Loss and Recovery of Soil Organic Carbon and Nitrogen in a Semiarid Agroecosystem

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Soils typically show 20 to 40% decline in soil organic carbon (SOC) due to cultivation, most of it in the first 10 yr, but studies on SOC depletion may actually underestimate losses of the original SOC. Starting 40 to 50 yr ago, expanding use of non-inversion tillage, fertilizers, and herbicides lead to reduced disturbance and increased residue production that undoubtedly began recovery of SOC depleted during previous decades when farmers used only intensive tillage to control weeds and stimulate release of nutrients from crop residues. We measured SOC and total N stocks, density fractions, and labile C and N at 10 study sites in two rain-fed production areas in southeastern Wyoming. Systems evaluated include historic inversion-tillage-based winter wheat (*Triticum aestivum* L.)–fallow with no inputs, conventional winter wheat–fallow, minimum- and no-till continuous rotations and permanent grass cover. Results were then compared to SOC under nearby native grasslands. Soils beneath historic wheat–fallow were the most depleted in SOC, with 13.8 and 17.6 Mg C ha^{-1} in the upper 30 cm at the two study areas, or 37% of the SOC under the two native sites. Soil OC contents were statistically similar across conventional, minimum-till, and no-till systems, ranging from 64 to 78% of native SOC levels, and significantly higher under permanent grass, with both sites having 90% of native SOC levels. Free light fraction organic carbon (LFOC) contents were lowest beneath the historic system, but increased in systems with fewer disturbances. When normalized by SOC and total N, the labile C and N pools generally increased with increasing disturbance, especially microbial biomass carbon (MBC) and dissolved organic carbon (DOC). Soil OC contents under the historic, inversion tillage system were much lower relative to native grasslands than found in other studies, which, together with other findings, suggest that SOC levels have begun to recover under the modern conventional system. Free LFOC and labile pool C and N contents indicate that conservation tillage systems in place for a relatively short time are facilitating further recovery of SOC.

Abbreviations: DOC, dissolved organic carbon; EC, electrical conductivity; LFN, light fraction nitrogen; LFOC, light fraction organic carbon; MBC, microbial biomass carbon; PMC, potentially mineralizable carbon; PMN, potentially mineralizable nitrogen; SOC, soil organic carbon; TOC, total organic carbon.

Studies of the effects of cultivation on SOC in the western United States show losses of 20 to 40%, much of which occurs during the first 10 yr after tillage began (reviewed by Davidson and Ackerman, 1993). Though these impacts represent drastic soil degradation, they may underestimate effects of early, intensive cultivation that included few inputs for soil fertility renewal. By the time studies of cultivation effects were conducted, farming practices had changed markedly from methods used during the first 50 to 70 yr after the prairie sod was broken

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(e.g., Schillinger and Papendick, 2008; Triplett and Dick, 2008). Most farmers in the western United States began using fertilizers, herbicides, improved crop varieties, and non-inversion tillage implements by the mid-1960s, and these soon became conventional practices. Resulting increases in residue production and decreases in soil disturbance probably began a period of SOC recovery that started long before researchers attempted to assess cultivated soils, and continues with changes in modern farming practices.

Starting 20 to 30 yr ago, adoption of reduced- and no-till practices led to further recovery of SOC contents through combinations of reduced disturbance, maintenance of soil cover, and less fallow leading to higher quantities of more diverse residue (Halvorson et al., 2002; Sherrod et al., 2005). Conservation tillage practices have not been uniformly adopted (Conservation Technology Information Center, 2004), however, in part because they require large investments in new equipment and new knowledge that may not be warranted in areas with inherently low productivity (Dalrymple et al., 1993; Krall et al., 1991).

In the northern High Plains ecoregion (USEPA, 2007), including southeastern Wyoming, farmers were slow to accept changes, and did not start using fertilizers until at least the 1960s and 1970s, probably because of high risk and low returns from crop production (Krall et al., 1991). Some farmers continue to practice historic methods that rely on tillage alone, principally with moldboard plows, and without inputs of fertilizers or herbicides (Krall et al., 1991; personal communication with cooperating farmers, 2008). Farmers in the western High Plains have also been slow to adopt conservation tillage practices (Conservation Technology Information Center, 2004). However, the Conservation Technology Information Center reported in 2004 that just over 20% of dryland wheat grown in Wyoming used some form of conservation tillage (defined as leaving at least 15% residue cover), and about 5% used no-till practices. While less than in surrounding states, adoption by some farmers suggests that the practices can be beneficial.

Several studies have measured higher SOC content under continuously cropped no till than conventional tillage with wheat–fallow rotations (e.g., Grant et al., 2002; Halvorson et al., 2002; Sherrod et al., 2003; Wienhold and Halvorson, 1998). Sherrod et al. (2005) compared SOC levels after 12 yr under four cropping systems to SOC levels under long-term grass cover. They found that SOC in active, slow, and passive pools under no-till continuous wheat where significantly closer to levels found under grass than were those under the wheat–fallow system. Active-pool SOC turns over on an annual basis to provide available nutrients, slow-pool SOC turns over on the order of decades, and passive pool on the order of centuries to millennia (Parton et al., 1987). Slow- and passive-pool SOC is typically protected from aeration and decomposition within soil microaggregates or in tight association with mineral soil particles (Sohi et al., 2001). Significant SOC increases, especially in slow and passive pools, after 12 yr of no-till continuous cropping (Sherrod et al., 2005) are important indicators of recovery of soil quality in a relatively short period.

Most of the flux in SOC and N following cultivation of native prairie soils, as well as recovery due to improved farming practices or establishment of permanent grass cover, occurs in free and occluded light fractions and in labile C and N components of active pools (Dou et al., 2008; López-Fando and Pardo, 2011; Sherrod et al., 2005). Although recovery of total SOC and N can take many years to detect, changes in light fractions occur more rapidly and translate to longer-term recovery of C and N stocks (Cookson et al., 2008; Murage et al., 2007).

