Bermudagrass Management in the Southern Piedmont USA. III. Particulate and Biologically Active Soil Carbon

A. J. Franzluebbers,* and J. A. Stuedemann

ABSTRACT

Quantifying the effects of forage management on soil C cycling improves our understanding of greenhouse gas emissions, agronomic productivity, and changes in soil quality in pasture ecosystems. We evaluated the effects of N fertilization strategy (inorganic only, crimson clover [*Trifolium incarnatum* L.] cover crop plus inorganic, and broiler litter) and forage harvest strategy (unharvested, low and high grazing pressure, and hayed; representing a gradient from low to high utilization) on particulate organic C (POC), soil microbial biomass C (SMBC), and potential C mineralization (CMIN) during 4 yr on a previously eroded site dominated by Typic Kanhapludults. Accumulation of POC, SMBC, and CMIN with time was greatest at a depth of 0 to 2 cm and was not different among fertilization strategies. To a depth of 6 cm, POC accumulated at a rate of 65 to 73 g m^{-2} yr^{-1} under unharvested or hayed strategies and at a rate of 136 to 144 g m^{-2} yr^{-1} under cattle grazing strategies. Accumulation rate of SMBC was also dependent upon forage utilization, averaging 5.1, 9.6, 11.9, and 7.4 g m^{-2} yr^{-1} under unharvested, low grazing pressure, high grazing pressure, and hayed strategies, respectively. The portion of total organic C as CMIN during 24 d increased from 16 g kg^{-1} initially to 44 ± 5 g kg^{-1} (mean ± standard deviation among 12 treatments) at the end of 4 yr, without significant treatment effects. Particulate and biologically active soil C pools increased under all forage management strategies, although cattle grazing imparted the greatest increase partly because of the return of feces to soil.

Soils in the humid southeastern USA have undergone severe erosion and degradation as a result of historically intensive conventional tillage for crop production (Trimble, 1974; Langdale et al., 1992). Erosion preferentially removes the lower density components of soil (i.e., organic matter) concentrated near the surface (Lowrance and Williams, 1988). Extreme losses of soil organic C have occurred in this region (e.g., soil organic C as low as 30% of precultivation levels [Giddens, 1957]) because of accelerated decomposition with cultivation and erosion. In contrast, long-term pasture management has been shown to promote soil aggregation and the accumulation of soil organic C by leaving the soil undisturbed and providing continuous soil cover (Franzluebbers et al., 2000b,c).

Particulate organic C is considered an intermediately available pool of organic C between active and passive pools (Parton et al., 1987; Cambardella and Elliott, 1992), and therefore, could be a sensitive indicator of changes in soil organic matter. Particulate organic C often increases with reduction in tillage intensity (Cambardella and Elliott, 1992; Wander et al., 1998) and can be the major fraction of total organic C near the soil surface under conservation management systems with undisturbed residue cover, such as under pastures (Franzluebbers et al., 1999; 2000b). The accumulation of POC from both aboveground residues and roots (Gale and Cambardella, 2000) is likely a direct source of organic material supporting the growth and activity of soil microorganisms.

Biologically active soil C pools, including SMBC and CMIN, have been observed to increase rapidly in response to conservation management techniques with high organic matter inputs and reduced soil disturbance (Powlson et al., 1987; Franzluebbers and Arshad, 1996; Franzluebbers et al., 1999). Quantifying these active soil C pools is important for understanding nutrient dynamics that can lead to (i) significant short-term N and P immobilization during periods of rapid microbial growth and activity and (ii) significant long-term storage and subsequent slow release of nutrients. Although there is plentiful information to suggest that biologically active soil C pools generally decrease with soil depth (Franzluebbers and Arshad, 1996; Franzluebbers et al., 1999), detailed information on the near-surface vertical distribution of these pools is lacking, especially under pasture management systems. In addition, knowledge of the quantitative and qualitative changes in biologically active soil C pools with adoption of pasture management systems is needed to understand the ecological impacts of cattle on soil quality.

Our objective was to determine the temporal and spatial responses of physically defined (i.e., POC) and biologically active (i.e., SMBC and CMIN) pools of soil organic matter to pasture management, including N fertilization source (i.e., inorganic vs. organic) and degree of forage utilization (i.e., unharvested, low and high cattle grazing pressure, and hayed).

MATERIALS AND METHODS

Site Characteristics

A 15-ha upland field (33° 22′ N lat., 83° 24′ W long.) in the Greenbrier Creek subwatershed of the Oconee River watershed near Farmington, GA had previously been convention-

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A.J. Franzluebbers and J.A. Stuedemann, U.S. Department of Agriculture–Agricultural Research Service, J. Phil Campbell Sr. Natural Resource Conservation Center, 1420 Experiment Station Road, Watkinsville, GA 30677-2373. Received 9 Apr. 2001. *Corresponding author (afranz@arches.uga.edu).

