



Soil profile carbon and nitrogen in prairie, perennial grass–legume mixture and wheat–fallow production in the central High Plains, USA



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ABSTRACT

Conversion of native prairie land for agricultural production has resulted in significant loss and redistribution of soil organic matter (SOM) in the soil profile ultimately leading to declining soil fertility in a low-productivity semiarid agroecosystem. Improved understanding of such losses can lead to development of sustainable land management practices that maintain soil fertility and enhance soil quality. This study was conducted to determine whether conservation practices impact soil profile carbon (C) and nitrogen (N) accumulation in central High Plains. Soil samples were taken at four-depth increments to 1.2 m in July of 2011 from five unfertilized fields under long-term management with varying degrees of soil disturbance: (1) historic wheat (*Triticum aestivum*)-fallow (HT) – managed with tillage alone, (2) conventional wheat–fallow (CT) – input of herbicides for weed control and fewer tillage operation than historic wheat–fallow, (3) no-till wheat–fallow (NT) – not plowed since 2000 and herbicides used for weed control, (4) grass–legume mixture – established in 2005 as in the Conservation Reserve Program (CRP), and (5) native mixed grass prairie (NP) – representing a relatively undisturbed reference location. Cumulative soil organic C (SOC) was not significantly different among the three wheat–fallow systems when the whole profile (0–120 cm) was analyzed. However, SOC, dissolved organic C (DOC), and total soil N contents decreased in the direction NP > CRP ≥ NT > HT ≥ CT in the surface 0–30 cm depth. In the surface 0–30 cm depth, estimated annual SOC storage rate averaged 0.28 Mg C ha⁻¹ year⁻¹ since the cessation of tillage in 2000 and 0.58 Mg C ha⁻¹ year⁻¹ since the establishment of CRP grass–legume mixture in 2005. Cumulative soil inorganic C (SIC) accumulation ranged between 8.1 and 24.9 Mg ha⁻¹ and was greatest under wheat–fallow systems, particularly at deeper soil layers, relative to the perennial systems (NP and CRP). Results from this study suggest that repeated soil disturbance induced by cropping and fallow favored large accumulation of SIC which presence may result in decline in soil fertility and productivity; whereas conversion from tilled wheat–fallow to CRP grass–legume mixture offers great SOC storage potential relative to NT wheat–fallow practices.

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1. Introduction

The central High Plains of USA is a semiarid, prairie and steppe landscape with an extensive area of dryland crop production (Hansen et al., 2012). The native vegetation in this region is largely dominated by mixed-grass prairie with limited areas of short- and tallgrass communities (Huggins et al., 1998; Padbury et al., 2002; DeLuca and Zabinski, 2011). Most prairie soils in this region historically accumulated C from thousands of years of plant biomass production, decomposition, and belowground storage in form of labile and stable SOM (DeLuca and Zabinski, 2011). However, conversion from native prairie to arable agricultural cropland and

accompanied by intensive tillage resulted in a significant loss of stored C to the atmosphere (Davidson and Ackerman, 1993) and loss of plant diversity by replacing perennial-dominated plant communities with annual grain crops (DuPont et al., 2010) ultimately leading to historical period of intensive soil erosion (Hansen et al., 2012). Consequently, arable landscapes, in general, maintain low levels of soil C and nitrogen (N) mainly due to belowground productivity that is several times smaller than that of perennial-dominated native prairie ecosystems (Sanford et al., 2012). For example, annual wheat fields, on a silt loam soil in Kansas, had 16.4 Mg ha⁻¹ less root biomass in a 1-m soil profile than that in adjacent perennial grasslands (Culman et al., 2010). This change in plant biomass inputs contributed to the depletion of SOM stored in annual cropping systems (DeLuca and Keeney, 1993; Huggins et al., 1998). Lal (2002) reported that cultivation of native prairies in the western USA resulted in a 30–60% loss in surface-soil total

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SOC, or 2.5–4.0 kg C m⁻², with most of this loss occurring shortly after initial plowing (Davidson and Ackerman, 1993).

Many large-scale dryland farming operations in the central High Plains region started by the late 19th and early 20th centuries (Huggins et al., 1998; Padbury et al., 2002; Schillinger and Papendick, 2008), when much of the prairie was plowed and converted to annual grain crops, primarily wheat (Schillinger and Papendick, 2008; Hansen et al., 2012). This region experiences a high level of temporal climate variability with recurring periods of severe drought and highly variable precipitation, frequent strong winds, and a low ratio of precipitation to potential evapotranspiration (Padbury et al., 2002; Liebig et al., 2004). Since dryland wheat farming in the central High Plains is vulnerable to failed crop establishment due to insufficient amount of soil profile stored moisture (Peterson et al., 1998; Nielsen et al., 2005), farmers adopted the two-year rotation of winter wheat–summer fallow, where wheat is typically grown during a 9-month period from planting in October to harvest in July followed by a 14-month fallow period before the next wheat planting (Shaver et al., 2002; Hansen et al., 2012). The use of herbicides in place of tillage for control of weeds can conserve an additional 2.5–15 cm of water during fallow period (Doran et al., 1998). However, not all farmers in the central High Plains region use chemical inputs due to low economic returns from crop production (Krall et al., 1991). Farmers who still follow the traditional or “historic” wheat–fallow practices with no other inputs rely on multiple, deep tillage passes to control weeds and create dust mulch to reduce evapotranspiration (Schillinger and Papendick, 2008). The repeated soil disturbance used as the only form of weed management, however, can cause rapid SOM mineralization and undermine the ability of these soils to retain C and N. For example, in a recent study in southeastern Wyoming, Norton et al. (2012) estimated that 63% of the native SOC has been lost due to historic, inversion–tillage wheat–fallow systems. The loss of SOC (as a proxy for SOM) is critical from both agronomic and environmental perspectives, as SOM is fundamental for long-term soil fertility (Tiessen et al., 1994), soil water holding capacity and structural stability (Tisdall and Oades, 1982; Six et al., 2000), as well as for global C cycling and greenhouse gas mitigation (Lal, 2004; Schmidt et al., 2011).

Because SOM plays an extremely important role as a key control of soil fertility and cropping system productivity and sustainability (Tiessen et al., 1994; Weil and Magdoff, 2004), particularly in low-productivity semiarid agroecosystems, the need to develop farming methods that conserve SOC and N is therefore of a great importance. Conservation practices, such as no-till (NT) farming, have the potential to achieve this while also reducing the need for external inputs (Lal, 2004). Although NT is a management practice that has been introduced to the central High Plains over thirty years ago (Hansen et al., 2012), only 5% of the dryland wheat production in Wyoming was estimated to be under NT management in 2004 (CTIC, 2004). Given that soils under conventional tillage (CT) experience translocation to the deeper layers within a soil profile and tend to store more C at deeper depths (e.g., Gál et al., 2007; David et al., 2009), it is not clear whether net C storage is actually increased with the adoption of NT relative to CT practices when considering the whole soil profile (Baker et al., 2007; Govaerts et al., 2009; Ogle et al., 2012).

