Carbon Sequestration in Native Prairie, Perennial Grass, No-Till, and Cultivated Palouse Silt Loam

T. J. Purakayastha*
Div. of Soil Science and Agricultural Chemistry
Indian Agricultural Research Institute
New Delhi 110012, India

D. R. Huggins
J. L. Smith
USDA-ARS
Pacific West Area Land Management and Water Conservation Research Unit
Pullman, WA 99164-6421

Comparative assessments for evaluating soil organic C (SOC) and its characteristics were made at different soil (Palouse silt loam) depths (0–5, 5–10, 10–20, and 0–20 cm) among sites with seven contrasting management histories: conventional inversion tillage (CT) followed by no-till (NT) for 4 (NT4) and 28 (NT28) yr; bluegrass (*Poa pratensis* L.) seed production for 9 yr followed by NT for 4 yr (BGNT4); a sequence of 10 yr NT, 3 yr CT, and 1 yr NT (NTR); CT followed by 11 yr perennial grass under the Conservation Reserve Program (CRP); long-term >100 yr CT; and native prairie (NP). Overall ranking of SOC, particulate organic C (POC), and microbial biomass C (MBC) at 0 to 20 cm was NP > NTR > NT4 = NT28 > CRP > BGNT4 = CT. Greater SOC, POC, and MBC in NTR than NT28 indicated that tillage rotation could result in more soil C sequestration, primarily by increasing C stocks in 5- to 20-cm depths. The POC was labile in nature as it highly correlated with C_{min} ($r = 0.69$, $P < 0.01$) and MBC ($r = 0.86$, $P < 0.01$) as well as SOC ($r = 0.89$, $P < 0.01$). We concluded that: (i) neither NT nor conversion to perennial vegetation would attain the SOC found in NP over 10 to 30 yr; and (ii) medium duration of NT (10 yr) combined with short intervals of CT (3 yr) followed by NT might increase SOC compared with continuous long-term NT under annual cropping.

Abbreviations: BGNT, bluegrass seed followed by no-till; C_{min}, carbon mineralization; CRP, Conservation Reserve Program; CT, conventional tillage; MBC, microbial biomass carbon; MQ, microbial quotient; NP, native prairie; NT, no-till; NTR, no-till reestablished, POC, particulate organic carbon; qCO_2, microbial metabolic quotient; SOC, soil organic carbon.

Accumulation of soil organic C (SOC) is a function of ecosystem processes that, in turn, are influenced by current and historic land management practices (Collins et al., 2000). Concerns about global climate change, linked to rising concentrations of atmospheric CO_2, have increased interest in evaluating land management effects on soil C sequestration (Grace et al., 2006). This interest is justified since terrestrial C pools are dynamic, readily respond to management changes, and contain more than two times atmospheric C levels (Council for Agricultural Science and Technology, 2004).

Loss of SOC following conversion of native prairie to agricultural uses was a major source of anthropogenic CO_2, contributed to the historical rise in global levels of atmospheric CO_2, and is considered to have created a potential SOC sink in many agricultural soils (Wilson, 1978; Flach et al., 1997). Atmospheric CO_2 can be recaptured in agricultural soils if SOC decomposition rates are slowed, greater biomass from crops is annually returned to the soil, and soil erosion is reduced. Several agricultural land management strategies achieve these goals including: establishment of permanent vegetative cover as in the Conservation Reserve Program (Huggins et al., 1997; Ogle et al., 2003); conservation tillage practices such as no-till (NT) (Halvorson et al., 2002; Bernacchi et al., 2005); increased return of organic C to soil through perennial crops, greater yields of annual crops, and reduction of fallow periods (Huggins et al., 1998; Machado et al., 2006). The extent to which agricultural practices result in changes in SOC storage depends on multiple factors, including the initial levels of SOC (Ismail et al., 1994) and the degree of system SOC saturation (Hassink and Whitmore, 1997); soil properties such as texture and aggregation (Balesdent et al., 2000; Six et al., 2004); artificial drainage (Sullivan et al., 1997) and productivity (Al-Kaisi et al., 2005); environmental conditions (Campbell et al., 1995); and time. If management practices and environmental conditions remain consistent with time, new steady-state levels of SOC may be realized (Paustian et al., 2001); however, the magnitude of this change is often unique for a given location or soil. The Palouse region of eastern Washington and northern Idaho has land uses and agricultural systems that include native prairie remnants, permanent vegetative cover, perennial grass seed production, and contrasting tillage practices such as inversion tillage and NT. Often, in this area, agricultural practices at a given location are not consistent with time, and changes that occur can create conditions that affect SOC storage. Consequently, a greater understanding of how changing management regimes impact SOC storage is relevant to this agricultural setting.

