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Labile soil organic carbon and nitrogen within a gradient of dryland agricultural land-use intensity in Wyoming, USA

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ABSTRACT

Tillage in dryland winter wheat (*Triticum aestivum* L.)–summer fallow cropping systems of the central High Plains, USA, has caused significant erosion and loss of soil organic matter (SOM), underscoring the need for more sustainable practices on marginally-productive semiarid lands. Conversion to no-till (NT) wheat–fallow or perennial grass–legume cover, as in the Conservation Reserve Program (CRP), provides viable alternatives to tillage-based wheat–fallow practices. However, the overall impact of transitioning on soil biogeochemistry is not fully understood. Labile SOM pools were determined on soil cores (0–120 cm) collected in July 2011 from five unfertilized fields that spanned a gradient in disturbance associated with land-use practices: a more intensively tilled wheat–fallow ('historic', HT) than a conventional (CT) wheat–fallow with limited herbicides combined with tillage, NT wheat–fallow that exclusively used herbicides for ≥10 years, formerly cultivated HT wheat–fallow planted to grass–legume mixture as in the CRP for 7 years, and native prairie (NP) with no history of agricultural disturbance. Significant differences in microbial biomass C (MBC), potentially mineralizable C (PMC) and nitrogen (PMN) were largely confined to the surface soil (0–30 cm), following the order NP > CRP > all wheat–fallow systems. When expressed on a per soil organic C (SOC) basis, both MBC and PMC followed the order CRP > NP > all wheat–fallow systems. In contrast, when normalized by total soil N (TN), PMN was higher in HT and CT soils than in other soils (NT, CRP, and NP). MBC and PMC were positively correlated with SOC whereas PMN, soil pH, and electrical conductivity (EC) showed a negative relationship with SOC. These results suggest more efficient conservation of SOM under perennial grass–legume system than NT wheat–fallow rotation. We suggest that cessation of tillage alone may not be sufficient for the recovery of labile-pool SOM degraded through long-term cultivation in the absence of inputs for soil fertility renewal.

1. Introduction

Historically, agricultural production in the prairie-dominated semiarid regions of the US Great Plains began with intensive tillage with no inputs to maintain soil fertility (DeLuca and Zabinski, 2011; DuPont et al., 2010; Huggins et al., 1998). Farmers received relatively high crop yields in the first few years following the conversion (Glover et al., 2010). However, plowing of native prairies caused a rapid decomposition of native soil organic matter (SOM) ultimately leading to dramatic reductions in native soil fertility and therefore crop yields, especially in marginally productive semiarid agroecosystems.

Most of the loss in SOM following conversion of perennial-dominated native prairies to annual row-crop production is attributed to (1) a loss of easily decomposable, labile-pool SOM (DeLuca and Keeney, 1993; Huggins et al., 1998), (2) low quantity and quality of crop residue and belowground root inputs (DuPont et al., 2010; Glover et al., 2010; Guzman and Al-Kaisi, 2010), and (3) a tillage-caused loss of physical protection to SOM through degradation of soil aggregation and therefore enhanced SOM decomposition (Six et al., 2000). In the central High Plains of the US, dryland cultivation of winter wheat–fallow rotation is the most commonly used cropping system (Hansen et al., 2012; Lyon and Peterson, 2005; Nielsen and Vigil, 2010). Many farmers have traditionally relied on the extensive use of mechanical tillage as the only form of weed control (hereafter referred to as 'historic' practice, HT), or sometimes on limited herbicides combined with tillage (hereafter referred to as 'conventional' practice, CT). Unfortunately, several decades of continuous wheat–fallow cropping practice, particularly under an intensive tillage regime that removes physical protection to SOM, has led to a loss in near surface (0–30 cm depth) SOM (Halvorson et al., 2002; Lyon and Peterson, 2005; Norton et al., 2012), including a loss of soil profile water associated with the tillage operations (Farahani et al., 1998; Hansen et al., 2012; Nielsen and Vigil, 2010). Doran et al. (1998), for instance, reported a 32% soil organic C (SOC) loss from the surface 0–30 cm depth within 27 years following winter wheat–fallow cropping in western Nebraska.

The expanding use of herbicides, improved crop varieties, and direct seeding methods enabled widespread adoption of conservation tillage

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practices, such as no-till (NT) farming (Conant et al., 2007; Lal, 2008; Sanford et al., 2012). The resulting increase in yield and residue production, along with decreases in soil disturbance, is also thought to increase crop residue contribution to SOC (Conant et al., 2007; Lal, 2008). The frequency of fallow has been greatly reduced in dryland production systems of the US Great Plains due to water conservation with NT management, which enabled intensification of crop rotation, such as wheat–corn/millet–fallow (Farahani et al., 1998; Halvorson et al., 2002; Hansen et al., 2012; Nielsen and Vigil, 2010). Intensification of crop rotation is also a key aspect to the observations of increased SOC levels, because it takes advantage of the improved water capture and storage during fallow potentially leading to greater biomass production and may therefore increase organic C input to the soil (Bowman et al., 1999; Halvorson et al., 2002). However, it is not well understood how SOC changes with NT in the absence of intensified crop rotation, such as wheat–fallow (i.e. only one crop in every 2 years system).