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Abbreviations: BSR, basal soil respiration; CMIN, potential C mineralization; POC, particulate organic C; SMBC, soil microbial biomass C.

ally cultivated with wheat (*Triticum aestivum* L.), soybean [*Glycine max* (L.) Merr.], sorghum [*Sorghum bicolor* (L.) Moench], and cotton (*Gossypium hirsutum* L.) for several decades prior to grassland establishment by sprigging of 'Coastal' bermudagrass [*Cynodon dactylon* (L.) Pers.] in 1991. Mean annual temperature is 16.5°C, rainfall is 1250 mm, and potential evaporation is 1560 mm. Sampled on a 30-m grid, the frequency of soil series was 46% Madison, 22% Cecil, 13% Pacolet, 5% Appling, 2% Wedowee (the previous five soils are described as fine, kaolinitic, thermic Typic Kanhapludults), 11% Grover (fine-loamy, micaceous, thermic Typic Hapludults), and 1% Louisa (loamy, micaceous, thermic, shallow Ruptic-Ultic Dystrudepts). Soil textural frequency of the Ap horizon (21 ± 12 cm) was 75% sandy loam, 12% sandy clay loam, 8% loamy sand, and 4% loam.

Experimental Design

The experimental design was a randomized complete block with treatments in a split-plot arrangement. The three blocks were delineated by landscape features (i.e., slight, moderate, and severe erosion classes). Main plots were fertilization strategy ($n = 3$) and split-plots were harvest strategy ($n = 4$) for a total of 36 experimental units. Individual grazed plots (paddocks) were 0.69 ± 0.03 ha. Spatial design of paddocks minimized runoff contamination and handling of animals through a central roadway. Each paddock contained a 3 by 4 m shade, mineral feeder, and water trough placed in a line 15 m long at the highest elevation. Unharvested and hayed exclosures within paddocks were 100 m^2.

Fertilization strategy consisted of (i) inorganic only (approximately 20 g N m^{-2} yr^{-1} as NH_4NO_3 broadcast in split applications in May and July), (ii) crimson clover cover crop plus supplemental inorganic fertilizer (approximately 20 g N m^{-2} yr^{-1} with half of the N assumed available from biological N fixation in clover biomass and the other half as NH_4NO_3 broadcast in July), and (iii) broiler litter (approximately 20 g N m^{-2} yr^{-1} broadcast in split applications in May and July). Details of fertilizer applications each year were reported in Franzluebbers et al. (2001). Crimson clover was direct drilled in clover treatments at approximately 1 g m^{-2} in October each year. All paddocks were mowed in late April following soil sampling and residue was allowed to decompose (i.e., clover plus weed biomass in clover plus inorganic treatment and winter annual weeds [primarily *Lolium multiflorum* Lam. and *Bromus catharticus* Vahl.] in other treatments).

Harvest strategy mimicked a gradient in forage utilization consisting of (i) unharvested (biomass cut and left in place at the end of growing season), (ii) low cattle grazing pressure (target of approximately 300 g m^{-2} of available forage), (iii) high cattle grazing pressure (target of approximately 150 g m^{-2} of available forage), and (iv) hayed monthly in summer to remove aboveground biomass at 4-cm height. Yearling Angus steers (*Bos taurus*) grazed two of these four treatments during a 140-d period from mid May until early October each year, except during the first year of treatment implementation (1994) when grazing began in July because of repairs to infrastructure following a tornado. No grazing occurred in the winter. The target available-forage levels were maintained with a put-and-take system, whereby animals were weighed, available forage determined, and paddocks restocked on a monthly basis to avoid under and overgrazing. Average cattle stocking density was $5.8 \pm 0.9 \times 10^{-4}$ and $8.7 \pm 1.9 \times 10^{-4}$ head m^{-2} and average live-weight gain was 62 and 73 g m^{-2} yr^{-1} in the low and high grazing pressure treatments, respectively (J.A. Stuedemann, unpublished data, 2001). Average quantity of hay harvested was 760 g m^{-2} yr^{-1} with an average N concentration of 16 mg g^{-1} (A.J. Franzluebbers, unpublished data, 2001). In the unharvested treatment, average forage mass during July and August was 650 g m^{-2} and average peak estimate of forage mass was 840 g m^{-2} (A.J. Franzluebbers, unpublished data, 2001).

