

Soil Organic Carbon Beneath Croplands and Re-established Grasslands in the North Dakota Prairie Pothole Region

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Abstract Grassland ecosystems established under the conservation reserve program (CRP) in the Prairie Pothole Region (PPR) currently provide soil conservation and wildlife habitat services. We aimed to determine if these lands also sequester soil organic carbon (SOC), as compared with neighboring croplands across multiple farms in the North Dakota PPR. We sampled soil from small plots at 17 private farms in the central North Dakota PPR, where long-term (≥ 15 years) grasslands managed under the CRP were paired with neighboring annual croplands. Cores were collected to 100 cm and split into 0–10, 10–20, 20–30, 30–40, 40–70, and 70–100 cm soil depth layers. We hypothesized the effect of land use on soil organic carbon (SOC), root carbon (C), and bulk density would be greatest near the surface. For 0–10 and 10–20 cm layers, grasslands managed under the CRP were lower in bulk density and higher in SOC. From 0 to 70 cm, grasslands managed under the CRP were higher in root C. Average (\pm standard error) SOC for re-established grasslands and croplands was 25.39 (0.91) and 21.90 (1.02), respectively, for the 0–10 cm soil layer and 19.88 (0.86) and 18.31 (0.82), respectively, for the 10–20 soil layer. Compared to croplands, re-established grasslands sampled in the North Dakota PPR were 3–13 % lower in bulk density and 9–16 % higher in SOC from 0 to 20 cm, while root C was 2–6 times greater from 0 to 70 cm.

Keywords Conservation reserve program (CRP) · Soil depth · Inorganic carbon · Land-use change · Carbon sequestration · Root carbon

Introduction

The U.S. Department of Agriculture Farm Services Agency (USDA-FSA) began administering the Conservation Reserve Program (CRP) in 1985 as a way to improve water quality, reduce soil erosion, and enhance wildlife habitat by establishing perennial vegetation on low-productivity agricultural lands for a 10–15 year time period. The CRP has continued, with over 12 million ha of land enrolled in the CRP as of 2012 (USDA-FSA Staff 2012). Conversion of former croplands to minimally disturbed grasslands managed according to the CRP guidelines has greatly enhanced wildlife habitat in the Prairie Pothole Region (PPR), where habitat is a critical ecosystem service supporting North American bird populations (Johnson et al. 2005). Re-established grasslands may also provide additional ecosystem services, such as carbon (C) sequestration, because of the high potential to store soil organic carbon (SOC) belowground (Gebhart et al. 1994; Reeder et al. 1998; Schlesinger 1999).

In recent years, high grain prices have contributed to conversion of grasslands previously enrolled in the CRP to annual croplands (Wright and Wimberly 2013). Between 2007 and 2009, more than 350,000 ha of CRP in North and South Dakota were converted from CRP to cropland, and North Dakota ranked second among the 50 states with respect to rates of CRP conversion in 2012 (USDA-FSA Staff 2012). The PPR provides valuable ecosystem wildlife habitat services (Johnson et al. 2005), and extensive CRP grasslands in the region help alleviate habitat fragmentation

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(Stephens et al. 2003). The value of additional ecosystem services, such as carbon sequestration, is now being considered (Ducks Unlimited Staff 2013). Carbon credit programs provide an avenue to ‘offset’ C emissions through purchase of C stored belowground. These programs, however, require accurate SOC inventory data to make appropriate market valuations associated with particular land uses (Cahill et al. 2009). Reliance on SOC models in the absence of soil data collected in the field could lead to inaccurate SOC estimates (Cahill et al. 2009).

Belowground allocation patterns in grasslands contribute significantly to soil C, so grassland re-establishment is expected to result in SOC accrual over the course of several years (Gebhart et al. 1994; Post and Kwon 2000; Robles and Burke 1997; Wiesmeier et al. 2012). Published estimates of SOC stocks in the Northern Great Plains indicate the potential for carbon sequestration beneath re-established grasslands managed under the CRP. In Wyoming, Reeder et al. (1998) observed SOC stocks of 30 Mg C ha⁻¹ beneath CRP grasslands in the upper 10 cm as compared to 22 Mg C ha⁻¹ for croplands. In Idaho, León and Johnson-Maynard (2013) observed SOC stocks of 25 Mg C ha⁻¹ in the upper 10 cm and 20 Mg C ha⁻¹ in the 10–20 cm soil layer for CRP grasslands. These stocks were comparable to adjacent native prairie. Additional comparisons are needed in the Northern Great Plains near the 100th meridian, where conversion of grasslands to croplands is occurring at a rapid rate (Wright and Wimberly 2013). Carbon sequestration potential varies spatially, so there is a need for regional SOC stock data across a spectrum of farms, soils, and management practices (Kucharik et al. 2001, 2003; Smith et al. 2012). Studies reporting multiple-farm data, to the best of our knowledge, are limited in the Northern Great Plains PPR.