Intensive tillage as in the HT and CT practices combined with strong and frequent winds in the central High Plains (Hansen et al., 2012) creates a great potential for wind erosion. This has led to the conversion of some dryland cropland back to perennial grass cover beginning in the 1985 through the USDA's Conservation Reserve Program (CRP) (Burke et al., 1995). Despite the widespread adoption of this program throughout the region and its great potential for SOC storage and ecosystem recovery (Baer et al., 2010; Norton et al., 2012; Sherrod et al., 2005), little is known about the recovery of labile-pool SOM from long-term cultivation following establishment of perennial grass–legume cover in Wyoming.

Here we report measures of soil profile labile (active)-pool SOM, including microbial biomass C (MBC), potentially mineralizable C (PMC) and nitrogen (PMN) from unfertilized fields that spanned a disturbance intensity gradient associated with land-use practices ranging from intensively tilled, no-fertility input wheat–fallow systems to perennial grass–legume cover. The majority of SOM is in forms that mostly turnover on the order of decades and centuries (Parton et al., 1987), and may therefore take several years to detect the recovery of SOC and N. Several previous studies demonstrate that labile C pools recover in shorter time frames than total SOC (e.g. Carpenter-Boggs et al., 2003; Dou et al., 2008; Sherrod et al., 2005). Therefore, by measuring labile-pool SOM, which turns over on an annual basis (i.e. shorter turnover time), we expected to detect early recovery trends following cessation of tillage and establishment of perennial cover. For this study we used a similar space-for-time substitution approach as that of Ihori et al. (1995), Burke et al. (1995) and Norton et al. (2012), in that a native mixed-grass prairie (hereafter referred to as “native prairie”, NP) with no history of agricultural disturbance was used to provide a benchmark for pre-agriculture soil properties due to the absence of temporal data. Our overall hypothesis was that soils beneath NT wheat–fallow and CRP perennial grass–legume cover would exhibit greater recovery of labile-pool SOM relative to tillage-based wheat–fallow practices (HT and CT), especially in near surface layers of soil profile, because soils under NT management and CRP cover experience less disturbance.

2. Materials and methods

2.1. Site description

We sampled soils from five experimental fields maintained by the University of Wyoming Sustainable Agriculture Research and Extension Center (SAREC) near Lingle, WY (42°5′ N, 104°23′ W, elevation 1314 m). All of these fields had the same parent material and were located in close proximity (within 3.5 km) with similar landscape position and soil type according to the USDA's Natural Resources Conservation Service (Soil Survey Staff, 2012). Soils at all five fields were confined to a Mitchell series (coarse-silty, mixed, superactive, calcareous, mesic Ustic Torriorthents) under the US Soil Taxonomy (Soil Survey Staff, 2012). These are relatively deep, well-drained soils developed from silty eolian deposits and/or silty alluvium derived from sedimentary rock with slopes ranging between 0 and 6%. Annual precipitation at this site averages 356 mm, of which approximately 75% is received from April through July.

2.2. Land-use practices

Until the initiation of SAREC, this area belonged to landowners and was first cultivated with dryland winter wheat–fallow rotation using either tillage alone (HT) or a combination of tillage and limited application of herbicides (CT) to control weeds. The HT wheat–fallow experienced greatest soil disturbance associated with tillage operation ($\geq$6 passes year^{-1}) compared with CT wheat–fallow that experienced 3 to 4 passes per year. Tillage in both HT and CT practices was done with a Krause tandem disk followed by Sunflower fallow king to a depth of 20 cm for more than 60 years. This period of continuous cultivation is thought to reduce soil C and N contents to lower equilibrium levels (Mann, 1986). This study was conducted to evaluate the recovery of labile-pool SOM degraded through long-term cultivation by converting tillage-based wheat–fallow (HT) to NT wheat–fallow or back to perennial grass–legume cover, and using native prairie (NP) that had no history of agricultural disturbance to provide a reference of soil properties prior to cultivation. Conversion from HT wheat–fallow to NT wheat–fallow was implemented in 2002, after the University of Wyoming procured this area for research and education purposes. The NT wheat–fallow rotation experienced only minimal soil disturbance during planting, and exclusively used herbicides for weed control both in the wheat and fallow phases. The three wheat–fallow practices (HT, CT, and NT) evaluated in our study received no input of fertilizers.

In 2005, perennial grass–legume cover was established by planting pubescent wheatgrass (*Agropyron trichophorum*) and alfalfa (*Medicago sativa*) on formerly cultivated HT wheat–fallow field as is the case in CRP (e.g. Baer et al., 2010). For clarity purposes we will use the term ‘CRP’ when referring to the mixed planting of pubescent wheatgrass and alfalfa. The CRP field had never been grazed by domestic livestock, nor received any input of fertilizers since establishment, whereas the native prairie is grazed yearly during late summer through early fall, with 0.19 animals ha^{-1}. Vegetation composition at our NP field is dominated by C_3 grasses including wheatgrass (*Elymus lanceolatus*) and needle-and-thread (*Hesperostipa comata*) as well as C_4 grasses such as blue grama (*Bouteloua gracilis*), with less common non-native annual grasses (*Bromus japonicus* and *Bromus tectorum*) interspersed throughout the dominant matrix species.