Dryland perennial grasses became commonly used as the preferred form of the Conservation Reserve Program (CRP) in the High Plains region after the establishment of the 1985 Food Security Act (USDA FSA, 2007). For example, CRP has been used as a financial incentive to assist farmers in reducing erosion and improving soil and water quality (USDA FSA, 2007). Under this program, farmers agree to establish and maintain a permanent plant cover, primarily grasses, on highly erodible cropland for a period of ten to 15 years in exchange for annual rental payments and cost-share

assistance of up to 50% of cover establishment costs. The High Plains region (Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming) has the largest concentration of CRP land, accounting for nearly half of the total 13.3 million hectares in the U.S. in 2007 (USDA FSA, 2007). As of September 2005, a total of approximately 114 thousand hectares of cropland were enrolled in the CRP in the state of Wyoming (USDA FSA, 2005). During the beginning of CRP in the late 1980's perennial introduced grasses and forages were allowed and widely planted, especially smooth brome, crested and pubescent wheatgrass, and alfalfa in this region while natives are required for better wildlife habitat. While conversion from cropland to perennial grasses or grass–legume mixtures may be valuable from the perspective of C sequestration in soil ecosystems, relatively little research exists related to soil C storage in CRP land in the central High Plains.

Soils in arid and semiarid ecoregions experience high abundance of soil inorganic C (SIC), defined as C present in the form of carbonates dominated by calcium carbonate (CaCO₃) (Batjes, 1998; Martens et al., 2005; Denef et al., 2008; Sanderman, 2012). According to a recent survey of global soils, SIC pool is estimated to be 947 petagrams (Pg; where 1 Pg = 1 × 10¹⁵ g) to a depth of 1-m which amounts to approximately 66% as much C as the C in SOC pool (Eswaran et al., 2000; Sanderman, 2012). Guo et al. (2006) estimated that 40% of the SIC in agricultural soils is found below 20 cm depth in the soil profile, suggesting that the SIC pool is less susceptible to disturbance compared to SOC pool. According to Lal (2002, 2003), agricultural soils in arid and semiarid regions have the potential to accumulate significant amounts of inorganic C and could act as C sinks, which indicates the necessity to include the SIC pool in soil C stock investigations in arid and semiarid agroecosystems (Denef et al., 2008). However, the SIC pool is often disregarded by studies investigating management effects on C stocks.

Hence, the objective of this study was to quantify SOC and SIC levels and their vertical distribution in soil profiles across a disturbance gradient, from intensively tilled wheat–fallow rotations to uncultivated mixed–grass prairie. The study is based on the assumption that native prairie soil represents pre-cultivation conditions and that each conservation management system represents a level of recovery relative to the historic, intensively tilled, no-input wheat–fallow rotations (Norton et al., 2012). We hypothesized that management strategies that use less tillage intensity and perennial grasses or grass–legume mixtures would correspond with higher SOC contents and lower SIC contents in soil profiles, especially in near-surface depths.

2. Materials and methods

2.1. Site and treatment description

This study was conducted at the University of Wyoming's Sustainable Agriculture Research and Extension Center (SAREC), near Lingle, WY (42°5' N, 104°23' W, elevation 1314 m). The soils are classified as Mitchell series (coarse-silty, mixed, superactive, calcareous, mesic Ustic Torriorthents) under the U.S. Soil Taxonomy (Soil Survey Staff, 2012) or a Calcaric Cambisol according to the FAO soil classification system. Soils are generally well drained and developed on silty eolian deposits and/or silty alluvium derived from sedimentary rock. The sampling fields had slopes between 3 and 6%. Precipitation averages 356 mm year⁻¹, with approximately 75% of this occurring between April and July. This region experiences extreme year-to-year variability in precipitation and short-term drought periods within the growing season are also common (Padbury et al., 2002; Hansen et al., 2012).

This study compared native mixed–grass prairie (NP) and CRP grass–legume mixture (two perennial systems) to three

Table 1
General site information for all fields sampled in this study at SAREC near Lingle, Wyoming, USA.

System ^a	Duration (year) ^b	Tillage intensity ^c	Herbicides
1 NP Mixed grass prairie consisting of needle-and-thread, thick-spike wheatgrass, blue grama, <i>Bromus japonicus</i> , and <i>B. tectorum</i>	Native prairie	Never-cultivated	None
2 CRP Perennial grass–legume mixture (pubescent wheatgrass and alfalfa) as under conservation reserve program (CRP)	7	None	None
3 NT Two-year rotation of winter wheat–summer fallow converted to no-till management, chemical weed control, no other fertility input	11	None	2,4-d; Roundup; Atrazine; Barrage; Affinity Broad Spec.; Express
4 CT Two-year winter wheat–summer fallow cropping system, intensive tillage, herbicides, no fertility input	>60	Four passes	2,4-d; Barrage; Affinity Broad Spec.; Express; Agility SG.
5 HT Two-year winter wheat–summer fallow cropping, no fertility input, no herbicides, intensive tillage only	>60	Six passes	None

^a NP, native prairie; CRP, conservation reserve program; NT, no-till; CT, conventional tillage; HT, historic tillage.

^b Continuous time since field has been under that specific management system.

^c Tillage intensity is defined as the number of soil penetrating passes per year.

wheat-fallow cropping systems with different level of external inputs. The wheat-fallow systems were an historic wheat-fallow with no chemical herbicides, but six tillage operations per year during fallow phase (HT); a conventional wheat-fallow with relatively less tillage intensity (4 tillage operations year⁻¹), and input of chemical herbicides for weed control during wheat phase (CT); and, a no-till wheat-fallow left undisturbed for at least 10 years, and input of chemical herbicides for weed control during both wheat and fallow phases (NT). CT and HT fields were already set up by local farmers (>60 years) when the land was purchased and both practices were continued the way they were set up. Tillage operations in the CT and HT fields were performed using a Krause tandem disk followed by Sunflower fallow king to a depth of approximately 20 cm. Winter wheat (variety Goodstreek) was planted on CT and HT fields at 67.3 kg ha⁻¹ with a JD 9300 hoe drill at a row spacing of 30 cm. Because Goodstreek has a hollow stem and found to be susceptible to sawfly in the NT field, a solid stem variety known as Genou was planted in this field at 67.3 kg ha⁻¹ with a JD 1560 drill at 18.8 cm row spacing. Wheat grain yield was determined by harvesting an area of 37.2 m² with a JD 9500 combine. Table 1 shows general site information for all individual sampled fields.