Most reports of SOC stocks following land-use conversion are largely focused on near-surface soils, where samples are often collected to 20 or 30 cm soil depths (Anderson and Bowman 2002; Bronson et al. 2004; Cahill et al. 2009; Norton et al. 2012). This is largely because significant SOC losses are expected within the surface layers when grasslands are converted to crops, reportedly ranging from 20 to 40 % in parts of the Central and Northern Great Plains (Aguilar et al. 1988; Davidson and Ackerman 1993). However, it is not clear to what depth C lost through cultivation is regained under long-term (≥ 15 years) CRP management in the PPR. Deeper soil layers (> 30 cm) may be important when evaluating the influence of land management on carbon accumulation because the physical and biological soil environment is altered by deep-rooted perennial grass species (Bell et al. 2012; Orgill et al. 2014; Schimel et al. 1985; Wang et al. 2008), and leaching and/or vertical soil mixing from tillage could re-distribute SOC deep in the soil profile (Aguilar

et al. 1988). Bell et al. (2012) reported 30–40 % of excess C found beneath re-established grasslands occurred in sub-soil. As such, surface and sub-soil data are needed before making generalizations about land use and depth of SOC stocks (Jandl et al. 2014).

If grasslands re-established under the CRP sequester C, then greater SOC stocks beneath CRP lands (relative to cropland) are expected across multiple farms within a physiographic region (Kucharik et al. 2003; Norton et al. 2012). We aimed to determine if there was evidence to support this expectation for farms in production in the PPR by comparing crop and CRP lands. Kucharik et al. (2003) evaluated this question using land-use pairs in Wisconsin, where grasslands had been managed under the CRP for at least 8 years. Here, we use a similar approach in the PPR, except that we use land-use pairs managed under the CRP for at least 15 years. Like Kucharik et al. (2003) and Anderson and Bowman (2002), we also measure soil particle sizes and pH to ensure land-use pairs were comparable with respect to these physical attributes. Bulk density and soil inorganic carbon (SIC) data are needed to convert percent C measurements to mass of C per unit volume for organic C only. Root data are important for identifying patterns between SOC and root C distributions with depth (Gill et al. 1999). We expected lower bulk density in grasslands because root mass would be greater and there would be less compaction by heavy machinery (Kucharik et al. 2003; Norton et al. 2012). We hypothesized that greater SOC and root C stocks, and lower bulk density would be observed beneath re-established grasslands managed under the CRP, as compared with adjacent croplands, across multiple sites in the North Dakota PPR. We expected land-use differences to vary with soil depth (land use \times depth interaction), with greatest differences in SOC, root C, and bulk density for layers nearest to the soil surface (Gill et al. 1999; Jobbagy and Jackson 2000). Understanding the mass of SOC per unit area with respect to management is fundamental to carbon sequestration programs in the PPR. Further, knowledge of where SOC changes are most likely to occur following grassland re-establishment is important to managers interested in retaining soil carbon for economic and/or soil quality benefits.

Materials and Methods

Area of Interest

The PPR is 77.8 million ha in total area and 12.8 million ha of the PPR is located in North Dakota. Nested inside the PPR is the Missouri Coteau, where Pothole wetland density (12–15 wetlands km⁻¹) and waterfowl breeding activity is