2.3. Soil sampling

Soil sampling occurred in July of 2011. Within each field, five sampling locations were selected based on similarities and uniformity in topography and soil type; each sampling location was geo-referenced with GPS. All fields but the NP were approximately 0.22 ha each, and the distance between two adjacent sampling locations was 18.3 m; in the NP field, which was approximately 50 ha, two adjacent sampling locations were separated by 100 m. Each of the five sampling locations per field was designated as “pseudoreplicates” for statistical purpose ($n = 5$). At each sampling location, triplicate soil cores (5 cm diameter) from 0 to 120 m depth were extracted using a hydraulic soil probe (Giddings Machine Co., Windsor, CO) and each core was separated into four depth increments (0–30, 30–60, 60–90, and 90–120 cm). The three cores that represented each sampling location were composited into a single representative sample. In the cultivated fields (HT, CT, and NT), soils were collected from adjacent strips in wheat and fallow phases. Samples were placed in separate polyethylene bags, kept in a cooler with frozen ice packs and transported to the laboratory. We recognize that our study design lacks true field replication due to physical space limitations. Nonetheless, we believe that our sampling design is adequate for comparative purposes among our land-use practices, and our goal was to evaluate system-level responses to long-term cultivation (i.e. HT and CT practices for >60 years), cessation of tillage (i.e. NT practice for ≥10 years), and establishment of perennial cover (i.e. CRP for 7 years) relative to native prairie with no history of agricultural disturbance.

2.4. Laboratory analyses

Once in the laboratory, stones, gravel, roots and other coarse fragments were removed, and soil samples were homogenized and stored at 4 °C until analyses. Each soil was subsampled for four separate analyses: gravimetric soil water content (GWC), inorganic N determination, fumigations for microbial biomass, and incubations for potentially mineralizable C and N. GWC was determined by oven drying ~10 g subsamples for 24 h at 105 °C. A 10 g subsamples were analyzed for nitrate (NO_3–N) (Doane and Horwath, 2003) and ammonium (NH_4–N) (Weatherburn, 1967) by extracting them with 50 ml of 0.5 M K_2SO_4 on a shaker for 1 h, and analyzing the extracts on a microplate spectrophotometer (BioTek, Inc., Winooski, VT).

Microbial biomass C (MBC) was estimated using the chloroform ($CHCl_3$) fumigation–extraction method (Horwath and Paul, 1994). Briefly, a 10 g well-mixed composite subsample was fumigated with ethanol-free $CHCl_3$ for 48 h. Following fumigation, the samples were extracted using 50 ml of 0.5 M K_2SO_4 on a shaker for 1 h. Total organic C in the extracts of both fumigated and unfumigated samples was determined on a TOC/TN analyzer (Model: TOC-V_{CSH} and TNM-1, Shimadzu Corp., Kyoto, Japan). Biomass C was calculated as the difference between fumigated and unfumigated TOC contents, and divided by a correction factor (k_c) of 0.35 (Voroney et al., 1991). In a few circumstances, where MBC estimates fell below zero, negative MBC values were rejected (i.e. treated as missing data) and statistical analysis was performed only using the positive data points.

Potential C mineralization (PMC) was estimated from the quantity of CO_2–C mineralized from soils during aerobic, 14-d incubation at 25 °C (Zibilske, 1994). A 22 g subsample of soil was weighed into a 50 ml specimen cup, adjusted to 50% of water-filled pore space and placed in a 940 ml mason jar with air-tight lid fitted with septa to allow for gas sampling. All jars were then sealed, and soils were incubated at 25 °C for 14 days, during which an aliquot of the jar headspace (triplicate 10 ml samples) was removed following 24 h of incubation, at days 7 and 14. Concentrations of CO_2 in the samples were measured by a CO_2 gas analyzer (Model: LI-820, LI-COR Inc., Lincoln, NE). Mineralized C from the three replicates were averaged and summed over the incubation period. At the end of the incubation, soils were analyzed for NH_4–N and NO_3–N as described above. Potential N mineralization (PMN) was calculated from the difference between initial (day 0) and final (day 14) inorganic N contents. Microbial biomass C, PMC and PMN data were corrected for gravel content, which was determined by sieving soil plus K_2SO_4 slurries using a 2 mm sieve. Results are reported as mg kg^{-1} on an oven-dry basis of soil.

Duplicate, air-dried 40 g subsamples were analyzed for soil texture with the standard hydrometer method (Gee and Bauder, 1986). Soil pH and electrical conductivity (EC) were measured in a 1:1 ratio of soil to water slurries (Thomas, 1996). In separate work conducted on the same experimental fields, we found no significant differences in soil bulk density associated with these land-use practices (Hurisso et al., 2013). Given this, no attempt was made to correct the SOM pools (MBC, PMC and PMN) by the approach of equivalent soil mass and only concentration data are reported in this paper.