Our overall goal was to evaluate short- and long-term influences of land use and associated practices on SOC storage and measures of SOC characteristics. Specifically, we assessed

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*Corresponding author (tapanjp@iari.res.in).

(i) differences in tillage-zone properties of Palouse silt loam soils compared with native prairie that had never been cultivated with respect to SOC, particulate organic C (POC), microbial biomass C (MBC), C mineralization (C_{min}), the microbial quotient (MQ), and the microbial metabolic quotient (qCO_2); and (ii) differences in SOC and measures of SOC characteristics resulting from soil management strategies consisting of conventional inversion tillage (CT) followed by annual cropping with no-till (NT) for 4 (NT4) and 28 (NT28) yr; perennial bluegrass seed production (9 yr) followed by NT for 4 yr (BGNT4); a sequence of annual cropping with 10 yr NT, 3 yr CT, and 1 yr NT (NTR); long-term >100 yr annual cropping with CT; CT followed by 11 yr perennial grass in the Conservation Reserve Program (CRP); and native prairie (NP). We hypothesized that SOC stocks based on length of time in perennial vs. annual vegetation and no-till vs. tillage would be NP > NT28 > CRP > BGNT4 > NTR > NT4 > CT. Deviations from this sequence would indicate the importance of other factors influencing SOC.

MATERIALS AND METHODS

Soil and Site Description

Seven sites with differing management history but the same soil classification and landscape position were identified to represent diverse land uses in the Palouse region of eastern Washington. Historically, conversion of NP to agricultural uses in the Palouse region occurred in the late 1800s, was dependent on inversion tillage using a moldboard plow, and resulted in annual soil erosion rates exceeding 25 Tg ha^{-1} (USDA-SCS, 1978). The sites were located in summit positions (0–3% slope) on Palouse silt loam soils (fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls), where the influence of soil deposition from historic erosion processes would be minimized. Palouse silt loam soils typically have 21% sand, 59% silt, and 20% clay. The seven sites are described in Table 1.

Soil Sampling

Soil samples consisted of eight soil cores (4-cm diameter) in depth increments of 0 to 5, 5 to 10, and 10 to 20 cm. Immediately after collection, soil samples were brought to the laboratory in a cooler and stored at 4°C. Soil moisture content was determined after drying at 105°C for 24 h. Soil samples from four cores were air dried, ground, and sieved through a 2-mm sieve in preparation for analysis of SOC and POC. Soil bulk density was calculated from weights of field-moist soil, the oven-dried subsample, and the volume of the core sampler following the method of Veihmeyer and Hendrickson (1948).

Soil Carbon Fractionation and Analyses

Total soil C was determined by dry combustion using a LECO (St. Joseph, MI) carbon analyzer (Tabatabai and Bremner, 1970). Carbonates do not occur in Palouse silt loam soils and total soil C was assumed to represent SOC. The particulate organic matter (POM) was separated from sieved (2-mm) soil following the method described by Cambardella and Elliott (1992) and the total C content of the POM fraction estimated by dry combustion. Soil microbial biomass was estimated by the substrate induced respiration method (Bailey et al., 2007) using a gas chromatograph (Model GC-17A, Shimadzu Scientific Instruments, Columbia, MD) and the following equation from Anderson and Domsch (1978):

$$x = 40.04\,y + 0.37 \qquad [1]$$

where x = microbial biomass C (mg kg^{-1} soil) and y = rate of CO_2 evolution (mL CO_2 kg^{-1} soil h^{-1}). Microbial quotient (MQ) was calculated as MBC/SOC (kg kg^{-1}).

Soil Carbon Dioxide Respiration

Mineralization of soil organic matter was determined from four intact cores (preserved at 4°C) collected from the 0- to 5-, 5- to 10-, and 10- to 20-cm depths at each site. Soil cores were moistened to field capacity (25% water by weight, −0.033 MPa) and placed in a 500-mL canning jar with a vial containing 5 mL of 1 mol L^{-1} NaOH to trap evolved CO_2 and a vial of water to maintain high humidity, and incubated for 26 wk at room temperature (20°C). During the initial 2 wk, the NaOH trap was replaced at half-week intervals and subsequently at weekly intervals through 26 wk. Control jars lacking a soil core were incubated in the same manner. The jars, including controls, were vented to the atmosphere during replacement of the NaOH trap. The quantity of CO_2–C evolved was determined by titration with 1 mol L^{-1} HCl using phenolphthalein as an indicator

Table 1. Location and management history of seven sites used for the study.