Sampling and Analyses

Soil and surface residue were sampled in April prior to grazing in 1994, 1996, 1997, and 1998. Hayed and unharvested exclosures were sampled in July, rather than April during 1994. Subsampling locations within grazed paddocks were within a 3-m radius of points on a 30-m grid. Because of the nonuniform dimensions of paddocks, subsampling sites within a paddock varied from four to nine, averaging 7 ± 1. Two subsampling locations were fixed within each hayed and unharvested exclosure. Surface residue was collected from a 0.25-m^2 area at each subsampling point following removal of vegetation at a height of approximately 4 cm. During 1994 and 1995, soil was sampled at depths of 0 to 2, 2 to 4, and 4 to 6 cm from the composite of two 8.5-cm diam cores within each subsampling location. From the spring of 1996 until the spring of 1998, soil was sampled to the same depths from the composite of nine 4.1-cm diam cores within each subsampling location. Soil was air-dried and ground to <2 mm in a mechanical grinder in 1994 and 1995. Soil was oven-dried (55°C, 72 h) and gently crushed to pass a 4.75-mm screen in all other years.

Soil bulk density was calculated from the oven-dried soil weight (55°C) and core volume (227 to 238 cm^3). During 1994 and 1995, soil was collected by scooping to a particular depth by a highly experienced technician. To mechanize the process, a tray with slots at 2, 4, and 6 cm for cutting soil sections with precision was used in 1996, 1997, and 1998. A 20- to 30-g soil subsample from each composite sample was ground to a fine powder in a ball mill for 3 min prior to analysis of total C with dry combustion at 1350°C (Leco CNS-2000, Leco Corp., St. Joseph, MI).[1] It was assumed that total C was equivalent to organic C because soil pH was near 6. Soil bulk density and total organic C were reported in Franzluebbers et al. (2001).

Particulate organic matter was collected from a 20- to 55-g subsample (subsample weight inversely proportional to estimated soil C content) that was shaken with 100 mL of 0.01 *M* $Na_4P_2O_7$ for 16 h on a reciprocating shaker and then passed through a 0.05-mm screen. Sand-sized material not passing the screen was transferred to a drying bottle, dried at 55°C for 72 h, weighed, ground in a ball mill for 5 min, and analyzed for POC using dry combustion.

Potential C mineralization was determined by placing two 20- to 55-g subsamples of soil packed to 1.1 to 1.3 Mg m^{-3} in 60-mL graduated glass jars, wetting the subsamples to 50% water-filled pore space, and placing them in 1-L canning jars along with 10 mL of 1 *M* NaOH to trap CO_2 and a vial of water to maintain humidity (Franzluebbers, 1999). Subsample weight was inversely proportional to estimated soil C content. Bulk density of samples in glass jars was the same within a soil depth and year, but bulk density differed among depths and years depending upon general quantity of organic matter. Samples were incubated at 25 ± 1°C for up to 24 d. Alkali traps were replaced at 3 and 10 d of incubation, and CO_2–C was determined by titration of entire trap with 1 *M* HCl in the presence of excess $BaCl_2$ to a phenolphthalein endpoint. Basal soil respiration was calculated as the linear rate of mineralization between 10 and 24 d. At 10 d, one of the subsamples

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[1] Trade and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the USDA.

was removed from the incubation jar, fumigated with $CHCl_3$ under vacuum, and vapors removed at 24 h. It was then placed in a separate canning jar along with vials of alkali and water and incubated at 25°C for 10 d. Soil microbial biomass C was calculated as the quantity of CO_2–C evolved following fumigation divided by an efficiency factor of 0.41 (Voroney and Paul, 1984; Franzluebbers et al., 1996).

Data from multiple samples within an experimental unit were averaged and not considered as a source of variation in the analysis of variance (SAS Institute, 1990). Within-depth, across-depth, within-year, and across-year analyses were conducted according to the split-plot design with three blocks. Across-depth analyses considered the bulk density of soil in calculating areal estimates of soil C pools to a depth of 6 cm. Across-year analyses considered years as repeated measures. Effects were considered significant at $P \leq 0.1$.

