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Soil C and N changes on conservation reserve program lands in the Central Great Plains

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Abstract

The Conservation Reserve Program (CRP) was initiated to reduce water and wind erosion on marginal, highly erodible croplands by removing them from production and planting permanent, soil-conserving vegetation such as grass. We conducted a field study at two sites in Wyoming, USA, in order to quantify changes in soil C and N of marginal croplands seeded to grass, and of native rangeland plowed and cropped to wheat–fallow. Field plots were established on a sandy loam site and a clay loam site on wheat–fallow cropland that had been in production for 60+ years and on adjacent native rangeland. In 1993, 6 years after the study was initiated, the surface soil was sampled in 2.5 cm depth increments, while the subsurface soil was composited as one depth increment. All soil samples were analyzed for total organic C and N, and potential net mineralized C and N. After 60+ years of cultivation, surface soils at both study sites were 18–26% lower (by mass) in total organic C and N than in the A horizons of adjacent native range. Six years after plowing and converting native rangeland to cropland (three wheat–fallow cycles), both total and potential net mineralized C and N in the surface soil had decreased and NO_3–N at all depths had increased to levels found after 60+ years of cultivation. We estimate that mixing of the surface and subsurface soil with tillage accounted for 40–60% of the decrease in surface soil C and N in long-term cultivated fields; in the short-term cultivated fields, mixing with tillage may have accounted for 60–75% of the decrease in C, and 30–60% of the decrease in N. These results emphasize the need to evaluate C and N in the entire soil solum, rather than in just the surface soil, if actual losses of C and N due to cultivation are to be distinguished from vertical redistribution. Five years after reestablishing grass on the sandy loam soil, both total and potential net mineralized C and N in the surface soil had increased to levels equal to or greater than those observed in the A horizon of the native range. On the clay loam soil, however, significant increases in total organic C were observed only in the surface 2.5 cm of N-fertilized grass plots, while total organic N had not significantly increased from levels observed in the long-term cultivated fields.

Keywords: CRP (Conservation Reserve Program); Soil organic matter; Soil quality; Nitrogen mineralization; Wheat–fallow

1. Introduction

In the semi-arid Great Plains, the use of summer fallow, or cropping every other year to conserve soil moisture, initially increased and stabilized wheat (*Triticum vulgare* L.) yields (Stewart et al., 1983). In the long-term, however, clean-till wheat–fallow agriculture has resulted in increased erosion, loss of tilth, decreased aggregate stability and increased soil salinity (Rennie, 1979; Dalal and Mayer, 1986; Tiessen et al., 1982). Summer fallow with intensive

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cultivation also has resulted in declining soil organic matter (SOM) levels, which has reduced the nutrient-supplying capacity of the soil (Salter and Green, 1933; Haas et al., 1957; Campbell and Souster, 1982; Tiessen et al., 1982; Schimel et al., 1985a; Aguilar et al., 1988; Bowman et al., 1989).

Haas et al. (1957) summarized changes in soil organic C and N caused by 30–40 years of dryland cropping at 17 experiment stations in the Great Plains. They reported concentration decreases of 28–59% (avg. 42%) in soil organic C, and 24–60% (avg. 36%) in soil organic N in the surface 15 cm. Subsequent studies have reported similar levels of decline in surface soil organic C and N as a result of cultivation on the Great Plains (Campbell and Souster, 1982; Tiessen et al., 1982; Aguilar et al., 1988; Bowman et al., 1989, 1990). On-site decreases in SOM with the use of clean-till cultivation result from increased exposure to losses by wind and water erosion; reduced additions of organic materials; and enhanced SOM decomposition through mixing, changes in temperature, moisture and aeration, and exposure of new soil surfaces to aggregate disruption (Bowman et al., 1990; Dalal and Mayer, 1986; Burke et al., 1997). Jenny (1933) proposed that SOM would reach a new lower equilibrium level after 50 years of cultivation. Haas et al. (1957) reported that new steady-state levels were attained after 30 years, whereas Martel and Paul (1974) revised this figure to between 60 and 70 years based on radiocarbon dating. More recently, Tiessen et al. (1982) reported that SOM continued to decline after 90 years of cultivation because of erosional losses.

The Conservation Reserve Program (CRP) was initiated to reduce water and wind erosion on marginal, highly erodible croplands by removing them from production and planting them into soil-conserving covers, such as grass, for a 10-year contract period (CAST, 1990). However, these lands were reseeded to grasses with little knowledge of their potential for sustained long-term production of good quality forage. A better understanding of the factors controlling SOM formation and degradation, and how these factors influence soil fertility, is needed if we are to successfully sustain long-term production of quality forage on these marginal lands. The objectives of this research were to quantify changes in soil organic C and N when native rangeland is converted to wheat–fallow cropping, and when a native-species grass community is reestablished on marginal, highly erodible wheat–fallow cropland.

