occurring within the context of the CRP, a large number of local-scale (e.g., county level to crop reporting district) studies might be crucial in the assessment process, particularly in regions with diverse topography, soil types, and land-use histories. Because there are several nonlinear processes that are known to affect C accumulation in soils such as microbial response to soil moisture and temperature and plant physiological response to atmospheric CO_2, light, and environmental stresses (e.g., temperature, water, and nutrients), applying an "average" probable C sequestration rate associated with the CRP to a large landscape scale (e.g., state

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or larger regions) is likely to lead to erroneous estimates. Many times, numerical modeling approaches that characterize these feedbacks are used to scale results from the individual field level to a larger regional scale (Paustian et al., 1997).

Currently, our knowledge of C and N cycling in prairie restorations as part of the CRP is limited by an incomplete understanding of (i) the relationship between soil order and the rate of soil C and N accumulation or loss in contrasting climates, (ii) the impact of varied species planted, and (iii) how the rate of accumulation or loss changes with the number of years since the last disturbance. While previous research has studied soil response to CRP management (Robles and Burke, 1998; Potter et al., 1999; Baer et al., 2000, 2002), the amount of data that depicts a clear relationship between age since last disturbance and soil C sequestration rate in the CRP is lacking. Moreover, few studies have examined the effect on soil C and N sequestration rates of plantings on different soil orders. This is primarily attributed to the CRP having been established in 1986; the idea of deliberately managing these landscapes for C sequestration has only materialized in the past 10 yr. Thus, many C sequestration rate estimates for the CRP have been made during the first 10 yr after re-establishment of native vegetation, when it is presumed that the rate of soil organic matter accumulation is the highest (Post et al., 2004).

It is generally assumed that, as a new equilibrium is established between C inputs and decomposition rates over several decades, the rate of soil C accumulation eventually decreases (Post et al., 2004). Jastrow (1996) and Post et al. (2004) used soil data from a chronosequence of four Illinois prairies (aged 1–10 yr) and an exponential regression model constrained by C storage in a prairie remnant to predict a declining rate of C accumulation: from 78 g C m^{-2} yr^{-1} during the first 15 yr, to 54 g C m^{-2} yr^{-1} during 30 to 45 yr since the last cultivation. These values are similar to those presented by Bruce et al. (1999), who suggested an average rate of C sequestration of 80 g C m^{-2} yr^{-1} during the first decade, with a decline thereafter. These numbers are also similar to data presented by Follett et al. (2001), who reported an average rate of soil C sequestration in the CRP of 74 g C m^{-2} yr^{-1} for 0 to 10 cm.

The aforementioned rates of soil C sequestration are significantly higher than those reported by Brye and Kucharik (2003) for prairie restorations across southern Wisconsin. Brye and Kucharik (2003) suggested that two topochronosequences (fine textured vs. coarse textured) had not significantly sequestered soil C during a span of 25 yr. Kucharik et al. (2003) further reported that soil C sequestration rates on CRP land enrolled for at least 8 yr were 24.7 g C m^{-2} yr^{-1}, and were only significant in the top 5 cm of soil. In contrast, a modeling study performed across the same general region of southern Wisconsin suggested that, if prairie restorations dominated by C4 grasses replaced current row crop agriculture on silt loam soils, they have the potential to sequester C at a rate of 74.5 g C m^{-2} yr^{-1} for the next 50 yr (Kucharik et al., 2001). The current study was motivated by an idea that low management intensity of Wisconsin CRP land to control invasive species and the application of generalized restoration practices, which do not explicitly consider previous land use history, species succession, or soil formation processes, may contribute to a decline with time (or even overall net losses) in the rate of soil C and N sequestration attributed to land use changes, and that the response may vary among the two dominant soil orders in the immediate region. The objectives of this study were: (i) to quantify SOC and TN stocks (to 25 cm) and surface soil bulk density (0–20 cm) on cropped land and CRP land for two key soil orders found in the U.S. Great Plains and Midwest (Alfisols and Mollisols); (ii) determine whether a change in land management (enrollment in the CRP) led to increases or decreases in SOC, TN, and soil D_b; and (iii) determine if rates of SOC and TN sequestration and total soil D_b changes were significantly affected by soil order and ecosystem age.

MATERIALS AND METHODS

Site Locations and Description

Dane County (43.1°N, 89.5°W) in south-central Wisconsin was the region chosen for the study (total area of 3127 km^2; Fig. 1). Mean annual precipitation in this region is approximately 780 mm, with a mean annual minimum temperature of 1.5°C and mean annual maximum of 13.1°C. The region lies to the south of an ecological tension zone that separates northern forest vegetation and associated soils from southern soils that developed under prairie and oak savanna vegetation (Curtis, 1959; Hole, 1976). While approximately 67% of the land area is devoted to agricultural land use today (National Agricultural Statistics Service, 2002), the region was originally dominated by tallgrass prairies and oak savannas in the mid-1800s, which were maintained by natural and human-induced fires before immigrant settlement (Curtis, 1959). As the population of Wisconsin changed from 3245 in 1830 to over 1.3 million in 1880, however, the amount of land devoted to agriculture also increased—from 161 880 ha in 1830 to 6.2 million ha in 1880 (Curtis, 1959)—and as Native Americans were pushed out, fires were suppressed.

Dane County has experienced contrasting soil development processes because the southwestern one-third of the county was untouched by the most recent glaciation of the Late Wisconsin time of the Quaternary period (Hole, 1980). This region (called the Western Uplands), which is within the Northern Mississippi Valley Loess Hills (Major Land Resource Area [MLRA] 105), was originally dominated by oak savanna vegetation (Curtis, 1959), but was also a northeastern extension of the larger expanse of wet (Aquolls) and drier (Udolls) prairie soils (Mollisols) once covering the U.S. and Canadian Great Plains (Hole, 1976). The surface soils here are primarily either windblown silt (loess) overlying dolomite on upland ridges or silt and loam on top of sandstone in valleys (Hole, 1976). Because the land is topographically diverse in the southwest portion, it is subject to an increased likelihood of surface erosion and therefore has a high concentration of land enrolled in the CRP. The soils within the eastern two-thirds of Dane County (MLRA 95B, Southern Wisconsin and Northern Illinois Drift Plain) developed under the influence of past glaciation, which last ended between 10 000 and 13 000 yr ago (Hole, 1980). The retreat of the glacier left behind a sandy-loam, calcareous till. A large percentage of soils in this region are Alfisols (Aqualfs [wet] and Udalfs [drier]), which subsequently formed under forest and oak-savanna vegetation, with some pockets of wet sedge meadows. The landscape is much less undulating than the western portions of the county, making it ideal for row crop agriculture. While Dane County has seen different soil formation processes, the widespread accumulation of windblown loess of varying thickness throughout the region has masked the original parent material. This contributed significantly to the development of a homogeneous pattern of vegetation across the region before immigrant settlement changed the land cover (Curtis, 1959).

During a 3-yr period from 2001 through 2003, 39 paired (adjacent) cropland and CRP study sites were identified using a database of approximately 1400 landowners (12 658 ha or 4% of the total county land area) currently possessing a contract with the CRP in south-central Wisconsin (Fig. 1). Paired sites were selected based on meeting the following criteria:

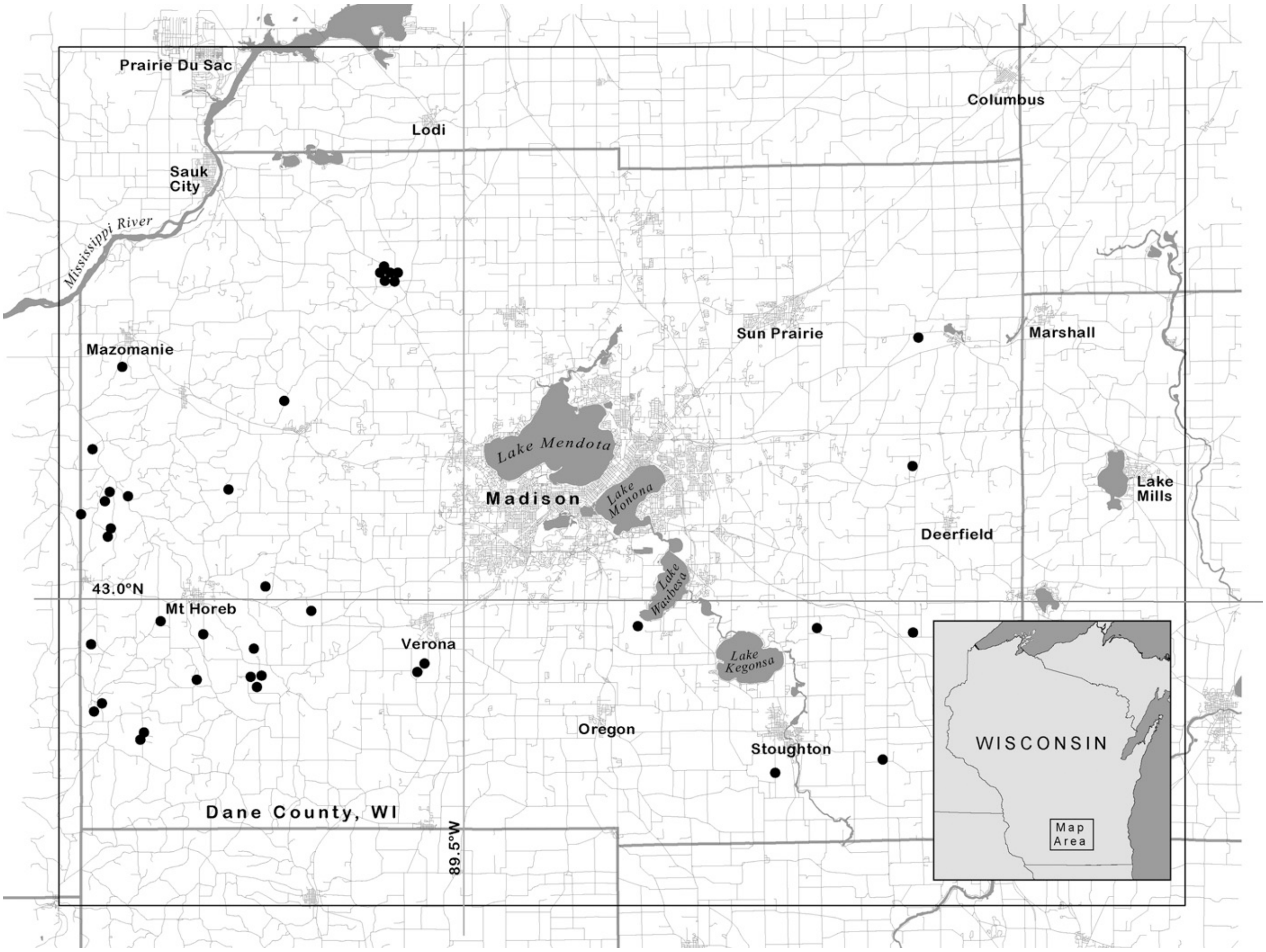

Fig. 1. Location of study region and 39 paired CRP–cropland soil sampling sites (denoted by dark circles) in southern Wisconsin.

(i) CRP land had been enrolled in either CP1 (permanent introduced grasses and legumes) or CP2 (establishment of permanent native grasses) for at least 4 yr or longer at the time of sampling, (ii) each CRP site was positioned adjacent to land that has been (and currently remains) in agricultural production (e.g., corn [*Zea mays* L.], soybean [*Glycine max* (L.) Merr.], and pea [*Pisum sativum* L.]) for at least 50 yr, with a preference for the pairing to have the same ownership, (iii) paired sites that were used to determine soil responses to land management were positioned on either the same soil series (preferred protocol) or soil order according to 30-m-resolution digitized USDA soil surveys, and (iv) CRP land and cropland could be sampled with corresponding elevation, slope, and aspect. Sites were not chosen based on seed mixtures used to re-establish the prairies because this information was not available with older contracts. The majority of the soils are classified as Typic Hapludalfs, Lithic Hapludalfs, Typic Endoaquolls, Mollic Hapludalfs, Typic Argiudolls, and Lithic Hapludalfs, with a total of 22 unique soil series sampled (Table 1).

Soil Sampling Protocol, Preparation, and Analyses

Five D_b (g cm^{-3}) cores were collected for each land-use type for the 0- to 10- and 10- to 20-cm soil layers using an 184-cm^3 stainless steel cylinder (4.8-cm inside diameter) inserted within a gravity-driven hammer attachment (Blake and Hartge, 1986; Elliott et al., 1999). Bulk density samples were dried for 48 h at 40°C, and weighed to determine the mass of soil on a dry-weight basis.

Soil samples for chemical analysis (e.g., organic C and total N) were also collected during the months of June and July for each land-use type at each paired site in 0- to 5-, 5- to 10-, and 10- to 25-cm fixed soil depth intervals. According to field observations and official soil series descriptions of the USDA-NRCS, the experimental design permitted sampling of soils that extended below the Ap horizon (12–23-cm depth). A handheld global positioning system (GPS) was used in coordination with digitized soil surveys to establish 50-m transects in adjacent CRP and cropped fields that either shared the same soil series, when possible, or were found on the same soil order. Thus, not all of the individual pairings of adjacent cropland and CRP were situated on matched soil series. Each pairing of CRP and cropland was completely sampled within a 3- to 6-h period on the same day. The average distance between the CRP and cropland soil sampling transects was typically between 25 and 150 m. Fifteen 2-cm-diameter cores (hand held, foot inserted) were collected along each CRP transect for each independent depth, well mixed, and combined to form a single composite sample. Soil sampling took place in a manner to form an average for each representation of CRP land at each site; thus, the soil probe was randomly positioned for each sample location along each transect and no preference was made to sample soils under prairie vegetation vs. between plants.

On cropped land, 15 2-cm-diameter soil cores were collected along 50-m transects in a systematic pattern so that all representative row position locations that were influenced by varied management (e.g., within rows, between rows, wheel-tracked interrow, non-wheel-tracked

Table 1. Classification and descriptive statistics of bulk density, soil organic carbon (SOC), and total soil nitrogen (TN). SE is the standard error of observations (for $n > 1$).