2.5. Statistical analysis

Analysis of variance was performed on MBC, PMC and PMN, % sand, % silt, and % clay, soil pH and EC results using PROC MIXED in SAS (version 9.2, SAS Institute Inc., Cary, NC). Hypothesis of interest for our data set involved testing for the main effect of land-use (HT, CT, NT, CRP, and NP). For each wheat–fallow field, data from the wheat and fallow strips were pooled, as no differences were evident between these two fields regardless of tillage regime. Comparisons were conducted separately for each sampling depth. Significant differences between land-use practices were determined using LSMEANS pairwise comparisons ($P <$ 0.05). Correlation analysis was performed using SOC, TN, inorganic N, MBC, PMC, PMN, % sand, % silt, % clay, pH, and EC to assess the associations between them ($n = 25$). It is acknowledged that our experimental design lacks true field replication due to limited resources. Despite this, we hoped that the presentation of these results may offer an insight into how labile SOM pools change with no-till in the absence of intensified crop rotations and with perennial grass–legume cover, especially in the light of very little information in the literature with regard to labile-pool SOM dynamics within dryland wheat–fallow cultivation that included no inputs for soil fertility renewal.

3. Results

3.1. Soil profile characteristics — texture, pH and electrical conductivity (EC)

All fields but NP had similar soil texture with silt loam throughout the soil profile (to 120 cm) (Table 1). Native prairie soils were sandy-loam with 63% sand, 24% silt, and 13% clay in the surface 0–30 cm depth, but soils deeper than 30 cm had similar texture as their subsurface (below 30 cm) counterparts under the other four fields. In our study, dryland cultivation of wheat–fallow under different tillage regimes (HT, CT, and NT) and CRP perennial grass–legume cover with no input of fertilizers did not alter soil pH and EC from pre-cultivation levels, as it was evident from the lack of significance in these two variables between prairie and the other four cultivated fields (HT, CT, NT, and CRP) throughout the entire soil profile (Table 1).

3.2. Labile SOM pools and inorganic N pool

Here below we report only statistically significant results for the main effect of land-use practice, with P-values <0.05. We begin with MBC, followed by PMC, PMN and inorganic N pool (NO_3–N + NH_4–N). Hereafter, 'tilled soils' strictly refers to continuously tilled wheat–fallow (HT and CT) and 'cropped soils' refers to all the three wheat–fallow systems (HT, CT, and NT).

Native prairie soils generally had a higher MBC concentration in the whole soil profile (to 120 cm) compared to all wheat–fallow and CRP cover, although the effect size diminished with increasing depth. MBC in tilled soils was <20% that of NP soil in the surface 0–30 cm depth (Fig. 1). MBC in soil managed with NT for ≥10 years did not differ from that of continuously tilled soils. Yet, 7 years after the establishment of perennial grass–legume cover on previously tilled soils, MBC from CRP soil was approximately five times as much as any of that from the cropped soils, but remained lower and 87% of NP soil. In the 30–60 cm depth, cropped soils had approximately 62% as much MBC as NP and CRP soils. In the 60–90 cm depth, MBC in CRP soil was <71% that of NP soil and was similar to that of cropped soils. The ratio of MBC:SOC was greatest in soil beneath CRP cover and lowest in cropped soils compared to NP soil to a depth of 60 cm (Fig. 1).

Overall, prairie soil had a higher concentration of PMC at near surface layer of the soil profile relative to CRP and cropped soils. In the surface 0–30 cm, PMC from the CRP soil was 1.5 times that of NT soil and more than double the values measured in tilled soils, but was lower than that of NP soil (Fig. 2). Surface (0–30 cm) NT soil also had >1.5 times as much PMC as the tilled soils. Moreover, the ratio of PMC:SOC in CRP soil was nearly 1.5 times as much as any of that in the cropped and NP soils (Fig. 2). In contrast, we did observe the opposite trend for PMN in the surface 0–30 cm, where the concentration of PMN was greater in tilled soils (57.4 mg kg^{-1} averaged over HT and CT) than that in NP and NT soils (33.2 and 37.9 mg kg^{-1}, respectively) and was

Table 1
Description of the experimental fields sampled in this study at Sustainable Agriculture Research and Extension Center (SAREC), Wyoming, USA.

Land-use	Field code	Description
Native prairie	NP	Native mixed-grass prairie with no history of agricultural disturbance, but managed with light controlled grazing (ca. 0.19 animals ha^{-1}). Wheatgrass (*Elymus lanceolatus*), needle-and-thread (*Hesperostipa comata*), and blue grama (*Bouteloua gracilis*) dominated vegetation composition.
Conservation Reserve Program	CRP	Previously under wheat–fallow with no chemical inputs (fertilizers or herbicides), but has been under mixed planting of pubescent wheatgrass (*Agropyron trichophorum*) and alfalfa (*Medicago sativa*) since 2005 to represent conservation practices required for USDA programs. This field had not been grazed since establishment.
No-till wheat–fallow	NT	A 2-year wheat–fallow rotation that was previously managed with intensive tillage, and converted to no-till management in 2002, with an exclusive use of herbicides for weed control in both wheat and fallow phases.
Conventional wheat–fallow	CT	A 2-year wheat–fallow rotation involving the use of some herbicides and tillage (3 to 4 passes per year) with Krause tandem disk and Sunflower fallow-king up to a depth of 20 cm for a relatively long period of time (>60 years).
Historic wheat–fallow	HT	A 2-year wheat–fallow rotation with no chemical inputs (fertilizers or herbicides), and managed with intensive tillage (up to (up to 6 passes per year) using Krause tandem disk and Sunflower fallow-king to a depth of 20 cm for more than 60 years.