Since one of the main goals of the dryland cropping system experiment at SAREC was to serve as a demonstration field site for research and extension purposes, starting in 2005 some management changes were introduced to reflect common cropping systems in the region. Specifically, a perennial grass–legume treatment was imposed on a wheat-fallow field by planting pubescent wheatgrass (*Agropyron trichophorum*) and alfalfa (*Medicago sativa*) as in the conservation reserve program. Pubescent wheatgrass and alfalfa were seeded at 10.1 and 2.24 kg ha⁻¹, respectively. The CRP field was not fertilized or treated with chemical herbicides, nor was it grazed by domestic animals prior to sampling for this study.

Baseline SOC data was unavailable, thus space was used as a surrogate for time (VandenBygaart et al., 2003; Ogle et al., 2005). Such space-for-time substitution studies compare management impacts to unmanaged reference sites, assuming that SOC levels remain at steady state under native plant communities providing no major disturbance (VandenBygaart et al., 2003). Thus, samples were taken from the NP field (~50 ha), located adjacent to wheat-fallow and CRP fields, to provide a low-intensity land-use by which to evaluate the impacts of management practices. Native vegetation is typical of the northern mixed-grass prairie and dominated by C₃ grass species: *Stipa comata* (needle-and-thread) and *Elymus lanceolatus* (thickspike wheatgrass). The dominant C₄ species is *Bouteloua gracilis* (blue grama). Annual grass weeds are less abundant and include *Bromus japonicus* and *Bromus tectorum*. The NP field was not

fertilized nor was it interseeded with introduced grass or legume species, but had been lightly grazed by cattle (0.19 animals ha⁻¹) with no visual indication of any significant disturbance. Importantly, light grazing intensity has been found to have no effect on SOC stock over a 21-year period in a northern mixed-grass prairie near Cheyenne, Wyoming, as no differences were evident between native grassland subjected to light grazing (<0.23 animals ha⁻¹) and adjacent non-grazed enclosure (Ingram et al., 2008). Biomass yield was determined by clipping aboveground biomass to ground level in twenty ($n = 20$) 0.5-m² quadrats.

In this study, the never plowed NP represents SOC storage potential; while CT and HT wheat-fallow systems represent historic loss of SOC from currently tilled soils; and, both CRP grass–legume mixture and NT wheat-fallow represent partial recovery of SOC. Although a number of factors are known to impact SOC levels, this study places emphasis on soil disturbance. Thus, we qualitatively ranked the five systems along a disturbance gradient of lowest to highest as follows: NP < CRP < NT < CT < HT. All the five systems were under similar edaphic and landscape conditions and the presence of a disturbance gradient afforded us the opportunity to quantify management-induced trends in whole soil profile stocks and depth distribution of soil C and N.

2.2. Soil sampling and soil processing

During July–August 2011, soil samples were collected from five adjacent fields each under different management, all mapped as Mitchell silt loam and with similar soil properties as determined by fine-scale grid sampling of SAREC. Within each field, five sample points were randomly established in the center of the fields and within close proximity of each other (<20 m), with exception of NP field where sample points were approximately 100 m apart (Fig. 1). At each sampling point, three 5.1-cm diameter cores were taken at least 1 m apart to a depth of 1.2 m, using a hydraulic Giddings soil probe. In fields under wheat stubble, two cores were taken between crop rows and one core was taken within a crop row to representatively capture the variation of a cultivated field. Each core was divided into 0–30 cm, 30–60 cm, 60–90 cm, and 90–120 cm increments. Samples from the three cores were bulked to provide a representative sample of that sampling point, kept in sealed plastic bags within cool boxes and transported to the lab, where all visible plant material and root segments were removed. Sub-samples (10 g) were taken from each composite sample for determination of gravimetric soil water content (105 °C, 24 h). A second set of sub-samples (10 g) was extracted with 0.5 M K₂SO₄ on a shaker for 1 h and analyzed for dissolved organic C (DOC) on

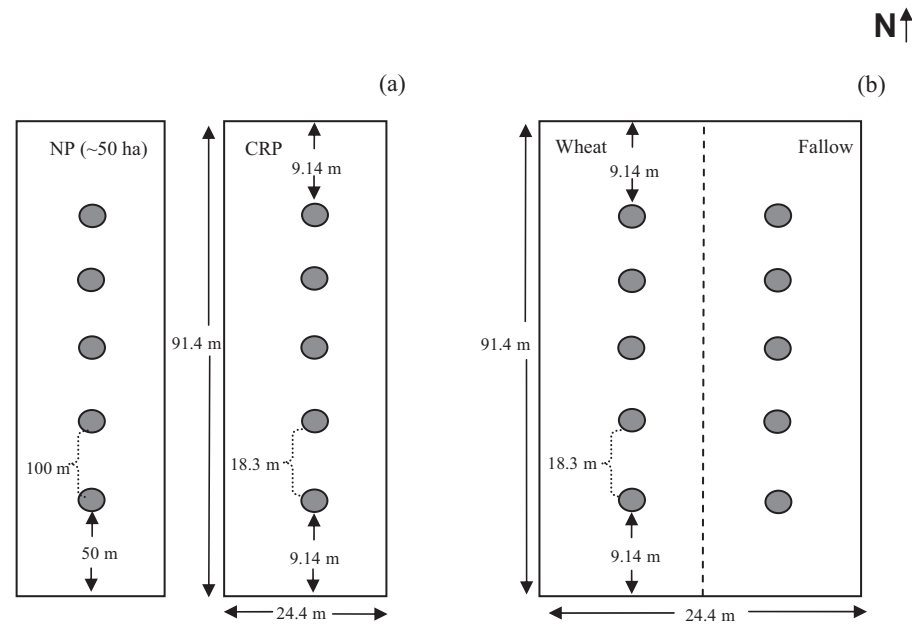


Fig. 1. Schematic overview of the sampled fields at SAREC near Lingle, Wyoming, with a detail of the soil sampling design. (a) NP and CRP fields (the two perennial systems), and (b) a winter wheat-fallow field representative of the three wheat-fallow systems under different tillage intensity (NT, CT, and HT). Within each field, the black circles represent sample points. Three soil cores were taken at each sample point and bulked. Each sample point was designated as a replicate for statistical purpose.

