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Particulate and non-particulate fractions of soil organic carbon under pastures in the Southern Piedmont USA

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"Capsule": *Pasture management can improve soil quality and soil carbon sequestration, especially in the particulate organic carbon pools.*

Abstract

Pasture management can be effective at sequestering soil organic C. We determined the depth distribution of particulate organic C (POC), non-particulate organic C (NPOC), particulate-to-total organic C (POC-to-TOC) ratio, and particulate organic C-to-N (POC-to-N) ratio under pastures near Watkinsville, GA, USA. POC was highly related with total organic C (TOC), but became an increasingly larger portion of TOC near the soil surface, where both pools were greatest. POC and NPOC were (i) greater under pasture than under conservation-tillage cropland, (ii) greater when pasture was grazed than when hayed, (iii) marginally greater with higher fertilization of pasture, (iv) greater with higher frequency of endophyte infection of tall fescue, and (v) greater under increasing stand age of grass. Soil under pasture comparisons that had greater TOC content had (i) larger improvements in POC than in NPOC and (ii) lower POC-to-N ratios, suggesting improvement in biochemical soil quality, as well as soil C sequestration. Published by Elsevier Science Ltd.

Keywords: Bermudagrass; Endophyte; Grazing; Haying; Tall fescue

1. Introduction

Soil organic C in the southeastern USA tends to be relatively low compared with other regions (Kern and Johnson, 1993), because of the warm and moist climate that favors decomposition of organic C inputs. Cultivation of soils in this region often leads to a rapid and dramatic decline in TOC (Giddens, 1957; Jones et al., 1966) that is not only due to oxidation of TOC upon disturbance, but also due to severe erosion resulting from intense rainfall during summer thunderstorms. Recent research indicates that conservation-tillage crop production in the region can increase the stratification of TOC compared with conventional tillage (Beare et al., 1994; Bruce and Langdale, 1997; Hendrix, 1997), but that the quantity of TOC within the traditional plow layer (i.e. 0 to 20 cm) may not be greatly affected (Hendrix et al., 1998; Franzluebbers et al., 1999a). Pasture management systems in the Southern Piedmont USA have been shown to stimulate even greater stratification of TOC than conservation-tillage cropping that leads to significant improvement in soil C sequestration within the plow layer (Franzluebbers et al., 2000).

Land management systems with minimum soil disturbance can lead to an accumulation of particulate organic matter (Franzluebbers and Arshad, 1997; Wander et al., 1998), with even greater accumulation in grassland systems compared with conservation-tillage cropping (Cambardella and Elliott, 1992; Six et al., 1999). The particulate organic matter pool is intermediate in turnover time (i.e. slow pool) between active and passive organic matter pools (Cambardella and Elliott, 1992). For soil C sequestration strategies to be effective in the long-term, it is likely they must increase the slow and passive pools of soil organic matter. There is a great need to understand how pasture management systems can increase soil C sequestration, especially in the Southern Piedmont USA where the land area of pasture is greater than that of cropland (Census of Agriculture, 1992).

Our objective was to determine the depth distribution of POC and NPOC pools under various pasture management strategies to gain a better understanding of how soil C sequestration could be enhanced.

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2. Materials and methods

2.1. Site characteristics

Land management systems were located at the J. Phil Campbell Sr. Natural Resource Conservation Center (33° 52′ N, 83° 25′ W) near Watkinsville, GA on Cecil–Madison–Pacolet (fine, kaolinitic, thermic Typic Kanhapludults) soil series with sandy loam, loam, or sandy clay loam surface textures. The location is characterized by mean annual temperature of 16.5°C, mean annual precipitation of 1250 mm, mean annual pan evaporation of 1560 mm, and mean elevation above sea level of 230 m.

2.2. Land management contrasts

2.2.1. Contrast I. Conservation-tillage cropland versus pasture

Prior to 1974, a single field (~10 ha) was managed under conventional-tillage cropping. From autumn 1974 onwards, one portion was managed with conservation-tillage. The other portion continued to be managed with conventional-tillage cropping until autumn of 1978, when tall fescue (*Festuca arundinacea* Schreb. cv. 'Kentucky 31') was planted. Conservation-tillage cropping consisted of summer crops of soybean [*Glycine max* (L.) Merr.], sorghum [*Sorghum bicolor* (L.) Moench], and cotton (*Gossypium hirsutum* L.) with winter crops of wheat (*Triticum aestivum* L.), rye (*Secale cereale* L.), barley (*Hordeum vulgare* L.), and crimson clover (*Trifolium incarnatum* L.) with minimum soil disturbance, except for in-row chisel at planting. Fertilization averaged 47–35–108 kg N–P–K ha^{-1} $year^{-1}$ during 24 years of conservation-tillage cropping from NH_4NO_3, superphosphate, and potash sources. Dolomitic limestone was applied six times during this period at a rate of 2.2 Mg ha^{-1}. The tall fescue pasture was grazed (ca. 6 months $year^{-1}$) with Angus cattle (*Bos taurus*) and, with time, was invaded by common bermudagrass (*Cynodon dactylon* L.) because of armyworm (*Pseudaletia unipuncta* Haworth) damage to tall fescue. Fertilization averaged 47–14–42 kg N–P–K ha^{-1} $year^{-1}$ during the past 7 years. Dolomitic limestone (2.2 Mg ha^{-1}) was applied once during the past 7 years.

2.2.2. Contrast II. Grazed versus hayed hybrid bermudagrass

Grazed pastures were two 15-year-old and one 19-year-old stands of 'Tifton 44' bermudagrass. Hayed fields were two 15-year-old stands of 'Coastal' and one 19-year-old stand of 'Tifton 44' bermudagrass. Grazing was with Angus cattle periodically (ca. 5 months $year^{-1}$) and haying was 3–4 times annually. During the past 7 years, grazed pastures received an average of 93–23–63 kg N–P–K ha^{-1} $year^{-1}$ and hayed fields received an average of 162–45–134 kg N–P–K ha^{-1} $year^{-1}$.