RESULTS AND DISCUSSION

Particulate Organic C

Particulate organic C was relatively uniformly distributed within the surface 6 cm of soil at initiation of the experiment in 1994 (Fig. 1), with values of 5.6 ± 1.0, 3.2 ± 0.3, and 3.0 ± 0.2 g kg^{-1} (mean ± standard deviation among 12 treatments) at depths of 0 to 2, 2 to 4, and 4 to 6 cm, respectively. Fertilization strategy had no effect on POC accumulation with time (data not shown). However, forage harvest strategy had a major effect on the accumulation of POC with time (Fig. 1; Table 1). At a depth of 0 to 2 cm, POC accumulation with time was greater with cattle grazing (6.1 to 6.6 g kg^{-1} soil yr^{-1}) than when unharvested or hayed (2.5 and 3.2 g kg^{-1} soil yr^{-1}, respectively). This same grazing effect was observed at a depth of 2 to 4 cm, although the magnitude of the effect was much smaller (1.1 vs. 0.8 g kg^{-1} soil yr^{-1}). At a depth of 4 to 6 cm, harvest strategy had no effect on POC accumulation, although POC accumulated at an average of 0.4 g kg^{-1} soil yr^{-1}. On an areal basis to a depth of 6 cm of soil, POC accumulated at a rate of 65 to 73 g m^{-2} yr^{-1} under unharvested or hayed strategies and at a rate of 136 to 144 g m^{-2} yr^{-1} under cattle grazing strategies (Table 2). These linear rates of accumulation suggest a doubling of POC to a depth of 6 cm within 3 yr under cattle grazing and within 6 yr under unharvested or haying strategies.

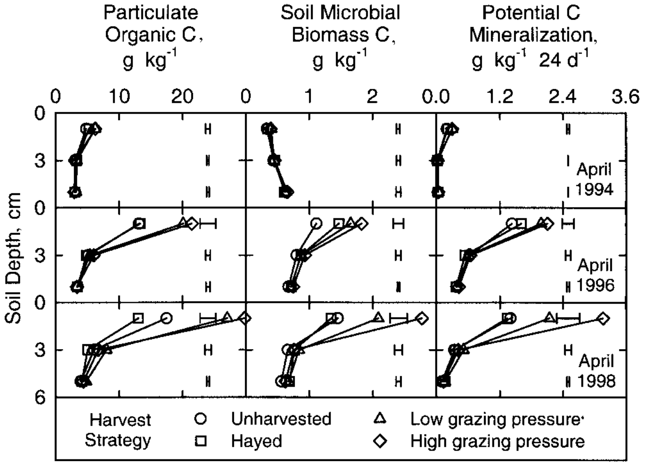

Fig. 1. Soil depth distribution of particulate organic C, soil microbial biomass C, and potential C mineralization during 24 d at 0, 2, and 4 yr of bermudagrass management varying in harvest strategy. LSD bars are $p = 0.1$ among harvest strategies within a soil depth and year.

The non-POC fraction was greater under cattle grazing than under unharvested or hayed strategies at all soil depths at the end of 4 yr (Table 1). Accumulation of non-POC with time, however, only occurred at a depth of 0 to 2 cm in all treatments. On an areal basis to a depth of 6 cm of soil, non-POC declined significantly under unharvested and hayed strategies, but remained unchanged under cattle grazing strategies (Table 2).

The non-POC fraction of soil is organic C associated with silt- and clay-sized particles and probably represents more stabilized and humified organic C with a slower turnover rate than POC (Hassink, 1995). The quantity of non-POC would likely fluctuate less than that of POC within this short evaluation period, assuming its humified characteristics. The warm, humid climate of the southeastern USA offers great potential for photosynthetic fixation of C, but also a high decomposition rate of organic matter inputs resulting in relatively low soil organic C levels (Kern and Johnson, 1993). The accumulation of non-POC only at a depth of 0 to 2 cm suggests either high C input or unfavorably dry conditions at the soil surface that would limit decomposition. Net loss of non-POC below 4-cm depth suggests low C input or favorable decomposition conditions. The fact that POC has accumulated within the 2- to 6-cm depth suggests root contributions from bermudagrass are a significant source of C input, which is consistent with previous observations (Gale and Cambardella, 2000).

Increases in POC at a depth of 0 to 2 cm likely reflect the input of plant residues and cattle dung returned to the soil surface continuously during the year. It seems obvious that haying removed most of the aboveground plant residues and, therefore, POC accumulation was restricted to input from root residues with only a small amount of aboveground plant residue input. Although the unharvested strategy did not have forage removed, it may not have contributed to as large of an accumulation of POC in soil compared with cattle grazing during the first 4 yr, partly because plant residues were accumulating to a greater extent above the mineral soil surface. Surface residue C was 40 to 100 g m^{-2} greater under unharvested forage than under cattle grazing strategies (Franzluebbers et al., 2001). Accumulation of POC plus surface residue C under the unharvested strategy was only 72 to 75% of that under cattle grazing strategies, suggesting that (i) grazing of forage may have stimulated plant productivity or (ii) aboveground residues may have decomposed before getting to the soil when unharvested. Coastal bermudagrass harvested once per year produced only 72 to 90% as much aboveground forage as when forage was hayed every 3 to 12 wk (Burton et al., 1963). In a mixed-grass prairie ecosystem, plant productivity measured throughout the summer via photosynthetic exchange was not different between grazed and ungrazed pastures (LeCain et al., 2000), yet soil organic C was greater when grazed than when ungrazed

Table 1. Rate of change in physical and biological soil C pools during the first 4 yr of management as a function of soil depth and in response to harvest strategy (UH is unharvested, LG is low grazing pressure, HG is high grazing pressure, and H is hayed) averaged across fertilization strategies.