Shimadzu TOC Analyzer (TOC-V Series, Shimadzu, Kyoto, Japan). All remaining soil was air-dried and passed through a 2 mm sieve before being analyzed for soil texture by the hydrometer method and pH and EC (1:1, w/v H₂O).

For bulk density (BD) determination, three 120-cm deep soil cores were also collected at each sample location, using a 2.1-cm diameter soil probe with a PETG copolyester liner (PN154 JMC Environmental Subsoil Probe). Each liner containing a soil core was labeled, capped and transported to the laboratory. Each core was separated into 0–30 cm, 30–60 cm, 60–90 cm, and 90–120 cm increments by cutting the liner and soil with a fine-tooth hand saw. Soil samples from the three cores were bulked to make a single representative sample for each successive depth. Bulk density was calculated using the mass of oven-dried soil (105 °C, 24 h) and the total soil sample volume (Blake and Hartge, 1986). Gravel (>2 mm) volume was subtracted from each sample's bulk density calculation.

2.3. Carbon and nitrogen determination

Sub-samples from the 2 mm sieved soils were ground and analyzed for total C and N by combustion using a NC-2100 soil analyzer (Carlo Erba Instruments, Milan, Italy). Soil inorganic C was determined by the modified pressure-calimeter method (Sherrod et al., 2002). Soil organic C was calculated as total C minus inorganic C. Bulk density measurements showed that the overall soil mass in the entire soil profile (0–120 cm) was not affected by management. Additionally, the trend for differences between management systems for SOC on a concentration basis (g C g⁻¹) was similar to the SOC mass data (Mg C ha⁻¹) when considering the entire soil profile; suggesting that effects of management were much more robust than the subtle differences in bulk density. We therefore did not convert C stocks to the same soil mass but instead summed the SOC contents from individual depths to obtain total SOC at 0–120 cm depth and report as SOC mass per area, using the approach of Batjes (1996):

$$\text{Total SOC}_{(0-120\text{cm})} = \sum_{j=1}^k BD_j \times D_j \times [C \text{ or } N] \times [1 - S_j]$$

where SOC is the total amount of organic C (Mg m⁻²), k is the number of soil layers, BD_j is the bulk density of the soil (Mg m⁻³), D_j is the soil thickness (m), [C or N] refers to the concentration of C or N in the soil layer of interest (g C g⁻¹), and S_j is the volume fraction of coarse fragments greater than 2 mm. SIC contents were calculated similarly.

SOC storage rates were estimated by dividing the difference in SOC between the initial (i.e. CT and HT wheat-fallow cropping systems) and alternative management practices (i.e. CRP grass-legume mixture and NT wheat-fallow) by the number of years since the new practice was implemented (i.e. 7 and 11 years for CRP grass-legume mixture and NT wheat-fallow, respectively) (VandenBygaert et al., 2003).

2.4. Statistical analysis

Bulk density, DOC, SOC, SIC, and total N values for soils sampled from wheat and fallow fields did not differ significantly between these two fields at any of the sampling depths ($P > 0.1$), regardless of tillage intensity (CT, HT, and NT). Therefore, we averaged data from the two fields within each wheat-fallow cropping system together to provide a more robust estimate of BD, DOC, SOC, SIC, and total N values. Differences among the five management systems were analyzed using ANOVA, with management treated as fixed effect and sample points (treated as blocks) considered a random variable. F -tests that utilized Type III sums of squares were used to test the significance of fixed effects. Mean separation was achieved with the PDIF option of the LSMEANS statement. Comparisons were conducted for the entire profile (0–120 cm) and independently for each sampling depth. Relationships between management (disturbance level) and soil properties (SOC and SIC) were examined using simple linear regression. Significance level for all statistical tests was set at $\alpha = 0.05$, unless otherwise stated. All analyses were conducted using SAS v.9.3 (SAS Institute, Cary, NC). Since the study was conducted on large fields (~0.22 ha each; except the NP field, which was ~50 ha) and all field work on wheat-fallow fields was done using production scale farm equipment, it did not have a traditional experimental design such as RCBD. Thus, for statistical purposes each of the five

Table 2
Winter wheat grain yields and biomass yields from native prairie (NP) over five-year period at SAREC. Statistical comparison was only made for wheat-fallow systems.

System ^a	Year of harvest					Average
	2007	2008	2009	2010	2011	
	kg ha ⁻¹					
NP	911	876	3144	2360	2505	1959
CRP	na	na	na	na	na	–
NT	518	1285	1258	1332	1224	1123a ^b
CT	705	1506	2118	2441	1513	1657a
HT	635	1856	2233	2024	1500	1650a

na = not available.

^a NP, native prairie; CRP, conservation reserve program; NT, no-till; CT, conventional tillage; HT, historic tillage.

^b Values with the same letter in the same column were not significantly different ($P < 0.05$) among wheat-fallow cropping systems.

sampling points per field was designated as replicates. The absence of field replication is of concern, but data obtained from a relatively long-term study is worthwhile information.

3. Results

3.1. Yield assessments

Averaged over five-years, biomass yield from the NP field was 1959 kg ha⁻¹; grain yield from the adjacent wheat fields ranged from 1123 to 1657 kg ha⁻¹ (Table 2). However, the grain yields did not differ between any of the wheat-fallow systems, averaging 1477 kg ha⁻¹; which is considerably lower than found in other more productive parts of the Great Plains (Halvorson et al., 2002).

3.2. Soil physical and chemical properties

Soil bulk density did not differ significantly between management systems at any of the sampling depths (Table 3). A similar trend was evident when bulk density was expressed on a whole soil profile basis (0–120 cm; data not shown). Soil pH and EC did not differ significantly between management systems (data not shown). Soil texture was the same across management systems at all depths, with silt loam, except for the NP site at 0–30 cm depth, which had sandy loam (data not shown).

3.3. Soil carbon and nitrogen

Significant differences in DOC were only observed in the surface 0–30 cm, where the two perennial systems (NP and CRP) and NT wheat-fallow had higher DOC concentrations than found under tilled wheat-fallow systems (Fig. 2). There were no significant differences in the DOC between management systems at 30–60 cm, 60–90 cm, and 90–120 cm soil depths. When the DOC data was expressed on an entire soil profile basis (0–120 cm), differences between management systems resembled those observed in the 0–30 cm soil depth.