similar to that in CRP soil (58.8 mg kg^{-1}) (Fig. 3). The ratio of PMN:TN in NP soil was not different from that of NT and CRP soils in the surface 0–30 cm (ranging from 4.6 to 6.0%), and was lower than that of tilled soils (10.3% average over HT and CT) (Fig. 3). Inorganic N pool, on the other hand, did not follow any of these trends and values were very low (<5% of TN) and equivalent among all five fields associated with different land-use practices. Data are not shown for inorganic N, but ranged from 20.7 to 38.7 mg kg^{-1} soil in the surface 0–30 cm, 10.4 to

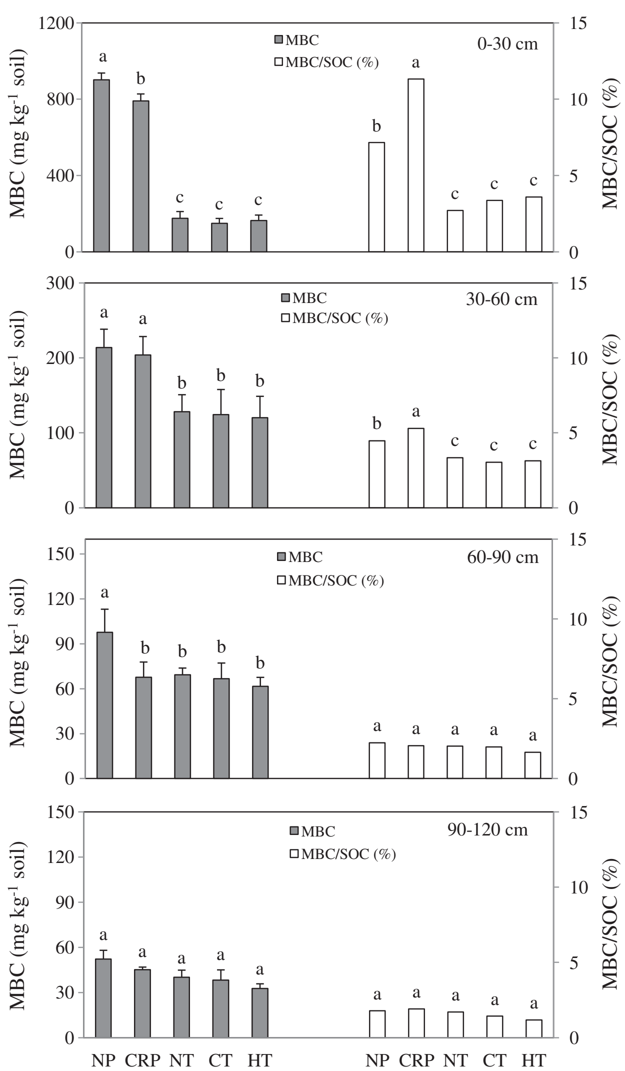

Fig. 1. Concentrations of microbial biomass C (MBC) and the ratio (×100) of MBC:SOC[‡] across five land-uses at four depth increments: 0–30, 30–60, 60–90, and 90–120 cm. [‡]Soil organic C (SOC) was determined by combustion using a Carlo Erba NC 2100 elemental analyzer and reported in Hurisso et al. (2013). NP = native prairie, CRP = Conservation Reserve Program, NT = no-till, CT = conventional tillage, and HT = historic wheat–fallow. Values with different letters were significantly different among land-uses ($P < 0.05$). Error bars represent standard error of the mean.