Site description	Location†	Management
Native prairie (NP)	Kramer Palouse Natural Area (KPNA) near Colton	never cultivated, Idaho fescue, blue bunch, wheat grass, June grass grow naturally
Conservation Reserve Program (CRP)	grower field near Albion	smooth bromegrass grown for 11 yr, no fertilization or cultivation
28 yr no-till (NT28)	grower field near Palouse	winter wheat–spring barley–spring grain legume (pea or lentil), seeding accomplished directly into the preceding year's crop residue by means of a coulter-type planter
Bluegrass, no-till (BGNT4)	grower field near Union Town	bluegrass seed (9 yr), no-till (4 yr), spring barley–spring lentil–winter wheat–spring barley grown annually for last 4 yr, seeding accomplished directly into the preceding year's crop residue by means of a coulter-type planter
4 yr no-till (NT4)	Palouse Conservation Field Station, Pullman	winter wheat–spring barley–spring wheat, seeding accomplished directly into the preceding year's crop residue by means of a coulter-type planter
No-till reestablished (NTR)	Cunningham Farm, USDA-ARS, Pullman	no-till (10 yr)–conventional tillage (3 yr)–no-till (1 yr); for no-till, seeding accomplished directly into the preceding year's crop residue by means of a coulter-type planter; for conventional tillage, moldboard plowed to 20–25 cm and disked to 8–10 cm
Conventional tillage (CT)	grower field adjacent to KPNA near Colton	cultivated for past 100 yr, currently under winter wheat–spring pea rotation, moldboard plowed to 20–25 cm and disked to 8–10 cm

† All management practices are situated in the state of Washington.

Table 2. Soil organic C (SOC), microbial biomass C (MBC), particulate organic C (POC), and C mineralization (C_{min}) stock in 0- to 20-cm Palouse silt loam under different management practices.

Management practice†	SOC	POC	MBC	C_{min}
	Mg ha^{-1}			
NP	63.7 a‡	19.6 a	4.0 a	6.34 a
CRP	37.0 d	6.30 d	2.11 c	4.95 bc
NT28	52.9 c	8.10 c	2.27 c	4.86 bc
BGNT4	30.2 e	4.80 de	1.46 d	5.22 b
NT4	50.0 c	6.30 b	1.85 cd	4.49 c
NTR	58.4 b	10.30 b	3.36 b	5.08 b
CT	27.9 e	4.20 e	2.02 c	4.56 c

† NP, native prairie; CRP, 11 yr perennial grass under the Conservation Reserve Program; NT28, conventional tillage followed by no-till for 28 yr; BGNT4, bluegrass seed production for 9 yr followed by no-till for 4 yr; NT4, conventional tillage followed by no-till for 4 yr, NTR, no-till reestablished for 1 yr following 10 yr no-till and 3 yr conventional tillage; CT, >100 yr conventional tillage.

‡ Values in the same column followed by a different lowercase letter within a soil parameter are significantly different at $P = 0.05$ according to Duncan's multiple range test for separation of means.

(Anderson, 1982). Amounts of respired CO_2 were calculated as milligrams CO_2–C per cubic centimeter and cumulative CO_2–C evolution was calculated and plotted over 26 wk. Microbial metabolic quotient (qCO_2) was estimated as the grams of CO_2–C evolved in the last week of incubation per kilogram MBC measured in the last week.

Statistical Analysis

Analysis of variance was performed on all variables using the DOS-based MSTATC Version C program developed by S.P. Eisensmith. Mean comparisons were made using Duncan's multiple range test at the 0.05 probability level. Correlation coefficients (r) between different soil parameters were determined using the same statistical package (r not presented). Management history had significant effects on soil bulk density, suggesting that the data be expressed on an equivalent-mass basis; however, due to the mass-altering impacts of significant soil erosion with time, data were expressed on a soil-volume basis (Ellert and Bettany, 1995).

RESULTS AND DISCUSSION

Soil Organic Carbon and Bulk Density

The greatest SOC stocks (0–20 cm) in Palouse silt loam soils occurred in NP, which averaged 63.7 Mg C ha^{-1}(Table 2). The adjacent soil under CT had the lowest SOC stocks, 27.9 Mg C ha^{-1} (0–20 cm), indicating a 56% reduction of SOC from NP during approximately 100 yr of CT. Reported reductions in SOC following conversion of NP to tillage-based agriculture typically range from 30 to 50% due to enhanced SOC mineralization from repeated cultivation (Paustian et al., 1997; Puget and Lal, 2005), reduced C inputs from annual crops (Huggins et al., 1998), and accelerated soil erosion (Rasmussen, 1999). The losses of SOC under long-term cultivation of Palouse silt loam soils are probably due to a combination of all these factors.