2. Material and methods

2.1. Field plot establishment and soil sampling

Field plots were established in April 1987 at two sites in Wyoming with similar growing season conditions but different soil types (Table 1). One site was located near Arvada in northeastern Wyoming approximately 75 km northwest of Gillette, on an Ulm clay loam (fine montmorillonitic, mesic, Ustollic Haplargid). The second site, located near Keeline in east central Wyoming approximately 32 km southwest of Lusk, was established on a Phiferson sandy loam (coarse-loamy, mixed, mesic Aridic Haplustoll). Plots were established on wheat–fallow cropland that had been in production for 60+ years, and on adjacent (<50 m away) undisturbed native rangeland of the same soil series. The native range on the clay loam soil was a shrub/grass community, with the dominant species being big sagebrush (*Artemesia tridentata*) and western wheatgrass (*Pascopyrum smithii*), whereas the native range on the sandy loam soil was a mixed grass prairie dominated by needle-and-thread (*Stipa comata*), prairie junegrass (*Koeleria pyramidata*) and blue grama (*Bouteloua gracilis*). Relatively flat terrain (<2% slope) was selected so as to avoid confounding erosional factors of soil loss or deposition, and soil water differences due to runoff or runon.

Treatments at each site included: (1) continued wheat–fallow cropping, (2) native rangeland, (3) plowed (15 cm deep) native rangeland cropped to wheat–fallow, and (4) reseeded grassland (C_3 cool-season species) on wheat–fallow cropped area. At each site, 9.8×19.5 m replicate plots were arranged in three blocks across native rangeland and adjacent cropland in a randomized block design. Although the plots were established in 1987, drought conditions prevented establishment of the reseeded grass treatment until the spring of 1989. The reseeded grass treatment was composed of a mixture of western wheatgrass, slender wheatgrass (*Agropyron trachycaulum*), streambank wheatgrass (*Agropyron riparium*), thickspike wheat-

Table 1
Location of experiments and descriptions of sites in Wyoming

	Site	
	Arvada, WY	Keeline, WY
Elevation, m	1186	1599
Latitude	44°56′	42°45′
Longitude	105°48′W	104°29′W
Temperature, ave. daily, °C	6.9	7.1
Ave. frost-free days	117	117
Ave. growing degree days	1944	1946
Pan evaporation, mm	143	146
Precipitation, ave. annual mm	304	403
Precipitation, growing season, mm	243	303
Native plant community	Shrub/Grass	Mixed-grass
Soil type	Ulm clay loam	Phiferson sandy loam
Soil horizons, native range	A: 0–8 cm	A: 0–10 cm
	Bt1: 8–25 cm	B2: 10–28 cm
	Bt2: 25–40 cm	Bk: 28–60 cm
	Ck: >40 cm	Ck: >60 cm
Soil texture, % (sand/silt/clay)		
Native range soil	A: 28/44*/28*	A: 67/25/8
	Bt1: 33/30/38	B2: 65/25/10
Cropped soil	0–8 cm: 34/26/40	0–10 cm: 62/27/12
	8–25 cm: 33/27/40	10–28 cm: 63/26/11

* Native range and cropped soils (0-8 cm) are significantly different in silt and clay contents ($p<0.10$).

grass (*Agropyron dasystachyum*) and green needlegrass (*Stipa viridula*). In the spring of 1990, the reseeded grass treatment plots were split and half of each plot fertilized with 34 kg N ha^{-1} as broadcast NH_4NO_3. The fertilizer treatment, repeated each spring thereafter, was included to evaluate the hypothesis that soil organic C regeneration would be enhanced by additions of N.

Although soil samples were collected annually beginning in 1987, this paper presents the results of soil samples collected in 1993 because this was the first year in which significant changes in the reseeded grass treatments were observed. In August 1993 soil samples were taken at four locations, approximately 4 m apart, down the center of each plot, and composited by depth increment. The sampling depth increments were aligned with the depths of soil horizons under native range conditions at both sites (Table 1). The surface horizon was sampled by hand in 2.5 cm increments by inserting a flat-bladed metal spatula horizontally into the vertical face of a small soil pit to remove each 2.5 cm increment. After removal of these samples, the subsoil was sampled with a 5 cm-diam. coring tube. The Ulm clay loam soil profile was sampled to 25 cm and partitioned as 0–7.5 cm (by 2.5 cm increment), and 7.5–25 cm. The Phiferson sandy loam was sampled to 28 cm and partitioned as 0–10 cm (by 2.5 cm increment), and 10–28 cm. Soil sampling was limited to the top two horizons in each soil because these horizons contained the majority of total plant root biomass, and thus encompassed the majority of the soil profile containing C and N. Determination of root distribution in the soil profiles was based on visual observations of test cores taken in 1987, which indicated that 80–90% of total native plant root biomass occurred within the top two horizons of both soil types. This estimate concurs with the findings of Sims et al. (1978) and Sims and Singh (1978), who reported that on average, 80% of the total plant material below ground in North American short-, mixed- or tall-grass prairie occurred within the top 30 cm of the soil; on the three mixed-grass prairie sites evaluated, 83–87% of total root biomass was within the top 30 cm.