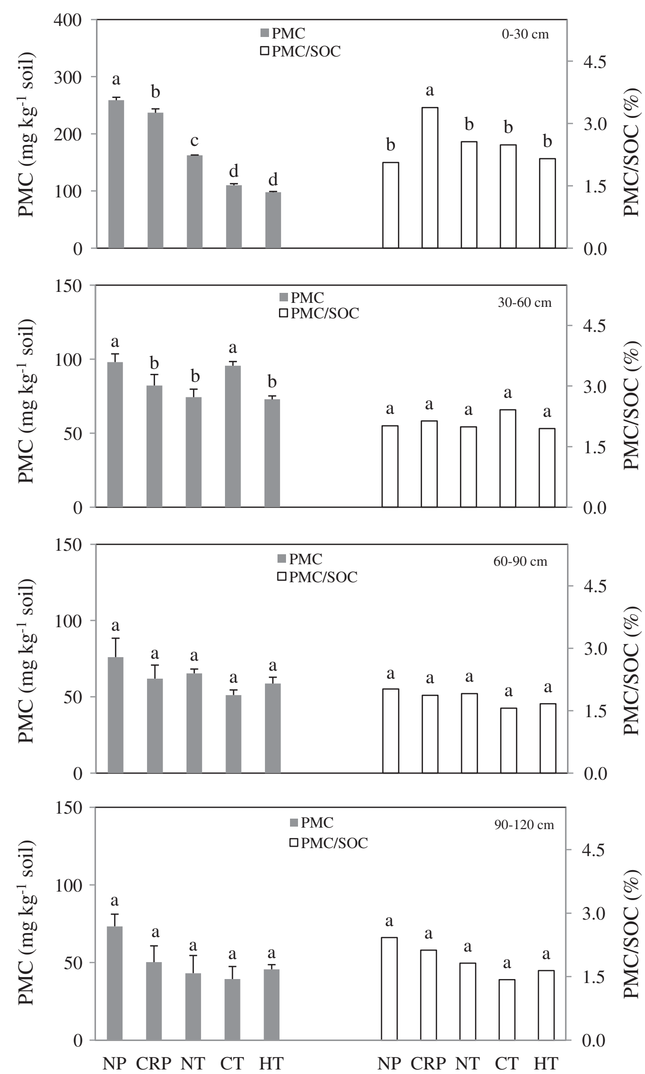

Fig. 2. Concentrations of potentially mineralizable C (PMC) and the ratio (×100) of PMC:SOC across five land-uses at four depth increments: 0–30, 30–60, 60–90, and 90–120 cm. NP = native prairie, CRP = Conservation Reserve Program, NT = no-till, CT = conventional tillage, and HT = historic wheat–fallow. Values with different letters were significantly different among land-uses ($P < 0.05$). Error bars represent standard error of the mean.

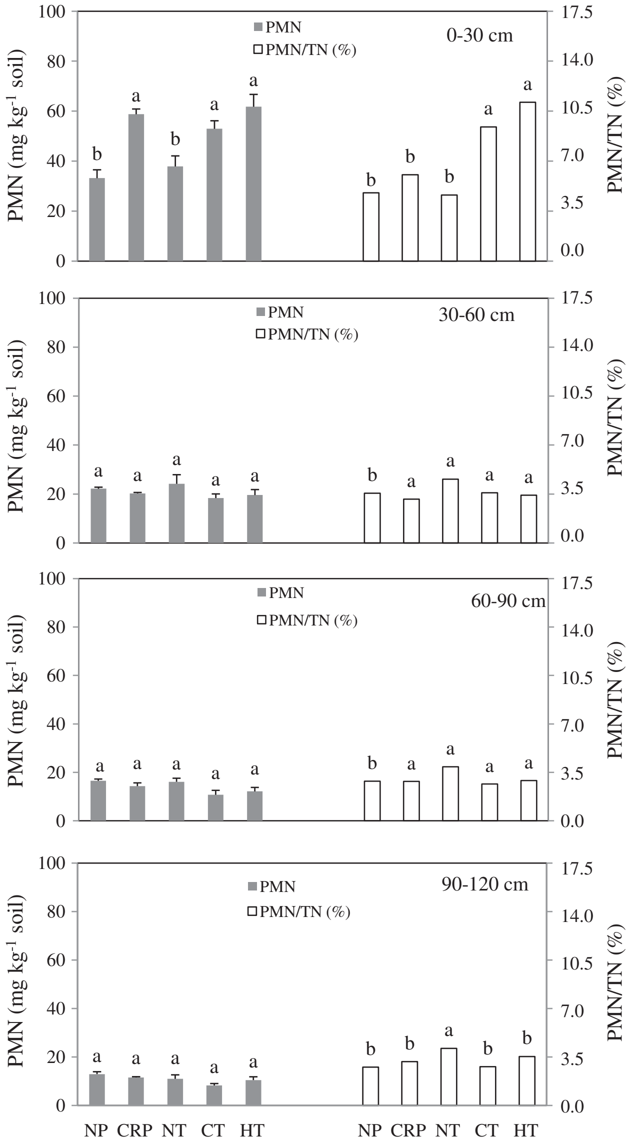

Fig. 3. Concentrations of potentially mineralizable N (PMN) and the ratio (×100) of PMN:TN across five land-uses at four depth increments: 0–30, 30–60, 60–90, and 90–120 cm. ‡Total soil N (TN) was determined by combustion using a Carlo Erba NC 2100 elemental analyzer and reported in Hurisso et al. (2013). NP = native prairie, CRP = Conservation Reserve Program, NT = no-till, CT = conventional tillage, and HT = historic wheat–fallow. Values with different letters were significantly different among land-uses ($P < 0.05$). Error bars represent standard error of the mean.

13.6 mg kg^{-1} soil in the 30–60 cm, 5.5 to 8.8 mg kg^{-1} soil in the 60–90 cm, and 3.9 to 6.2 mg kg^{-1} soil in the 90–120 cm.

3.3. Correlations of labile SOM pools with soil texture, pH, and EC

Surface soils (0–30 cm) from all the five land-uses were compared to determine the relationship between various biochemical and physical measures of soil. MBC and PMC were positively correlated with SOC ($r = 0.82$ and 0.85, respectively, $P < 0.0001$ for both; Table 3). PMN, soil pH, and EC were negatively correlated with SOC ($r = -0.56$, -0.51, and -0.49 respectively, $P < 0.05$). None of the biochemical measures (SOC, TN, MBC, PMC, and PMN) significantly correlated with soil texture (% sand, % silt, or % clay). Based on a stepwise linear regression model, MBC, the ratio of MBC:SOC, PMC and the ratio of PMC:SOC were better predictors of changes in total SOM within the surface 0–30 cm depth.