Stocks of SOC (0–20 cm) at sites with the other agricultural management histories ranged between the CT and NP sites as follows: NP > NTR > NT28 > NT4 > CRP > BGNT4 > CT and differs from our original hypothesis (Table 2). Interestingly, SOC in NTR was 92% that of NP in the surface 20 cm, although greater relative storage of SOC in NP probably occurs at soil depths below 20 cm due to the influence of long-term C accumulation under NP vegetation. Deviations from the hypothesized sequence could arise from several factors: (i) differences among the sites in initial levels of SOC before management changes; (ii) relatively poor biomass production in CRP due to lack of fertilization; (iii) burning of surface residues during production of bluegrass seed; and (iv) positive rather than negative effects of short-term inversion tillage when following NT on SOC. Insights into the influence of these factors on SOC can be gained through examining SOC depth stratification and measures of labile SOC constituents.

Substantial stratification of SOC with depth occurred in NP, NT28, CRP, BGNT4, and NT4, but not in NTR or CT (Table 3). Many studies credit soil mixing through tillage as providing a more even depth distribution of SOC within the tillage zone (Collins et al., 1992; Sainju et al., 2005; Huggins et al., 2007). In addition, NT with annual cropping primarily returns organic residues (stover and roots) to the surface and shallow soil depths, thereby resulting in greater SOC accumulations in the surface of NT soils (Salinas-Garcia et al., 1997; Alvarez, 2005).

Stratification of SOC under low soil disturbance systems can provide insights into initial SOC levels. In the annually cropped areas where Palouse silt loam soils occur, SOC levels under short-term (<30-yr) NT tend to be greater near the surface and decrease with depth to SOC levels similar to those found under tillage-based systems (Fuentes et al., 2004). Comparisons of SOC at the 10- to 20-cm depth show the lowest levels under CRP, BGNT4, and CT, while significantly greater amounts of SOC were found at all other sites (Table 3). These data indicate that the CRP and BGNT4 sites probably had lower initial SOC levels when conversion occurred from CT to perennial vegetation or NT. The NTR site had SOC levels at 10- to 20-cm depths that were greater than all other agricultural

Table 3. Distribution of soil organic C (SOC) and bulk density (D_b) at 0- to 5-, 5- to 10-, and 10- to 20-cm depths in Palouse silt loam under different management practices.

Management practice†	SOC			D_b		
	0–5 cm	5–10 cm	10–20 cm	0–5 cm	5–10 cm	10–20 cm
	mg cm^{-3}			Mg m^{-3}		
NP	46.1 a‡	31.5 c	26.8 cde	0.93 i	0.93 i	1.05 h
CRP	24.2 de	17.0 fg	16.4 fg	1.22 g	1.26 fg	1.35 ef
NT28	38.0 b	24.7 de	21.5 ef	1.22 g	1.35 ef	1.41 de
BGNT4	21.5 ef	15.6 fg	11.6 g	1.53 bc	1.64 a	1.58 ab
NT4	29.3 cd	28.5 cd	21.1 ef	1.25 g	1.46 cd	1.42 de
NTR	27.2 cde	31.2 c	29.2 cd	0.92 i	1.22 g	1.20 g
CT	14.4 g	13.8 g	13.8 g	1.29 fg	1.34 def	1.42 de

† NP, native prairie; CRP, 11 yr perennial grass under the Conservation Reserve Program; NT28, conventional tillage followed by no-till for 28 yr; BGNT4, bluegrass seed production for 9 yr followed by no-till for 4 yr; NT4, conventional tillage followed by no-till for 4 yr, NTR, no-till reestablished for 1 yr following 10 yr no-till and 3 yr conventional tillage; CT, >100 yr conventional tillage.

‡ Values in the same column or row followed by a different lowercase letter within a soil parameter are significantly different at $P = 0.05$ according to Duncan's multiple range test for separation of means.

Table 4. Distribution of particulate organic C (POC), microbial biomass C (MBC) and C mineralization (C_{min}) at 0- to 5-, 5- to 10-, and 10- to 20-cm depths in Palouse silt loam under different management practices.