Likewise, labile C and N components of active-pool SOC, including mineral N, potentially mineralizable carbon (PMC) and nitrogen (PMN), MBC, and DOC, respond rapidly to changes in tillage and residue management, allowing early detection of recovery trends. Soil ecosystems shift from mineralizing, C-limited microbial environments under frequent disturbance, toward more immobilizing, N-limited microbial environments typical of conservative nutrient cycling under native prairie (Halpern et al., 2010; Purakayastha et al., 2008; Schimel, 1986).

The objective of this study was to evaluate SOC and N stocks in total, labile, and density-fraction pools under farm fields across a disturbance intensity gradient, ranging from intensively tilled, no-input wheat–fallow systems to permanent grass cover. We compared total C stocks from our study sites to those of soils beneath nearby native grasslands quantified in studies by Ingram et al. (2008) and Ihori et al. (1995). Information on how changing farming practices impact loss and recovery of SOC stocks is needed to support development of further improved systems and promote adoption of conservation agriculture practices. The need for adoption is expected to become more acute with increased climatic extremes in the form of drought, wind, and pulses of moisture that are expected in this region (e.g., Leung et al., 2004).

MATERIALS AND METHODS

For this on-farm, observational study, we used USDA NRCS soil surveys combined with on-site evaluations to select fields with similar soil and landscape parameters in two climatic zones under historic wheat–fallow, conventional wheat–fallow, minimum-till, and no-till management systems and perennial grass under CRP (Table 1). The Albin (41°25’12” N, 104°5’60” W) and Slater Bench (41°45’ N, 104°49’12” W) sites are located about 60 km east and 90 km northeast of Cheyenne, WY, respectively. Cultivation became widespread in these areas after the 1909 Enlarged Homestead Act (Cassity, 2011). Slater Bench receives 399 +/−87 mm of precipitation on average per year, 71% of which falls within the April to September growing season of 110 to 130 days per year. The more productive Albin area receives an average of 459 +/−90 mm of precipitation per year, 70% of which falls between April and September, with an average annual growing season of 120 to 150 d (Western Regional Climate Center, 2011a; Albin and Chugwater Weather Stations). Soils of both study areas are sandy loams classified predominantly as Aridic Argiustolls (Table 1) (Soil Survey Staff,

Table 1. Agronomic, climatic, and soil classification information for the 10 study sites and two native grasslands in the study areas.

Area: Slater Bench (Platte County)†
Mean annual precipitation: 399 mm; Mean annual temperature: 8.0°C; Mean annual growing degree days (Base 10°C): 2017

System	Description/Rotation	Soil classification‡
Historic	2-yr, winter wheat–fallow; no fertility inputs; intensive tillage only.	coarse-loamy, mixed, superactive, mesic Aridic Haplustolls coarse-loamy, mixed, superactive, mesic Torriorthentic Haplustolls
Conventional	2-yr, winter wheat–fallow; low rates of fertilizer; intensive tillage + herbicides.	fine-loamy, mixed, superactive, mesic Aridic Argiustolls coarse-loamy, mixed, superactive, mesic Aridic Calciustolls
Min. till	3-yr winter wheat–oat–fallow; moderate rates of fertilizer; shallow tillage;	fine-loamy, mixed, superactive, mesic Aridic Argiustolls coarse-loamy, mixed, superactive, mesic Aridic Calciustolls
No till	3-yr winter wheat–oat–fallow; moderate fertilizer; chemical fallow.	fine-loamy, mixed, superactive, mesic Aridic Argiustolls loamy, mixed, superactive, mesic, shallow Torriorthentic Haplustolls
Grass	15-yr conservation reserve program dominated by crested wheat grass.	fine-loamy, mixed, superactive, mesic Aridic Argiustolls coarse-loamy, mixed, superactive, mesic Aridic Calciustolls
Native§	Shortgrass steppe dominated by blue grama [*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths], and buffalograss [*Buchloe dactyloides* (Nutt.) Englem.].	fine-loamy, mixed, superactive, mesic Aridic Argiustolls

Area: Albin (Laramie County)†
Mean annual precipitation: 458 mm; Mean annual temperature: 8.5°C; Mean annual growing degree days (Base 10°C): 2336

System	Description/Rotation	Soil classification
Historic	2 yr, winter wheat–fallow; no fertility inputs; intensive tillage only.	fine-loamy, mixed, superactive, mesic Pachic Argiustolls fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Aridic Argiustolls
Conventional	2-yr, winter wheat–fallow; low rates of fertilizer; intensive tillage + herbicides.	fine-loamy, mixed, superactive, mesic Aridic Argiustolls
Min. till	4-yr continuous cropping: winter wheat–sunflower–proso millet–corn; moderate fertilizer; shallow tillage.	coarse-loamy, mixed, superactive, mesic Pachic Haplustolls
No till	4-yr continuous cropping: winter wheat– sunflower–proso millet–corn; moderate fertilizer; chemical weed control only.	fine-loamy, mixed, superactive, mesic Pachic Argiustolls fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Aridic Argiustolls
Grass	15-yr conservation reserve program dominated by smooth brome.	coarse-loamy, mixed, superactive, mesic Pachic Haplustolls
Native¶	Northern mixed-grass prairie dominated by western wheatgrass [*Pascopyrum smithii* (Rydb.) A. Löve], needle-and-thread [*Hesperostipa comata* (Trin & Rupr.) Barkworth], and blue grama.	fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Aridic Argiustolls fine-loamy, mixed, superactive, mesic Aridic Argiustolls

† Slater Bench means are from 1900 to 2010 at the Chugwater climate station and Albin means are from 1948 to 2010 at the Albin climate station (Western Regional Climate Center, 2011b).

‡ Soil classification for Slater Bench from Staples (2003) and for Albin from Stevenson et al. (1983).Two families under soil classification result from the soil association level of mapping in the soil survey (map units represent more than one soil series).

§ From Ihori et al. (1995) and Soil Survey Staff (2011).