On total SOC stock basis (0–120 cm), soils beneath NP contained 1.8 times more SOC (60.2 Mg C ha⁻¹) than soils under CRP (34 Mg C ha⁻¹; $P < 0.05$) and over twice as much as any of the wheat-fallow systems (Fig. 3; 30.0, 27.8, and 24.1 Mg C ha⁻¹ under NT, CT, and HT, respectively; $P < 0.0001$). Among the tilled and previously tilled systems, SOC stocks did not differ significantly between CRP and NT, but did between CRP and tilled wheat-fallow systems; CRP had significantly higher SOC stock. When examining the overall SOC storage rates since 2000, differences between NT wheat-fallow and tillage-based wheat-fallow systems averaged 0.33 Mg C ha⁻¹ year⁻¹ in the entire 0–120 cm depth, whereas about 1.15 Mg C ha⁻¹ year⁻¹ was gained since

Table 3
Soil bulk density (g cm⁻³) for the two perennial systems (NP and CRP) and the three winter wheat-fallow under different tillage intensity (CT, HT, and NT).

System ^a	Depth			
	0–30 cm	30–60 cm	60–90 cm	90–120 cm
NP	1.11 ^a	1.21 ^a	1.23 ^a	1.22 ^a
CRP	1.09 ^a	1.19 ^a	1.27 ^a	1.23 ^a
NT	1.13 ^a	1.25 ^a	1.24 ^a	1.31 ^a
CT	1.19 ^a	1.27 ^a	1.23 ^a	1.29 ^a
HT	1.17 ^a	1.22 ^a	1.21 ^a	1.29 ^a

Values with the same superscript letter were not significantly different ($P < 0.05$) among management systems in the same sampling depth.

^a NP, native prairie; CRP, conservation reserve program; NT, no-till; CT, conventional tillage; HT, historic tillage.

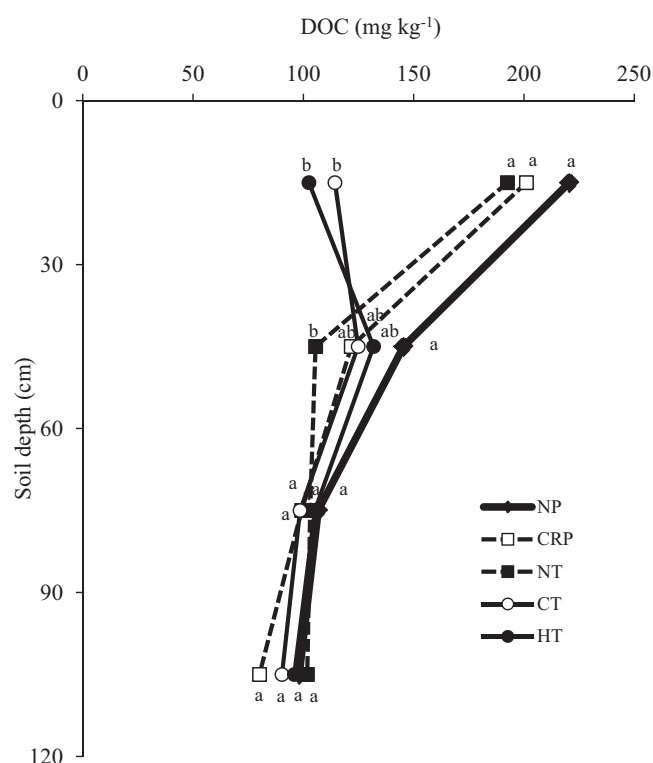


Fig. 2. Dissolved organic C (DOC) of soils sampled from the two perennial systems (NP and CRP) and three wheat-fallow cropping systems under different tillage intensity (NT, CT, and HT). Values with different letters were significantly different ($P < 0.05$) among management systems in the same sampling depth.

establishment of the CRP grass-legume mixture in 2005 (data not shown). As illustrated in Table 5, SOC showed a negative relationship with increasing disturbance level.

When expressed as a function of depth, soils under NP had between 2.1– and 2.3-times more SOC in the surface 0–30 cm than soils under CRP and NT, respectively, and approximately 3 times greater than found under tilled wheat-fallow systems (CT and HT) (Fig. 4). SOC did not differ significantly between CRP and NT at 0–30 cm soil depth, but both differed from the tilled wheat-fallow systems, with CRP and NT having higher SOC content (Fig. 4). In the surface 0–30 cm soil depth, the estimated SOC storage rates since the cessation of tillage in 2000 and establishment of CRP grass-legume mixture in 2005 were 0.28 and 0.58 Mg C ha⁻¹ year⁻¹, respectively, averaged over CT and HT wheat-fallow (Table 4). In the subsurface 30–60 cm and 60–90 cm soil depths both CT and HT generally had higher SOC levels than found under NT. In the 90–120 cm soil depth, SOC did not differ between management systems (Fig. 4). Overall, the results for total soil N closely resembled the trends seen for SOC (Fig. 5).

Soil inorganic C (SIC) did not differ significantly between any of the wheat-fallow systems (Figs. 3 and 6), but did between wheat-fallow systems and the two perennial systems (NP and CRP); wheat-fallow systems had significantly higher levels of SIC than the perennial systems. In the wheat-fallow systems SIC comprised about

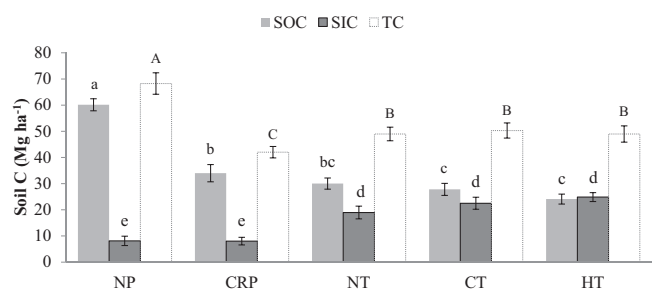


Fig. 3. Soil organic C (SOC) and inorganic C (SIC) stocks and total C (TC = SOC + SIC) in the whole profile (0–120 cm) of soils sampled from the two perennial systems (NP and CRP) and three wheat-fallow cropping systems under different tillage intensity (NT, CT, and HT). Values with different letters a–c, d and e, and A–C were significantly different ($P < 0.05$) among management systems for SOC, SIC, and TC, respectively.

Table 4
Soil organic C (SOC) sequestered following conversion from conventional (CT) and historic (HT) wheat-fallow cropping systems to CRP grass-legume mixture and no-till (NT) wheat-fallow.