Management practice†	POC			MBC			C_{min}		
	0–5 cm	5–10 cm	10–20 cm	0–5 cm	5–10 cm	10–20 cm	0–5 cm	5–10 cm	10–20 cm
	mg cm^{-3}								
NP	15.3 a‡	9.98 b	6.99 c	2.56 a	1.90 bc	1.82 bcd	5.59 a	3.38 cd	1.86 gh
CRP	5.64 cd	2.44 efg	2.25 efg	1.78 bcd	0.79 ghi	0.83 ghi	4.65 b	2.16 fg	1.54 ghi
NT28	9.57 b	2.57 efg	2.06 fg	2.26 ab	0.72 i	0.78 ghi	5.42 a	1.91 gh	1.19 hi
BGNT4	4.30 de	2.86 efg	1.18 g	1.35 def	0.63 i	0.47 i	4.92 ab	2.59 ef	1.46 ghi
NT4	5.34 cd	3.79 def	1.75 fg	1.34 def	0.88 fghi	0.74 i	3.92 c	2.79 def	1.13 i
NTR	5.41 cd	5.28 cd	4.97 cd	2.39 a	1.37 def	1.48 cde	3.74 c	3.30 cd	1.56 ghi
CT	2.52 efg	2.51 efg	1.73 fg	1.27 efg	1.26 efgh	0.76 hi	3.73 c	3.22 cde	1.09 i

† NP, native prairie; CRP, 11 yr perennial grass under the Conservation Reserve Program; NT28, conventional tillage followed by no-till for 28 yr; BGNT4, bluegrass seed production for 9 yr followed by no-till for 4 yr; NT4, conventional tillage followed by no-till for 4 yr, NTR, no-till reestablished for 1 yr following 10 yr no-till and 3 yr conventional tillage; CT, >100 yr conventional tillage.

‡ Values in the same column or row followed by a different lowercase letter within a soil parameter are significantly different at $P = 0.05$ according to Duncan's multiple range test for separation of means.

sites and statistically equivalent to the NP site (Table 4). The greater SOC (10–20 cm) of NTR could also be a consequence of greater initial levels of SOC, but inversion CT following NT could bury substantial amounts of surface SOC that had accumulated during the initial 10-yr period of NT. These data are significant as: (i) they emphasize the importance of initial SOC levels when making comparative assessments of SOC accumulation even when sites have been selected to reduce differences due to site characteristics; (ii) they indicate that greater initial SOC can result in more rapid convergence toward steady-state SOC levels and less overall change in SOC storage following conversion of CT to conservation cropping systems; and (iii) they indicate that greater or more rapid accumulations of SOC could be achieved through a combination of NT and CT sequences. The latter can occur because short-term tillage may alleviate SOC saturation of surface soils under NT and provide a mechanism for greater C inputs within the tillage zone (Huggins et al., 2007).

The SOC decrease in CT was accompanied by an average increase in soil bulk density of 39% compared with NP (Table 3). Soil bulk densities <1 Mg m^{-3} are often reported for surface soils of NP, while cultivated sites are typically >1 Mg m^{-3} (Six et al., 2000). Soil bulk densities in CT were generally greater than in NT, while the greatest bulk densities were found in the site with a recent history of bluegrass seed production followed by NT (BGNT4) (Table 3). Conversion of cultivated sites to NT or perennial vegetation have shown inconsistent effects on soil bulk density, with either increases (Gascho et al., 1998), decreases (Wander et al., 1998), or no change (Huggins et al., 2007) reported.

Particulate Organic Carbon

Native prairie had the greatest amount of POC in the surface 20 cm (19.6 Mg C ha^{-1}), more than four times the levels in CT (4.2 Mg C ha^{-1}) (Table 2). Compared with CT, the NTR, NT28, NT4, CRP, and BGNT4 sites had 6.1, 3.9, 2.1, 2.1, and 0.6 Mg C ha^{-1} (0–20 cm) more POC, respectively. Russell et al. (2005) reported POC in Midwestern prairie Mollisols to be 2.6 times higher than unfertilized, cultivated land.

Pronounced stratification of POC with depth occurred in NP, CRP, NT28, BGNT4, and NT4 but not in NTR or CT sites (Table 4). Depth stratification of POC in the untilled sites of NT28, CRP, BGNT4, and NT4 resulted in greater surface levels (0–5 cm) of POC compared with CT; however, at subsurface depths, NTR had the greatest POC within the agricultural sites.

Particulate organic C makes up a large portion of the light fractions of SOC (Cambardella and Elliott, 1992) and is comprised of plant residues as well as microbial and microfaunal debris (Nichols and Wright, 2006). Therefore, POC is composed of a large proportion of relatively labile organic materials, often of recent origin. Stratification of POC in NT sites was more extreme than SOC and indicated that little mixing of recently added organic residues occurred with depth in these conservation systems, even after nearly 30 yr of NT. The presence of augmented levels of POC at subsurface depths at the NTR site indicates that short-term tillage (3 yr) was effective in distributing labile C components that had accumulated during 10 yr of NT to deeper depths. Unknown is whether or not the buried POC in the NTR site will persist for an equivalent time period as POC in surface depths of NT if the NTR remains in NT. If this occurs, sequences of NT followed by short periods of CT and then a return to NT may result in greater sequestration of SOC than continuous NT. Bezdicek et al. (1998) reported that continuous NT in drier regions of the Palouse, where annual cropping is not practiced, resulted in less SOC in the subsoil compared with CT systems and little overall difference in SOC storage. Alternatives to tillage rotation for increasing subsurface SOC storage include a shift to perennial vegetation and crops. The BGNT and CRP sites, however, did not achieve the subsurface storage of POC found in NTR after similar periods of time. This result may have been reversed if burning had been eliminated from the bluegrass seed production system and the CRP site fertilized to promote biomass additions to the soil (Huggins et al., 1997).