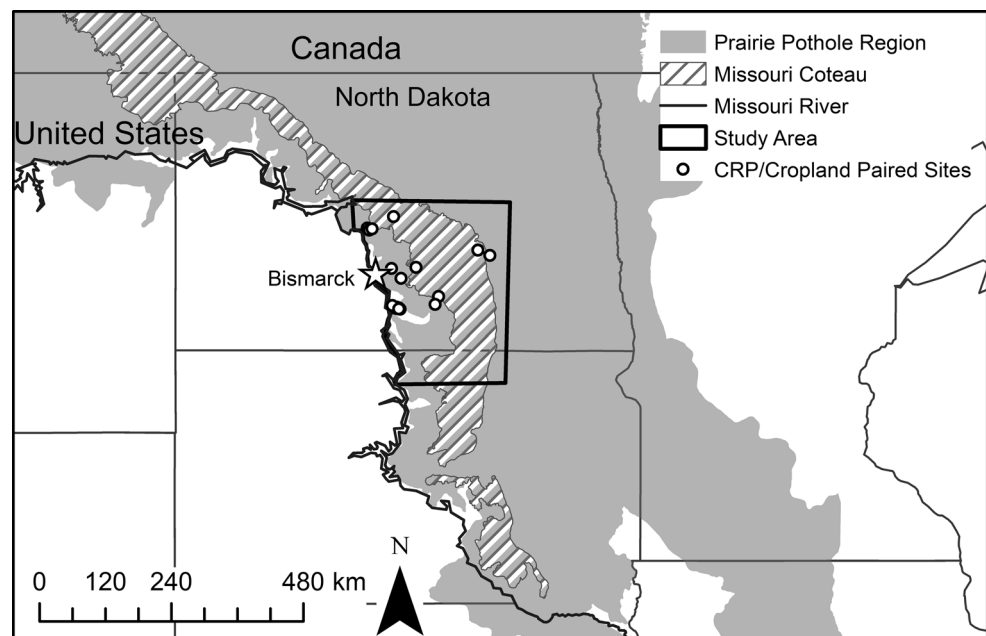
notably higher than in other sections of the PPR (Beeri and Phillips 2007). These agricultural wetland ecosystems provide water quality, wildlife habitat, and food production services (Johnson et al. 2005). We delineated a 2.9 million ha area of interest (AOI) with a center point near Steele, North Dakota (Fig. 1). Approximately 7 % of the area was enrolled in CRP during the 1990 s, as compared with 4 % in 2012 (USDA-FSA Staff 2012). The AOI lies within the Northwestern Glaciated Plains ecoregion (Omernik 1987), where kettle holes, kames, and moraines are common among gently rolling continental glacial till plains. Vegetation for this region is commonly a mix of western wheatgrass [*Pascopyrum smithii* (Rydb.) A. Love], needle-and-thread [*Hesperostipa comata* (Trin. and Rupr.) Barkworth], green needlegrass [*Nassella viridula* (Trin.) Barkworth], and blue grama [*Bouteloua gracilis* (Willd. Ex Kunth) Lag. Ex Griffiths], as described by Barker and Whitman (1988). Long-term (30 years) weather within the AOI varied between northwest and southeast corners, so weather data for both stations are reported. Average annual rainfall was 430 mm in the northwest (48°20′45″N, 100°24′18″W) and 494 mm in the southeast (45°46′19″, 99°38′25″W), while average annual temperature ranged from 10° to 12°, respectively (Menne et al. 2013). Land use is predominantly agricultural, with 50 % in annual crop production and 20–30 % in grass production. The remaining 20–30 % of land area is covered by wetlands, shrub-woodlands, and anthropogenic structures (Strong et al. 2005). Conservation Reserve Program enrollment requires seeding fields to perennial grasses, typically mixtures of smooth brome [*Bromus inermis* (Leyss.)], crested wheatgrass [*Agropyron cristatum* (L.)], western

wheatgrass, needle-and-thread, and alfalfa (*Medicago sativa*) species (USDA-FSA Staff 2012). Qualification for CRP enrollment includes a land-use history of cropping and highly erodible soils. Lands enrolled in the CRP are not fertilized, are generally left undisturbed, and not grazed by livestock. Regulations do allow grass harvest approximately every 3–5 years in autumn. Failure to comply with regulations will result in forfeit of government payments.

Study Sites Selection and Sampling

We stratified the AOI into cropland and grassland production areas using the major land-use resource area map (Soil Survey Staff 2006) and soil survey data (Soil Survey Staff 2010). We queried the database to select areas where (a) perennial grasslands adjoined croplands and (b) soil series for the two land uses were identified within the same soil series (Soil Survey Staff 2006). Points were located near a road or section line where the two land uses were nearest to each other (not to exceed 100 m). Over 100 candidate paired sites in the AOI were identified and needed additional evaluation to determine pair suitability. First, we needed to contact landowners and request permission to access farms. Attempts to contact landowners were often unsuccessful, and permission requests by phone were often denied. Permission was usually granted following direct communication with land owners. We then needed to navigate to each point and identify small plots (10 × 5 m) where landscape positions were similar within each land use. We used one plot per land-use pair. Similar to Reeder et al. (1998), relatively flat terrain (<5 % slope)

Fig. 1 Map of study area, located in south-central Missouri Coteau section of North Dakota within the Prairie Pothole Region, USA. Farms sampled are denoted within study area bordered by the Missouri river to the west



was selected so as to avoid confounding erosional factors of soil loss or deposition, and soil water differences due to runoff or runoff. Paired plots were located at least 30 m from nearby structures, roads and fences, and were physically <80 m from each other. Landscape position criteria were met at only 17 of the 20 farms where access was granted.

Land Management

Management under the CRP is strictly regulated, so re-established grasslands at all sites were managed similarly. Cropland management varied, with the exception that crop residue at all sites was allowed to remain standing over-winter and tillage (if any) occurred in spring. Farms were grouped together according to major management classes (Fig. 2). At sites numbered one through five, no-till drills or air-seeders were used for planting, and were classified as no tillage. At sites numbered six through eight, soils were lightly disked or cultivated (<5 cm depth) prior to seeding and were classified as reduced tillage. At sites numbered nine through 11, soils were occasionally chisel-plowed from 12 to 20 cm deep and were classified as high tillage. One high-tillage cropland site (number 12) was certified organic, and chisel plowing was needed every 3 years to incorporate green manure. Moreover, manure was applied in autumn. This site was classified separately as organic. The 12 cropland sites described above had a long history of cropping (>30 years).