System ^a		Depth	SOC storage rate (Mg C ha ⁻¹ year ⁻¹)
Initial	New		
CT wheat-fallow	CRP grass-legume	0–30 cm	0.67 ^a
HT wheat-fallow	CRP grass-legume	0–30 cm	0.49 ^a
CT wheat-fallow	NT wheat-fallow	0–30 cm	0.33 ^b
HT wheat-fallow	NT wheat-fallow	0–30 cm	0.22 ^b

Values with different superscript letters were significantly different ($P < 0.05$) between management systems. There were no significant differences at other sampling depths. ^a CRP grass-legume mixture and NT wheat-fallow had been in place for ~7 and 11 years, respectively, when sampled for this study.

Table 5
Relationship between management systems and soil organic C (SOC) and inorganic C (SIC) at each sampling depth and the entire soil profile ($n = 25$). The regression coefficient 'x' represents disturbance level (i.e., rating disturbance 1–5 from the relatively undisturbed native prairie (NP) to more intensively tilled historic (HT) wheat-fallow).

Depth	SOC			SIC		
	Regression line equation	R ²	P-value	Regression line equation	R ²	P-value
0–30 cm	$Y_{SOC} = -4.45x + 29.47$	0.6713	0.089	$Y_{SIC} = 0.57x + 0.77$	0.7472	0.059
30–60 cm	$Y_{SOC} = -0.98x + 11.14$	0.6244	0.112	$Y_{SIC} = 1.14x + 0.66$	0.7778	0.048
60–90 cm	$Y_{SOC} = -1.5x + 10.78$	0.8282	0.039	$Y_{SIC} = 1.62x + 0.12$	0.9148	0.011
90–120 cm	$Y_{SOC} = -0.89x + 7.01$	0.804	0.032	$Y_{SIC} = 1.48x + 0.52$	0.9269	0.009
0–120 cm	$Y_{SOC} = -7.82x + 58.7$	0.7375	0.062	$Y_{SIC} = 4.81x + 2.07$	0.9051	0.013

Soil disturbance level within the management practices increased in the direction NP < CRP < NT < CT < HT.

45% of the total C stock, when averaged across the three wheat-fallow systems, whereas SIC in the two perennial systems accounted for 16% of the total C stock for the entire 0–120 cm depth (Fig. 3). Differences in the SIC between wheat-fallow and the perennial systems were most pronounced in the subsurface layers (Fig. 6). There were also significant positive correlations between SIC and disturbance level (Table 5).

4. Discussion

As would be expected, variation in SOC and total soil N across the management systems corresponded with their qualitative ranking

in disturbance level. In this study, SOC and total soil N contents were statistically equivalent in the historic and conventional wheat-fallow systems (Figs. 3 and 4). This indicates that the sampled HT and CT wheat-fallow systems were similar from soil management point of view; both were more intensively tilled. This is particularly clear when SOC and total soil N in these tilled systems were compared against those beneath native mixed grass prairie, which was relatively undisturbed. SOC and total soil N contents were found to be significantly lower in the historic and conventional wheat-fallow systems relative to native mixed grass prairie. Our hypothesis was

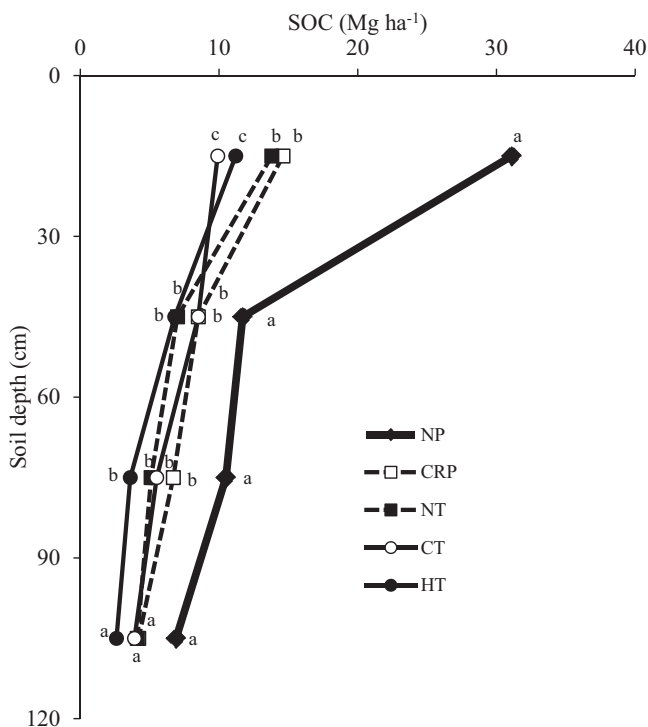


Fig. 4. Soil organic C (SOC) distribution with depth for soils sampled from the two perennial systems (NP and CRP) and three wheat-fallow cropping systems under different tillage intensity (NT, CT, and HT). Values with different letters were significantly different ($P < 0.05$) among management systems in the sampling depth.

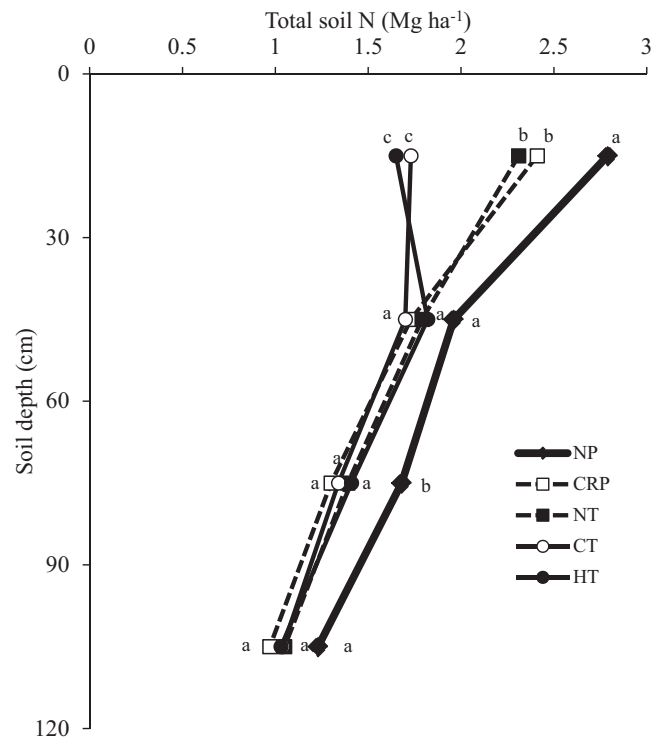


Fig. 5. Total soil N distribution with depth for soil sampled from the two perennial systems (NP and CRP) and three wheat-fallow cropping systems under different tillage intensity (NT, CT, and HT). Values with different letters were significantly different ($P < 0.05$) among management systems in the same sampling depth.