The POC was a significant fraction of overall SOC in NP, comprising 33, 32, and 26% at 0 to 5, 5 to 10, and 10 to 20 cm, respectively (Table 5). These proportions of POC were similar to reported values of 32% of SOC in a virgin tallgrass prairie site in Minnesota (Huggins et al., 1997) and 39% of SOC as POC in a virgin grassland soil in Nebraska (Cambardella and Elliott, 1994). The fraction of SOC comprised of POC under long-term

Table 5. Particulate organic C (POC)/soil organic C (SOC) percentage, C mineralization (C_{min})/SOC percentage, microbial quotient (microbial biomass C [MBC]/SOC), and metabolic quotient (qCO_2) at 0- to 5-, 5- to 10-, and 10- to 20-cm depths in Palouse silt loam under different management practices.

Management practice†	POC/SOC			C_{min}/SOC			Microbial quotient (MBC/SOC)			qCO_2		
	0–5 cm	5–10 cm	10–20 cm	0–5 cm	5–10 cm	10–20 cm	0–5 cm	5–10 cm	10–20 cm	0–5 cm	5–10 cm	10–20 cm
	%									g CO_2–C h^{-1} kg^{-1} MBC		
NP	33.0 a‡	31.6 a	25.9 b	12.3 a	10.9 efg	7.0 gh	5.6 cde	6.0 cd	7.2 abc	0.23ef	0.22 ef	0.16 f
CRP	23.2 bc	14.4 efgh	13.6 efghi	19.4 bc	12.7 def	10.0 efgh	7.4 abc	4.7 cdef	5.6 cdef	0.62 bcd	0.44 cdef	0.53 bcdef
NT28	25.3 b	10.3 hij	9.5 ij	14.3 de	7.8 fgh	5.6 h	5.9 cd	2.9 f	3.6 def	0.62 bcd	0.76 bc	0.60 bcde
BGNT4	20.0 cd	17.9 def	10.2 hig	22.9 ab	17.0 cd	12.6 def	6.3 bcd	6.0 cd	4.1 def	0.50 bcdef	1.42 a	0.57 bcde
NT4	17.9 def	13.3 fghi	8.2 j	14.4 de	10.0 efgh	5.5 h	4.8 cdef	3.1 ef	3.6 def	0.79 bc	0.66 bcd	0.85 b
NTR	19.9 cd	17.0 defg	17.2 defg	13.7 de	10.6 efgh	5.4 h	8.8 ab	4.4 def	5.0 cdef	0.76 bc	0.42 cdef	0.22 ef
CT	17.6 def	18.3 de	12.5 ghij	26.0 a	23.7 ab	8.0 fgh	8.8 ab	9.2 a	5.5 cdef	0.66 bcd	0.60 bcde	0.34 def

† NP, native prairie; CRP, 11 yr perennial grass under the Conservation Reserve Program; NT28, conventional tillage followed by no-till for 28 yr; BGNT4, bluegrass seed production for 9 yr followed by no-till for 4 yr; NT4, conventional tillage followed by no-till for 4 yr, NTR, no-till reestablished for 1 yr following 10 yr no-till and 3 yr conventional tillage; CT, >100 yr conventional tillage.

‡ Values in the same column or row followed by a different lowercase letter within a soil parameter are significantly different at $P = 0.05$ according to Duncan's multiple range test for separation of means.

no-till (NT28) was 25% and, in CRP, 23% in the surface layer (0–5 cm) and ranged from 8 to 20% of the total in the other sites. Low POC/SOC ratios in the subsurface of NT28 and NT4 are supportive evidence that sources of POC for subsurface layers are comparatively limited under NT (Table 5).