Sites numbered 13 through 17 were more recently converted from long-term CRP grassland (≥ 15 years) to

cropland in the last 2–4 years. Previous CRP grassland soils were extensively worked and fertilized as part of the conversion from grassland to cropland. Following conversion to annual cropping, crop residue was allowed to remain standing over-winter and tillage was minimal. Since these were recent conversions (from grasslands to croplands), they are classified separately.

All croplands sampled were in the business of grain production and all except the organic farm occasionally used synthetic fertilizers, with rates varying from 0 to 80 kg N ha⁻¹. Crop rotations including spring wheat, sunflower, oats, and corn were most common. None of the farms sampled were irrigated. For re-established grasslands, producers followed CRP guidelines, where they harvested grass in autumn approximately every 4 years.

Soil Measurements

Soils were collected during 2013 using truck-mounted, hydraulically operated coring equipment (Giddings Machine Co., Inc, Windsor, CO). Seven pairs were sampled in spring, prior to working the soil and ten pairs were sampled in autumn because of the limited time window between physical access and sowing during this unusually wet spring. Difference in sampling season could have an effect on bulk density and root C near the surface, so differences between pairs were plotted over time to visually assess potential biases associated with season of collection. The data indicated that time of sampling did not need to be included as a covariate in the statistical analyses (Fig. 3). Within each farm and land use, three cores (4.3 cm diameter) were collected at random from plots (identified in Sect. [Study sites selection and sampling](#)) at least 3 m apart from each other and between crop rows. Three cores were collected to include variance within plots for key variables directly affecting soil C stocks: SOC, SIC, and bulk density. The three cores were composited by depth for additional measurements of soil particle sizes, pH, and root mass. Before coring, grass plants were clipped to ground level and litter was removed from the soil surface. Cores were collected at 0–10, 10–20, 20–30, 30–40, 40–70, and 70–100 cm, and bulk density was measured for each core. Preliminary core tests indicated coring continuously to 1 m resulted in variable levels of compaction, depending on soil and environmental conditions. Compaction was avoided during this 6-month field campaign by targeting 10-cm cores for the top 40 cm, and 30-cm cores below 40 cm. Each sample was saved in a plastic bag and placed in cold storage at 5 °C until processing, which occurred within 4 days of core collection.

Soil samples were dried at 35 °C for 3–4 d and ground by hand to pass a 2.0-mm sieve. Water content was determined for a 30 g subsample by measuring the difference in mass before and after drying at 105 °C for 48 h. We

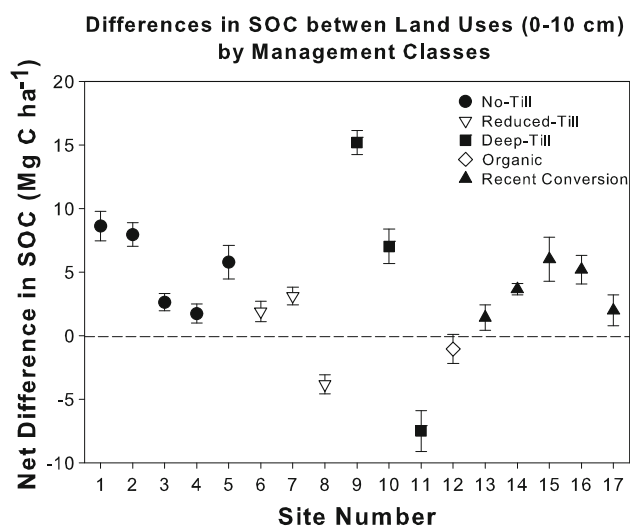


Fig. 2 Net average (\pm standard error) difference between land uses for SOC at each site classified by major management group (see methods). Average (3 cores per farm and land use) cropland SOC (0–10 cm) at each site was subtracted from average re-established grassland SOC (0–10 cm)

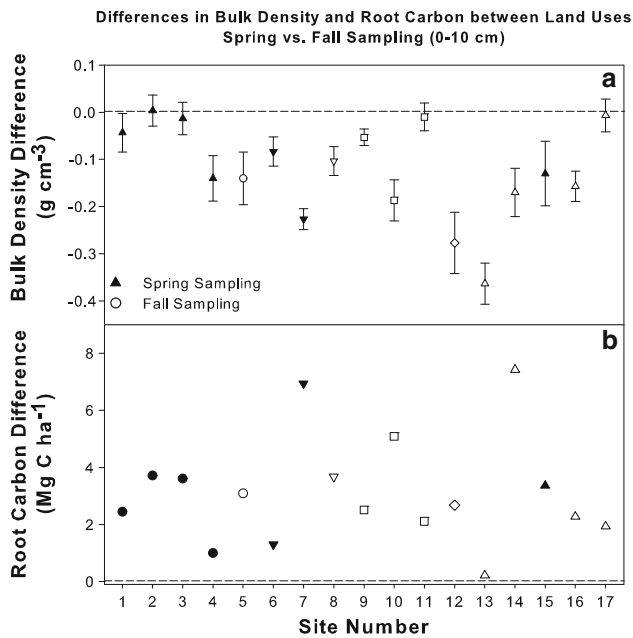


Fig. 3 Net average (\pm standard error) difference between land uses for bulk density (a) and root carbon (b), where filled symbols represent cores collected in spring and open symbols in autumn. Major management groups are defined by symbols according to Fig. 2 legend. Average cropland data (0–10 cm) were subtracted from re-established grassland data (0–10 cm). No error bars are depicted in 3b because three cores were composited for each farm and land use for measurements of root C