¶ From Ingram et al. (2008).

2010). Calciustolls are also common in the Slater Bench area but do not occur in the Albin area. Soils beneath native mixed-grass prairie plant communities that matched the Slater Bench (evaluated by Ihori et al., 1995; 40°49’12” N, 107°46’48” W) and that matched the Albin site (evaluated by Ingram et al., 2008; 41°10’48” N, 104°52’48” W) were identified for comparison of soils of our study sites to uncultivated soils.

Space-for-time substitution studies that compare management impacts to uncultivated reference sites assume that SOC and N contents remain constant beneath native plant communities with evidence of no major disturbances for millennia. In fact, SOC and N contents can change beneath grasslands as plant communities shift among bunchgrasses, rhizomatous grasses, shrubs, and more recently, exotic weeds (Norton et al., 2004), and recover from disturbances such as fires, heavy grazing, burrowing animals, and others. The sites analyzed by Ihori et al. (1995) and Ingram et al. (2008) had been moderately grazed by cattle (*Bos taurus*) for many years without evidence of other major disturbance.

In the wheat–fallow systems, winter wheat is typically planted in September and harvested the following July. After harvest the stubble is left on the field until the need for tilling for weed control, which typically occurs in the following spring, or in the fall if needed. Most tillage during the fallow period is done with moldboard or chisel plows to a depth of 20 to 30 cm. Between harvest and planting of the next wheat crop, fields are usually plowed six times under the historic system and four times under the conventional system. Farmers practicing conventional wheat–fallow production commonly use herbicides for additional weed control and apply fertilizers at rates of approximately 45 kg N and 22 kg P ha^{-1}. The conventional system is prevalent in the western High Plains region and has generally been practiced for 30 to 40 yr (personal communication with cooperating farmers, 2008). Typical winter wheat yields reported by farmers were approximately 1360 to 1630 kg ha^{-1} under historic and 2020 to 2360 kg ha^{-1} under conventional wheat–fallow management (Mukhwana, 2011).

The minimum-tillage system in the Slater Bench area uses a wheat–oat (*Avena sativa* L.)–fallow rotation in place for 13 yr and in the Albin area uses continuously cropped wheat–corn (*Zea mays* L.)–proso millet (*Panicum miliaceum* L.)–sunflower (*Helianthus annuus* L.) rotation, also in place for 13 yr. The cropping sequence and species are more flexible in the Albin system, with oats, sorghum [*Sorghum bicolor* (L.) Moench], or fallow sometimes included in the 4-yr rotation depending on moisture, weeds, and markets. Farmers using the minimum-till systems have many options for weed control and take advantage of diverse cropping sequences, broad-spectrum and selective herbicides, and innovative shallow-tillage implements that kill weeds but leave surface residues largely intact. Farmers using minimum-till systems report using similar amounts of N and P fertilizers for wheat as those using conventional wheat–fallow. Typical winter wheat yields reported by farmers were approximately 1920 to 2430 kg ha^{-1} under minimum-till management (Mukhwana, 2011).

The no-till systems used the same crop rotations described above for minimum till at the Slater Bench and Albin areas. The wheat–oat–fallow no-till system at Slater Bench had been in place for 13 yr and the continuously cropped no-till system at Albin for 17 yr. Farmers also use similar amounts of N and P fertilizers, but rely more on injection of liquid fertilizers below crop residues than on topdressing and incorporating dry products. In addition, they use herbicides and cropping sequences without tillage for weed control. Typical winter wheat yields reported by farmers were approximately 2160 to 2690 kg ha^{-1} under no-till management (Mukhwana, 2011).

Information recorded during interviews with each cooperating farmer confirmed that a relatively narrow set of agronomic practices is necessary for optimal production in this region, and that the farmers use similar approaches toward weed and pest control, row spacing, varieties planted, and other practices that might affect SOC content and characteristics. Straw is left on the field except after rare exceptionally high yields when it is profitable to harvest it.

Experimental Design and Sampling

Soil samples were collected three times per year during 2008 and 2009 from three 15- by 15-m plots that were established at least 50 m from field edges in the wheat phase of each cropping system. The wheat–fallow and minimum-till systems use narrow strips for the rotations so one plot was established in each of three wheat strips. The no-till systems and perennial grass occurred in much larger contiguous fields so plots were established at least 100 m apart within the same field.

Soil samples were collected by extracting five 3- by 30-cm cores from each 15- by 15-m plot in July of 2008 and compositing them by 0- to 15-cm and 15- to 30-cm depths ($n = 3$ for each area × system treatment). Samples were packed on ice for transport to the laboratory. A separate composite sample of three cores was collected for determination of bulk density (Blake and Hartge, 1986) during each sampling event from each plot. Stable soil properties (SOC, soil texture, total nitrogen (TN), pH, electrical conductivity (EC), and density fractions) were measured in only one bulk sample collected at two depths (0–15 and 15–30 cm) from each plot ($n = 3$) collected in summer (July) 2008. Dynamic soil properties (MBC, DOC, PMN, PMC, and Min N) were measured in samples collected three times (in spring, summer, and fall) from each plot in 2008 and 2009 (six sampling times total).

Laboratory Analyses

Basic soil properties were quantified from one sampling event in the 0- to 15-cm and 15- to 30-cm depth samples. Analyses included particle-size distribution by the hydrometer method (Gee and Bauder, 1986), pH and EC by electrode (Thomas, 1996), total C and N by combustion on an EA1100 Soil C/N analyzer (Carlo Erba Instruments, Milan, Italy), inorganic C by modified pressure-calcimeter (Sherrod et al., 2002), and gravimetric moisture. Total organic C was determined by subtracting inorganic C from total C. In the studies of soils beneath native grasslands, Ihori et al. (1995) and Ingram et al. (2008) analyzed SOC in the upper 30 cm by combustion.