Bulk density was measured for the surface and subsurface depth increments in each plot by the core method described by Blake and Hartge (1982). Two separate 7.5 cm-long cores were taken from each plot to measure the average bulk density of the surface horizon (0–7.5 or 0–10 cm), and the average bulk density of the subsoil horizon. The lower cores were taken from the center of the subsurface horizon (7.5–25 or 10–28 cm).

2.2. Laboratory and statistical analyses

Total soil N was determined by the micro-Kjeldahl procedure described by Schuman et al. (1973), and inorganic N (NH_4^+–N and NO_3^-–N) by extraction with 1 M l^{-1} KCl for 0.5 h and colorimetric analyses of the extracts with a Technicon[1] Autoanalyzer (Technicon Industrial Systems, 1986, 1987). Total soil organic C was determined by the wet oxidation procedure described by Nelson and Sommers (1982). An aerobic incubation procedure was used to determine potential net soil C and N mineralization. The incubation unit consisted of a tightly closed 0.47 l Mason jar containing a small vial of 1 M NaOH (7 ml) which served as a CO_2 trap, and a 20 g soil sample in a 50 ml Erlenmeyer flask. The soil was wetted with distilled water to a soil water content corresponding to −0.033 MPa soil water potential, then samples were incubated at 30°C for 21 days. At the end of the incubation period, soils were extracted with 1 M KCl at a 1:10 soil: extract ratio and analyzed for NH_4^+–N and NO_3^-–N as described above. The amount of CO_2 released during the incubation was measured by titrating excess base in the CO_2 traps with standardized HCl (Stotzky, 1965). The initial NH_4^+–N and NO_3^-–N concentrations of the soil were subtracted from the post-incubation inorganic N concentration to calculate net N mineralization.

Bulk density data were used to convert soil C and N concentrations (mg kg^{-1}) to C and N mass (kg ha^{-1}) in the soil. Bulk densities of the Ulm clay loam soil were not significantly different among treatments. Average values were 1.25 Mg m^{-3} for the surface horizon (0–7.5 cm), and 1.48 Mg m^{-3} for the subsurface horizon (7.5–25 cm). In the Phiferson sandy loam soil, bulk densities of the surface horizon (0–10 cm) were not significantly different among treatments, with an average value of 1.19 Mg m^{-3}. In the subsurface horizon (10–28 cm) of the sandy loam soil, however, bulk densities varied significantly among treatments. Average values were 1.28, 1.36, 1.41, 1.38 and 1.29 Mg m^{-3} for the native, plowed, cropped, grass, and fertilized grass treatments, respectively ($LSD_{0.10}$=0.09).

Analyses of variance were used to evaluate treatment comparisons for soil C and N masses of each soil depth increment. Least-significant-differences (LSD) procedures were used for mean separation at $P \leq 0.10$ (Steel and Torrie, 1980).

[1]Trade names are included only for the benefit of the reader and do not constitute any preferential endorsement by the USDA over similar products on the market.

3. Results

3.1. Effects of cultivation on soil C and N

Total organic C and N were significantly lower in the surface soil (7.5–10 cm) of long-term-cultivated plots than in the A horizons of the adjacent native range on both soil types; however, total organic C and N in the soil profiles to 25–28 cm were not significantly different ('cropped' and 'native' treatments, Tables 2 and 3). The majority of the decrease in C and N with cultivation occurred in the surface 2.5 cm of both soil types. Potential net mineralized C and N in the sandy loam soil were significantly lower in long-term-cropped plots than native range only in the surface 2.5 cm. In the 2.5–10 cm depth of the sandy loam soil profiles, potential net mineralized C was not significantly different between native and long-term cropped plots, while potential net mineralized N was significantly higher in the long-term cropped treatment. In the clay loam soil, potential net mineralized C was significantly lower in the surface 7.5 cm of the cropped soil, whereas potential net mineralized N was significantly lower in the surface 2.5 cm, but significantly higher in the 2.5–7.5 cm depth of the profile. In both soil types, inorganic NO_3–N was significantly higher in all depth increments in the cropped than in the native soil profiles.