2.2.3. Contrast III. Stand age of grass

Stand ages of grazed 'Kentucky-31' tall fescue (i.e. 10, 17, and 50 years) and of hayed 'Coastal' bermudagrass (i.e. 6, 15, and 40 years) were evaluated. Ten- and 17-year-old tall fescue pastures were replicated field experiments receiving 336–37–139 kg N–P–K ha^{-1} $year^{-1}$. Two of the replications sampled were with high endophyte infection and two were with low endophyte infection. The 50-year-old tall fescue pasture was endophyte infected and received fertilizer sporadically with only one application of 45–20–37 kg N–P–K ha^{-1} during the past 7 years. The 6-year-old bermudagrass field was fertilized with an average of 149–35–105 kg N–P–K ha^{-1} $year^{-1}$. The 15- and 40-year-old bermudagrass fields received an average of 162–45–134 kg N–P–K ha^{-1} $year^{-1}$ during the past 7 years.

2.2.4. Contrast IV. Low versus high rate of fertilization of tall fescue pasture

Four replicate paddocks (0.7 ha each) of 'Kentucky-31' tall fescue were fertilized with a low rate (134–15–56 kg N–P–K ha^{-1} $year^{-1}$) and four paddocks were fertilized with a high rate (336–37–139 kg N–P–K ha^{-1} $year^{-1}$). Two of the replicates of each fertilization level had low endophyte levels (29±7%) and two had high endophyte levels (65±8%). Paddocks were sown in autumn 1981, resown in spring 1982 to increase stand, and grazed each year primarily in spring and autumn by Angus cattle.

2.2.5. Contrast V. Low versus high endophyte infection level of tall fescue pasture

Paddocks described in Contrast IV were evaluated for comparison of low (29±7%) and high (65±8%) endophyte levels in tall fescue that was 15 years old. Four other paddocks (0.8 ha each) comprising two replications of low (1±1%) and high (94±4%) endophyte levels in 'Kentucky-31' tall fescue were sown in autumns of 1987 and 1988, fertilized yearly with 336–37–139 kg N–P–K ha^{-1} $year^{-1}$, and grazed each year primarily in spring and autumn by Angus cattle.

2.2.6. Contrast VI. Long-term cropped, hayed, grazed, and forested land uses

Cropland was the 24-year-old conservation-tillage system described in Contrast I. Hayland and pastureland were the 40- and 50-year-old bermudagrass and tall fescue systems, respectively, described in Contrast III. Forestland was a loblolly pine (*Pinus taeda* L.) plantation established after the Civil War (1860s), with pines harvested in the mid 1960s and hardwoods (*Quercus, Carya,* and *Pinus*) allowed to regrow.

2.3. Soil sampling

Soil samples were collected in May 1997 from fields (3±2 ha) in Contrasts I, II, III, and VI in four zones, which served as pseudoreplicates for analyses. A few of the comparisons of soil organic C and N analyses from this sampling were reported in Franzluebbers et al. (2000). Fields were separated by a maximum of 4 km. Zones were separated by ⩾30 m. Each zone was divided into six sites on a 2×3 grid. Sites were separated by ~10m. At each site, plant material above 4 cm from the soil surface was removed from within a 0.3-m-diam ring. Surface residue (all organic material at 0- to 4-cm height above mineral soil) was cut with battery-powered hand shears and collected. Soil under forest was moder, therefore we defined the soil surface as the mineral layer and placed the Oi and Oa horizons into the surface residue component. One soil core (4.1-cm diam) within each ring was divided into 0- to 5-, 5- to 12.5-, and 12.5- to 20-cm increments. A second core to a depth of 0 to 5 cm within the ring was added to the first core. Samples from the six sites within each zone were composited.

Soil samples from paddocks in Contrasts IV and V were collected in January–February 1997 at depths of 0–2.5, 2.5–7.5, 7.5–15, and 15–30 cm at distances of 1, 10, 30, 50, and 80 m from permanent shade and water sources. A few of the comparisons of soil organic C and N analyses from this sampling were reported in Franzluebbers et al. (1999b). Eight cores (4.1-cm diam) were composited within each depth and distance.

All soil samples were dried at 55 °C for 48 h, weighed, and gently crushed to pass a 4.75-mm screen to homogenize samples and remove stones (<1% weight).

2.4. Soil analyses

Particulate organic fraction was determined with modifications to a procedure described by Cambardella and Elliott (1992). A 20–65 g subsample (weight inversely related to expected TOC content) was shaken in 100 ml of 0.1 M $Na_4P_2O_7$ for 16 h, diluted to 1 l with distilled water, the suspension allowed to settle for 5 h, and the particulate material caught on a 0.06-mm screen (Franzluebbers et al., 2000). Material retained on the screen was transferred to a drying bottle and weighed after oven-drying (55 °C, 72 h).

Subsamples of whole soil and of the particulate organic fraction were ground in a ball mill for 5 min and analyzed for total C and N using dry combustion at 1350 °C (Leco CNS-2000, St. Joseph, MI).[1] Organic C was assumed to be equivalent to total C, because soils had pH<6.5. Particulate organic N was assumed to be equivalent to total N, since inorganic N would have been washed from sample during processing. NPOC was calculated as the difference between TOC and TOC.

[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 US Department of Agriculture. 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 US Department of Agriculture.

2.5. Statistical analyes

Soil properties from each depth and from the weighted mean of the 0- to 20-cm depth were analyzed for variance using the general linear models procedure of SAS (SAS Institute, 1990). Ratios of soil properties were calculated for each independent sample to be able to analyze differences among treatments. Differences among treatments were considered significant at $P \leqslant 0.1$. The effect of stand age on soil properties within a soil depth was described with linear regression in Contrast III.