4. Discussion

In our study prairie soil that had never been under agricultural use represents an undisturbed, pre-cultivation reference conditions by which we compared the other four management practices; namely historic wheat–fallow, conventional wheat–fallow, no-till wheat–fallow, and CRP grass–legume cover. The native prairie sampled in this study was managed with light controlled grazing for many years, but light grazing is not expected to change SOC levels in prairie soils. For example, Ingram et al. (2008) imposed different grazing treatments on a northern mixed-grass prairie in Wyoming to study the long-term (>21 years) soil C and microbial dynamics to a depth of 60 cm. That study showed that neither SOC nor microbial biomass was altered by light grazing (≤0.23 animals ha^{-1}) compared to ungrazed control. Perhaps most importantly, we did observe significantly greater concentrations of MBC and PMC in prairie soil throughout the whole profile (to 120 cm) than any of the cropped soils and soil beneath CRP grass–legume cover (Figs. 1 and 2), despite the native prairie field having slightly sandier texture near the soil surface (0–30 cm) (Table 2). Given the lack of significant correlation between soil texture and any of the labile SOM pools (see Table 3), SOM storage does not appear to be influenced by soil texture at our study sites, which may be attributed to the low variability in clay content among all the five fields we sampled.

Due to fewer disturbances in what are considered best management scenarios, we expected to see greater recovery of labile SOM pools following cessation of tillage and establishment of CRP perennial grass–legume cover relative to tilled soils. However, we found that MBC and PMC concentrations from soil under no-till management for ≥10 years were not different than those from continuously tilled soils regardless of depth of sampling (Figs. 1 and 2). This contradicts with Acosta-Martinez et al. (2007) and Dou et al.'s (2008) observations of greater labile SOC pool following adoption of no-till management in the more productive parts of Great Plains. Several phenomena related to our study design and the unique attributes of cropping systems may explain why no-till management did not influence mineral and labile SOM pools (i.e. inorganic N, MBC, PMC, and PMN; see Figs. 1–3). However, we suspect that the absence of difference in this study may be more explained by the lack of fertilizer inputs for soil fertility renewal

Table 2
Particle size distribution (% sand, % silt, and % clay), soil pH and electrical conductivity (EC) to 120 cm depth, with standard errors in the parentheses. Land-use type: native prairie (NP), Conservation Reserve Program (CRP), no-till (NT), conventional (CT) and historic (HT) wheat–fallow practices.

		Particle size distribution (%)				
Land-use	Depth (cm)	Sand	Silt	Clay	pH	EC
NP		63 (3.4)	24 (1.4)	13 (1.7)	7.31 (0.7)	0.57 (0.03)
CRP		42 (4.3)	50 (1.4)	8 (1.7)	7.47 (0.4)	0.67 (0.02)
NT	0–30	39 (4.4)	50 (1.4)	11 (1.4)	8.12 (0.2)	0.62 (0.01)
CT		36 (5.4)	51 (2.0)	13 (1.4)	8.52 (0.1)	0.72 (0.15)
HT		41 (4.3)	50 (2.0)	9 (2.0)	8.28 (0.2)	0.77 (0.12)
NP		42 (2.7)	50 (3.2)	8 (1.3)	8.35 (0.1)	0.65 (0.03)
CRP		41 (2.7)	51 (2.4)	8 (1.4)	8.23 (0.1)	0.73 (0.03)
NT	30–60	38 (3.1)	50 (2.3)	12 (1.7)	7.85 (0.3)	0.79 (0.03)
CT		36 (1.9)	53 (2.1)	11 (1.4)	8.56 (0.1)	1.04 (0.02)
HT		40 (2.0)	52 (2.1)	8 (1.6)	8.31 (0.1)	1.11 (0.02)
NP		38 (1.4)	50 (1.7)	12 (2.1)	8.16 (0.2)	0.79 (0.11)
CRP		34 (1.4)	54 (1.7)	12 (2.1)	8.28 (0.2)	0.81 (0.12)
NT	60–90	40 (1.2)	50 (1.6)	10 (1.3)	8.12 (0.1)	0.98 (0.11)
CT		35 (1.3)	56 (1.3)	9 (2.3)	7.11 (0.3)	1.11 (0.08)
HT		37 (1.4)	51 (1.3)	12 (1.1)	8.39 (0.1)	1.13 (0.07)
NP		41 (2.0)	51 (1.7)	8 (2.2)	8.34 (0.1)	0.96 (0.07)
CRP		36 (2.0)	52 (1.3)	12 (1.1)	8.44 (0.1)	0.88 (0.07)
NT	90–120	33 (2.0)	54 (1.2)	13 (1.0)	8.55 (0.1)	1.02 (0.07)
CT		42 (1.8)	50 (1.2)	8 (1.6)	8.43 (0.2)	1.03 (0.08)
HT		40 (1.8)	51 (1.3)	9 (1.8)	8.24 (0.1)	1.01 (0.07)

Table 3
Correlation (r) between various measures of soil biochemical and physical properties across all the five land-uses in the surface 0–30 cm depth. Significant values are indicated in asterisk.