Ratios of total C:N and mineralized C:N were significantly narrower in the surface soil of long-term-cropped than native plots on the sandy loam soil (avg. 0–10 cm), but there were no significant differences between sandy loam cropped and native

Table 2
Carbon and nitrogen masses and distribution with depth in the Phiferson sandy loam soil from native grasslands, plowed and cultivated native grasslands (6th year), cropped land cultivated for 60+ years, grassland reestablished on cropped land (4th year), and reestablished grassland fertilized annually with 34 kg N ha^{-1}

Soil profile (cm)	Native (kg ha^{-1})	Plowed	Cropped	Grass	Grass+N	$LSD_{0.10}$	Native	Plowed	Cropped	Grass	Grass+N	$LSD_{0.10}$
Total organic carbon							Total organic nitrogen					
0–2.5	3483	2224	2454	3395	3933	956	313	217	230	307	338	54
2.5–5	2680	2207	2144	2817	3391	379	261	213	221	263	270	40
5–7.5	2587	2136	2176	3018	3236	366	246	209	211	253	259	nsd
7.5–10	2660	1990	2022	2728	2907	603	237	202	207	248	256	nsd
10–28	15243	15827	17015	18740	21638	nsd	1510	1616	1671	1737	1667	nsd
0–10	11409	8560	8795	11959	13468	1972	1057	841	869	1070	1123	162
0–28	26652	24386	25810	30699	35106	6089	2567	2457	2540	2807	2791	nsd
Potential net mineralized CO_2–C							Potential net mineralized N					
0–2.5	191	67	104	185	271	73	18.2	9.7	10.1	19.0	24.1	4.8
2.5–5	52	37	53	101	108	38	4.7	5.8	6.4	7.8	9.7	1.8
5–7.5	44	15	31	97	89	24	4.5	4.1	5.4	5.5	7.1	1.8
7.5–10	38	21	43	107	73	34	1.9	3.5	4.9	5.3	5.8	2.0
2.5–10	134	73	127	306	270	71	11.1	13.5	16.6	18.6	22.6	3.8
0–10	326	140	231	491	541	133	29.3	23.2	26.8	37.6	46.6	9.1
Extractable NH_4-N							Extractable NO_3–N					
0–2.5	0.47	0.91	0.70	0.32	0.75	nsd	1.05	2.08	3.07	0.26	1.10	1.33
2.5–5	0.41	0.74	0.63	0.28	0.59	nsd	0.19	1.75	2.20	0.07	0.03	0.46
5–7.5	0.42	0.50	0.67	0.29	0.39	nsd	0.07	2.10	2.60	0.03	0.02	0.67
7.5–10	0.43	0.68	0.54	0.34	0.44	nsd	0.04	2.56	3.01	0.02	0.00	1.00
10–28	2.38	5.74	10.68	2.34	3.04	2.56	0.59	16.24	13.44	0.57	0.43	2.29
0–10	1.73	2.83	2.54	1.23	2.17	nsd	1.35	8.48	10.88	0.38	1.16	3.21
0–28	4.11	8.56	13.22	3.57	5.21	3.81	1.93	24.72	24.32	0.95	1.58	2.96

fields in the average proportions (0–10 cm) of total organic C and N that were mineralized (Table 4). In the clay loam soil, average (0–7.5 cm) ratios of total C:N, mineralized C:N and mineralized C :total organic C were significantly narrower in cropped than native plots, whereas the two treatments were not significantly different in the average (0–7.5 cm) ratio of mineralized N:total organic N (Table 5).

After six years of cultivation, short-term cultivated plots were not significantly different from the long-term cultivated plots in total organic C and N, and potential net mineralized C and N in the surface 7.5–10 cm, or in levels of NO_3–N to 25–28 cm ('plowed' and 'cropped' treatments, Tables 2 and 3). In the sandy loam soil, plots cultivated for 6 years were not significantly different in ratios of total C:N, mineralized C:N, and net mineralized N:total organic N, than fields cultivated for 60+ years, but the average (0–10 cm) ratio of mineralized CO2-C:total organic C was significantly narrower (Table 4). In the clay loam soil, there were no significant differences between short-term and long-term cultivated plots in these four ratios (Table 5).

We estimated decreases in cultivated soil C and N that were due to mixing of the A and B horizons by the initial plowing of the native range by comparing levels of surface soil C and N immediately after plowing in 1987 with levels of C and N under native range and with long term cropping (Table 6). Vertical redistribution of C and N caused by plowing in 1987 decreased surface soil C concentrations by approximately 17%, and N concentrations by approximately 12% in the clay loam soil, and by about 10% and 5%, respectively, in the sandy loam soil. These levels of decline represent about 60% of the total decrease in surface soil C and N measured in 1993 after 6 years of cultivating the clay loam soil, and represent about

Table 3
Carbon and nitrogen masses and distribution with depth in the Ulm clay loam soil from native grasslands, plowed and cultivated native grasslands (6th year), cropped land cultivated for 60+ years, grassland reestablished on cropped land (4th year), and reestablished grassland fertilized annually with 34 kg N ha^{-1}