3. Results

3.1. Contrast I. Conservation-tillage cropland versus pasture

Twenty-year-old tall fescue-common bermudagrass pasture contained significantly greater POC than an adjacent field of 24-year-old conservation-tillage cropland at depths of 0–5 cm (2.5 times greater) and 12.5–20 cm (34% greater), but not at 5–12.5 cm (Fig. 1a). Similar depth distribution effects were observed between these two management systems in NPOC (Fig. 1b). TOC, POC, and NPOC concentrations averaged within the surface 20 cm were all greater under pasture than under cropland (10.9 vs 7.8 g kg^{-1}, $P<0.01$ for TOC; 3.0 vs 1.7 g kg^{-1}, $P<0.001$ for POC; 7.8 vs 6.1 g kg^{-1}, $P<0.1$ for NPOC).

The POC-to-TOC ratio decreased with soil depth in both management systems, but was significantly greater under pasture than under cropland at a depth of 0–5 cm (Fig. 1c). The POC-to-N ratio tended to increase with soil depth under both management systems, but was lower under pasture than under cropland at a depth of 0–5 cm (Fig. 1d).

3.2. Contrast II. Grazed versus hayed hybrid bermudagrass

Hybrid bermudagrass that was grazed for 15–19 years contained 60% greater POC than when hayed at a depth of 0–5 cm, but similar amounts at lower depths (Fig. 2a). Similar management and soil depth trends were observed for NPOC (Fig. 2b). TOC, POC, and NPOC concentrations averaged within the surface 20 cm were greater under grazed than under hayed bermudagrass (13.0 vs 10.6 g kg^{-1}, $P<0.1$ for TOC; 3.9 vs 2.9

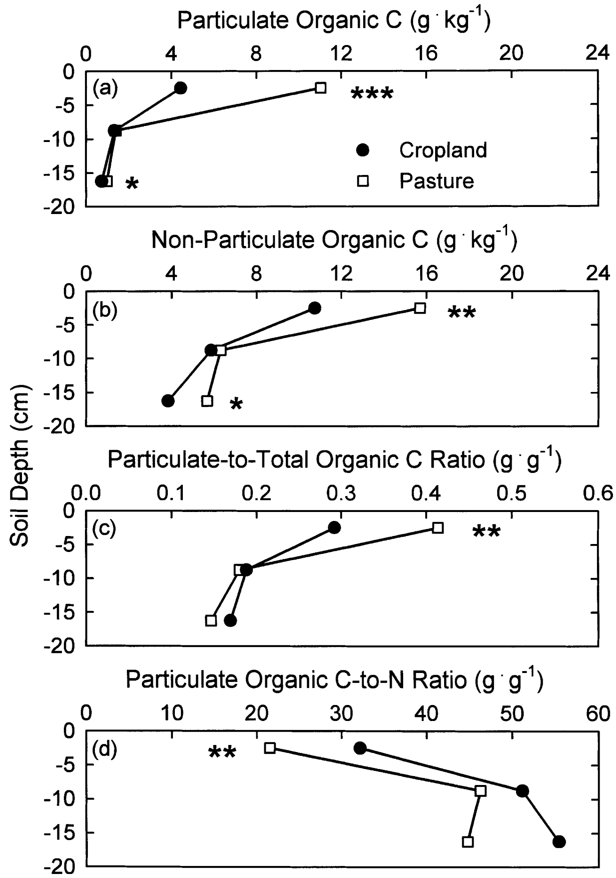

Fig. 1. Depth distribution of (a) particulate organic C, (b) non-particulate organic C, (c) particulate-to-total organic C ratio, and (d) particulate organic C-to-N ratio under side-by-side fields of 24-year-old conservation-tillage cropping and 20-year-old tall fescue-common bermudagrass pasture. *, **, and *** indicate significance within a soil depth at $P=0.1$, $P=0.01$, and $P=0.001$, respectively.

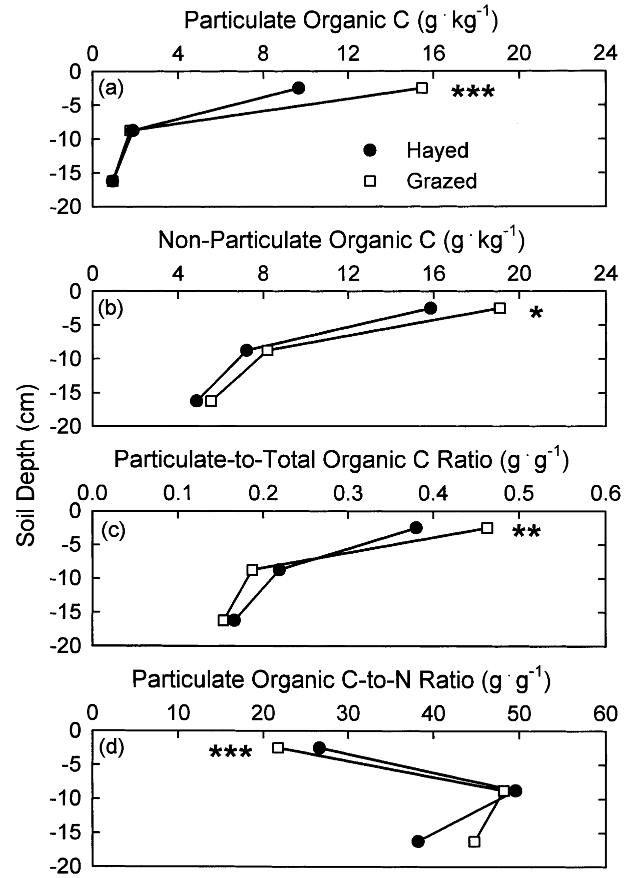

Fig. 2. Depth distribution of (a) particulate organic C, (b) non-particulate organic C, (c) particulate-to-total organic C ratio, and (d) particulate organic C-to-N ratio under triplicate paired fields of 15- to 19-year-old hayed and grazed hybrid bermudagrass. *, **, and *** indicate significance within a soil depth at $P=0.1$, $P=0.01$, and $P=0.001$, respectively.

g kg^{-1}, $P<0.001$ for POC; 9.1 vs 7.8 g kg^{-1}, not significant for NPOC). These soil differences occurred despite a lower rate of fertilization under grazed than under hayed management.