Series	Classification	Texture, Ap horizon	n†	Bulk density, 0–10 cm				Soil organic C to 25 cm				Total N to 25 cm			
				Mean	Min.	Max.	SE	Mean	Min.	Max.	SE	Mean	Min.	Max.	SE
				g cm^{-3}				kg C m^{-2}				kg N m^{-2}			
Conservation Reserve Program prairie plantings															
Griswold	Typic Argiudoll	loam	2	1.41	1.36	1.46	0.05	7.94	6.55	9.33	1.39	0.79	0.70	0.87	0.09
Sable	Typic Endoaquoll	silty clay loam	1	1.20	–	–	–	7.63	–	–	–	0.33	–	–	–
St. Charles	Typic Hapludalf	silt loam	1	1.50	–	–	–	7.47	–	–	–	0.43	–	–	–
Kegonsa	Mollic Hapludalf	silt loam	1	1.31	–	–	–	7.43	–	–	–	0.46	–	–	–
Orion	Aquic Udifluvent	silt loam	1	1.17	–	–	–	7.13	–	–	–	0.36	–	–	–
New Glarus	Typic Hapludalf	silt loam	4	1.29	1.25	1.36	0.03	7.08	6.17	9.56	0.83	0.46	0.38	0.71	0.08
Ringwood	Typic Argiudoll	silt loam	1	1.32	–	–	–	6.68	–	–	–	0.69	–	–	–
Edmund	Lithic Argiudoll	silt loam	6	1.32	1.24	1.43	0.03	6.64	4.41	9.27	0.77	0.41	0.32	0.53	0.04
Dunbarton	Lithic Hapludalf	silt loam	9	1.32	1.24	1.39	0.02	6.38	2.87	15.67	1.29	0.41	0.19	0.60	0.05
Batavia	Mollic Hapludalf	silt loam	1	1.41	–	–	–	6.20	–	–	–	0.36	–	–	–
Dresden	Mollic Hapludalf	silt loam	2	1.43	1.42	1.44	0.01	6.03	4.31	7.75	1.72	0.57	0.44	0.71	0.13
Troxel	Pachic Argiudoll	silt loam	2	1.30	1.23	1.37	0.07	5.80	5.09	6.51	0.71	0.60	0.50	0.69	0.10
Ashdale	Typic Argiudoll	silt loam	1	1.34	–	–	–	5.75	–	–	–	0.32	–	–	–
Spinks/Plainfield	Lamellic Hapludalf	loamy sand	1	1.50	–	–	–	5.73	–	–	–	0.53	–	–	–
McHenry	Typic Hapludalf	silt loam	3	1.42	1.31	1.63	0.11	5.61	4.99	5.97	0.31	0.53	0.48	0.60	0.04
Virgil	Udollic Endoaqualf	silt loam	1	1.40	–	–	–	4.81	–	–	–	0.30	–	–	–
Hixton	Typic Hapludalf	loam	1	1.32	–	–	–	4.37	–	–	–	0.26	–	–	–
Dodge	Typic Hapludalf	silt loam	1	1.61	–	–	–	4.04	–	–	–	0.39	–	–	–
Cropland‡															
Sogn	Lithic Haplustoll	silty clay loam	1	1.12	–	–	–	16.28	–	–	–	0.85	–	–	–
Kegonsa	Mollic Hapludalf	silt loam	1	1.40	–	–	–	10.47	–	–	–	0.63	–	–	–
Plano	Typic Argiudoll	silt loam	2	1.48	1.47	1.49	0.01	8.22	6.99	9.44	1.23	0.71	0.67	0.75	0.04
Ringwood	Typic Argiudoll	silt loam	1	1.48	–	–	–	8.14	–	–	–	0.78	–	–	–
Griswold	Typic Argiudoll	loam	1	1.49	–	–	–	8.02	–	–	–	0.74	–	–	–
Sable	Typic Endoaquoll	silty clay loam	2	1.52	1.44	1.59	0.07	6.61	5.02	8.20	1.59	0.42	0.41	0.43	0.01
Orion	Aquic Udifluvent	silt loam	1	1.19	–	–	–	6.23	–	–	–	0.31	–	–	–
Edmund	Lithic Agriudoll	silt loam	6	1.35	0.93	1.52	0.09	5.99	4.31	8.88	0.67	0.32	0.20	0.43	0.03
Dunbarton	Lithic Hapludalf	silt loam	10	1.46	1.23	1.59	0.04	5.56	3.78	7.17	0.39	0.44	0.24	0.78	0.06
McHenry	Typic Hapludalf	silt loam	2	1.63	1.49	1.76	0.13	5.45	4.82	6.09	0.64	0.57	0.50	0.64	0.07
Seaton	Typic Hapludalf	silt loam	1	1.60	–	–	–	5.39	–	–	–	0.52	–	–	–
New Glarus	Typic Hapludalf	silt loam	4	1.31	1.22	1.39	0.04	4.92	3.89	5.51	0.37	0.32	0.26	0.37	0.03
Dodge	Typic Hapludalf	silt loam	2	1.68	1.54	1.82	0.14	4.79	4.71	4.86	0.07	0.48	0.45	0.52	0.03
Dresden	Mollic Hapludalf	silt loam	2	1.65	1.65	1.65	0.00	4.70	4.70	4.70	0.00	0.53	0.53	0.53	0.00
Virgil	Udollic Endoaqualf	silt loam	1	1.43	–	–	–	3.56	–	–	–	0.21	–	–	–
Batavia	Mollic Hapludalf	silt loam	2	1.39	1.39	1.39	0.00	3.45	3.45	3.45	0.00	0.24	0.24	0.24	0.00

† The number (*n*) of CRP sites on unique soil series do not always match the total number reported for cropland sites because some individual pairings were not situated on the same soil series.

‡ All cropped sites have been estimated as being in production >50 yr as of the year 2000.

interrow) contributed to the overall field average. This deliberate systematic sampling pattern was necessary to minimize any chance that all cores were taken in similar positions with respect to row orientation. In the event that planting and tillage practices followed a similar tracking pattern in the long term across fields for several decades, systematic patterns of soil C and N storage could develop, and could be correlated with row placement. Kucharik et al. (2006) noted, however, that because agricultural practices thoroughly mix soils in the plow layer over long time periods, within-site variation of soil properties (i.e., the variability among individual cores in a contiguous field) are lower than what is typically found within native or restored prairies. As with the CRP sampling, the 15 samples for each depth were well mixed and combined to form a single composite sample at each cropped site.

Soil samples were dried in a gravity convection oven for 48 h at 33°C. Dried soil samples to be used for determining SOC and TN were mechanically ground to pass through a 2-mm sieve, at which time any visible plant roots and residue were discarded from the sample. These soil samples were reground by hand with a mortar and pestle until they passed through a 150-μm sieve. Soil C and N percentages were determined on finely ground soil subsamples (5 g) by high-temperature catalytic combustion using a Carlo-Erba Model NA 1500 C and N analyzer (Carlo Erba Instruments, Milan, Italy). While these soils are calcareous in origin, no removal of inorganic soil C took place before SOC and TN were determined because free carbonates were not detected with an acid test consisting of 1 *M* HCl. All soil C and N concentration data (g kg^{-1} oven-dry soil) were multiplied by mean D_b values and fixed sampling depth increments (soil layer thickness in centimeters) to convert C and N to an area basis (kg m^{-2}) for fixed-depth comparisons. We applied the mean 0- to 10-cm D_b values to both the 0- to 5- and 5- and 10-cm depths, and the mean 10- to 20-cm D_b values were applied to the 10- to 25-cm layer because sampling equipment only allowed for 10-cm increments of soil to be sampled that could not be subdivided with reliable precision. Soil depths were not adjusted to account for changes in soil D_b from CRP to cropland, which in some cases may lead to an underestimated rates of soil C and N sequestration (Ellert and Bettany, 1995; Post and Kwon, 2000).

Statistical Analyses

All descriptive statistics (means and coefficients of variation [CV = standard deviation/mean]) and comparative analyses were performed using the JMP (version 5.01a) software package (SAS Institute, Cary, NC). In many cases, either a log, inverse ($1/x$), or square-root transformation was needed to achieve a normal distribution. Statistical differences between grouped means (e.g., effect of soil order and ecosystem age) of SOC, TN, and D_b as a function of soil depth for CRP and cropped fields were made using Tukey's pairwise comparison. Multiple regression analysis was performed to determine the significance of soil order, ecosystem age, and the interaction of both in controlling SOC and TN storage, soil D_b and the rates of SOC and TN sequestration as a function of depth. Annual average SOC and TN sequestration rates were calculated by using the numerical difference between CRP and adjacent cropland, divided by the age of the CRP land at sampling. A one-way ANOVA as a function of soil depth was used to test for significant differences ($P < 0.05$) between CRP and cropland for mean soil SOC, TN, and D_b. Each pair of the CRP and cropland sites within the varied groupings (e.g., ecosystem age, soil order, and combined age and soil order) was treated as a replicate for the overall *t*-test. Tukey's pairwise comparison was also used to determine whether rates of soil SOC and TN sequestration or changes in soil D_b were significantly affected by soil order, ecosystem age, or combinations of both. For some statistical results, a 95% confidence interval (CI) is also reported. This analysis assumes that there have been no significant changes in SOC and TN in cropped sites during the past ~4 to 15 yr. This is a fair assumption because typical crop management practices and overall crop productivity have not changed appreciably in the region during this time (National Agricultural Statistics Service, 2002; Conservation Tillage Information Center, 2004).

All 39 paired sites (Fig. 1) were used to develop averages for CRP and cropland SOC and TN stocks and D_b according to the soil order and age grouping. In the calculations of SOC and TN sequestration rates and soil D_b changes attributed to CRP management, four sites were removed from the statistical analyses because the soil order was not similar between the adjacent cropland and CRP land sampled. Because a single paired site was found on Entisols, this site was also removed from statistical calculations that studied the effects of soil order on SOC and TN sequestration rates and D_b changes. This site is, however, included in the ANOVA for prairie age effects on SOC and TN sequestration rates and D_b changes. For the purpose of some statistical analysis and reporting of results, CRP prairie plantings were grouped according to their age or years since last disturbance; young sites were 4 to 5 yr old ($n = 18$), mid-aged sites were 6 to 10 yr old ($n = 5$), and the oldest sites were 11 to 16 yr old ($n = 16$).