measured SOC, (SIC), and bulk density for each individual core, while soil particle size, pH, stone, and root mass were measured using composites (all three cores) collected at each sample plot. Samples were analyzed for total C by dry combustion on soil ground to pass a 0.106-mm sieve (Nelson and Sommers 1996). Using the same fine-ground soil, inorganic C was measured by quantifying the amount of CO_2 produced using a volumetric calcimeter after application of dilute HCl stabilized with FeCl_2 (Loeppert and Suarez 1996). Soil organic C was calculated as the difference between total C and inorganic C. Subtraction of carbonates was required for each sample to ensure SOC data did not include SIC. The standard error of analysis for SOC, evaluated using three replicate subsamples at 0–10, 10–20, and 20–30 cm depths for 18 cores, ranged from 0.02 to 0.13 %. Following this analysis, only one laboratory sample per core and depth was analyzed for SOC. Gravimetric data were converted to a volumetric basis for each sample using field-measured soil bulk density (Blake and Hartge 1986). Soil pH was measured with an electrode (Model 9107 and Orion 4-Star, Thermo Scientific, Beverly, MA, USA) in 1:5 soil:deionized water mixtures at each depth after equilibrating 1 h. During the sieving process, roots were manually removed, washed with deionized water and then dried at 55 °C for at least 24 h before

determination of dry weight. Root C content was determined on dried, ground roots by combustion analysis, similar to C and N. Soil texture was determined hydrometrically (Gee and Bauder 1986), and bulk density was calculated as the quotient of oven-dried mass divided by core volume and was corrected for stone content. Concentration data (g kg^{-1} dry soil) were multiplied by bulk density and sampling depth (soil layer thickness) to convert SOC, SIC, and root C to an area basis (Mg ha^{-1}) for fixed-depth comparisons (Elbert and Bettany 1995).

Statistical Analysis

A linear mixed model was used to compare soil variables (SOC, SIC, bulk density, root C, pH, sand, silt, and clay) between land-use types and across soil depths. Individual cores collected within each farm and land use were not independent, so a nested hierarchical model was used, with core as subject nested within farm and land use (Littell et al. 1996). Depth was the repeated factor, and residual variance–covariance among depths was modeled as a first-order autoregressive heterogeneous covariance structure (Gill et al. 1999; León and Johnson-Maynard 2013). Depth, land use, and the interaction between land use and depth were modeled as fixed effects. Farm site was treated as a random effect. We tested for the fixed effects of land use, depth, and their interaction using F-tests based on the fitted model. Post hoc comparisons were determined using Tukey's multiple comparison tests. Log transformations were employed when data did not meet the assumptions of normality. All statistical analyses were performed using SAS Version 9.3 (SAS System for Windows, copyright© 2002–2013, SAS Institute Inc., Cary, NC, USA) and the significance level was set to $\alpha = 0.05$.

Results

Soil Variables

The effect of land use on SOC varied with depth (depth \times land use interaction; $P < 0.001$). Tukey-adjusted, post hoc comparisons by depth indicated SOC stocks were greater near the surface (at 0–10 and 10–20 cm) beneath re-established grasslands (Fig. 4). Average [\pm standard error (SE)] SOC in the upper 10 cm was 25.39 (0.91) Mg ha^{-1} for CRP and 21.90 (1.02) Mg C ha^{-1} for cropland, for a net difference of 3.48 Mg C ha^{-1} . Average SOC in the 10–20 cm soil layer was 19.66 (0.86) for CRP and 18.31 (0.82) for cropland, for a net difference of only 1.57 Mg C ha^{-1} (Table 1). Below 20 cm, SOC declined sharply and values were similar for both land uses (Fig. 4). The upper 20 cm contained 49 % of the total SOC to 1 m for