The POC-to-TOC ratio decreased with soil depth under both grazing and haying, but was greater when grazed than when hayed at a depth of 0–5 cm (Fig. 2c). The POC-to-N ratio was significantly lower when grazed than when hayed at a depth of 0–5 cm, but statistically similar at lower depths (Fig. 2d).

3.3. Contrast III. Stand age of grass

POC increased with stand age of grass mostly at a depth of 0–5 cm (slope of 0.16 g kg^{-1} year^{-1} in Fig. 3a). Like previous management contrasts, POC decreased with soil depth. At a depth of 0–5 cm, POC was 83% greater under grazed tall fescue than under hayed bermudagrass. NPOC responded similarly to stand age of grass as that of POC (slope of 0.26 g kg^{-1} year^{-1} at a depth of 0–5 cm in Fig. 3b). The linear effect of stand age on POC averaged to a depth of 0–20 cm was significant for hayed bermudagrass ($POC=1.9+0.037\times$ year, $P<0.01$), but not for grazed tall fescue ($POC=4.0+0.007\times$year, not significant). In contrast, the linear effect of stand age on NPOC averaged to a depth of 20 cm was not significant for hayed bermudagrass ($NPOC=6.6+0.014\times$year, not significant), but was significant for grazed tall fescue ($NPOC=7.5+0.053\times$ year, $P<0.01$). Combining these two fractions as TOC, the linear effect of stand age was significant for both hayed bermudagrass ($TOC=8.5+0.050\times$year, $P<0.1$) and grazed tall fescue ($TOC=11.5+0.061\times$year, $P<0.01$).

The POC-to-TOC ratio was not consistently affected by stand age of grass (Fig. 3c). Linear effects of stand age on this ratio were significant and positive at depths of 5–12.5 and 12.5–20 cm under hayed bermudagrass, but significant and negative at a depth of 0–5 cm under grazed tall fescue. Averaged to a depth of 20 cm, the POC-to-TOC ratio was positively related to stand age under hayed bermudagrass ($\text{POC-to-TOC}=0.23+0.002\times$ year, $P<0.1$) and negatively related to stand age under grazed tall fescue ($\text{POC-to-TOC}=0.35-0.001\times$year, $P<0.1$).

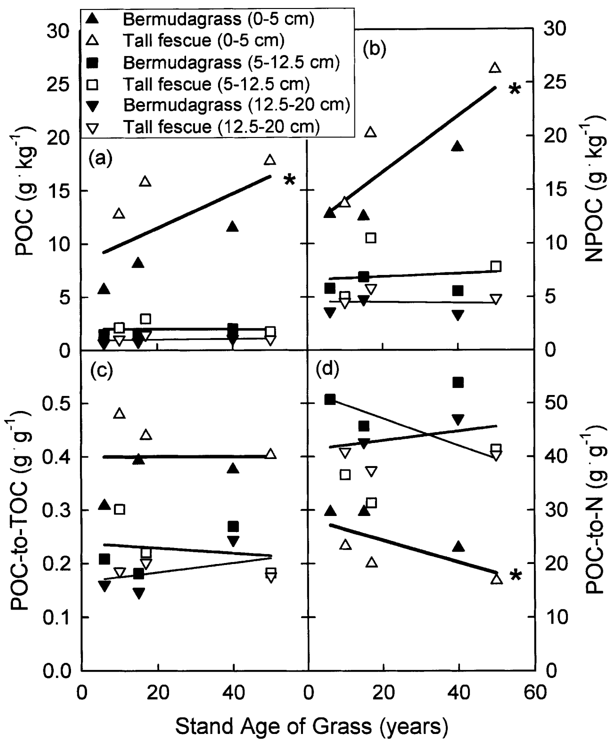

Fig. 3. Concentration of (a) particulate organic C (POC), (b) non-particulate organic C (NPOC), (c) particulate-to-total organic C ratio (POC-to-TOC), and (d) particulate organic C-to-N ratio (POC-to-N) under grazed tall fescue and hayed hybrid bermudagrass as a function of stand age and soil depth. Regression lines combine grass types within a soil depth. * indicates significance of regression within a soil depth at $P=0.1$.

The POC-to-N ratio decreased significantly (-0.2 g g^{-1} $year^{-1}$) with stand age at a depth of 0–5 cm, but was little affected by stand age at lower depths (Fig. 3d). Averaged to a depth of 20 cm, the POC-to-N ratio decreased linearly under both hayed bermudagrass (POC-to-PON $=36-0.2\times$year, $P<0.1$) and grazed tall fescue (POC-to-PON $=27-0.1\times$year, $P<0.1$).

3.4. Contrast IV. Low versus high rate of fertilization of tall fescue pasture

POC was unaffected by fertilization rate at each individual depth increment (Fig. 4a), but averaged to a depth of 30 cm was greater under high than under low fertilization rate (4.2 vs 3.7 g kg^{-1}, $P<0.1$). In contrast, NPOC was significantly greater under high than under low fertilization rate at a depth of 2.5–7.5 cm (Fig. 4b), but not significantly different when averaged to a depth of 30 cm.