Density fractionation (Sohi et al., 2001) was used to separate and quantify OC and TN in free and aggregate-occluded light SOC fractions known to respond differently to changing management conditions, and in the more stable mineral-associated fraction. Following separation, the three SOC fractions were dried at 105°C for 24 h and analyzed on an EA1100 Soil C/N analyzer (Carlo Erba Instruments, Milan, Italy) to determine LFOC and light fraction nitrogen (LFN) in the free and occluded light fractions, as well as mineral-associated OC and N.

To quantify available and readily mineralizable C and N, 10-g subsamples were extracted with 0.5 M K_2SO_4 and analyzed for nitrate (NO_3^-) (Doane and Horwath, 2003) and ammonium (NH_4^+) (Weatherburn, 1967) by microplate spectrophotometer (BioTek, Inc., Winooski, VT). Dissolved organic C was measured using a UV-persulfate total organic carbon (TOC) Analyzer (Phoenix 8000, Tekman-Dorhmann, Cincinnati, OH). Microbial biomass was analyzed on fresh, refrigerated soil samples within 72 h of collection by the fumigation-extraction method (Horwath and Paul, 1994). Mineralizable C and N was analyzed by aerobic incubation (Zibilske, 1994).

Statistical Analysis

The analysis of stable soil properties, conducted separately for each soil depth, was done using a two factor factorial analysis of variance set in a completely randomized design. Hypotheses of interest for this first set of analyses involved testing for the main effects of area and cropping/tillage system plus an area × cropping/tillage system interaction ($\alpha = 0.05$). The analysis

Table 2. Soil properties of the two study areas averaged across all study fields.

Location	Organic C				Total N		Bulk density			pH		
	0–15 cm		15–30 cm		0–15 cm	15–30 cm	0–15 cm	15–30 cm		0–15 cm		15–30 cm
	g m^{-2}						g cm^{-3}					
Slater Bench	1581	*	990	†	141	98	1.27	1.28	*	7.78	*	7.82
Albin	1982		1133		155	103	1.32	1.34		6.85		7.3

Location	EC‡		Sand		Silt		Clay	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
	dS m^{-1}				%			
Slater Bench	0.59	0.72	64.8	65.5	21.2	20.2	13.9	14.4
Albin	0.48	0.62	62.5	63.1	24.1	22.6	13.3	14.3

* Values are significantly different between the two study areas at $P < 0.05$.
† Values are significantly different between the two study areas at $P < 0.10$.
‡ EC, electrical conductivity.

of dynamic soil properties was done using a mixed model and testing for the main effects of years, seasons, as well as areas and systems plus their various interactions. In this analysis, effects of years were considered to be random. Statistical computations for the first design were facilitated through use of the GLM procedure of the Statistical Analysis System (ver. 9.2, SAS Institute, Cary, NC). Statistical computations for the second design were facilitated through use of the MIXED procedure of the Statistical Analysis System. Mean separations for fixed effects factors were conducted using the LSD function in PASW Statistics 18 (IBM Corporation, Somers, NY).

RESULTS

Total SOC and N showed significant effects by area (Table 2). On average across systems, surface soils of the Albin fields contained significantly more TOC than those of the Slater Bench fields in surface (P = 0.017) but not subsurface (P = 0.084) depths (Table 2). Soils of both areas contained similar amounts of total N on average at both depths. Soil pH and EC were lower at the Albin sites than at the Slater Bench sites, but were not impacted by system (Table 2). Bulk density of surface soils was statistically similar across areas and systems (Table 1, Fig. 1), but was significantly less in 15- to 30-cm soils of the inversion-tilled systems (historic and conventional) than those of the minimum till, no till, and grass cover (Fig. 1). Surface soils were significantly less dense (P = 0.016) than subsurface soils under grass cover, but statistically similar between the two depths in each of the farmed systems. Soil texture was sandy loam in all the plots of both areas, ranging from 57 to 68% sand and 11 to 15% clay, and about 1% more clay in the 15- to 30-cm depth than the 0- to 15-cm depth.

Differences in OC and TN among systems followed very similar trends (Fig. 2) in both areas. Soils under conventional, minimum-till, and no-till systems each contained just over 1800 g TOC m^{-2} and between 141 and 163 g TN m^{-2} in the 0- to 15-cm depth, significantly more than soils under historic systems and less than soils under long-term grass cover. At the 15- to 30-cm depth, both SOC and N increased steadily with decreasing disturbance, but diverged from levels in the surface depth, with subsurface soils under the historic systems having 71% as much SOC as surface soils, and subsurface soils under grass having just over half as much SOC as surface soils.

Soil organic carbon stocks in the upper 30 cm follow a similar trend, increasing with decreasing disturbance. The historic system contained about 37% as much SOC as the native grassland sites evaluated by Ingram et al. (2008) and Ihori et al. (1995), while soils beneath the conventional, minimum-till, no-till, and grass systems contained about 65, 68, 78, and 90% of that beneath the native grasslands, respectively (Fig. 3).

Soil organic carbon in the free light fraction showed an area × system interaction, with soils of both areas generally increasing in free LFOC with decreasing disturbance (Fig. 4a and 4b). At the Albin area, soils under no till had significantly more free LFOC than those of both conventional and historic inversion tillage systems (P = 0.04 and 0.005, respectively; Fig. 4b), while soils under minimum till had significantly more than those under historic (P = 0.004) but not conventional (P = 0.20) management. At the Slater Bench area, soils under minimum-till

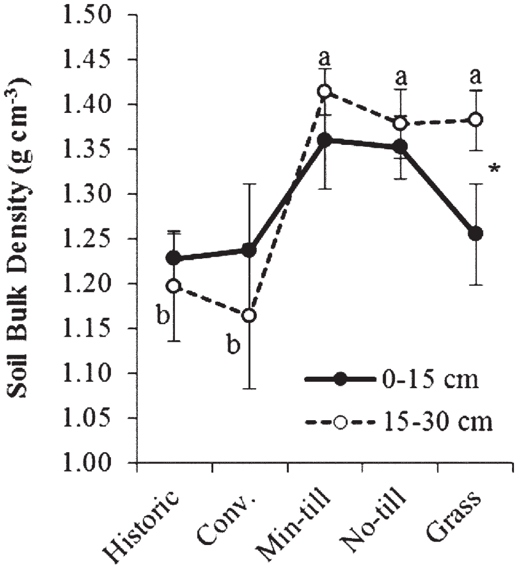

Fig. 1. Soil bulk density for the two sampling depths averaged by system across the two study areas. Points within a sampling depth with different letters are significantly different at the $P < 0.05$ level. There were not significant differences at the 15- to 30-cm depth. * denotes significant difference ($P < 0.05$) between the two sampling depths. Error bars represent the standard error of the mean ($n = 6$).

management had significantly more free LFOC than other tillage systems ($P = 0.03$ for no till, $P = 0.09$ for conventional, and $P < 0.001$ for historic; Fig. 4a), with a statistically similar amount to soils under grass.