		Harvest strategy					
Soil depth	R^2	**Intercept**	**UH**	**LG**	**HG**	**H**	**LSD$_{(P=0.1)}$†**
cm		g kg^{-1}	g kg^{-1} yr^{-1}				
			Particulate organic C (POC)				
0 to 2	0.76	7.1	3.2	6.1	6.6	2.5	0.9
2 to 4	0.64	3.4	0.9	1.2	1.0	0.7	0.2
4 to 6	0.42	3.0	0.3	0.4	0.4	0.4	0.2
			Non-particulate organic C (NPOC)				
0 to 2	0.62	11.2	1.5	2.2	2.4	1.1	0.5
2 to 4	0.33	10.7	−0.3	−0.1	0.0	−0.3	0.3
4 to 6	0.61	10.8	−0.7	−0.5	−0.4	−0.7	0.2
		mg kg^{-1}	mg kg^{-1} yr^{-1}				
			Soil microbial biomass C (SMBC)				
0 to 2	0.80	497	257	440	567	298	65
2 to 4	0.36	550	82	109	104	90	39
4 to 6	0.13	648	−26	−8	−11	−9	25
			Potential C mineralization during 24 d (CMIN$_{0\text{–}24\text{ d}}$)				
0 to 2	0.71	500	308	525	705	379	102
2 to 4	0.39	167	100	121	109	108	42
4 to 6	0.15	144	26	38	40	39	27
			Basal soil respiration (BSR)				
0 to 2	0.62	9.3	8.0	14.9	20.1	10.0	3.6
2 to 4	0.26	4.1	1.9	2.3	2.0	2.1	1.1
4 to 6	0.07	3.5	0.2	0.5	0.5	0.4	0.6
			Flush of CO_2–C in 3 d (CMIN$_{0\text{–}3\text{ d}}$)				
0 to 2	0.53	240	90	135	178	92	38
2 to 4	0.45	54	41	50	46	44	15
4 to 6	0.14	55	11	16	18	16	12

† Least significant difference separates slope estimated among harvest strategy treatments and whether these slopes are significantly different from zero.

(Schuman et al., 1999). Grazing of forage likely promotes root death and regeneration, which could increase root contributions to POC. Frank et al. (2002) presented evidence that grazing by wild ungulates on rangeland in Yellowstone National Park stimulated both aboveground and belowground biomass production compared with ungrazed controls. Stimulation of root production by grazing is in contrast to some observations of lower root biomass when forages have been mechanically clipped (Biswell and Weaver, 1933; Archer and Tieszen, 1983; Reuss et al., 1998).

The POC/total organic C ratio increased significantly with time in all management systems at all soil depths (Table 3). The POC/total organic C ratio increased more with cattle grazing than with unharvested or hayed strategies at a depth of 0 to 2 cm, but not consistently at lower depths. Total organic C accumulation was greater under cattle grazing than under unharvested or haying strategies at all soil depths (Franzluebbers et al., 2001). Carbon input to the soil surface via ungrazed plant residues and partially digested forage in cattle dung supplied the soil with more POC than in harvest strategies without cattle.

Across all management systems and years, there was a strong relationship between total organic C and POC (TOC = 8.6 + 1.35 POC; $r^2 = 0.97$, $n = 144$). Total soil organic C accumulation in these forage management systems under a warm, humid climate appears to be largely composed of increases in the POC pool, at least within the first few years. The relationship between total organic C and POC suggests that for every unit of total organic C accumulated, approximately three-fourths will consist of POC and one-fourth will consist of non-POC. This partitioning was different than the approximately equal partitioning into POC plus residue compared with non-POC at the end of 1 yr of oat (*Avena sativa*) residue and root incubations in soil (Gale and Cambardella, 2000). Under long-term pastures in the Southern Pied-

Table 2. Rate of change in physical and biological soil C pools during the first 4 yr of management summed to a depth of 6 cm and in response to harvest strategy (UH is unharvested, LG is low grazing pressure, HG is high grazing pressure, and H is hayed) averaged across fertilization strategies.