Fertilization level had no significant effect on the POC-to-TOC ratio at any soil depth, nor when averaged to a depth of 30 cm (Fig. 4c). The POC-to-N ratio was significantly smaller under high than under low fertilization rate at a depth of 0 to 2.5 cm (Fig. 4d), but similar at lower depths. Averaged to a depth of 30 cm, the POC-to-N ratio was smaller under high than under low fertilization rate (22 vs 26 g g^{-1}, $P<0.001$).

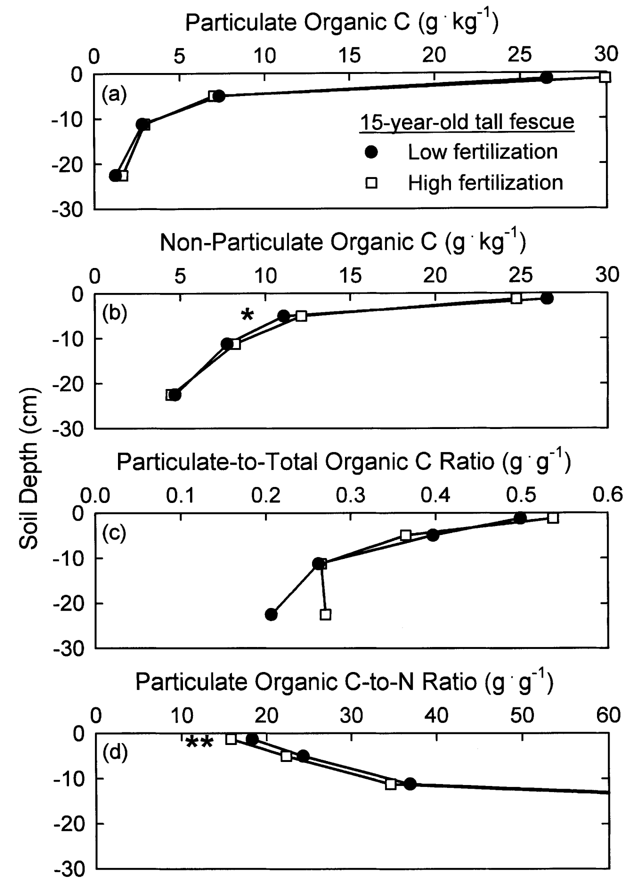

Fig. 4. Depth distribution of (a) particulate organic C, (b) non-particulate organic C, (c) particulate-to-total organic C ratio, and (d) particulate organic C-to-N ratio under low (134–15–56 kg N–P–K ha^{-1} $year^{-1}$) and high (336–37–139 kg N–P–K ha^{-1} $year^{-1}$) fertilization of 'Kentucky-31' tall fescue for 15 years. *, **, and *** indicate significance within a soil depth at $P=0.1$, $P=0.01$, and $P=0.001$, respectively.

3.5. Contrast V. Low versus high endophyte infection level of tall fescue pasture

Endophyte infection of tall fescue resulted in greater POC than endophyte-free tall fescue at a depth of 7.5–15 cm (Fig. 5a) and averaged to a depth of 30 cm (3.0 vs 2.6 g kg^{-1}, $P<0.1$) in 8-year-old pastures. In 15-year-old pastures, POC was significantly greater under high than under low endophyte infection level only at a depth of 0–2.5 cm (Fig. 6a). Averaged to a depth of 30 cm, POC was similar under high and low endophyte infection level in 15-year-old pastures (4.1 vs 3.9 g kg^{-1}, not significant).

NPOC in 8-year-old pastures was greater with than without the endophyte at a depth of 2.5–7.5 cm (Fig. 5b), but not different at other depths or when averaged to a depth of 30 cm (5.3 g kg^{-1} under both levels). In 15-year-old pastures, higher endophyte

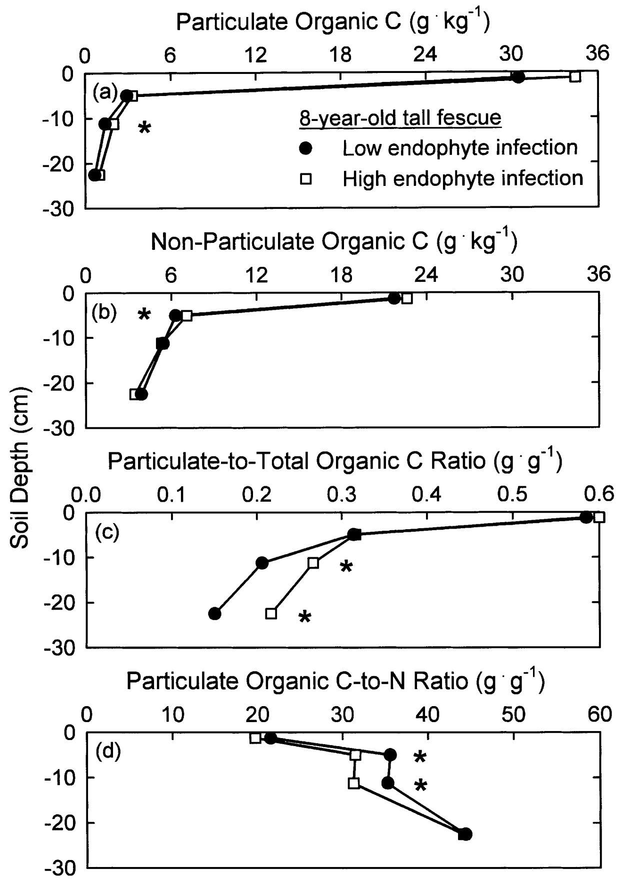

Fig. 5. Depth distribution of (a) particulate organic C, (b) non-particulate organic C, (c) particulate-to-total organic C ratio, and (d) particulate organic C-to-N ratio under low (0%) and high (94%) endophyte infection of 'Kentucky-31' tall fescue at the end of 8 years. *, **, and *** indicate significance within a soil depth at $P=0.1$, $P=0.01$, and $P=0.001$, respectively.