RESULTS AND DISCUSSION

Conservation Reserve Program Vegetation and Crop Residue Management

The mesic tallgrass prairie restorations ranged in size from ~0.4 to 50 ha, and consisted of dominant species, in no specific order of abundance, including big bluestem (*Andropogon gerardii* Vitman), little bluestem [*Schizachyrium scoparium* (Michx.) Nash], prairie dropseed [*Sporobolus heterolepis* (A. Gray) A. Gray], switch grass (*Panicum virgatum* L.), Indian grass [*Sorghastrum nutans* (L.) Nash], smooth brome (*Bromus inermis* Leyss.), Canadian goldenrod (*Solidago canadensis* L.), wild parsnip (*Pastinaca sativa* L.), purple-coneflower [*Echinacea purpurea* (L.) Moench], black-eyed-Susan (*Rudbeckia hirta* L.), purple prairie-clover (*Dalea purpurea* Vent.), June grass [*Koeleria macrantha* (Ledeb.) Schult.], and lead-plant (*Amorpha canescens* Pursh).

At the time of crop soil sampling, the percentage of the soil surface covered with residue was <20%. These numbers corroborate what we would expect to find in a representative corn–soybean rotation in Dane County during the early to mid-summer based on the adoption of three typical residue management schemes. Data from the Conservation Technology Information Center (2004) showed that the typical percentage of acreage that is farmed with conventional tillage (<15% of surface is covered with residue after planting) in Dane County is ~50%, and the remainder of acreage planted in corn and soybean used conservation tillage (~25% of total acreage) and reduced tillage practices (~25% of total acreage). These estimates are similar to those provided by Johnson et al. (2005), who suggested that 33% of total Wisconsin cropland was planted using conservation tillage and 15% with reduced tillage.

Soil Bulk Density

Table 1 summarizes the range in soil D_b across the region according to individual soil series sampled on CRP and cropped land. The CRP soil D_b in each soil layer sampled was not significantly different between Alfisols and Mollisols, and was not significantly affected by planted prairie age across all sites (Table 2). Similarly, the 0- to 10- and 10- to 20-cm mean soil D_b on cropped land was not significantly different between Alfisols and Mollisols (Table 2).

Mean changes in soil D_b attributed to enrollment in the CRP were computed by averaging the net difference between cropland and CRP land. In addition to considering the effects of soil order and ecosystem age on soil D_b changes, data were also subdivided within each of the two main soil orders (Alfisols and Mollisols) with respect to the three potential age classifications. The 0- to 10-cm soil D_b decreased significantly as a result of land-use change to CRP among all Alfisol soils ($P < 0.0001$), but the soil D_b decrease associated with CRP management on Mollisol soils was not significant (Table 3). When the effects of planted prairie age were considered, the oldest and youngest CRP age grouping produced the largest decreases in soil D_b that was statistically significant (Table 3). When the Alfisol soil order was subdivided as a function of planted prairie age, the oldest prairies planted on Alfisols showed the largest and most significant decrease in soil D_b, and this change was significantly different than the observed change that occurred within the youngest planted prairies on Alfisols (Table 3). Overall, 0- to 10-cm soil D_b

Table 2. Amount and distribution of soil organic carbon (SOC) stocks measured in Conservation Reserve Program (CRP) and cropped soils for depth increments of 0 to 5, 5 to 10, 10 to 25, and 0 to 25 cm, and observed 0- to 10- and 10- to 20-cm soil bulk density (D_b).

			0–5 cm		5–10 cm		10–25 cm		0–25 cm		0–10 cm		10–20 cm	
Categorization†	**df**	***n***	**SOC**	**CV**	**SOC**	**CV**	**SOC**	**CV**	**SOC**	**CV**	**D_b**	**CV**	**D_b**	**CV**
			kg C m^{-2}	%	kg C m^{-2}	%	kg C m^{-2}	%	kg C m^{-2}	%	g cm^{-3}	%	g cm^{-3}	%
Alfisols (CRP)	24	25	1.71 a‡	29.8	1.26 a	43.3	3.21 a	48.6	6.19 a	40.6	1.37 a	7.7	1.43 a	8.2
Alfisols (crops)	25	26	1.44 b	34.8	1.17 a	43.3	3.07 a	57.2	5.68 a	46.1	1.46 b	11.5	1.37 a	8.8
Mollisols (CRP)	12	13	1.84 a	23.7	1.35 a	23.3	3.54 a	25.7	6.72 a	23.2	1.33 a	5.9	1.36 a	4.9
Mollisols (crops)	11	12	1.52 a	27.6	1.41 a	26.5	3.88 a	29.9	6.81 a	25.3	1.39 a	12.4	1.37 a	9.9
Young (CRP)	17	18	1.74 a	28.1	1.31 a	39.7	3.59 a	47.3	6.65 a	40.2	1.33 a	7.0	1.38 a	8.7
Young (crops)	17	18	1.44 b	38.2	1.21 a	49.4	3.58 a	59.7	6.23 a	50.5	1.38 b	11.0	1.36 a	9.9
Mid (CRP)	4	5	1.92 a	23.0	1.53 a	42.8	3.34 a	28.1	6.79 a	26.1	1.41 a	11.3	1.59 a	10.0
Mid (crops)	4	5	1.44 b	28.6	1.16 a	27.9	2.76 a	26.4	5.36 a	26.1	1.57 a	8.5	1.40 a	8.6
Old (CRP)	15	16	1.71 a	28.8	1.21 a	28.4	3.05 a	32.3	5.97 a	29.0	1.35 a	6.4	1.38 a	5.6
Old (crops)	15	16	1.49 a	27.6	1.31 a	26.8	3.25 a	30.7	6.05 a	25.5	1.47 b	12.2	1.38 a	6.9
CRP averages	38	39	1.75 a	27.3	1.30 a	36.4	3.34 a	40.6	6.39 a	34.4	1.35 a	7.4	1.39 a	8.3
Cropped averages	38	39	1.46 b	32.2	1.24 a	37.9	3.34 a	48.0	6.05 a	39.4	1.44 b	11.9	1.37 a	9.0
Source of variation among all CRP sites, ANOVA $P > F$														
Soil order (O)	2		0.467		0.616		0.463		0.473		0.202		0.210	
Age (A)†	2		0.970		0.659		0.359		0.517		0.525		0.269	
O • A	4		0.185		0.199		0.144		0.143		0.853		0.966	
Source of variation among all crop sites, ANOVA $P > F$														
O	2		0.711		0.203		0.154		0.201		0.404		0.900	
A†	2		0.693		0.633		0.553		0.825		0.249		0.950	
O • A	4		0.444		0.475		0.397		0.390		0.045		0.960	

† Three age categories were established: young were enrolled for 4–5 yr at time of sampling (n = 18), mid-aged 6–10 yr (n = 5) and old 11–16 yr (n = 16). For statistical analysis, crop sites were categorized according to the age of their paired CRP counterpart.

‡ Within columns and paired categories for statistical analysis (CRP vs. crops), levels not connected by the same letter are significantly different (LSD 0.05).

in the CRP soils decreased on average by 6.8% (P = 0.0001) for the 35 paired sites used in the statistical analysis.

The decrease of soil D_b with soil depth and the higher CV among the 39 cropped sites is in contrast to the observed increase of soil D_b with depth and lower CV among the CRP sites (Table 2). These observations are evidence of how different land management has impacted soil structural properties in the top 25 cm. Because overall soil D_b was significantly different between CRP and crop land, there is strong evidence to suggest that CRP prairie plantings are indeed changing soil structure, aiding in increased porosity. The statistical analysis suggests that CRP prairie restorations occurring on Alfisols are contributing to a greater and more significant change in 0- to 10-cm soil D_b (–8.1%) than is occurring when CRP prairies replace croplands on Mollisols (–4.7%). This might be partially attributed to the fact that the cropland soil D_b was higher on Alfisols than Mollisols to begin with; therefore, similar land management changes on each soil order might lead to a more pronounced effect on the Alfisol soils in a shorter period of time. It appears that soil structure is continuing to recover as planted CRP prairies age on

Table 3. Annual average rates of soil organic C (SOC) sequestration and total soil bulk density changes based on observed differences between Conservation Reserve Program (CRP) soils and cropped soils grouped by soil order and ecosystem age.