Microbial Biomass Carbon and Microbial Quotient

Microbial biomass C in the surface 20 cm displayed similar trends among the systems as POC, with the greatest amount of MBC in NP (4.04 Mg C ha^{-1}), which was twice that of CT (2.02 Mg C ha^{-1}) (Table 2). Among the management scenarios, NTR had significantly greater MBC (0–20 cm), while the MBC in CRP, NT28, and NT4 did not differ significantly from CT, but were greater than BGNT4 (1.46 Mg C ha^{-1}). Microbial biomass C generally decreased with soil depth, with no clear pattern between management treatments. In the surface (0–5-cm) soil depth, MBC for the NP, NTR, and NT28 sites was greater than for the other management sites (Table 4); however, only NP and NTR maintained larger amounts of MBC in subsurface soils.

Microbial biomass C is a relatively small (1–4% of the total SOC pool), labile fraction that quickly responds to C availability (Smith and Paul, 1990). Conversion from tillage-based systems to CRP has generally resulted in greater MBC (Huggins et al., 1997). Experiments conducted long enough for SOC to approach equilibrium with C inputs have reported a direct relationship between MBC and SOC (Sparling, 1985). Correlations of MBC and SOC in this study were significant at all depths (r not shown). The microbial quotient (MQ = MBC/SOC) in our study varied between 2.9 and 9.2%, with the highest values occurring in CT and NTR (Table 5). Reported ranges in MQ are 2 to 5% (Smith and Paul, 1990; Rudrappa et al., 2006). The greater values of MQ in this study may result from conserved MBC due to annual C additions in sites that have been degraded with respect to SOC.

Soil Organic Carbon Mineralization and Microbial Metabolic Quotient

Cumulative amounts of C_{min} (0–20 cm) for 26-wk incubations ranged from 4.49 Mg C ha^{-1} in NT4 to 6.3 Mg C ha^{-1} in NP (Table 2). The C_{min} in CT, NT28, CRP, and NTR were 4.56, 4.86, 4.95, 5.08, and 5.22 Mg ha^{-1} (0–20 cm), respectively. In the surface soil (0–5 cm), greater evolution of CO_2–C occurred during the initial 2 wk, particularly in NP, as easily decomposable C substrates were metabolized (Fig. 1). At the end of the 26-wk incubation, NP, NT28, BGNT4, and CRP had greater cumulative C_{min} than NT4, NTR, or CT in the surface soil (0–5 cm, Table 4, Fig. 1). Although the magnitude of cumulative C_{min} was greater in NP, NT28, BGNT4, and CRP (0–5 cm), the percentage of SOC lost from C_{min} was greater for CT (Table 5).

The NP, NTR, and CT sites tended to have the greatest cumulative C_{min} in the subsurface 5- to 10-cm depth, followed by NT4 and BGNT4, with CRP and NT28 showing the lowest values (Fig. 1, Table 4). The similar amounts of cumulative C_{min} in NP and NTR at this depth occurred as a consequence of different CO_2–C evolution patterns (Fig. 1). In NP, CO_2–C evolved rapidly during the first 2 wk, which were followed by a slower rate of evolution. In contrast, CO_2–C evolved at a more constant rate throughout the incubation period in NTR. These differences in cumulative C_{min} patterns indicate that NP has a very labile SOC pool that is greatly reduced or absent at the other sites. In addition, it appears that burial of more labile organic C constituents following no-till, as in NTR, resulted in a larger subsurface C pool that is less labile than in NP or CT (Fig. 1). Consequently, the C_{min} percentage of SOC was greater in CT than in NTR (Table 5).

The NP site had the greatest cumulative C_{min} in the 10- to 20-cm depth, largely as a result of rapid CO_2–C evolution during the first 2 wk of incubation (Fig. 1). The NTR, CRP, and BGNT4 sites tended to have similar C_{min} patterns, as did NT28 and NT4 (Table 4). The CT site had similar cumulative C_{min} as NT28 and NT4 at this depth, but much of this occurred as a result of greater initial evolution of CO_2–C. The absence of a larger labile C pool in subsurface soil depths under NT is probably due to a lack of crop residue additions.

The microbial metabolic quotient of NP was <50% of the qCO_2 of the agricultural sites (Table 5). This suggests a more stable microbial population and a greater microbial efficiency in utilizing C substrates under NP than under the agricultural sites (Smith, 2002). Conversion of NP to agriculture can result in reductions in the population and diversity of soil organisms due to desiccation, mechanical destruction, soil compaction, a smaller pore volume, and a reduced quality of C compounds (Giller, 1996).

In the surface 0 to 5 cm, there was little significant difference in qCO_2 between agricultural management practices. This held true for the lower depths except for BGNT4 in the 5- to 10-cm depth and the surprising result of NTR and CT being similar to NP in the 10- to 20-cm depth.