Soils under grass and no till at the Albin area had marginally more free LFOC than those at the Slater Bench area ($P = 0.15$ and 0.06, respectively), whereas soils under minimum till and historic had marginally more ($P = 0.10$ and 0.11, respectively), and soils under conventional had equivalent amounts of free LFOC, as soils under those systems at Albin. Light fraction OC of the 15- to 30-cm depth also shows significant effects of system ($P < 0.0001$), increasing with decreasing disturbance at slower rates than the free LFOC so that free LFOC is increasingly stratified with decreasing disturbance.

Analysis of variance revealed significant impacts of area and system for surface SOC in the occluded light fraction, but no area × system interaction (Fig. 4b). Occluded LFOC levels were very low in soils under historic wheat–fallow management, with little difference between the two depths. They were much higher, and statistically similar, in soils under the conventional, minimum till, no till, and grass cover. Organic C in the mineral-associated SOC fraction (Fig. 4c) was significantly lower in the 0- to 15-cm depth under historic systems than the other soils measured but was similar across all systems in the 15- to 30-cm depth, with most stratification under grass cover.

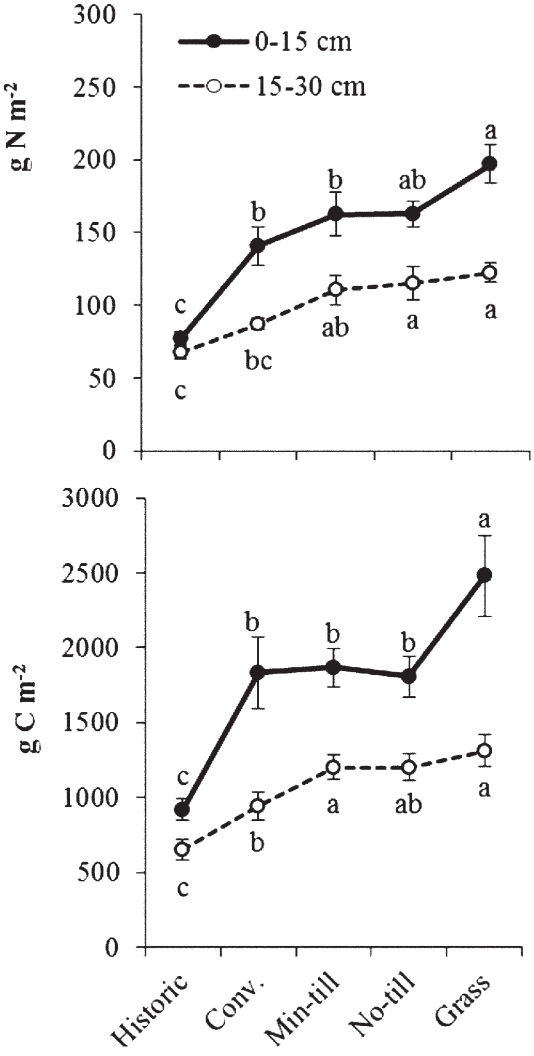

Fig. 2. Total soil N and organic carbon (OC) for the two sampling depths averaged by system across the two study areas. Data points with different letters are significantly different ($P < 0.05$) among systems and within sampling depths. Error bars represent the standard error of the mean ($n = 6$).

Of the labile-pool SOC and N components we evaluated, none showed significant effects by year or area. Dissolved OC, PMN, MBC, and PMC concentrations showed significant effects by system ($P < 0.10$; Table 3), following similar trends to SOC and TN described above, with soils beneath historic systems having the lowest concentrations, those under grass the highest, and those under conventional, minimum till, and no till having similar concentrations. Differences diminished but values became more variable with depth (Table 3).

Only MBC and DOC concentrations were significantly impacted by the main effect of season ($P < 0.05$), with higher concentrations in summer than spring or fall on average across systems (data not shown). Only DOC showed a significant system × season interaction ($P < 0.05$; Fig. 5), with concentrations in soil as proportions of SOC beneath both inversion-tillage-based systems responding differently than those beneath the lower-