Soil order and age grouping†	**df**	***n***	**SOC**								**Bulk density, 0–10 cm**	
			0–5 cm		**5–10 cm**		**10–25 cm**		**0–25 cm**			
			Mean‡	***P > F*§**	**Mean**	***P > F***	**Mean**	***P > F***	**Mean**	***P > F***	**Mean**	***P > F***
			g C m^{-2} yr^{-1}								g cm^{-3}	
Alfisol, young	10	11	68.1 a	0.066	32.2 a	0.395	69.7 a	0.441	170.1 a	0.218	−0.054 a	0.087
Alfisol, mid	3	4	61.2 a	0.033	55.6 a	0.219	92.1 a	0.369	208.9 a	0.171	−0.131 ab	0.228
Alfisol, old	7	8	1.9 a	0.809	−13.8 a	0.033	−19.4 a	0.227	−31.3 a	0.260	−0.194 b	<0.0001
Mollisol, young	4	5	79.7 a	0.121	13.3 a	0.898	−37.9 a	0.767	55.1 a	0.976	−0.103 a	0.106
Mollisol, old	5	6	24.7 a	0.059	−10.1 a	0.493	−35.8 a	0.354	−21.1 a	0.746	−0.037 a	0.707
Alfisols	22	23	43.9 a	0.011	20.3 a	0.469	42.6 a	0.468	106.8 a	0.194	−0.116 a	<0.0001
Mollisols	10	11	49.7 a	0.008	0.5 a	0.689	−36.8 a	0.435	13.5 a	0.880	−0.067 a	0.243
Young	15	16	71.7 a	0.013	26.3 a	0.403	36.1 a	0.759	134.1 a	0.350	−0.070 a	0.013
Mid	3	4	61.2 ab	0.033	55.6 a	0.219	92.1 a	0.369	208.9 a	0.171	−0.131 a	0.228
Old	14	15	12.7 b	0.062	−10.0 a	0.110	−23.8 a	0.139	−21.2 a	0.403	−0.120 a	0.012
Cumulative	34	35	45.2	0.0002	14.1	0.5821	16.8	0.9936	76.1	0.3125	−0.098	0.0001
Source of variation: SOC sequestration rates, ANOVA $P > F$												
Soil order (O)	2		0.698		0.609		0.424		0.549		0.321	
Age (A)†	2		0.050		0.346		0.633		0.329		0.639	
O • A	4		0.990		0.773		0.712		0.741		0.032	

† Three age categories were established: young were enrolled for 4–5 yr at time of sampling (n = 18), mid-aged 6–10 yr (n = 5) and old 11–16 yr (n = 16). For statistical analysis, crop sites were categorized according to the age of their paired CRP counterpart.

‡ Within columns and unique groupings (three Alfisol age categories, two Mollisol age categories, two soil orders, three age categories), levels not connected by the same letter are significantly different (LSD 0.05).

§ Level of statistical significance for differences in SOC stocks when comparing CRP and crop soils.

Alfisols, even after 10 yr since restorations were initiated, whereas this was not observed on Mollisols.

Soil Organic Carbon and Total Nitrogen Stocks

Across all soil series sampled, the total SOC stocks in the top 25 cm differed by a factor of four between the highest and lowest values on both CRP land and cropped land (Table 1). Soil organic C stocks in the 0- to 5-, 5- to 10-, and 10- to 25-cm depth intervals were not significantly affected on CRP land by soil order or age when they were analyzed as independent or interactive (two-way ANOVA) controlling factors (Table 2). Overall, the prairie restorations on Mollisols contained 8.6% more SOC (0.53 kg C m^{-2}) in the 0- to 25-cm layer than Alfisols.

On cropped soils, soil order was not found to have a statistically significant effect on SOC stocks in any of the layers sampled even though Mollisol SOC stocks were 6, 21, and 26% greater than Alfisols in the 0- to 5-, 5- to 10-, and 10- to 25-cm layers, respectively (Table 2). Cropped sites were also subdivided and analyzed according to the age categories that were established for CRP restorations (e.g., each crop site was categorized according to the adjacent CRP age grouping). These statistical tests were performed to determine whether the arbitrary choice of study locations led to significant trends or differences in cropland sites with respect to CRP age, thereby negating any observed trends with age that were detected within the CRP sample size. Neither the independent effect of planted prairie age or interaction with soil order produced statistically significant differences among crop sites according to the CRP age categorization (Table 2).

Statistically significant increases in SOC stocks attributed to conversion of agricultural land to CRP were detected on Alfisols in the 0- to 5-cm soil layer, and for the young and mid-age prairie groupings (Table 2). The oldest prairies planted on Alfisols (n = 8), however, did not contain significantly greater SOC than their paired cropland sites (Table 2). This potentially suggests that either SOC was lost over time or this result is an artifact of the soil sampling scheme and site selection.

Across all 39 paired sites and soil series sampled, TN also differed by a factor of four between the highest and lowest values on both CRP land and cropland (Table 1). Table 4 shows the amount, distribution, and statistical analysis of TN for CRP and cropped soils as a function of soil order and age groupings. On CRP land, soil order did not significantly affect TN storage as a function of depth. When the effect of planted prairie age on TN in CRP restorations was tested, no significant differences were found in the 0- to 5- and 5- to 10-cm layers, but were statistically significant in the 10- to 25- ($P < 0.001$) and 0- to 25-cm ($P = 0.002$) depth increments (Table 4). The TN for the young prairie age grouping was approximately 58 and 30% less than the mid- and old-age groupings in the 10- to 25- and 0- to 25-cm layers, respectively. The combined effect of ecosystem age and soil order were significant in determining TN in the 0- to 5- ($P < 0.1$) and 5- to 10-cm ($P = 0.03$) depth intervals (Table 4). Given the small number of replicates in this study when subdividing the paired sites, statistical significance may be more appropriately established at the 10% level (Brye and Kucharik, 2003).

On cropped soils, soil order was not found to have a significant effect on TN storage in any soil depth interval (Table 4). When the effect of the chosen CRP age groupings on TN in cropland was

Table 4. Amount and vertical distribution of total soil nitrogen (TN) stocks measured in Conservation Reserve Program (CRP) soils and cropped soils for depth increments of 0 to 5, 5 to 10, 10 to 25, and 0 to 25 cm.

Categorization†	df	n	0–5 cm		5–10 cm		10–25 cm		0–25 cm	
			TN‡	CV	TN	CV	TN	CV	TN	CV
			kg N m^{-2}	%	kg N m^{-2}	%	kg N m^{-2}	%	kg N m^{-2}	%
Alfisols (CRP)	24	25	0.157 a	23.2	0.113 a	28.1	0.172 a	61.0	0.442 a	29.7
Alfisols (crops)	25	26	0.145 a	34.4	0.122 a	36.5	0.178 a	61.7	0.445 a	39.0
Mollisols (CRP)	12	13	0.178 a	23.3	0.129 a	22.6	0.199 a	66.8	0.506 a	36.0
Mollisols (crops)	11	12	0.141 b	26.8	0.128 a	25.0	0.206 a	73.1	0.475 a	43.1
Young (CRP)	17	18	0.160 a	19.5	0.116 a	25.3	0.101 a	35.9	0.376 a	18.7
Young (crops)	17	18	0.141 b	37.6	0.123 a	41.5	0.108 a	55.7	0.372 a	41.3
Mid (CRP)	4	5	0.176 a	20.0	0.132 a	29.4	0.242 a	30.5	0.550 a	19.7
Mid (crops)	4	5	0.148 a	30.9	0.118 a	26.8	0.273 a	48.6	0.539 a	37.2
Old (CRP)	15	16	0.163 a	29.4	0.117 a	26.9	0.249 a	50.3	0.529 a	33.9
Old (crops)	15	16	0.143 a	27.3	0.125 a	22.9	0.243 a	51.6	0.511 a	34.7
CRP averages	38	39	0.163 a	23.7	0.118 a	26.2	0.179 a	63.0	0.461 a	32.6
Cropped averages	38	39	0.143 b	31.9	0.123 a	32.5	0.185 a	66.1	0.450 a	40.1
Source of variation among all CRP sites, ANOVA $P > F$										
Soil order (O)	2		0.122		0.158		0.549		0.245	
Age (A)†	2		0.560		0.566		0.000		0.002	
O • A	4		0.060		0.030		0.599		0.164	
Source of variation among all crop sites, ANOVA $P > F$										
O	2		0.747		0.757		0.852		0.919	
A†	2		0.729		0.733		0.003		0.035	
O • A	4		0.533		0.258		0.596		0.444	

† Three age categories were established: young were enrolled for 4–5 yr at time of sampling (n = 18), mid-aged 6–10 yr (n = 5) and old 11–16 yr (n = 16). For statistical analysis, crop sites were categorized according to the age of their paired CRP counterpart.