	SOC	TN	Inorganic N	MBC	PMC	PMN	% sand	% silt	% clay	pH	EC
SOC	1										
TN	0.32	1									
Inorganic N	−0.16	0.32	1								
MBC	0.82***	0.51*	0.60**	1							
PMC	0.85***	0.65**	0.72**	0.94***	1						
PMN	−0.56*	0.43*	0.49*	0.91***	0.87***	1					
% sand	0.37	−0.04	−0.13	0.39	0.28	−0.37	1				
% silt	−0.42	0.09	0.22	−0.37	−0.37	0.25	−0.98***	1			
% clay	0.44	−0.28	−0.25	0.18	0.24	−0.33	0.51*	−0.66**	1		
pH	−0.51*	−0.58*	−0.56*	−0.61**	−0.63**	−0.54*	−0.73**	0.67**	−0.14	1	
EC	−0.49*	−0.27	−0.17	−0.39	−0.31	−0.32	−0.47*	0.49*	−0.41	0.44	1

*** $P < 0.0001$
** $P < 0.01$
* $P < 0.05$

which may have lead to underperforming no-till wheat–fallow cropping system, particularly in low-productivity agroecosystems such as the one reported here. Supporting this explanation, we did not find any differences in winter wheat grain yields (averaged across 5 years) between no-till (1.26 Mg ha^{-1}) and tilled wheat–fallow systems (1.86 Mg ha^{-1}, averaged over HT and CT; Hurisso et al., 2013). If there was a smaller concentration of PMN and lower ratio of PMN:TN in no-till soil (see Fig. 3), crop yield for no-till wheat–fallow was likely limited by low soil N availability resulting from reduced SOM mineralization which is typical in no-till soils due to reduced residue mixing and low temperatures (Drury et al., 2005). Previous studies have suggested that greater recovery of SOC in no-till cropping systems may be due to intensified crop rotations, such as wheat–millet/corn–fallow (Bowman et al., 1999; Halvorson et al., 2002; Liebig et al., 2004; Sherrod et al., 2005). However, we were unable to address this possibility because our study used the same wheat–fallow rotation in each of the cropped soils.

We therefore suggest a shift in management towards N additions. One potential change that may enhance N availability in these low fertility cropped soils is to substitute a portion of the fallow period with a short season leguminous green manures. This approach has been used with great success in semiarid Canada (Biederbeck et al., 2005) and northern Montana, USA (Miller et al., 2011), where green manure legumes such as lentil (*Lens culinaris*) and winter pea (*Pisum sativum*) when terminated early improved soil N availability without excessive depletion of soil water reserves for the subsequent wheat crop. Moreover, the use of short season legumes as partial fallow replacement can add crop-derived C to the soil and may also create great potential for weed control in conservation tillage systems (Hansen et al., 2012).

When expressed on a per SOC basis, MBC (in the 0–30 and 30–60 cm depths) and PMC (in the surface 0–30 cm depth) concentrations in CRP soil were significantly higher than any of those in the cropped soils (Figs. 1 and 2). Considering the relatively shorter time period (≤7 years) since the establishment of the CRP grass–legume cover, it was surprising that MBC and PMC concentrations (expressed on a per SOC basis) were also greatest in CRP soil compared to prairie soil. As new C inputs first become incorporated into the soil, both MBC and PMC are thought to represent this recently-added labile C pool (Baer et al., 2010). Our observations with regard to greater ratio of MBC:SOC and PMC:SOC associated with CRP soil point to a possible shift towards high quality and quantity plant litter inputs under the mixed planting of pubescent wheatgrass and alfalfa (Sparling, 1992). In perennial systems, such as the grass–legume cover in this study, a larger percentage of root biomass (mainly fibrous root and root hairs) is often concentrated near the soil surface (to 40 cm), thereby creating a much larger pool of cycling labile C compared to annual row crop systems (Rasse et al., 2005; Culman et al., 2010). The inclusion of alfalfa in the CRP field can contribute not only to the total quantity of residue produced (above- and belowground biomass), but also to substrate quality by lowering the C:N ratio of the residue input and thereby enhancing C availability for microbial biomass (Haynes and Beare, 1997; Sainju and Lenssen, 2011). It is also noteworthy that CRP plantings were mostly introduced grass species that are often more productive with deeper and extensive root systems compared to native prairie grasses that are often short and less productive (Ingram et al., 2008; M. Smith, personal communication). Altogether, our findings suggest that labile SOM pools (mainly MBC and PMC) degraded through long-term and uniform wheat–fallow practices with intensive tillage regime would rebound more quickly when tilled soils are restored to perennial grass–legume cover rather than when converted to no-till management, particularly in low fertility dryland cropping systems.

5. Conclusions

Our hypothesis regarding changes in labile SOM pools in response to cessation of tillage and grass–legume establishment was only partially supported by the results of this study, because the concentrations of MBC and PMC were statistically equivalent among all the three cropped soils (HT, CT, and NT). Although we acknowledge that more research is needed to better understand the factors that are responsible for limited response in labile SOM pools observed in the no-till soil, we suggest that the lack of inputs for soil fertility renewal likely played a major role, particularly in these most vulnerable marginally productive agroecosystems. In contrast, both MBC and PMC (expressed as a per SOC basis) in CRP soil were above those measured in prairie and any of those in the cropped soils, despite the shorter time frame (≤7 years) since the establishment of the perennial grass–legume cover. This implies that the degrading effects of historic and conventional wheat–fallow practices would disappear more quickly when soils are restored back to perennial grass–legume systems rather than when converted to no-till wheat–fallow rotation.

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