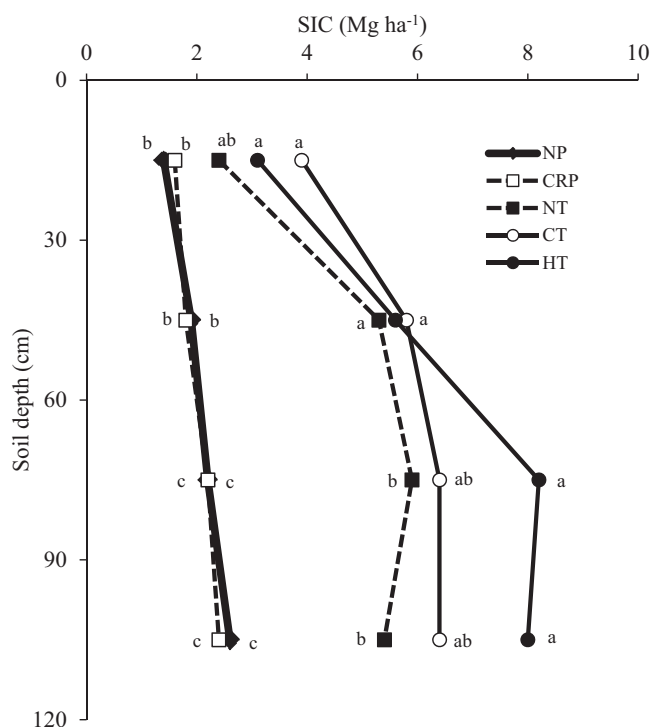


Fig. 6. Soil inorganic C (SIC) distribution with depth for soils sampled from the two perennial systems (NP and CRP) and three wheat-fallow cropping systems under different tillage intensity (NT, CT, and HT). Values with different letters were significantly different ($P < 0.05$) among management systems in the same sampling depth.

that conversion from intensive, tillage-based wheat-fallow production to NT wheat-fallow would increase SOC and N contents, particularly in near surface depths of soil profile, as a consequence of reduced soil disturbance and increased residue cover. In semi-arid regions, no-till crop production is often said to conserve soil water, particularly during the fallow period, and therefore considered more sustainable than widespread conventional agriculture (Peterson et al., 1998; Nielsen et al., 2005). This increased water availability (infiltration and storage) generally leads to increased plant litter and root production thereby increasing biomass yield (Halvorson et al., 2002; Sainju et al., 2009), and possibly the proportion of residue-derived C returned to the soil (Campbell et al., 1995; Kong et al., 2005). Significantly more SOC and total soil N contents were found in the NT wheat-fallow relative to tilled wheat-fallow systems in the surface 0–30 cm depth (Fig. 4), corroborating our hypothesis. Given that biomass yield harvested in the form of grain did not differ significantly ($P > 0.1$; Table 2) among any of the wheat-fallow systems, it is clear that factors other than plant productivity and residue-C input may have caused this difference. It is possible the reduced soil disturbance in the no-till fields, which tend to have cooler soils than conventionally tilled fields (Drury et al., 2005), might have slowed surface residue decomposition leading to SOC storage in the surface soil layers.

The estimated average storage rate of SOC in the surface 0–30 cm depth following the cessation of tillage in 2000 was $0.28 \pm 0.15 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ (Table 4). This observation is therefore generally consistent with the findings of VandenBygaart et al. (2003), and fall contrary to those reported in West and Post (2002) who, in a global analysis of 67 long-term studies, found SOC storage rates to be considerably lower in wheat-fallow systems managed with no-tillage. In our study, the no-till fields were converted from tilled wheat-fallow production system nearly 4 years earlier than fields under CRP grass-legume mixture. Despite this, SOC levels

in the surface 0–30 cm depth did not differ significantly between NT wheat-fallow system and CRP grass-legume mixture (Fig. 4). However, the average SOC storage rate in the CRP grass-legume mixture since conversion from tillage-based wheat-fallow production was approximately two times higher than found under NT wheat-fallow (Table 4). Consequently, results from this study suggest that although there may be a potential for SOC storage at near surface soil depths in NT wheat-fallow system, it appears that the process is much more gradual than initially thought, especially given that NT fields have been in place for a relatively longer period of time (approximately 11 vs. 7 years for NT and CRP grass-legume mixture, respectively). In other parts of the Great Plains farmers increase fertilizer use when they convert to NT production as these systems conserve more soil water and thus increase yield potential (Halvorson et al., 2002). Therefore, the increased SOC storage rate that could potentially be accrued with NT conversion may be limited by the lack of fertilizer use in this study. Additionally, the NT conversion in our study did not involve an intensification of crop rotation (e.g., winter wheat-maize/millet-fallow system), which have often been thought to utilize the improved water capture and storage under NT systems and result in greater biomass production and consequently increased SOC storage (Nielsen and Vigil, 2010; Hansen et al., 2012). It is, therefore, possible that the limited response in SOC observed in this study could also be due to the absence of more intensified crop rotations in the NT system.

Although there were generally no differences in the subsurface DOC concentrations between tilled wheat-fallow systems and no-till wheat-fallow (Fig. 2), CT and HT wheat-fallow generally had greater SOC contents in the 30–60 cm and 60–90 cm depth intervals than NT wheat-fallow (Fig. 4). This implies that the differences in surface SOC storage between tilled and non-tilled wheat-fallow systems are offset by higher SOC storage at deeper depths in tilled wheat-fallow systems when considering SOC changes over the entire soil profile. Although SOC translocation or leaching from upper to lower soil layers has been suggested as a mechanism for SOC accumulation in subsurface layers of tilled systems (Gál et al., 2007; David et al., 2009), our DOC data does not support this view, as the subsurface DOC concentrations were the same in tilled wheat-fallow systems and no-till wheat-fallow (Fig. 2). This suggests other factors may be responsible for the subsurface SOC accumulation in CT and HT wheat-fallow systems, including (1) decreasing SOC turnover with depth, resulting in higher SOC accumulation per unit of C input in deep soil layers and (2) increasing root turnover with depth, causing higher C inputs per unit of standing root biomass in deep soil layers (Jobbagy and Jackson, 2000). Qin et al. (2005) found that winter wheat root density in deeper layers was higher in soils managed with tillage relative to no-till soils. It is possible such an increase in root biomass might also increase levels of subsoil SOC above those of the no-till fields (Baker et al., 2007). The higher subsoil SOC levels when taking into account the whole soil profile such as demonstrated in this study and those of Gál et al. (2007) and David et al. (2009) calls for an improved understanding of the mechanism responsible for subsoil SOC storage.