CONCLUSIONS

Substantial depletion of soil C pools including SOC (56%), POC (79%), MBC (50%), and C_{min} (28%) occurred following conversion of NP to CT in Palouse silt loam soils of southeastern Washington. Considering strategies for increasing the SOC of depleted soil, our hypothesis was that practices that included NT and perennial vegetation and crops would result in soil C pool increases compared with CT in the following order: CT < NT4 < NTR < BGNT4 < CRP < NT28 < NP. Our data, however, deviated significantly from this sequence. Notably, CRP and BGNT4 provided relatively less SOC increase than expected and, in contrast, larger than expected gains in SOC were measured when NT was followed by a short period of CT and then returned to NT (the NTR site). Greater SOC in subsurface depths of the NTR site, compared with NT28 and CRP, provided supporting evidence that physical movement of SOC via tillage from surface to subsurface depths could be a mechanism for increasing SOC under predominantly NT management. In addition, comparative C_{min} data among sites suggested that gains in subsurface SOC through tillage rotation may be relatively persistent. Future research efforts should explore the possible benefits of intermittent tillage for increasing SOC stocks in sites with long-term histories of NT or CRP.

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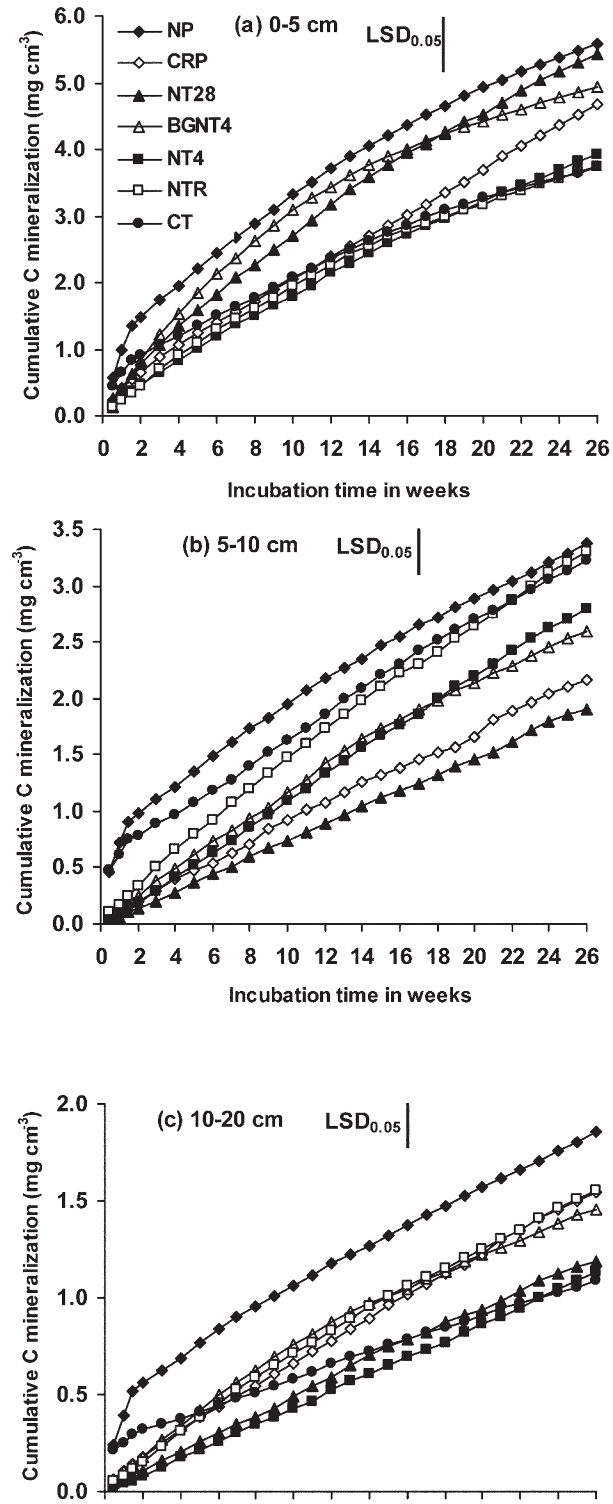

Fig. 1. Cumulative C mineralization from soils with management practices of native prairie (NP), 11 yr perennial grass under the Conservation Reserve Program (CRP), conventional tillage followed by no-till for 28 yr (NT28), bluegrass seed production for 9 yr followed by no-till for 4 yr (BGNT4), conventional tillage followed by no-till for 4 yr (NT4), no-till reestablished for 1 yr following 10 yr no-till and 3 yr conventional tillage (NTR), and >100 yr conventional tillage (CT) at three soil depths. Vertical bars indicate the least significant difference (LSD) at *P* = 0.05 for interaction of weeks of incubation and cumulative C mineralization.

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