Soil profile (cm)	Native	Plowed	Cropped	Grass	Grass+N	$LSD_{0.10}$	Native	Plowed	Cropped	Grass	Grass+N	$LSD_{0.10}$
	(kg ha^{-1})											
Total organic carbon							Total organic nitrogen					
0–2.5	8275	4837	4961	5672	6559	1460	629	399	414	455	506	113
2.5–5	6077	4812	4934	4790	5008	nsd	487	392	420	392	398	nsd
5–7.5	5459	4544	4770	4626	4741	nsd	447	409	401	383	388	nsd
7.5–2.5	33899	36342	36771	35593	35690	nsd	2848	2970	3144	2952	2943	nsd
0–7.5	19811	14193	14665	15088	16308	3334	1563	1199	1234	1230	1292	nsd
0–2.5	53710	50535	51436	50681	51998	nsd	4411	4169	4378	4182	4235	nsd
Potential Net Mineralized CO_2–C							Potential net mineralized N					
0–2.5	277	103	102	311	418	69	21.6	7.5	9.5	11.7	18.2	2.5
2.5–5	123	65	86	141	186	34	7.3	7.2	9.3	4.0	5.4	1.4
5–7.5	96	56	57	105	149	15	4.7	6.8	7.1	3.7	4.5	0.9
2.5–7.5	219	122	143	246	336	75	12.0	14.0	16.4	7.7	9.8	2.6
0–7.5	496	225	245	557	753	185	33.6	21.5	25.8	19.5	28.0	5.2
Extractable NH_4–N							Extractable NO_3–N					
0–2.5	0.31	0.98	1.27	0.52	0.39	0.29	0.24	5.42	6.97	0.15	0.25	2.49
2.5–5	0.24	0.61	1.01	0.47	0.24	0.40	0.02	3.39	5.05	0.09	0.05	1.40
5–7.5	0.31	0.53	1.18	0.57	0.27	0.36	0.00	2.97	3.27	0.04	0.04	1.07
7.5–25	2.17	3.80	11.14	7.37	1.95	2.71	0.89	28.35	17.39	0.49	0.88	5.17
0–7.5	0.86	2.12	3.46	1.56	0.90	0.97	0.27	11.79	15.29	0.28	0.35	3.90
0–25	3.04	5.92	14.60	8.92	2.85	3.50	1.16	40.13	32.68	0.77	1.22	8.16

Table 4
Carbon and nitrogen ratios by depth increment in the profile of Phiferson sandy loam soil from native grasslands, plowed and cultivated native grassland, (6th year), cropped land in cultivation for 60+ years, reestablished grassland on cropped land (4th year), and reestablished grassland fertilized annually with 34 kg N ha^{-1}.

Soil profile (cm)	Native	Plowed	Cropped	Grass	Grass+N	$LSD_{0.10}$	Native	Plowed	Cropped	Grass	Grass+N	$LSD_{0.10}$
	(kg ha^{-1})											
Total organic carbon:Total organic N							Mineralized CO_2–C:Net mineralized N					
0–2.5	11.2	10.2	10.7	11.0	11.5	nsd	10.2	6.9	10.9	10.0	11.4	nsd
2.5–5	10.3	10.4	9.7	10.8	12.6	1.0	11.0	6.4	8.2	12.6	11.3	3.1
5–7.5	10.5	10.2	10.3	12.0	12.6	1.3	9.8	4.2	6.0	17.8	12.7	4.8
7.5–10	11.2	9.8	9.8	11.0	11.3	0.9	20.4	6.1	9.2	20.5	12.5	5.7
10–28	10.1	9.8	10.2	10.9	13.3	nsd						
0–10	10.8	10.2	10.1	11.2	12.0	0.5	12.9	5.9	8.6	15.2	11.9	2.6
0–28	10.7	10.1	10.1	11.1	12.3	0.6						
Mineralized CO_2–C:Total organic C (×100)							Net mineralized N:Total organic N (×100)					
0–2.5	5.49	3.06	4.23	5.35	7.18	1.88	5.82	4.47	4.37	6.09	7.34	1.42
2.5–5	1.93	1.70	2.46	3.51	3.21	1.11	1.82	2.75	2.90	2.95	3.65	0.73
5–7.5	1.72	0.70	1.43	3.19	2.75	0.70	1.83	1.99	2.57	2.18	2.78	0.79
7.5–10	1.42	1.05	2.23	4.06	2.46	1.71	0.78	1.72	2.36	2.16	2.29	0.49
0–10	2.64	1.63	2.59	4.03	3.90	0.88	2.56	2.73	3.05	3.35	4.02	0.78

Table 5
Carbon and nitrogen ratios by depth increment in the profile of Ulm clay loam soil from native grasslands, plowed and cultivated native grassland, (6th year), cropped land in cultivation for 60+ years, reestablished grassland on cropped land (4th year), and reestablished grassland fertilized annually with 34 kg N ha^{-1}