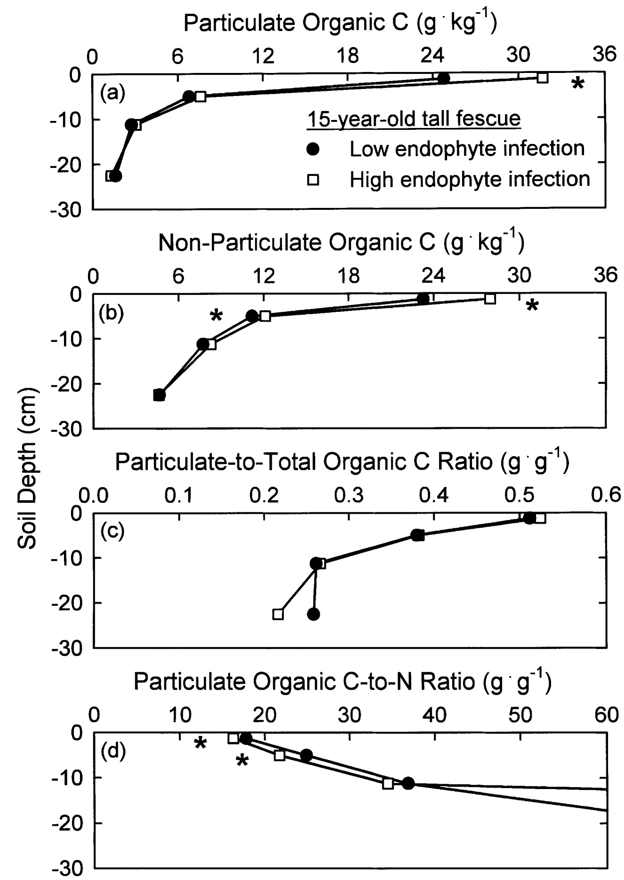

Fig. 6. Depth distribution of (a) particulate organic C, (b) non-particulate organic C, (c) particulate-to-total organic C ratio, and (d) particulate organic C-to-N ratio under low (29%) and high (65%) endophyte infection of 'Kentucky-31' tall fescue at the end of 15 years. *, **, and *** indicate significance within a soil depth at $P=0.1$, $P=0.01$, and $P=0.001$, respectively.

infection level led to greater NPOC at depths of 0–2.5 and 2.5–7.5 cm (Fig. 6b), but had no significant effect when averaged to a depth of 30 cm (7.8 vs 7.4 g kg^{-1}, not significant).

The POC-to-TOC ratio was significantly greater at the end of 8 years under endophyte-infected than under endophyte-free tall fescue at depths of 7.5–15 and 15–30 cm (Fig. 5c), but not when averaged to a depth of 30 cm (0.37 vs 0.33 g g^{-1}, not significant). No differences associated with endophyte infection level were observed in this ratio at any soil depth in 15-year-old pastures (Fig. 6c).

The POC-to-N ratio in 8-year-old pastures was lower under endophyte-infected than under endophyte-free tall fescue at depths of 2.5–7.5 and 7.5–15 cm (Fig. 5d), but was similar when averaged to a depth of 30 cm (25 vs 27 g g^{-1}, not significant). In 15-year-old pastures, the POC-to-N ratio was lower under high than under low endophyte infection level at depths of 0–2.5 and 2.5–7.5 cm (Fig. 6d), as well as when averaged to a depth of 30 cm (23 vs 25 g g^{-1}, $P<0.01$).

3.6. Contrast VI. Long-term cropped, hayed, grazed, and forested land uses

Comparison of 130-year-old forestland with 24-year-old conservation-tillage cropland revealed significant differences in all soil properties at a depth of 20 cm, except in NPOC (Table 1). Soil under forestland contained 41% greater TOC and 2.2 times the POC, but only 16% greater NPOC than cropland at a depth of 0–20 cm. The relative difference in TOC between forestland and cropland was consistent throughout the sampling depths, ranging from 41 to 43%. However, the relative difference in POC between forestland and cropland increased with soil depth, i.e. 1.9 times greater under forestland than under cropland at a depth of 0–5 cm, 2.5 times greater at a depth of 5–12.5 cm, and 3.6 times greater at a depth of 12.5–20 cm.

Pastureland contained 36% greater TOC, 28% greater POC, and 39% greater NPOC than hayland at a depth of 0–20 cm (Table 1). All of the difference in POC between these two grass management systems occurred at a depth of 0–5 cm.

Table 1
Depth distribution of total organic C (TOC), particulate organic C (POC), non-particulate organic C (NPOC), particulate-to-total organic C ratio (POC-to-TOC), and particulate organic C-to-N ratio (POC-to-N) under four long-term land management systems[a]

Soil property/depth	Long-term land management system				
	High ←←← external inputs ←←← Low Low →→→ naturalization →→→ High				
	Crop	Hay	Pasture	Forest	$LSD_{(p=0.1)}$
TOC (g kg^{-1} soil)					
0–5 cm	15.2	30.5	44.0	21.8	5.5
5–12.5 cm	7.2	7.6	9.6	10.4	1.7
12.5–20 cm	4.6	4.5	5.9	6.5	2.2
0–20 cm	7.8	10.4	14.1	11.0	1.7
POC (g kg^{-1} soil)					
0–5 cm	4.4	11.5	17.7	8.2	3.0
5–12.5 cm	1.3	2.0	1.8	3.2	0.6
12.5–20 cm	0.7	1.1	1.1	2.5	1.0
0–20 cm	1.7	3.3	4.3	3.9	0.8
NPOC (g kg^{-1} soil)					
0–5 cm	10.8	18.9	26.2	13.6	3.4
5–12.5 cm	5.9	5.6	7.8	7.2	1.3
12.5–20 cm	3.8	3.4	4.9	4.0	1.4
0–20 cm	6.1	7.0	9.8	7.1	1.1
POC-to-TOC (g g^{-1})					
0–5 cm	0.29	0.38	0.40	0.37	0.07
5–12.5 cm	0.19	0.27	0.18	0.31	0.05
12.5–20 cm	0.17	0.24	0.18	0.37	0.08
0–20 cm	0.23	0.32	0.30	0.35	0.04
POC-to-N (g g^{-1})					
0–5 cm	32	23	17	38	8
5–12.5 cm	51	54	41	94	20
12.5–20 cm	55	47	40	84	33
0–2 0 cm	37	29	20	58	10