‡ Within columns and paired categories for statistical analysis (CRP vs. crops), levels not connected by the same letter are significantly different (LSD 0.05).

tested with ANOVA, no significant differences were found in the 0- to 5- and 5- to 10-cm layers, but statistically significant differences existed between the young age grouping and the mid- and old-age groupings in the 10- to 25- ($P = 0.003$) and 0- to 25-cm ($P = 0.035$) depth increments. The TN for the young prairie age grouping, when applied to the adjacent cropped sites, was approximately 60 and 30% less than the mid- and old-age groupings in the 10- to 25- and 0- to 25-cm layers, respectively. Statistically significant increases in TN stocks attributed to conversion of agricultural land to CRP were detected on Mollisols in the 0- to 5-cm soil layer, and for the young prairie age grouping (Table 4).

A general observation was that greater variability (CV) of SOC storage on Alfisols existed for both CRP and crop management practices compared with Mollisols, by approximately a factor of 2:1 (Table 2). Furthermore, the amount of between-site variation increased with sampling depth for Alfisols for both crop and CRP management, but this observation was not reproduced among samples collected on Mollisols. Increased variability among Alfisols may be a result of a greater sample size or properties of the soil order itself. Otherwise, these findings may suggest that the soils in the plow layer (e.g., samples down to a 10-cm depth) that have been continually tilled and mixed have more consistent properties than soils below the Ap zone. The fact that the differences in variation (as a function of soil depth) are still present in CRP soils regardless of ecosystem age or soil order may suggest that the impacts of past agricultural land management are still evident. Among the 39 paired sites sampled, however, the amount of variation in TN storage was less on CRP land than on the adjacent cropland—particularly in the 0- to 10-cm soil depth interval (Table 4). Even though planted prairie age appeared to have a significant effect on CRP TN storage in the 10- to 25- and 0- to 25-cm depth intervals, significant differences also existed on cropland at these depths when the crop sites were categorized according to CRP age; thus, the observed differences on CRP land cannot be attributed solely to prairie age and were more likely a result of the experimental design (Table 4).

Soil Carbon/Nitrogen Ratio

Soil C/N ratios were analyzed to determine whether soil order, soil depth, ecosystem age, and land use (CRP vs. cropland) were responsible for observed differences. On CRP land, soil order did not significantly effect C/N, and soil depth did not effect soil C/N within each soil order grouping (Table 5). Ecosystem age also did not independently contribute to statistically significant differences in soil C/N on CRP land in the 0- to 5- and 5- to 10-cm layers, but a significant difference was detected between young-aged ($n = 18$) prairie restorations and the oldest planted prairies ($n = 16$) in the 10- to 25-cm layer (Table 5). The combined effect of soil order and prairie age explained observed differences at the 10% statistical level ($P = 0.059$) in the 0- to 5-cm layer. Soil depth did not contribute significantly to the observed differences in soil C/N. On cropped

Table 5. Carbon/nitrogen ratios of Conservation Reserve Program (CRP) soils and cropped soils as a function of depth by soil order and prairie age for depth increments of 0 to 5, 5 to 10, and 10 to 25 cm.

Categorization†	df	*n*	0–5 cm			5–10 cm			10–25 cm		
			C/N	*P*‡	CV	C/N	*P*	CV	C/N	*P*	CV
					%			%			%
						CRP					
Alfisols	24	25	10.61 Aa§	0.026	8.0	10.61 Aa	0.067	9.6	10.68 Aa	0.881	19.1
Mollisols	12	13	10.38 Aa	0.631	9.2	10.53 Aa	0.440	14.4	10.56 Aa	0.158	13.6
Young (4–5yrs)	17	18	10.48 Aa	0.277	6.8	10.74 Aa	0.390	11.6	11.31 Aa	0.813	17.6
Mid (6–10 yr)	4	5	10.93 Aa	0.230	14.2	11.36 Aa	0.105	14.5	11.17 ABa	0.082	12.6
Old (11–16 yr)	15	16	10.56 Aa	0.676	8.4	10.31 Aa	0.590	10.3	9.8 Ba	0.059	14.5
CRP averages	38	39	10.57 a	0.108	8.5	10.64 a	0.297	11.7	10.67 a	0.414	17.1
Source of variation among all CRP sites, ANOVA *P* > *F*											
Soil order (O)	2			0.485			0.958			0.952	
Age (A)†	2			0.589			0.068			0.014	
O • A	4			0.059			0.115			0.612	
						Crops					
Alfisols	25	26	9.96 Aa		5.7	10.03 Aa		5.4	10.37 Aa		16.0
Mollisols	11	12	10.81 Ba		8.5	11.02 Ba		9.9	12.51 Ba		29.6
Young CRP	17	18	10.21 Aa		7.8	10.42 Aa		9.3	11.76 Aa		28.9
Mid CRP	4	5	9.76 Aa		5.3	9.85 Aa		4.3	9.41 Ba		6.4
Old CRP	15	16	10.42 Aa		7.8	10.44 Aa		8.0	10.84 ABa		14.7
Cropped averages	38	39	10.24 a		7.7	10.36 ab		8.4	11.08 b		23.6
Source of variation among all crop sites, ANOVA *P* > *F*											
O	2			0.002			0.001			0.011	
A†	2			0.804			0.426			0.161	
O • A	4			0.570			0.763			0.870	

† Three age categories were established: young were enrolled for 4–5 yr at time of sampling ($n = 18$), mid-aged 6–10 yr ($n = 5$) and old 11–16 yr ($n = 16$). For statistical analysis, crop sites were categorized according to the age of their paired CRP counterpart.

‡ *P* values that are reported for individual soil orders and age groupings represent the results of tests of significance comparing CRP and crop soils.

§ Within CRP and crop groupings of the two soil orders and three age categories, levels not connected by the same uppercase letter in each column are significantly different (LSD 0.05). Across rows (three soil layers), levels not connected by the same lowercase letter are significantly different (LSD 0.05).

land, soil order had a significant effect on soil C/N at all depths, as Mollisols had higher soil C/N than Alfisols at each depth interval (Table 5). Soil depth did not have a significant effect on soil C/N within individual soil orders or age groupings, but significant differences were apparent between the 0- to 5- and 10- to 25-cm depths for the aggregated values across all 39 sites (Table 5). The prairie ecosystem age groupings did not significantly contribute to observed differences in cropland soil C/N. Significant differences between CRP and cropland soil C/N existed in the 0- to 5-cm layer (P = 0.016) and 5- to 10-cm layer (P = 0.06) for the Alfisol order grouping. Across the 35 paired sites that had common soil orders between CRP and cropland, significant differences were not apparent due to land management change to CRP at any sampling depth.

Soil Carbon and Nitrogen Sequestration Rates

The vertical distributions of SOC (Table 3) and TN (Table 6) sequestration rates were calculated by taking the net difference in SOC and TN stocks between CRP land and the adjacent cropland sites and dividing by the planted CRP prairie age. Annual sequestration rates were assumed to result from a land-use change from cropping practices to CRP. When the vertical distribution of SOC sequestration rates were analyzed (Table 3), significant differences were only found to exist in the 0- to 5-cm soil depth interval. The grouping of planted prairies across (i) all Alfisols and Mollisols, (ii) the youngest and mid-aged planted prairies on Alfisols, and (iii) the oldest Mollisols yielded significant results. The average annual 0- to 5-cm SOC sequestration rate for all prairies planted on Alfisol soils was lower (−13.2%) than those restorations taking place on Mollisol soils, but the results for the two soil order groupings were not significantly different from each other (Table 3). When annual average SOC sequestration rates (0–5 cm) were analyzed for the three prairie age categories, each grouping produced statistically significant results (P < 0.1), and each group was significantly different from each other (P = 0.05). The average SOC sequestration rates were 71.7 (95% CI 33.9–109.5), 61.2 (95% CI 14.4– 136.8), and 12.7 (95% CI 26.4– 51.7) g C m^{-2} yr^{-1} for the young, mid-aged, and old planted prairies, respectively, in the 0- to 5-cm layer. The result points to a declining average annual rate of SOC sequestration with prairie maturity (Table 3).