Soil profile (cm)	Native	Plowed	Cropped	Grass	Grass+N	$LSD_{0.10}$	Native	Plowed	Cropped	Grass	Grass+N	$LSD_{0.10}$
	(kg ha^{-1})											
Total organic carbon:Total organic N							Mineralized CO_2–C:Net mineralized N					
0–2.5	13.2	12.1	12.0	12.5	13.0	0.8	13.0	13.7	10.8	26.2	23.7	6.3
2.5–5	12.5	12.3	11.8	12.2	12.6	0.4	16.8	9.0	9.0	34.4	37.3	14.6
5–7.5	12.2	11.2	11.9	12.1	12.3	nsd	20.6	8.3	8.1	31.0	34.3	8.8
7.5–25	11.9	12.2	11.7	12.1	12.1	nsd						
0–7.5	12.6	11.9	11.9	12.2	12.6	0.5	16.8	10.9	9.3	30.5	31.8	6.3
0–25	12.4	12.0	11.8	12.0	12.5	0.4						
Mineralized CO_2–C:Total organic C (×100)							Net Mineralized N:Total organic N (×100)					
0–2.5	3.37	2.12	2.07	5.37	6.31	1.36	3.49	1.89	2.30	2.54	3.66	0.98
2.5–5	2.03	1.38	1.76	2.90	3.67	0.95	1.52	1.84	2.22	1.03	1.38	0.60
5–7.5	1.76	1.24	1.20	2.29	3.15	0.33	1.05	1.69	1.77	0.93	1.17	0.33
0–7.50	2.39	1.58	1.68	3.52	4.38	0.68	2.02	1.81	2.09	1.50	2.07	nsd

Table 6
Estimates of the decreases in cultivated surface soil C and N that were due to mixing of the A and B horizons by initial plowing of the native range

Treatment	Ulm clay loam		Phiferson sandy loam	
	0–7.5 cm		0–10 cm	
	C	N	C	N
	g kg^{-1}	mg kg^{-1}	g kg^{-1}	mg kg^{-1}
(1) Native – spring 1987	21.6	1630	8.3	840
(2) Plowed – spring 1987 (immediately after plowing)	17.9	1430	7.4	800
(3) Long-term cropped – spring 1987	15.4	1280	7.8	740
(4) Plowed – 1993 (after 6 years of cropping)	15.2	1290	7.1	700
	%	%	%	%
(5) Decrease after plowing in 1987 [(1)−(2)/(1)]×100	17.1	12.3	10.8	4.8
(6) Total decrease in long-term cropped [(1)−(3)/(1)]×100	28.7	21.5	6.0	11.9
(7) Estimated % of total decrease in long-term cropped due to mixing by plowing (5)/(6)×100	59.7	57.1	55.6	40.0
(8) Total decrease after 6 years cropping [(1)−(4)/(1)]×100	29.6	20.9	14.5	16.7
(9) Percentage of total decrease in 6-year cropped due to mixing by plowing (5)/(8)×100	57.8	58.9	74.5	28.7

75% of the decrease in surface soil C, and 30% of the decrease in surface soil N in the sandy loam soil. Assuming that the levels of C and N measured in 1987 in the native range soil profiles correctly represent native conditions at the onset of cultivation 60+ years ago, we estimate that the decrease in surface soil C and N due to mixing by initial plowing of the native range may account for 40–60% of the total decrease in surface soil C and N observed in the long-term cultivated plots.

3.2. *Effects of grass reestablishment on soil C and N*

Five years after reestablishing grass on plots of the sandy loam soil that had been cultivated for 60+ years, total organic C and N, and potential net mineralized C and N in the top 10 cm had increased to levels equal to or greater than those observed in the native range (Table 2). Annual applications of 34 kg N ha^{-1} to reseeded grass plots did not significantly increase total C or N in the sandy loam soil, but did result in a significantly wider total C:N ratio throughout the 28 cm soil profile (avg. 0–28 cm) (Table 4). The fertilized grass plots were also significantly higher in levels of mineralized C in the surface 2.5 cm, and mineralized N in the surface 5 cm, while the average (0–10 cm) ratio of mineralized C:N was significantly narrower than in non-fertilized grass plots. In reestablished grass plots on the clay loam soil, significant increases in total organic C were observed only in the surface 2.5 cm of the N-fertilized grass plots, while total organic N had not significantly increased from levels in the long-term cultivated fields (Table 3). A significant increase in potential net mineralized C to a level comparable to or greater than that in the native range soil was observed in the top 7.5 cm of the reestablished grass plots, but levels of potential net mineralized N had not significantly increased from levels observed in the cultivated treatments (Table 3). Annual applications of 34 kg N ha^{-1} to reseeded grass plots on the clay loam soil significantly increased potential net mineralized C and the proportion of total organic C that was mineralized in the top 7.5 cm, whereas increases in potential net mineralized N and the proportion of total organic N that was mineralized were limited to the top 2.5 cm of the soil profile (Table 5).