[a] Crop is 24-year-old conservation-tillage cropland, Hay is 40-year-old hybrid bermudagrass hayland, Pasture is 50-year-old tall fescue grazingland, and Forest is 130-year-old woodland.

The average of the two grass management systems contained 29–35% greater TOC, POC, and NPOC at a depth of 0–20 cm than the average of cropland and forestland (Table 1). Soils under grass management systems were more enriched in organic matter pools at a depth of 0–5 cm than other systems, with increases of 100% in TOC, of 132% in POC, and of 85% in NPOC at this depth.

POC-to-TOC ratio was lower in conservation-tillage cropland than in other land management systems at a depth of 0–5 cm (Table 1). At lower depths, POC-to-TOC ratio of forestland was generally greater than that of all other land management systems. The greater POC-to-TOC ratio under forestland was accompanied by 82±36% (mean±standard deviation among comparisons and soil depths) greater POC-to-N ratio compared with other land management systems at each depth.

4. Discussion

Both conservation-tillage cropland and permanent pasture rely on management techniques with minimal disturbance of the soil. The lack of disturbance allows soil organic matter pools to accumulate at the surface (Fig. 1). Above-ground residues in these systems have minimal contact with the soil, which otherwise would increase opportunities for decomposition by providing more consistent moisture and temperature regimes, access to soluble nutrients, and location with more diverse soil faunal and microbiological activity. Greater TOC, POC, and NPOC pools under tall fescue-common bermudagrass pasture compared with an adjacent field of conservation-tillage cropland could have been due to a variety of factors, including greater overall rate of photosynthetic activity (i.e. C input to the soil) throughout the year because of the growth capabilities of perennial versus annual plant species, drier surface soil that limited decomposition due to differences in plant growth rates, and less organic C exported via cattle body growth compared with grain harvest.

Grazing of pasture returns feces and urine to the soil surface resulting in accumulation of POC relative to hayed management (Fig. 2). Surface residue C-to-N ratio of grazed bermudagrass in this study was lower than that of hayed bermudagrass (22 vs 34 g g^{-1}, $P<0.001$; Franzluebbers et al., 2000), which was similar to the POC-to-N ratio at a depth of 0–5 cm (22 vs 27 g g^{-1}, $P<0.001$; Fig. 2d). This similarity between C-to-N ratio of pools suggests that POC at the soil surface in pasture management systems is derived mostly from the surface residue pool and that accumulation of the POC pool in the long-term is dependent upon the quantity of surface residue produced and its eventual incorporation into the soil, whether that be from trampling by cattle, soil faunal activity, or slow physical movement of particles and solutes with rainfall. The long-term effect of a greater supply of surface residue on POC and NPOC pools was significant at a depth of 0–5 cm, but not below this depth (Fig. 3a, b).

Fertilization of pastures increases productivity (Follett and Wilkinson, 1985) and did have a positive impact on accumulation of TOC and POC pools (Fig. 4). However, the fossil-fuel-derived C cost of additional fertilizer applied in this study [1.5–3.7 Mg C ha^{-1} during 15 years of application based on either 0.5 g C g^{-1} N applied (IPCC, 1996) or 1.23 g C g^{-1} N applied (Izaurralde et al., 1998)] would have been approximately equivalent to the quantity of additional C stored in this soil as TOC at a depth of 0–30 cm (2.6 Mg ha^{-1}; Schnabel et al., 2001).

Endophyte infection of tall fescue has been reported to increase TOC in soil, possibly due to reduction in soil microbial activity and alteration in soil microbial community structure (Franzluebbers et al., 1999b). Endophyte infection appears to have preferentially increased the POC pool size (Fig. 5c), as well as the quality of this pool, as reflected by the reduction in the POC-to-N ratio (Figs. 5d and 6d).

Pasture management systems that sequestered more soil C in this study, also resulted in preferential accumulation of POC compared with NPOC near the soil surface. Sequestration of POC compared with NPOC in the surface soil depth (either 0–5 or 0–2.5 cm) was 6.6 vs 5.0 g kg^{-1} in Contrast I (pasture–cropland), 5.8 vs 3.2 g kg^{-1} in Contrast II (grazed–hayed), 3.3 vs −1.8 g kg^{-1} in Contrast IV (high−low fertilization), 3.9 vs 0.9 g kg^{-1} in Contrast V (high–low endophyte, 8 years), and 6.9 vs 4.0 g kg^{-1} in Contrast V (high–low endophyte, 15 years). A plot of POC and NPOC against TOC suggests that improved pasture management systems in the Southern Piedmont USA will increase both POC and NPOC pools, but preferentially the POC pool when TOC exceeds ~30 g kg^{-1} (i.e. the point beyond which slopes tend to deviate from near parallelism; Fig. 7).