Several recent studies have suggested that the rate of soil C sequestration may decline with age as part of prairie restoration efforts (Bruce et al., 1999; Brye and Kucharik, 2003; Post et al., 2004). Brye et al. (2002a, 2002b) even suggested that a 24-yr-old prairie restoration on silt loam soils in southern Wisconsin had done little to build the SOC above levels seen in an adjacent cropped field. Figure 2 summarizes the weak but significant linear relationships that were found in this study between prairie age and the SOC sequestration rate in the 0- to 5-cm layer (r^2 = 0.13, P = 0.031) and 0- to 10-cm soil D_b changes (r^2 = 0.175, P = 0.013) across all of the paired sites (n = 35) used in the analysis.

Investigation of the impact of prairie age within each individual soil order helped to better understand how SOC sequestration rates differed as a function of age and soil formation processes. The young prairies planted on Mollisol soils did not produce a significant result in the 0- to 5-cm layer, but the old planted prairies had statistically significant rates of SOC sequestration (Table 3). The more significant trends were found when age effects were analyzed within the Alfisol soil order. The young (n = 11) and mid-aged (n = 4) prairies had sequestered SOC at statistically significant rates (P < 0.1); the highest rates were associated with the young prairies, with lower average rates for the mid-aged prairies. The old (n = 8) planted prairies on Alfisol soils, however, did not show statistically significant rates of SOC sequestration in the 0- to 5-cm

Table 6. Annual average rates of total soil nitrogen (TN) sequestration based on observed differences between Conservation Reserve Program (CRP) soils and cropped soils grouped by soil order and ecosystem age for depth increments of 0 to 5, 5 to 10, 10 to 25, and 0 to 25 cm.

Soil order and age grouping†	df	n	0–5 cm		5–10 cm		10–25 cm		0–25 cm	
			Mean	$P > F$‡	Mean	$P > F$	Mean	$P > F$	Mean	$P > F$
			g N m^{-2} yr^{-1}		g N m^{-2} yr^{-1}		g N m^{-2} yr^{-1}		g N m^{-2} yr^{-1}	
Alfisol, young	10	11	6.00 a§	0.065	−0.11 a	0.954	−0.27 a	0.948	5.61 a	0.405
Alfisol, mid	3	4	3.16 a	0.388	2.40 a	0.468	−3.01 a	0.470	2.54 a	0.826
Alfisol, old	7	8	−0.51 a	0.428	−1.61 a	0.000	−0.53 a	0.882	−2.65 a	0.367
Mollisol, young	4	5	7.06 a	0.116	0.86 a	0.874	0.64 a	0.877	8.56 a	0.477
Mollisol, old	5	6	3.27 a	0.021	0.05 a	0.833	−0.60 a	0.791	2.73 a	0.319
Alfisols	22	23	3.24 a	0.107	−0.20 a	0.462	−0.84 a	0.574	2.21 a	0.911
Mollisols	10	11	5.00 a	0.003	0.42 a	0.778	−0.04 a	0.868	5.38 a	0.188
Young	15	16	6.33 a	0.012	0.19 a	0.877	0.02 a	0.978	6.54 a	0.248
Mid	3	4	3.16 a	0.388	2.40 a	0.468	−3.01 a	0.470	2.54 a	0.826
Old	14	15	1.14 a	0.133	−0.81 a	0.085	−0.43 a	0.847	−0.11 a	0.965
Cumulative	34	35	3.74	0.002	0.01	0.673	−0.52	0.602	3.23	0.377
Source of variation: TN sequestration rates, ANOVA $P > F$										
Soil order (O)	2		0.407		0.748		0.752		0.578	
Age (A)†	2		0.072		0.671		0.904		0.366	
O • A	4		0.729		0.867		0.879		0.898	

† Three age categories were established: young were enrolled for 4–5 yr at time of sampling (n = 18), mid-aged 6–10 yr (n = 5), and old 11–16 yr (n = 16). For statistical analysis, crop sites were categorized according to the age of their paired CRP counterpart.

‡ Level of statistical significance for differences in TN stocks comparing CRP and crop soils.

§ Within columns and unique groupings (three Alfisol age categories; two Mollisol age categories; two soil orders; three age categories) levels not connected by the same letter are significantly different (LSD 0.05).

layer; maybe more importantly, in the 5- to 10-cm layer for this grouping, the rate of SOC accumulation suggested an average loss of -13.8 g C m^{-2} yr^{-1} (Table 3). Thus, there is some evidence that the rate of SOC sequestration on Alfisol soils may be declining with age more rapidly than on Mollisols, and may be better explained statistically if the sample size for each categorization (soil order or age) were increased in the future with additional sampling. Furthermore, these results also suggest that short-term accumulations of SOC could be lost with time after CRP conversion, or this could be an artifact of the sampling scheme and overall site selection.

As might be expected, the statistical analysis of TN sequestration rates followed some of the same general trends seen in SOC results (Table 6). In general, there were no statistically significant gains in TN observed below 5 cm, and soil order did not have a significant effect on explaining variation in soil N sequestration rates. However, in the 5–10 cm layer for the oldest prairies planted on Alfisols, there was a significant loss of TN over time as the average rate of TN accumulation was–1.61 g N m^{-2} yr^{-1} (Table 6). Furthermore, in the oldest age grouping (n = *15*), there was also a loss of TN with time, significant at the $P < 0.1$ level. The rate of soil N sequestration was only found to be significant in Mollisols (n = 11) and also the youngest prairie age grouping (n = 16) (Table 6). When the impacts of age on TN sequestration rates were tested, the differences between age groupings were found to be significant at the $P < 0.1$ level (Table 6) in the 0- to 5-cm layer, which follows the same general pattern for SOC sequestration rates. The detection of prairie age impacts on TN sequestration rates in the 10- to 25- and 0- to 25-cm layers is confounded by the fact that the sampling scheme preferentially chose sites that had much higher TN stocks for the mid-age and old groupings. Even though this pattern was replicated on both CRP and cropland (adding confidence to the sampling approach), some uncertainty remains as to why these age groups and prairies had elevated TN stocks compared with the young grouping. These data suggest that SOC and TN were being sequestered in the top 5 cm in an average ratio of 12.1 when using the cumulative rates across all sites (45.2 g C m^{-2} yr^{-1} for SOC and 3.742 g N m^{-2} yr^{-1} for TN, respectively). The average rates of SOC and TN sequestration on Alfisols were occurring at a C/N of 13.6 ($P < 0.1$) compared with 9.9 ($P < 0.05$) for Mollisols, but the differences were not significant.

Impact of Sampling Protocol on Results

In this study, CRP and cropland sites were sampled during a 3-yr period to gain a better understanding of how planted prairies consisting of grasses and forbs were contributing to improving soil structure and soil C and N sequestration in southern Wisconsin. Because of time and money limitations, it was only possible to identify a subset of study sites that were representative of the larger CRP program in this local region. Similar obstacles may confront future efforts in other states and regions to quantify rates of soil C and N sequestration to be used in C-crediting programs, so the current approach is not unrepresentative of what may be required. Upon categorizing the original 39 CRP–cropland site pairs as a function of soil order, age, or a combination of both, rather small sample sizes (ranging from 4 to 23) resulted. This undoubtedly compromised the detection of significant differences as a function of each independent variable (Garten and Wullschleger, 1999; Kucharik et al., 2003), but many statistically significant results were still observed. The statistical power of these results, however, would probably be improved if new sites were identified in the future to help fill voids (particularly for prairies planted on Mollisols) where a rather limited number of samples exist. Because of the effect of climate, soil formation processes, and specific CRP management practices, the numerical results of this study are only assumed applicable to the immediate study region.