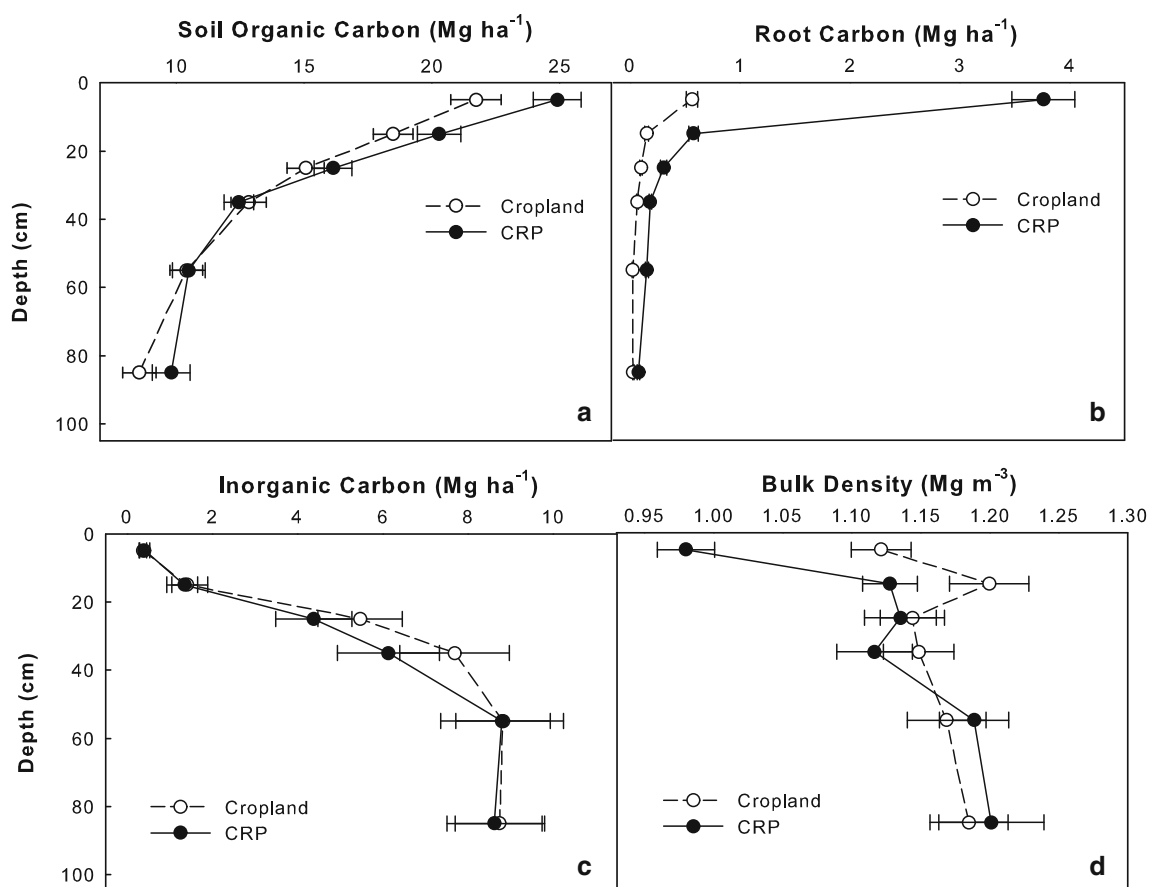


Fig. 4 Mean (\pm standard error) soil organic carbon (a), root carbon (b), soil inorganic carbon (c), and bulk density (d) for croplands versus CRP grasslands

Table 1 Mean (\pm standard error) soil particle sizes (sand, silt and clay), pH, root carbon, soil organic carbon (SOC), soil inorganic carbon (SIC) and bulk density for croplands and re-established grasslands by soil depth increment

Depth (cm)	Land use	Sand (g kg ⁻¹)	Silt (g kg ⁻¹)	Clay (g kg ⁻¹)	pH	Root C (Mg ha ⁻¹)	SOC (Mg ha ⁻¹)	SIC (Mg ha ⁻¹)	Bulk density (Mg m ⁻³)
0–10	Cropland	702 (41)	223 (29)	75 (22)	6.72 (0.16)	0.52 (0.08)	21.90 (1.02)	0.38 (0.08)	1.12 (0.02)
	CRP	710 (42)	211 (35)	79 (21)	6.76 (0.11)	3.66 (0.45)	25.39 (0.91)	0.43 (0.13)	0.98 (0.02)
10–20	Cropland	645 (45)	250 (29)	106 (25)	6.97 (0.12)	0.15 (0.03)	18.31 (0.82)	1.52 (0.52)	1.20 (0.03)
	CRP	590 (55)	308 (51)	102 (24)	6.95 (0.14)	0.57 (0.08)	19.88 (0.86)	1.37 (0.32)	1.13 (0.02)
20–30	Cropland	633 (48)	247 (29)	120 (38)	7.31 (0.13)	0.10 (0.02)	14.64 (0.72)	5.83 (1.05)	1.14 (0.02)
	CRP	618 (52)	253 (29)	130 (35)	7.20 (0.16)	0.32 (0.05)	15.86 (0.76)	4.66 (0.95)	1.14 (0.03)
30–40	Cropland	625 (59)	231 (33)	144 (41)	7.45 (0.14)	0.06 (0.01)	12.66 (0.69)	8.22 (1.36)	1.15 (0.03)
	CRP	620 (62)	237 (31)	143 (49)	7.38 (0.15)	0.19 (0.02)	12.37 (0.57)	6.48 (1.25)	1.12 (0.03)
40–70	Cropland	656 (65)	223 (33)	121 (44)	7.60 (0.12)	0.03 (0.01)	10.75 (0.73)	9.35 (1.19)	1.17 (0.03)
	CRP	682 (64)	203 (39)	115 (40)	7.56 (0.11)	0.16 (0.03)	10.76 (0.70)	9.50 (1.57)	1.19 (0.02)
70–100	Cropland	632 (68)	238 (36)	130 (43)	7.70 (0.15)	0.03 (0.01)	8.82 (0.70)	9.15 (1.13)	1.19 (0.03)
	CRP	693 (80)	207 (44)	101 (48)	7.81 (0.08)	0.09 (0.02)	9.86 (0.77)	9.32 (1.21)	1.20 (0.04)