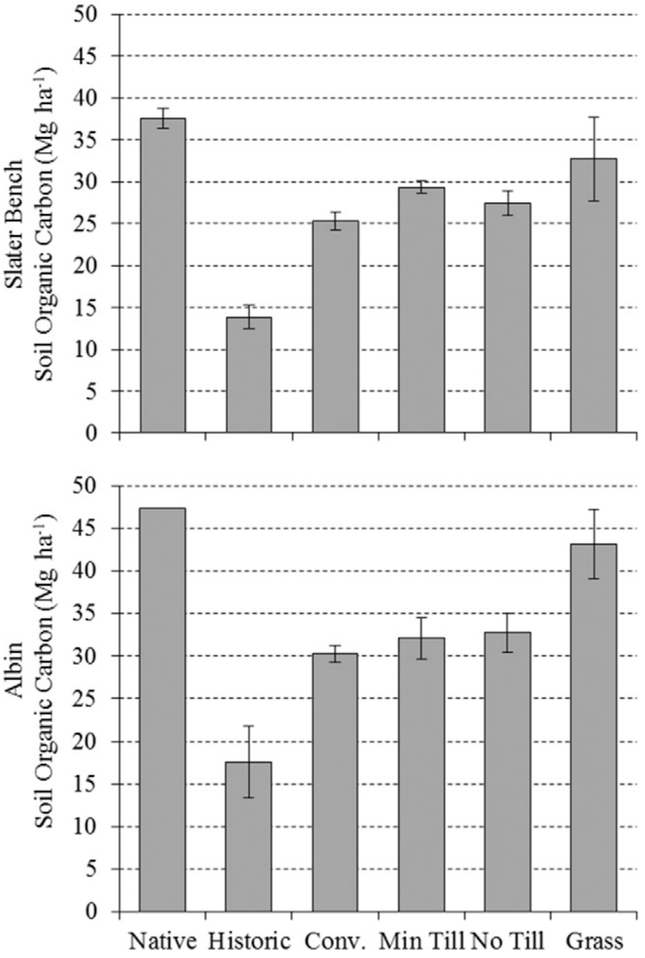

Fig. 3. Soil organic carbon content in upper 30 cm of the two study areas and corresponding native short-grass steppe (Ihori et al., 1995) for Slater Bench and mixed-grass prairie (Ingram et al., 2008) for Albin. Error bars represent the standard error of the mean. Ingram et al. (2008) did not provide standard error values.

disturbance systems. The system, season, and system × season impacts described above occurred in the 0- to 15-cm depth and did not extend to the 15- to 30-cm depth.

Normalized by SOC and TN concentration, none of the parameters showed significant impacts by the sources of variation in our ANOVA model, but soils beneath historic wheat–fallow systems had significantly higher MBC and PMC per unit SOC than those beneath other systems (Table 4). These differences in MBC and PMC per unit SOC occurred in both soil depths.

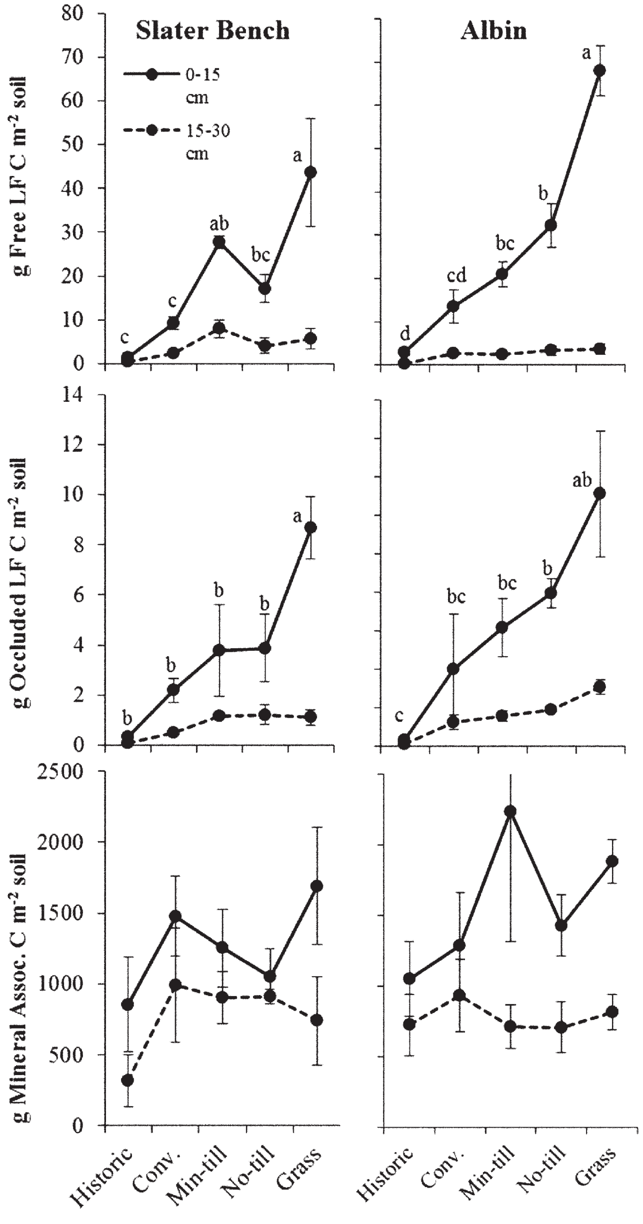

Fig. 4. Density fraction C contents by system at both study sites. Error bars represent standard error (n = 3). There is a significant area × system interaction for the free light fraction organic carbon (LFOC) and a significant area and system effects, but no interaction, for occluded LFOC. Data points for the 0- to 15-cm depth with different letters are significantly different ($P < 0.05$) among systems. Error bars represent the standard error of the mean (n = 3).

DISCUSSION

Our results show differing SOC processes along a disturbance intensity gradient and suggest that reduced- or no-till practices, along with increased frequency and diversity of cropping, lead to recovery of SOC and improved sustainability compared to long-term crop fallow. Although total SOC and N values were not significantly different among conventional, minimum till, and no till at the two study sites, our measurements of light and labile fractions indicate that less disturbance and more frequent cropping support more conservative SOC cycling. Other studies have shown similar results with respect to total SOC and N content. Murage et al. (2007), for instance, found significantly higher SOC in surface 0- to 5-cm depth after 11 yr under no-till than conventional tilled corn, but significantly less in the 5- to 20-cm depth, resulting in no significant difference over the 0- to 20-cm depth. Sainju et al. (2007) found about a third more SOC beneath treatments with continuous cropping and reduced or no tillage than beneath conventional crop–fallow in a Montana spring wheat system.

The four farming systems we studied represent a progression of dryland crop production practices from intensive inversion tillage techniques without other inputs as practiced for approximately a century of cultivation in the high plains (represented by historic) to increased use of synthetic fertilizers and herbicides for 50 yr or more (represented by conventional), that has increased wheat grain yield and biomass returned to the soil and also reduced the need for plowing to control weeds, supporting increasing SOC levels, to the most recent adoption of low-disturbance practices for <20 yr made possible by modern tillage equipment, pesticides, and herbicide-resistant crop varieties (represented by minimum till and no till).