The calculation of soil D_b changes and soil C and N sequestration rates using a paired-site approach is based on a key assumption: the vertical distribution (to 25 cm) of soil properties, structure, and C and N concentrations were identical in the current cropped and CRP land at the time each prairie was planted. Even though adjacent (cropland–CRP) study sites on similar soil series or soil orders were chosen to minimize differences, this does not completely eliminate the likelihood that differences may have originally existed (Knops and Tilman, 2000; Brye and Kucharik, 2003). The sampling approach also cannot

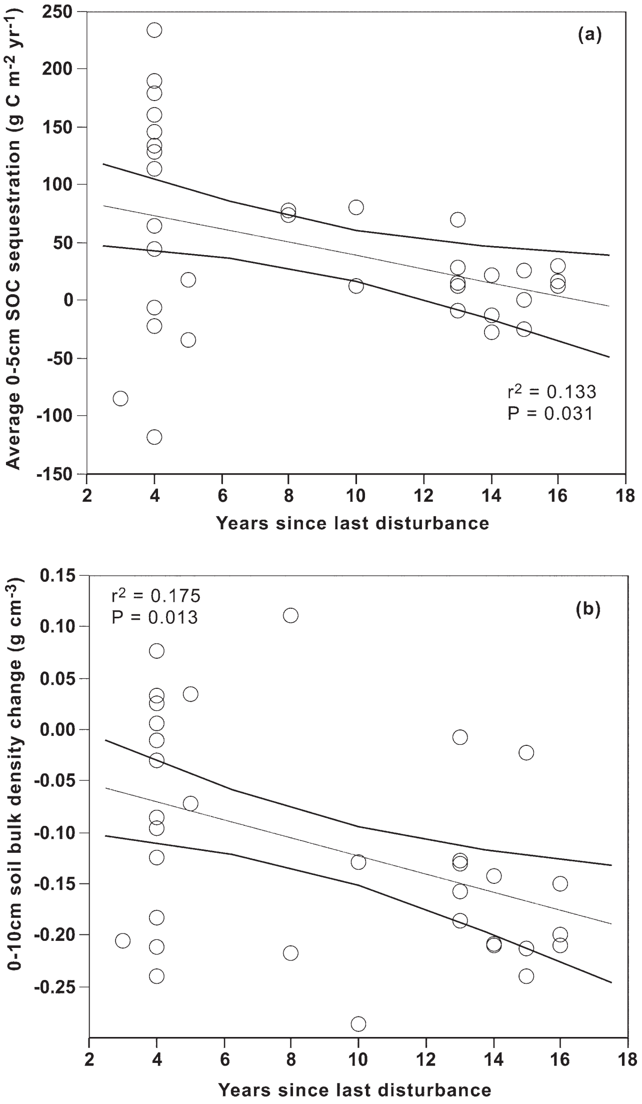

Fig. 2. Changes in (a) soil organic C (SOC) sequestration rate in the 0- to 5-cm layer and (b) soil bulk density at 0 to 10 cm as a function of years since last disturbance for Conservation Reserve Program prairies planted on Alfisols and Mollisols. The center line is the result of the linear regression, and the outside bounding lines represent the 95% confidence interval.

determine the precise "net" changes associated with the land-use change to CRP because the cropped soil properties such as D_b and soil C and N concentrations may have also changed after the prairie restoration was initiated due to a variety of soil, climate, and management factors. In fact, some research suggests that improved crop production and better management in the late 20th century may be helping to create C sinks on current agricultural land (Buyanovsky and Wagner, 1998). Thus, some planted prairies may not show a significant increase in SOC and TN when compared with today's agricultural row crops. In fact, in this study there were a total of 9 of 35 sites that suggested a change to CRP management led to decreased SOC when compared with cropped land SOC stocks in the 0- to 5-cm layer. To help assess future changes to soil C and N as a result of crop vs. CRP land management, each study site has been georeferenced with physical markers and with a GPS so resampling can take place to help resolve some of the aforementioned uncertainty. Future sampling will also assess individual C pools (e.g., labile and recalcitrant) to determine which type of C is being sequestered (Sollins et al., 1999; Bronson et al., 2004).

Nonetheless, the outcomes of this study are significant for the assignment of C credits—and C sequestration forecasting of land management associated with the CRP. While it has been hypothesized that soil types have a significant impact on soil C storage, there have been few reported studies that have investigated the effect of soil order and ecosystem age (restoration) on SOC and soil N recovery. This study suggests that, in the future, we might expect to see similar rates of long-term (>15 yr) SOC and TN sequestration on Alfisols and Mollisols, but more rapid decreases in soil D_b and increases in SOC pools may occur preferentially on Alfisols in this region. Furthermore, it is noted that, depending on how an experimental setup is devised and how soils data are categorized for statistical analysis, the determination of SOC and TN sequestration rates can lead to widely varying results. In this study, SOC sequestration rates varied from ∼25 ± 26 g C m^{-2} yr^{-1} for planted prairies >10 yr old on Mollisols to 68 ± 116 g C m^{-2} yr^{-1} for 4- to 5-yr-old prairies planted on Alfisols, with an average of 45.2 ± 78 g C m^{-2} yr^{-1} across all sites considered. When prairie age groupings were used to calculate SOC rates, they varied from 12.7 ± 25 g C m^{-2} yr^{-1} on the oldest prairies to 71.7 ± 105 g C m^{-2} yr^{-1} on the youngest. Because some categorizations and subsequent statistical analyses suggested that SOC and TN losses occurred over the long term, however, it is possible that the short-term gains could eventually be lost.

The rates of TN sequestration were more widely varying and produced less significant results among the varied statistical groupings that were considered. The overall average rate of SOC sequestration is similar to other previous meta-analyses that have looked at land management effects on SOC accumulations (Post and Kwon, 2000; West and Post, 2002; Post et al., 2004; Johnson et al., 2005). It is possible, however, that cropped land SOC and TN might have also changed during the period that prairies have been growing, and thus not all of the sequestered SOC and TN may be a net gain attributed to conversion of cropland to the CRP. Furthermore, it is also possible that cropped land SOC and TN stocks may have *decreased* during the prairie growth periods, which would cause any net changes attributed to CRP management to be underestimated.

CONCLUSIONS

There were several key outcomes that could be drawn from this study in association with agricultural land conversion to CRP: (i) planted prairies led to a soil D_b decrease on Alfisols but not Mollisols; (ii) SOC sequestration rates were not significantly different between Mollisols (49.7 ± 64 g C m^{-2} yr^{-1}) and Alfisols (43.9 ± 86 g C m^{-2} yr^{-1}), but were only detectable ($P < 0.05$) in the top 5 cm, and whole SOC and TN to a depth of 25 cm did not change significantly with conversion to CRP; (iii) the annual average SOC sequestration rate declined ($P < 0.05$) as prairie age increased (from 72 ± 105 to 13 ± 25 g C m^{-2} yr^{-1} for youngest to oldest age groupings); and (iv) short-term SOC and TN increases with CRP conversion could be lost with time. This last concluding result could be attributed to either the soil sampling scheme or a low number of replicated paired sites in some groupings used in the statistical analysis. Nonetheless, this last point implies that increases in SOC and TN stocks may not always occur or be sustained in the long term in this region of Wisconsin after agricultural land is converted to prairie as part of the CRP.

The next series of important questions to tackle are related to specific effects of varied CRP management practices on soil C and N recovery. It is important to understand whether there is a discontinuity between the level of continuing management that is needed to build what are considered good representations of native ecosystems, and the amount of resources that the CRP has to achieve this type of ecosystem functioning. It is possible that more intensely and properly managed high-production agricultural row crop systems could have a greater potential to sequester C at a faster rate than low-management-intensity CRP prairie plantings. A review by Johnson et al. (2005) reported that rates of SOC sequestration (∼40 g C m^{-2} yr^{-1}) associated with no-tillage agriculture (compared with conventional tillage) in the central USA were comparable to the overall average rates of annual sequestration associated with this study of the CRP. This doesn't necessarily mean, however, that these same rates could be attained on highly erodible or degraded CRP land because crop productivity would probably be lower. Because of low follow-up management intensity on the CRP (e.g., burning and control of invasive species), rates of C sequestration may be declining with time as the quality of prairie degrades and becomes less representative of the native ecosystem that was once present that contributed to the original, millennia-time-scale buildup of large storage pools of soil C and N.

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