One reason for the observed higher SOC storage rate under CRP could be related to root biomass, as perennial systems, like the CRP grass-legume mixture in this study, are generally undisturbed systems and allocate large resources belowground over longer periods of time (Glover et al., 2010; Sanford et al., 2012). Although we cannot conclusively state that root biomass yield was higher under CRP grass-legume mixture relative to fallow containing wheat fields, recent studies shown that perennial grasslands produce far larger root biomass than annual cropping systems (Culman et al., 2010; DuPont et al., 2010; Glover et al., 2010). Of particular relevance are the findings of Culman et al. (2010) who observed almost six times more root biomass in perennial grasslands than found in adjacent wheat fields in the surface 0–40 cm depth of silt loam soil in Kansas,

USA (12.5 vs. 2.2 Mg ha⁻¹, respectively). In a similar experimental setup, Glover et al. (2010) observed higher root C and SOC (4 and 43 Mg ha⁻¹, respectively) under unfertilized perennial grasslands than found under adjacent wheat fields in the surface 1 m soil profile. Bremer et al. (2002) compared pubescent wheatgrass dominated grassland and wheat-fallow fields in Canada, on a clay loam soil, which also received N- and P-fertilizers. At the end of a 6-year period since grassland conversion, they found SOC levels to be higher by 3 Mg C ha⁻¹ (i.e., approximately 0.5 Mg C ha⁻¹ year⁻¹) in the more densely rooted grassland than in the wheat-fallow fields. They attributed this greater SOC storage in the grassland to a combination of increased belowground biomass input and a slow decomposition rates. Cambardella and Elliott (1992), using stable C isotope demonstrated that wheat-derived C turns over faster than grass-derived C. Given that N application can greatly contribute to SOC sequestration (Paustian et al., 1992; Bremer et al., 2002; VandenBygaart et al., 2011), it seems that higher SOC storage rate under CRP grass-legume mixture in our study would likely be associated with improved N addition from alfalfa in the CRP field.

If we assume the total acreage enrolled in the CRP as of September 2005 in Wyoming remained in the program, then the conversion of 114 thousand hectares of cropland would have resulted in a total soil C storage equivalent to about 1.7 teragrams (Tg; where 1 Tg = 1 × 10¹² g) of C in the surface 30 cm of soil. While the higher SOC storage potential in the CRP system, as indicated above, would likely contribute to its expanded implementation and continued adoption throughout the Great Plains, questions persist as to what will happen to the CRP land when the contracts expire. For example, a total of 55.4 thousand hectares of CRP land in Wyoming expired as of September 2011 and was not re-enrolled, with an estimated 32 thousand currently enrolled hectares scheduled to exit the program by 2018 (USDA FSA, 2012a,b). Although there is currently no enough evidence that this acreage will convert back to cropland if it does exit the CRP, previous study suggested that rising crop prices have impacted CRP enrollment and farmers planned to convert portions of expired CRP land back to cropland (Hellerstein and Malcolm, 2011). Recent review also indicates that there is a negative correlation between CRP enrollment and crop prices since 2007, suggesting that at least some of the acreages exiting CRP are likely to be converted back to cropland (Hellerstein and Malcolm, 2011). These authors also concluded that a robust C market that offsets the impacts of high commodity prices on the cost of maintaining CRP land would help contribute toward continued slowing of future CRP conversion. Therefore, we suggest that such efforts should be supported and expanded if we are to retain SOC stored under the CRP land. Finally, if CRP land returns back to agricultural production, adoption of conservation tillage practices would not only preserve the improved overall soil quality and soil fertility but also create an opportunity of designing more intensified crop rotations alternative to winter wheat-fallow.

In this study the greatest SIC levels were associated with wheat-fallow systems, particularly in the deepest soil layers (Figs. 3, 6 and Table 5). This relationship has been found in northeastern Colorado (Denef et al., 2008), demonstrating that frequent disturbance of the upper soil layers increases SOM mineralization leading to decreased topsoil SOC levels, as already discussed, and also can result in an increased SIC contents in the deeper soil layers. Cihacek and Ulmer (2002) also reported large gains in SIC content in dryland agricultural systems in the Northern Great Plains. Similarly, Mikhailova and Post (2006) found that after >80 years of crop-fallow production on Mollisols in Russia, SIC levels were two times greater than found under adjacent native grassland. This was explained by the additions of Ca-containing fertilizers and manure. In semiarid agroecosystems, higher SIC levels in cultivated systems than native grasslands have been attributed to

differences in soil water availability (Cihacek and Ulmer, 2002). Wheat-fallow systems can simultaneously increase soil water storage, particularly during fallow periods (Lyon and Peterson, 2005; Nielsen and Vigil, 2010), and also increase soil CO₂ concentration due to tillage-induced SOM mineralization; both of which could lead to the formation of secondary carbonates. Given that annual crops tend to have smaller root biomass compared with perennial grasses (Culman et al., 2010; Glover et al., 2010), more water is expected to move into deeper soil layers, causing the precipitation of carbonates. However, it remains to be determined whether cultivation-induced changes in soil CO₂ concentration and water regimes were the controlling factors for carbonate formation in these low-input dryland cropping systems we evaluated. Eswaran et al. (2000) argued that an increase in management-induced SIC content should not be considered as a sequestration of atmospheric CO₂. Recent reviews, however, indicate that both dissolution and secondary carbonate precipitation can generally act as C sinks if driven by elevated soil CO₂ concentration because of decomposition of SOC (Martens et al., 2005; Sanderman, 2012). These differing viewpoints demonstrate the importance of more research to determine whether or not these gains of SIC could be a viable greenhouse gas offset strategy.

5. Conclusions

This study evaluated the long-term impacts of widespread forms of land management practices across the central High Plains on soil C and N. Results from this study suggest that there is little SOC gained eleven years after conversion from tillage-based wheat-fallow production to NT wheat-fallow practice. This suggests that the impacts of NT conversion with little other effort to enhance soil fertility are slower to materialize in marginally productive dryland cropping systems such as those investigated here. In contrast, SOC levels in the surface 0–30 cm depth as well as the whole soil profile (0–120 cm) significantly increased after just seven years following the establishment of grass-legume mixture, despite receiving no fertilization. We suggest that the CRP grass-legume mixture has great potential to improve soil quality and productivity in this region. Results also indicate that gains of SIC could occur under tilled wheat-fallow systems in these semiarid soils, which may result in decline in soil fertility. However, further research seems necessary to improve our understanding of the mechanism behind carbonate formation in these low-input semiarid agroecosystems.

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