		Harvest strategy					
Soil property	R^2	**Intercept**	**UH**	**LG**	**HG**	**H**	**LSD$_{(P=0.1)}$†**
		g m^{-2}	g m^{-2} yr^{-1}				
Particulate organic C	0.78	398	73	136	144	65	19
Non-particulate organic C	0.44	983	−41	−19	−9	−42	21
Soil microbial biomass C	0.64	49.9	5.1	9.6	11.9	7.4	2.1
Potential C mineralization in 24 d	0.54	22.8	8.5	13.2	16.4	11.4	3.6
Basal soil respiration, d^{-1}	0.45	0.46	0.20	0.35	0.43	0.28	0.11
Flush of CO_2–C in 3 d	0.42	10.0	2.6	3.7	4.5	3.2	1.3

† Least significant difference separates slope estimates among harvest strategy treatments and whether these slopes are significantly different from zero.

Table 3. Rate of change in physical and biological soil C pools relative to total soil organic C during the first 4 yr of management as a function of soil depth and in response to harvest strategy (UH is unharvested, LG is low grazing pressure, HG is high grazing pressure, and H is hayed) averaged across fertilization strategies.

			RHarvest strategy				
Soil depth	R^2	**Intercept**	**UH**	**LG**	**HG**	**H**	$\mathrm{LSD}_{(P=0.1)}$†
	cm	g kg^{-1}	g kg^{-1} yr^{-1}				
Particulate organic C/total organic C ratio							
0 to 2	0.52	370	46	68	71	40	17
2 to 4	0.60	244	45	50	45	37	11
4 to 6	0.47	217	28	33	29	36	12
0 to 6	0.65	289	43	58	58	39	11
Soil microbial biomass C/total organic C ratio							
0 to 2	0.52	26.5	4.2	5.2	6.9	7.3	1.8
2 to 4	0.24	39.2	3.8	4.0	3.7	5.0	2.5
4 to 6	0.21	48.4	−0.8	−0.7	−1.0	0.4	2.0
0 to 6	0.38	36.6	2.6	3.0	3.8	4.6	1.5
Potential C mineralization in 24 d/total organic C ratio							
0 to 2	0.47	24.0	6.5	7.9	10.6	10.5	2.9
2 to 4	0.33	11.6	6.0	6.3	5.7	6.6	2.6
4 to 6	0.15	11.0	2.2	2.7	2.9	3.3	2.1
0 to 6	0.42	16.4	5.5	6.6	7.9	7.7	2.5
Basal soil respiration/total organic C ratio							
0 to 2	0.38	0.41	0.20	0.28	0.36	0.32	0.11
2 to 4	0.21	0.28	0.11	0.12	0.10	0.13	0.07
4 to 6	0.07	0.27	0.02	0.03	0.03	0.04	0.05
0 to 6	0.33	0.33	0.13	0.18	0.22	0.19	0.08
Flush of CO_2–C in 3 d/total organic C ratio							
0 to 2	0.21	12.2	1.2	0.9	1.5	1.8	1.0
2 to 4	0.40	3.7	2.4	2.6	2.4	2.7	0.9
4 to 6	0.13	4.2	0.9	1.1	1.3	1.4	0.9
0 to 6	0.32	7.2	1.7	1.7	2.0	2.1	0.8

† Least significant difference separates slope estimates among harvest strategy treatments and whether these slopes are significantly different from zero.

mont USA, organic C accumulation was partitioned 57% into POC and 43% into non-POC (Franzluebbers and Stuedemann, 2002).

Soil Microbial Biomass Carbon

Soil microbial biomass C increased significantly with time at a depth of 0 to 2 and 2 to 4 cm, but remained the same at a depth of 4 to 6 cm (Fig. 1; Table 1). Fertilization strategy had no significant effect on SMBC accumulation with time at any soil depth (data not shown). At a depth of 0 to 2 cm, SMBC accumulation was greater under high than that under low grazing pressure, both of which were greater than under unharvested or hayed strategies (Fig. 1; Table 1). Harvest strategy did not significantly affect SMBC accumulation below 2 cm of soil. On an areal basis to a depth of 6 cm of soil, SMBC accumulation increased with degree of forage utilization from unharvested to low grazing pressure to high grazing pressure and then decreased with highest utilization under haying (Table 2).

Our results are consistent with those reported by Bardgett et al. (1997) and Franzluebbers et al. (2000b), where SMBC was greater under long-term grazed pastures than under ungrazed or hayed grasslands. Observation of greater SMBC with higher than with lower grazing intensity is also consistent with the results from the Serengeti National Park, where SMBC increased with grazing intensity (Reuss and McNaughton, 1987). In contrast, Kieft (1994) observed no significant difference in SMBC along a chronosequence of grazing withdrawal in the Sevilleta National Wildlife Refuge. Even more surprising was the greater rate of SMBC accumulation under hayed compared with unharvested strategy, given the continuous removal of aboveground forage assumed to be necessary for growth and development of the soil microbial community. Instead, greater rooting activity in the surface soil following herbage removal appears to be more critical for accumulation of SMBC.