Loss and Recovery of Soil Organic Carbon

Soils beneath uncultivated mixed grass prairie in similar soil series to our Albin study sites contained 47.3 Mg SOC ha^{-1} in the upper 30 cm (Ingram et al., 2008), while those in similar soil series to our Slater Bench sites contained 37.5 Mg SOC ha^{-1} in

Table 3. Concentrations of labile C and N components. Values within a column followed by different letters are significantly different ($P < 0.05$).

System	Depth	PMN†	Min. N	DOC	MBC	PMC
	cm	mg kg^{-1}				
Historic	0–15	15.4c	5.69c	36.2c	226d	75.8c
Conventional		28.3b	14.4a	71.2b	298c	104b
Min. till		28.3b	6.92bc	70.6b	358ab	125b
No till		28.9b	9.59b	77.3b	327bc	113b
Grass		37.4a	14.9a	89.0a	364a	149a
Historic	15–30	11.9b	5.14b	28.7c	207b	68.8c
Conventional		19.8a	7.91ab	51.3a	227b	82.7b
Min. till		16.8a	8.37a	39.4b	286a	87.2ab
No till		16.1a	7.84ab	42.0b	221b	71.2c
Grass		18.4a	9.15a	52.0a	236b	96.7a

† PMN, potentially mineralizable nitrogen; DOC, dissolved organic carbon; MBC, microbial biomass carbon; PMC, potentially mineralizable carbon.

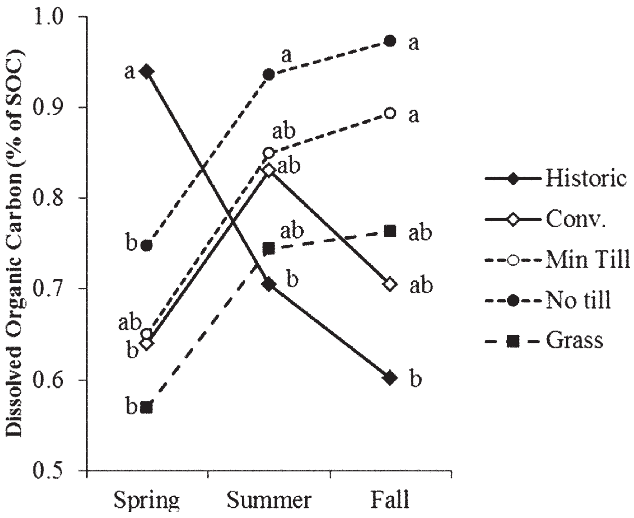

Fig. 5. System and season impacts on dissolved organic carbon as a proportion of total soil organic carbon (SOC) in the 0- to 15-cm depth averaged across study areas and years (each point represents three replications of 4 site-years; *n* = 12). Data points with different letters are significantly different (*P* < 0.05) among systems within seasons.

the upper 30 cm (Fig. 3; Ihori et al., 1995). This compares to 17.6 and 13.8 Mg SOC ha^{-1} beneath the historic, intensively tilled wheat–fallow systems at Albin and Slater Bench, respectively, which represents a 63% loss of SOC due to cultivation in each area. This is a higher percentage than reported in studies summarized by Davidson and Ackerman (1993) and is much higher than the 26% loss calculated by Ihori et al. (1995) on similar soils in northern Colorado. This suggests that either the historic wheat–fallow system had particularly destructive effects on soils of southeastern Wyoming, or that previous comparisons evaluated cultivated soils already partially recovered from historic inversion-tillage practices following years of the now-conventional yield- and biomass-increasing practices.

Our data suggest that long-term grass cover as planted under the CRP program provides the best recovery of SOC, with about 90% as much SOC as those beneath the mixed-grass prairie (43.1 and 32.7 Mg ha^{-1} at Albin and Slater Bench, respectively). Sherrod et al. (2005) found similar results beneath CRP fields in eastern Colorado and determined that the grass cover provides the maximum possible SOC recovery and storage in this agroecosystem.

Table 4. Labile C and N components as proportions of total soil organic carbon (SOC) and N. Values within a column followed by different letters are significantly different (*P* < 0.05).

System	Depth	PMN†	Mineral N	DOC	MBC	PMC
	cm	%				
Historic	0–15	3.66a	1.41b	0.749b	4.69a	1.55a
Conventional		3.63a	2.00a	0.725b	3.06c	1.07c
Min. till		3.67a	0.96b	0.798ab	4.03b	1.35ab
No till		3.66a	1.16b	0.885a	3.77b	1.30b
Grass		3.63a	1.40b	0.693b	2.90c	1.18bc
Historic	15–30	3.22b	1.40a	0.766b	5.97a	2.03a
Conventional		4.07a	1.68a	1.02a	4.52bc	1.67b
Min. till		3.31ab	1.55a	0.718b	5.15ab	1.57bc
No till		2.87b	1.55a	0.733b	3.91c	1.24c
Grass		3.15b	1.52a	0.853ab	3.83c	1.57bc

† PMN, potentially mineralizable nitrogen; DOC, dissolved organic carbon; MBC, microbial biomass carbon; PMC, potentially mineralizable carbon, PMC per unit MBC.

Soils beneath the conventional wheat–fallow systems we evaluated, with higher yields and somewhat less tillage than the historic wheat–fallow system, had 64 to 67% as much SOC as soils under the mixed-grass prairies, with 30.2 and 25.3 Mg ha^{-1} at Albin and Slater Bench, respectively. Soils under minimum- and no-tillage systems had from 68 to 78% as much SOC as those under mixed grass prairie, ranging from 27.5 to 32.7 Mg SOC ha^{-1}. These values are similar to those found by López-Fando and Pardo (2011) under a semiarid wheat production tillage experiment in Spain.