4. Discussion

4.1. Effects of cultivation on soil C and N

The amount of C and N in the soil at a given location on a landscape is a function of biological and physical processes. Biological processes affecting the amount of C in soil include additions from plant residues and losses by respired CO_2, while the amount of N in soil is determined by the balance between gains from microbial N-fixation and losses by denitrification, volatilization of NH_3 gas, and NO_3 leaching (Jenny, 1980). Physical processes such as water and wind erosion can result in losses of soil C and N from one landscape position, and additions to another position by deposition (Morgan, 1986; Aguilar and Heil, 1988). Both biological and physical processes can cause vertical redistribution of C and N in the soil profile, which can be misinterpreted as 'losses' or 'gains' of surface soil C and N from a landscape position if only the surface soil, and not the entire soil solum, is evaluated.

Data collected in 1993 show that after 60+ years of cultivation, surface soils at both study sites were 23–26% lower (by mass) in total organic C, and 18–21% lower in total organic N, than in the A horizons of adjacent native range. Other studies have reported higher losses of surface soil organic C and N with long-term cultivation, but these studies generally have included measurements from hill slope positions which are subject to losses by water erosion (Tiessen et al., 1982; Schimel et al., 1985a; Woods and Schuman, 1988; Burke et al., 1995). Positioning our plots on relatively level terrain minimized the potential for soil loss by water erosion. Moreover, the potential for loss by wind erosion was low on the clay loam soil due to the tendency for clod formation with tillage, while the lack of measurable change in surface soil particle size distribution with long-term cultivation suggests that losses by wind erosion have not been severe on the sandy loam soil (Table 1). In the clay loam soil, losses of SOM with long-term cultivation also may have been reduced because of the increase in clay content of the surface soil caused by mixing of the surface soil with higher-clay-content subsoil (Table 1), which may have increased the physical and chemical protection of SOM by the clay complex (Tisdall and Oades, 1982; Schimel et al., 1985b; Bowman et al., 1989).

The onset of cultivation resulted in rapid declines in surface soil organic C and N on both soil types. Six years after plowing and converting native rangeland to cropland (three wheat–fallow cycles), total C and N in the surface soil had decreased, and mineral N at all depths had increased, to levels equivalent to those observed after 60+ years of cultivation. Significantly higher levels of inorganic N in cultivated than native soil profiles were the result of enhanced N mineralization rates, and suggest that the decrease in surface soil N with cultivation may be due in part to losses by leaching of NO_3 below the rooting zone. These results demonstrate the rapidity by which a large-scale belowground perturbation such as cultivation can alter nutrient storage and cycling, and influence the character and size of the active SOM fraction and available nutrient pools (Burke et al., 1997). Our results support the well-documented premise that cultivation narrows the ratios of total C:N and mineralized C:N because of greater losses of C than N with tillage (Campbell and Souster, 1982; Schimel et al., 1985a; Schimel, 1986; Bowman et al., 1990; Burke et al., 1995). However, our results do not support the often-cited relationship between relative SOM loss and soil texture, i.e., that relative losses of SOM due to cultivation are higher on coarse-textured than on fine-textured soils (Tiessen et al., 1982; Schimel et al., 1985a; Aguilar et al., 1988; Burke et al., 1989). That the sandy loam and clay loam soils were comparable in the proportional decrease in surface soil total organic C and N with cultivation (i.e., 23–26% decrease in C, and 18–21% decrease in N) can be attributed in part to differences in the distribution of organic C and N within the two soil profiles. The profile of the sandy loam soil under native range exhibited a more uniform soil texture, as well as a more gradual decline in SOM with depth than in the clay loam soil profile. Cultivation therefore had less effect on the amount and redistribution of C and N in the sandy loam profile. Schimel et al. (1985a) reported similar differences in SOM distribution between coarse and fine textured soil profiles. They attributed the gradual decline of SOM with depth in coarse textured soils to deeper penetration of water, which resulted in a more uniform depth distribution of roots, as well as a greater potential for translocation of organic matter.

Actual losses of C and N need to be distinguished from vertical redistribution of C and N within the soil profile if changes in SOM and plant nutrients with cultivation are to be accurately described. The lack of significant differences between native range and long-term-cultivated fields in total C and N within the rooting depth of the soil profiles (Tables 2 and 3) suggests that much of the decrease in long-term-cultivated surface soil C and N was the result of vertical redistribution with tillage, rather than actual losses of C and N from the cultivated field plots. We estimated that mixing of the surface and subsurface soil with tillage may have accounted for approximately 40–60% of the total decrease in surface soil organic C and N in long-term cultivated fields (Table 6). The rapid declines in surface soil organic C and N in both soil types after only 6 years of cultivation to levels associated with 60+ years of cultivation also may be partly attributed to mixing of the A and B horizons by the initial plowing of the native range in 1987. Our estimates indicate that approximately 60% of the rapid declines in surface soil C and N in the clay loam was due to mixing of the shallow A-horizon with subsoil by plowing in 1987. At the sandy loam location, we estimated that about 75% of the decrease in organic C, and about 30% of the decrease in organic N was due to mixing of the A and B horizons by plowing in 1987. These results emphasize the need to evaluate C and N in the entire soil solum, rather than in just the surface soil, if the effects of cultivation on system nutrient storage and cycling are to be accurately described (Tiessen et al., 1982).