The portion of total organic C as SMBC increased with time at a depth of 0 to 2 and 2 to 4 cm, but not at a depth of 4 to 6 cm in all treatments (Table 3). At a depth of 0 to 2 cm, the portion of total organic C as SMBC increased with increasing degree of forage utilization from unharvested to hayed strategies. Fertilization and harvest strategies had no effect on the portion of total organic C as SMBC below a depth of 2 cm.

Soil microbial biomass C appears to be sensitive to changes in C inputs via forage harvest strategy. It also appears that both aboveground and belowground C inputs were important to the dynamics of SMBC. The curvilinear response in SMBC accumulation as a function of forage utilization suggests that the quantity of cattle dung supplied to the soil may have stimulated SMBC compared with aboveground residue supply alone, since there was a large response to grazed compared with unharvested forage. The positive, linear response in the portion of total organic C as SMBC as a function of forage utilization suggests that belowground C inputs via roots must also be a significant substrate for the accumulation of SMBC. Increasing intensity of forage removal has been hypothesized to stimulate root exudation and root regeneration (Bardgett et al., 1998), which could contribute to soil microbial biomass development without increasing total soil organic C content. However, overgrazing of pastures can lead to a significant reduction in SMBC compared with well-managed pastures (Holt, 1997).

Potential Carbon Mineralization

Potential C mineralization during 24 d (CMIN$_{0\text{–}24\ \mathrm{d}}$) increased with time under all management systems at all soil depths (Fig. 1; Table 1). The responses in CMIN$_{0\text{–}24\ \mathrm{d}}$ were similar to those observed for SMBC, where fertilization strategy had no effect on the rate of increase with time and the effect of forage harvest strategy was limited to the surface 2 cm of soil. In addition, basal soil respiration (BSR) and the flush of CO_2–C during 3 d following rewetting of dried soil (CMIN$_{0\text{–}3\ \mathrm{d}}$) exhibited very similar responses to fertilization and forage harvest strategies compared with CMIN$_{0\text{–}24\ \mathrm{d}}$ (Table 1).

All of the biologically active soil C pools (i.e., SMBC, CMIN$_{0\text{–}24\ \mathrm{d}}$, BSR, and CMIN$_{0\text{–}3\ \mathrm{d}}$) increased with time at a depth of 0 to 2 and 2 to 4 cm (Table 1). At a depth of 4 to 6 cm, BSR and SMBC remained the same, while CMIN$_{0\text{–}24\ \mathrm{d}}$ and CMIN$_{0\text{–}3\ \mathrm{d}}$ increased significantly with time under all management systems, except under the unharvested strategy. On an areal basis to a depth of 6 cm of soil, CMIN$_{0\text{–}24\ \mathrm{d}}$, BSR, and CMIN$_{0\text{–}3\ \mathrm{d}}$ increased with increasing forage utilization from unharvested to low grazing pressure to high grazing pressure and then decreased when forage was hayed (Table 2). This response to forage utilization suggests that at least a low intensity of animal grazing might enhance soil N mineralization (McNaughton et al., 1997) and subsequent plant productivity potential (Bardgett et al., 1998) compared with no grazing. Frank and Groffman (1998) observed greater rates of potential C and N mineralization, as well as in situ N mineralization, under grazed than under ungrazed exclosures in Yellowstone National Park. Our results suggest that domesticated ungulates in managed pastures can have an equally large impact on active soil C pools as wild ungulates on native rangeland.

The portion of total organic C as CMIN$_{0\text{–}24\ \mathrm{d}}$, BSR, or CMIN$_{0\text{–}3\ \mathrm{d}}$ increased with time at all soil depths, except for BSR at a depth of 4 to 6 cm (Table 3). This increasing portion of total organic C as biologically active soil C pools suggests that C inputs to soil under grass management systems have increased the potential biological activity of soil organic matter compared with the previous land management system at the site (i.e., conventionally tilled cropland), and therefore, these biologically active soil C pools could be sensitive indicators of changes in soil quality.