re-established grasslands and 46 % for croplands. Average (SE) total SOC to 1 m was 87.08 (4.68) Mg C ha⁻¹ for cropland and 94.12 (4.57) Mg C ha⁻¹ for re-established grassland. The average difference between land uses for the soil profile to 1 m was 7.04 Mg C ha⁻¹.

The effect of land use on bulk density also varied with depth (land use \times depth interaction; $P < 0.001$). Similar to SOC, post hoc comparisons indicated differences with land use occurred only at the 0–10 and 10–20 cm soil layers (Fig. 4; Table 1). Bulk density beneath grasslands

managed under the CRP was 13 % lower than cropland bulk density for the 0–10 cm soil layer and 6 % lower for the 10–20 cm soil layer (Table 1). Soil inorganic C did not vary with land use at any depth but significantly increased with depth ($P < 0.0001$), with the greatest SIC deeper in the profile (Fig. 4; Table 1). Near the surface, SIC was $<1 \text{ Mg ha}^{-1}$, but below 40 cm, SIC was $>9 \text{ Mg ha}^{-1}$. The effect of land use on root C also varied with depth (depth \times land use interaction; $P < 0.0001$), with greater differences in root C nearest to the surface (Fig. 4; Table 1). Post hoc comparisons by depth indicated root C was significantly greater for CRP grasslands to 70 cm. The upper 20 cm contained 90 % of the total root C to 1 m for re-established grasslands and 76 % of the total root C for croplands (Fig. 4).

Land use did not significantly affect pH or particle sizes, and trends with depth were similar for sand, silt, clay, and pH (Table 1). Across all sites and depths, sand content ranged from 590 to 702 g kg^{-1} , while silt ranged from 207 to 308 g kg^{-1} , and clay ranged from 75 to 144 g kg^{-1} . Soil pH ranged from 6.72 to 7.81. While sand, silt, clay, and pH did not vary with land use, pH and particle sizes varied with soil depth. There was a significant effect of depth for pH ($P < 0.0001$), sand ($P < 0.005$), clay ($P < 0.01$), and silt ($P < 0.05$). Within the 1 m soil profile, sand content was greatest at 0–10 cm, silt content was greatest at 10–20 cm, and clay content was greatest at 30–40 cm soil layers (Table 1).

Land Management

Figure 2 depicts the difference in SOC stocks with respect to land use and management classification groups described in methods, while Fig. 3 depicts differences in bulk density and root C with respect to land use and timing of soil collection for the 0–10 cm soil layer. If re-established grasslands were all greater in SOC than croplands, then these data would all be positive (Fig. 2). While no-till and reduced-till sites tended to be higher in SOC, we observed one reduced-till and one deep-till site with higher SOC than CRP grassland. The SOC for the organic cropland-CRP pair were similar, and all recently converted cropland pairs were lower in SOC than CRP grasslands. Conservation reserve program grassland bulk density was similar or lower than cropland bulk density (Fig. 3a), while CRP root C was greater (Fig. 3b). We found no evidence that timing of soil collection affected differences in bulk density or root C.

Discussion

The data reported here indicate conversion of cropland to perennial grassland under the CRP does increase SOC in the central North Dakota PPR (Fig. 4), despite variations in