4.2. Effects of grass reestablishment on soil C and N

Five years of reestablished grass has been sufficient to regenerate total and potentially mineralizable C and N in the top 10 cm of the sandy loam soil to levels comparable to or greater than levels under native range conditions. Recovery of soil C and N with reestablishment of grass has been rapid in the sandy loam soil in part because the initial levels of SOM under native range were low, and the relatively small decreases in surface soil C and N due to cultivation required relatively small inputs to achieve recovery. The rapid accumulation of surface soil C and N also is the result of inputs from high levels of plant biomass production. Average annual production (1990–1993) was 64% higher, and aboveground litter accumulation was 100% higher, on reseeded grass plots than native range (2300 vs. 1400 kg ha^{-1} aboveground biomass at peak standing crop; 2300 vs. 1100 kg ha^{-1} aboveground litter). Four annual applications of 34 kg N ha^{-1} increased average grass production by about 17%; the significant increase in the ratio of total soil C/N reflects the apparent increase in C inputs into the soil due to N fertilization. The 136 kg ha^{-1} fertilizer N added over 4 years, however, was insufficient to result in a measurable increase in total soil N, but did result in a significant increase in potentially mineralizable C and N in the top 2.5 cm of the soil.

In contrast to the sandy loam soil, five years of reestablished grass on the clay loam soil has resulted in significant increases in soil C and N only in the surface 2.5 cm. of N-fertilized grass plots. Recovery of surface soil C and N in the clay loam has been slower than in the sandy loam soil in part because the initial levels of A-horizon C and N, and the decrease in surface soil C and N with cultivation, were approximately twice as high in the clay loam than in the sandy loam soil. Average annual production (1990–1993) and aboveground litter accumulation were high on the reseeded grass plots (3300 and 2000 kg ha^{-1}, respectively) compared to 1100 and 1500 kg ha^{-1} production and litter, respectively, on the native range. However, five years of high plant biomass production has been insufficient to supply inputs of about 5000 kg C ha^{-1} and 350 kg N ha^{-1} required to recover surface soil C and N to levels comparable to those in the A horizon of the native range. The increase in potential net mineralized C in the top 7.5 cm of the reseeded grass plots to levels comparable to those found in the A-horizon of the native range suggests that the active pools of SOM (i.e., that part of the SOM responsible for nutrient supply) are recovering more rapidly than total SOM. However, levels of potential net mineralized N remain significantly lower, and immobilization ratios (CO_2 evolution/net N mineralization) remain significantly higher, in the top 7.5 cm of the reseeded grass plots than in the A horizon of the native range. These results indicate that the microflora of the reseeded grass plots are N-limited, and net N mineralization from SOM (a measure of the availability of N for plants) is limited by microbial immobilization. While C is accumulating in the soil because of net input into the ecosystem from photosynthetic fixation of atmospheric CO_2, N accumulation in the soil, in the absence of additions by N fertilization, is primarily a result of redistribution of ecosystem N (Burke et al., 1995). The four annual applications of 34 kg N ha^{-1} did not significantly increase average grass production on the reseeded grass plots, nor did the added fertilizer N decrease microbial immobilization ratios. These results suggest that this low rate of annual N application may be insufficient to sustain plant growth at the high production levels observed in the first 4 years after grass establishment. Moreover, since changes in soil C and N have been observed in the surface 2.5 cm that are not apparent in average C and N values for the surface soil (7.5–10 cm), our results also demonstrate the need to sample the full surface soil in small depth increments.

Schimel et al. (1985a) used the ecological terminology ‘resistant’ and ‘resilient’ to classify the behavior of soils with cultivation. ‘Resistant’ soils require intense perturbation by cultivation to change the initial status of soil properties, and may or may not return to the initial state following cultivation, whereas the properties of ‘resilient’ soils change with cultivation but return quickly to the prior state when cultivation is discontinued. Our data suggest that the grassland ecosystems on both soil types were not resistant to the large-scale below-ground perturbation caused by cultivation, which directly affects SOM, the largest storage compartment of C and N in grasslands (Burke et al., 1997). After cultivation was initiated, however, both soil types were relatively resistant to SOM loss via erosion, but the sandy loam soil is more resilient in regenerating SOM with the reestablishment of a grass community.

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