The flush of CO_2–C during 3 d following rewetting of dried soil was strongly related to all other soil C pools measured in this study (Fig. 2). The weaker relationship between CMIN$_{0\text{–}3\ \mathrm{d}}$ and non-POC compared with other pools suggests that the flush of CO_2–C does not necessarily reflect the size of this more resistant soil organic C pool. The flush of CO_2–C following rewetting of dried soil has been shown to form strong associations with SMBC and CMIN$_{0\text{–}24\ \mathrm{d}}$ in other soils (Franzluebbers et al., 2000a). Further, the flush of CO_2–C could be a good indicator of potential N mineralization as it was highly related to annual forage N uptake of hayed bermudagrass (Haney et al., 2001). The flush of CO_2–C appears to be a good indicator of biologically active soil C, not only because of its strong relationship with other soil C pools, but also because of its repeatability, simplicity, and similar response to management as more involved procedures (Tables 1 and 2).

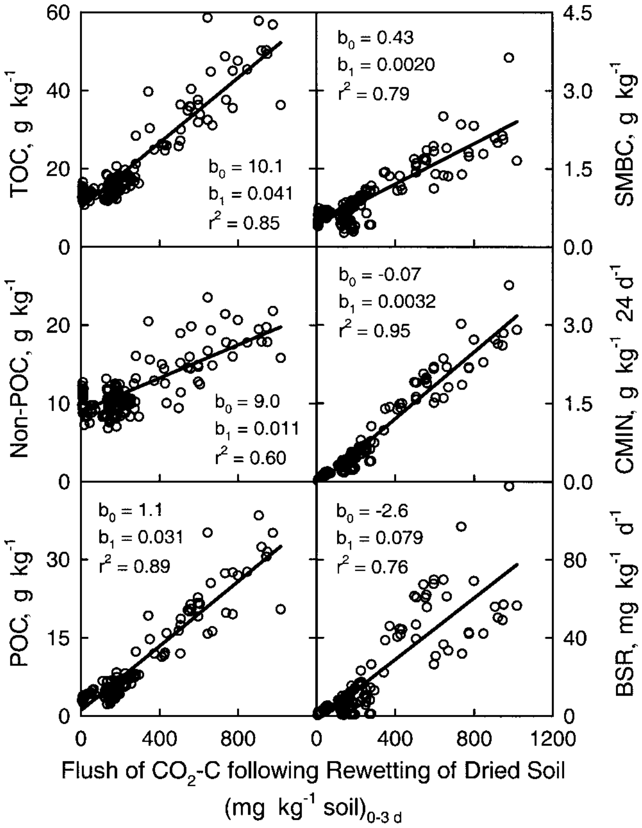

Fig. 2. Relationships of total organic C (TOC), nonparticulate organic C (Non-POC), particulate organic C (POC), soil microbial biomass C (SMBC), potential C mineralization during 24 d (CMIN), and basal soil respiration (BSR) with the flush of CO_2–C following rewetting of dried soil. Values are treatment means within a year and soil depth (n = 144).

SUMMARY AND CONCLUSIONS

The rate of accumulation of POC, SMBC, and CMIN$_{0\text{–}24\ \mathrm{d}}$ was similar, whether fertilization of bermudagrass forage during the first 4 yr of management with approximately 20 g N m^{-2} yr^{-1} was supplied either (i) inorganically, (ii) with clover cover crop plus inorganic supplement, or (iii) with broiler litter. The manner in which forage was harvested, however, had a major impact on the quality of organic C in soil. With no harvest of forage, POC, SMBC, CMIN$_{0\text{–}24\ \mathrm{d}}$, BSR, and CMIN$_{0\text{–}3\ \mathrm{d}}$ at a depth of 0 to 6 cm all accumulated significantly with time, but at significantly lower rates than with cattle grazing. High grazing pressure further enhanced accumulation of biologically active soil C pools compared with low grazing pressure at a depth of 0 to 2 cm. Accumulation of biologically active soil C pools was often higher under hayed strategy, but not significantly different than under unharvested strategy. Enrichment of soil with POC decreased with depth, with 65 ± 29, 27 ± 6, and 12 ± 4% average annual increases at depths of 0 to 2, 2 to 4, and 4 to 6 cm, respectively (mean ± standard deviation among 12 treatments). Likewise, annual increases in $\mathrm{CMIN}_{0\text{–}24\,\mathrm{d}}$ were 96 ± 34, 66 ± 10, and 25 ± 6% at depths of 0 to 2, 2 to 4, and 4 to 6 cm, respectively. Further research is needed to determine if such large changes in biologically active soil C pools will continue and for how long. The portion of total organic C as biologically active soil C pools increased with increasing forage utilization, suggesting that harvesting forage especially by grazing with subsequent return of feces to soil stimulates the biomass and activity of soil microorganisms. Therefore, cattle grazing can have beneficial impacts on biological soil quality.

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