cropland management (Fig. 2). We report 16 % greater SOC for the 0–10 cm layer and 9 % greater SOC for the 10–20 cm layer (Table 1). For the sites sampled in our study region, variances in soil particle sizes between CRP grasslands and croplands were similar for each soil layer, with average particle size distributions (Table 1) indicating loamy sand to sandy loam textures (Soil Survey Staff 1993). The positive effect of grassland re-establishment on SOC is reportedly greater for sandy loam soils, as compared to clay loam soils (Reeder et al. 1998). Reeder et al. (1998) found rapid re-establishment of SOC in the surface 10 cm within 5 years following conversion from cropland to grassland for sandy loam soils at a Wyoming experimental site, with 40 % greater SOC beneath grasslands. In that case, deep plowing induced vertical mixing of the A and B horizons, so cropland SOC increased with depth (Reeder et al. 1998). Here, we found SOC was greatest near the surface, and SOC steadily declined to 40–50 cm depth for both land uses (Fig. 4). Differences in the depth distribution between the Reeder et al. (1998) study and this study are likely due to the adoption of minimum tillage practices observed on farms in production. Our results indicate higher SOC differences between land uses than those reported by Kucharik et al. (2003). Kucharik et al. (2003) sampled silt loam soil at 14 farm pairs in Wisconsin and found an average of 32 Mg C ha^{-1} beneath CRP grasslands and 30 Mg C ha^{-1} beneath croplands in the surface 10 cm. Similar to Kucharik et al. (2003) and Norton et al. (2012), we also observed significantly lower bulk density near the surface (0–20 cm) beneath these long-term CRP grasslands, which is expected for perennial grasslands where root density is high (Ampleman et al. 2014; Gill et al. 1999).

Distributions of SOC and root C are closely aligned and known to vary with climatic region (Jobbagy and Jackson 2000). Our study area is located in a dry sub-humid/semi-arid transition zone, where rainfall is highly variable and grassland productivity is closely tied to precipitation (Todhunter 1995). We found 90 % of the total root C in the upper 20 cm (Table 1), which is similar to data reported by Gill et al. (1999) for native grasslands in the shortgrass steppe. Similar to the semi-arid shortgrass steppe (Gill et al. 1999), root C and SOC distributions were heavily weighted near the surface, as expected in regions where net primary production is limited by precipitation (Jobbagy and Jackson 2000; Post and Kwon 2000). In the context of grasslands and croplands worldwide, Jobbagy and Jackson (2000) found 40–45 % of SOC in the upper 20 cm of the soil profile. Average SOC reported here for the PPR were slightly higher, with the upper 20 cm containing 46 % of the total SOC to 1 m for croplands and 49 % for grasslands. Average grassland SOC to 1 m is reportedly 117 Mg C ha^{-1} (Jobbagy and Jackson 2000). Average

SOC to 1 m reported here for re-established grasslands in the PPR is 94 Mg C ha⁻¹, while average SOC to 1 m for the drier region of the shortgrass steppe is 70 Mg C ha⁻¹ (Gill et al. 1999).

There is widespread concern that conversion of perennial grasslands to croplands in the PPR will seriously impact waterfowl production through loss of habitat (Stephens et al. 2003) and significantly deplete belowground C stocks that could be conserved or enhanced to offset carbon dioxide (CO₂) emissions (Lal 2004). Consequently, programs are under development which provide incentives to avoid conversion of grasslands or to re-establish grasslands, and these require regionally representative SOC data across a broad spectrum of land managers to ensure market valuations are accurate (Cahill et al. 2009). A number of factors affect SOC, including climate, soils, plant functional group (Ampleman et al. 2014), net ecosystem production, and historical management. In this study, climate, soils, and plant functional groups were broadly similar, but management varied (Fig. 2). For example, SOC for the organically managed cropland and CRP grassland (site 12) were similar, where cropland SOC was likely enhanced by annual applications of manure. Most producers (82 %) used minimal or no tillage in their operations, which is a more modern-day management practice that could indirectly influence rates of carbon turnover (Kucharik et al. 2001). Those fields recently converted from CRP to cropland (sites 13–17) were 1–7 Mg C ha⁻¹ lower in SOC near the surface than neighboring CRP fields (Fig. 2), suggesting SOC accrued from long-term grassland re-establishment could be rapidly lost as a result of conversion. Nonetheless, re-establishment of perennial grasslands in the PPR provides a C sequestration service, in addition to other services reported in the literature (Werling et al. 2014). Studies are needed that identify more ways of enhancing this service through plant and soil management, such as incorporation of deep-rooted grass species (Ampleman et al. 2014) to enhance vertical distribution of SOC.

Conclusions

The primary purpose of this investigation was to determine if SOC stocks beneath re-established grasslands were greater than adjacent croplands following long-term (≥ 15 years) management under the CRP in the North Dakota PPR. Cropland management practices varied, but most producers here emphasized minimum tillage. Results indicated grasslands under the CRP were greater in root C and SOC stocks and lower in bulk density for the surface 20 cm. The grassland 0–20 cm layer contained 90 % of root C and 49 % of SOC. Average SOC stocks for grasslands re-establishment under the CRP in the PPR were

5.06 Mg C ha⁻¹ greater than adjacent croplands for the upper 20 cm. Fields recently converted from CRP to cropland were lower in SOC, suggesting long-term SOC accrued during CRP may be released to the atmosphere when they are returned to crop production. The majority of SOC accrued while grasslands were managed under the CRP are located near the surface in the PPR. To maintain these stocks of SOC and minimize losses to the atmosphere as CO₂, disturbance of soils near the surface should be avoided when converting CRP land back to cropland.

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