The quality of the particulate organic matter pool, in general, depended upon the quantity of TOC in soil (Fig. 8). POC-to-N ratio was high when TOC was low. Low TOC levels were those at lower soil depths in all management systems. This relationship suggests that POC at lower depths is probably a reflection of root and root-derived decomposition products, since root C-to-N ratios are often high [29±5 g g^{-1} in the 0- to 60-cm depth of mixed-grass prairie (Schuman et al., 1999); 29 g g^{-1} in wheat (*Triticum aestivum* L.; Jawson and Elliott, 1986); 14–64 g g^{-1} in maize (*Zea mays* L.; Mary et al., 1993)]. Greater POC at lower depths under forestland with larger, longer living roots than under cropland (Table 1) supports this suggestion that the POC pool is a reflection of root-derived products. Ecologically, particulate organic matter with high C-to-N ratio, such as that observed at lower soil depths, should decompose slower than particulate organic matter with low C-to-N ratio (Vigil and Kissel, 1991), but combined with more stable and favorable moisture and temperature regimes at lower depths this material likely decomposes equally or more rapidly than material at the soil surface.

Assuming the four long-term land management systems we studied could be viewed as a gradient in degree of naturalization (i.e. contrary to management), which would be inversely related to level of external inputs, then TOC, POC, and NPOC pools averaged to a depth of 20 cm responded similarly to increasing naturalization by increasing to a maximum, but then reaching a plateau or decreasing at a point between pastureland and forestland uses (Table 1). This response to degree of naturalization suggests that optimization of soil C sequestration (which does not include above-ground C sequestration) could be best achieved with a cattle grazing or forestland system in the Southern Piedmont region of the USA. The long-term grazed pasture system was lowest in POC-to-N (Table 1) and TOC-to-N ratios (Franzluebbers et al., 2000). Low C-to-N ratios suggest high N content, which would be of benefit to future land uses concerning nutrient cycling and availability and soil quality.

The estimate of TOC under land management systems in Table 1 does not include surface residue C, which was substantially greater under forestland (19.4 Mg ha^{-1}) than under other land uses (2.5±0.6 Mg ha^{-1}; Franzluebbers et al., 2000). Surface residue plus TOC to a depth of 20 cm under forestland was significantly greater than under pastureland (17%), hayland (39%), and cropland (81%; Franzluebbers et al., 2000).

There are external factors that could have influenced standing stock of TOC among the long-term management systems. Soil degradation prior to implementation of a management system could have reduced the initial

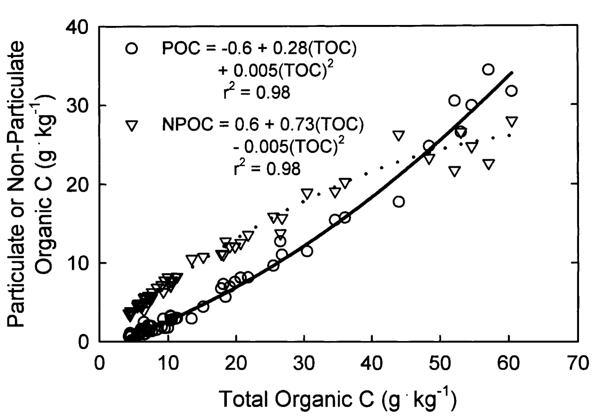

Fig. 7. Relationships of particulate and non-particulate organic C pools with total organic C (n = 66, mean values of treatments for each soil depth in Contrasts I–VI).

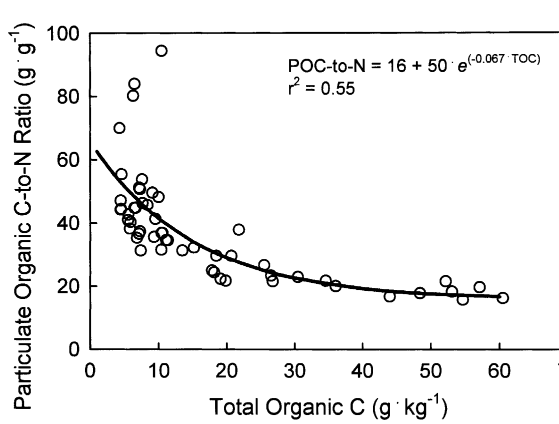

Fig. 8. Relationship between particulate organic C-to-N ratio and total organic C (n=63, mean values of treatments for each soil depth in Contrasts I–VI, without three outliers with particulate organic C-to-N ratios of >170 g g^{-1} and total organic C of 6 g kg^{-1}).

TOC level, as well as other soil quality properties, which could have limited plant development and fixation of C. It is unclear what the extent of previous erosion on each of these sites was, but if clay content could be used as an indicator of previous erosion, then the site with pastureland probably had experienced the greatest loss of topsoil prior to establishment of the pasture. More eroded soil would have likely been lower in initial TOC than less eroded soil. It is likely that most surface soils in the region were low in clay content, but increased in clay content with loss of topsoil and exposure of clayey subsoil. Clay content of the 0–20 cm soil depth was 29% under pastureland and 11–19% under other management systems.

5. Conclusions

Pastures in the Southern Piedmont USA could be managed to sequester greater quantities of soil organic C (i) compared with conservation-tillage cropland because of higher photosynthetic capacity, perennial vegetation, and lack of soil disturbance, (ii) when grazed compared with hay removal mainly due to return of feces to soil, (iii) with greater length of time because of deposition of residues, (iv) with higher than with lower fertilization because of enhanced plant production, and (v) with endophyte infection of tall fescue than without because of either reduced soil microbial activity or enhanced plant productivity. Accumulation of soil organic C occurred primarily in the particulate rather than the non-particulate organic C pool. The particulate organic matter pool probably has an intermediate turnover time (i.e. passive pool) between extremes of active and slow organic matter pools, which could be susceptible to more rapid decomposition if soil were to be disturbed. Particulate organic C near the soil surface reflects contributions to soil organic C from surface plant residues and animal manures, while accumulation below the surface 5 cm of soil reflects contributions from plant roots.

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