These data suggest that wide-spread adoption of minimum- and no-tillage practices is part of a continuous trend toward farming practices that conserve more and more SOC and support multiple ecosystems services. Reduced disturbance often accompanies reduced inputs of fuel, fertilizers, and even water in irrigated systems, supportive of overall conservation agriculture systems that conserve energy, act as net sinks of atmospheric C, and improve soil health and sustainable yields compared to widespread conventional systems.

Measurements of free and occluded LFOC indicate that loss and recovery of SOC occurs mostly in these light fractions. Soils beneath grass, averaged across both of our study sites, had about 2.4 times more SOC in the 0- to 15-cm depth than soils beneath the historic wheat–fallow system (Fig. 2), but 25 times more free LFOC and 34 times more occluded LFOC (Fig. 4). Increased biomass combined with less tillage due to use of fertilizers and herbicides under conventional wheat–fallow apparently caused a fivefold increase in free and a 10-fold increase in occluded LFOC compared to soils under the historic, zero-input system. The minimum- and no-till systems, with reduced disturbance and higher inputs and diversity of crop residues each increased free LFOC by a factor of 11, and occluded LFOC by factors of 16 and 18, respectively, compared to the historic system. This suggests that even though total SOC was statistically equivalent (Fig. 2), the conservation tillage systems are contributing more effectively to recovery of SOC and soil quality than the conventional system. Sherrod et al. (2005) attribute similar trends in particulate OC they observed to the increased residue inputs under reduced tillage systems more to continuous cropping than to reduced disturbance.

Higher proportions of PMC and MBC per unit SOC under the historic systems compared to the other systems we measured suggests (Table 4) that, in these soils, the plow effect continues to expose SOC to mineralization, in a pulse-driven, C-limited microbial environment that probably causes continued decline in SOC levels. The lower proportions but higher overall levels of labile C and N under the conservation tillage systems suggest a shift toward more N-limited conditions where SOC inputs are conserved. This is supported by the seasonal effect on DOC contents that showed that under both inversion-tillage, wheat–fallow systems, DOC levels as proportions of SOC declined from midsummer to fall in both study areas (Fig. 5), suggesting a more mineralizing, C-limited environment than under the lower-disturbance systems. The proportionally higher MBC per unit SOC in soils under historic systems compared to other systems may reflect a combination of intensive tillage, which creates microbial substrate, and lack of N fertilizer, which slows activity, possibly sustaining higher MBC through the growing season than in other systems that include fertilizer. Mixing via tillage stimulates microbial activity, which rapidly depletes available C, thereby slowing down the consumption of available N. Dou et al. (2008) also recorded higher PMC and MBC per unit SOC under conventional tillage than no till in a 20-yr experiment in Texas. In their study, MBC ranged from 5 to 8% of SOC (Dou et al., 2008), while ours ranged from about 3 to 5% in the upper 15 cm (Table 4). For PMC per unit SOC, they found similar values to our study ranging from 1.2 to 2.0% (Table 4).

Since the conventional wheat–fallow system on our study sites has been in use much longer than the conservation tillage systems, we suspect that the larger contributions to the light fraction indicate that SOC contents are still recovering and will eventually stabilize at higher levels than under the conventional system (e.g., Grant et al., 2002; Halvorson et al., 2002). Increase in occluded LFOC is a particularly important indicator of soil quality recovery, because reformed aggregates after many years of intense tillage sequester C and improve soil tilth (Six et al., 1998), representing a reversal in the tillage-degradation spiral where loss of SOC and soil structure makes even more tillage necessary.

The apparent soil-building virtues of both conservation tillage systems suggest that the superior SOC recovery under long-term CRP cover might be conserved to contribute to sustainable yields under continuous cropping if converted to minimum- or no-till systems rather than resuming wheat–fallow rotations.

CONCLUSIONS

Our results suggest SOC losses due to cultivation have been underestimated in previous studies. Tillage-intensive, low productivity practices used during the first 50 to 70 yr of cultivation on the Great Plains changed toward higher residue production and less disturbance under modern conventional cropping systems in use for approximately 40 to 50 yr. We measured 63% loss of SOC compared to native grasslands at two study sites under historic, inversion-tillage-intensive wheat–fallow systems in place since the early 20th century. Onset of intensive tillage of previously uncultivated soils is known to cause rapid oxidation of SOC, with most of the total SOC lost within the first few years (Davidson and Ackerman, 1993). Decades of intensive tillage in wheat–fallow systems with no inputs probably lead to low and stable SOC contents related more closely to annual fluctuations in weather and residue inputs than continued loss due to tillage. This is supported by reports of highly variable yields from cooperating farmers practicing the historic system.

Our results suggest that the currently accepted conventional wheat–fallow system, in place since about 1970 at our study sites, increased SOC contents by 12.0 Mg C ha^{-1} to 66% of native SOC contents compared to the historic system. Conservation tillage systems in place for a much shorter period increased SOC content by 14.7 Mg C ha^{-1} from historic levels, to about 73% of native SOC contents. Measurements of light and labile C and N fractions suggest trends toward higher SOC, particularly under no-till systems. Establishment of permanent grass in place for about 15 yr under the CRP increased SOC content by 22.2 Mg C ha^{-1}, to 90% of levels under native grasslands.

These results show that implementation of reduced- and no-till practices has benefits to SOC recovery from historic lows from intensive moldboard plowing, though recovery may be slower than in more humid environments. Accounts from cooperating farmers show that no till results in the highest wheat yields of the systems we evaluated. These systems produce crops every year or 2 yr in 3, so that they should perform better economically than wheat–fallow systems, and also provide more diversity in production.

The high SOC under CRP grass cover should be conserved as these lands return to production by transitioning to reduced- or no-till systems so that productivity that accompanies high SOC levels can be sustained. Returning CRP lands to intensive tillage-based systems would likely result in initial release of nutrients to support high yields, but SOC and related soil quality would rapidly decline, just as it did after initial cultivation of native grasslands approximately 100 yr ago.

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