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Soil organic C and N pools under long-term pasture management in the Southern Piedmont USA

A.J. Franzluebbers*, J.A. Stuedemann, H.H. Schomberg, S.R. Wilkinson

US Department of Agriculture, Agricultural Research Service, J. Phil Campbell Sr. Natural Resource Conservation Center, 1420 Experiment Station Road, Watkinsville, GA 30677-2373, USA

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Abstract

Soil organic matter pools under contrasting long-term management systems provide insight into potentials for sequestering soil C, sustaining soil fertility and functioning of the soil–atmospheric interface. We compared soil C and N pools (total, particulate and microbial) under pastures (1) varying due to harvest technique (grazing or haying), species composition (cool- or warm-season), stand age and previous land use and (2) in comparison with other land uses. Grazed tall fescue-common bermudagrass pasture (20 yr old) had greater soil organic C (31%), total N (34%), particulate organic C (66%), particulate organic N (2.4 fold) and soil microbial biomass C (28%) at a depth of 0–200 mm than adjacent land in conservation-tillage cropland (24 yr old). Soil organic C and total N at a depth of 0–200 mm averaged 3800 and 294 g m^{-2}, respectively, under grazed bermudagrass and 3112 and 219 g m^{-2}, respectively, under hayed bermudagrass. A chronosequence of grazed tall fescue suggested soil organic N sequestration rates of 7.3, 4.4 and 0.6 g m^{-2} yr^{-1} to a depth of 200 mm during 0–10, 10–30 and 30–50 yr, respectively. Soil C storage under long-term grazed tall fescue was 85 to 88% of that under forest, whereas soil N storage was 77 to 90% greater under grazed tall fescue than under forest. Properly grazed pastures in the Southern Piedmont USA have great potential to restore natural soil fertility, sequester soil organic C and N and increase soil biological activity. Published by Elsevier Science Ltd.

Keywords: Carbon mineralization; Grazing; Haying; Land-use changes; Microbial biomass; Soil organic matter

1. Introduction

Soil organic matter pools provide insight into the potential stabilization or degradation of the soil resource by various long-term land management systems (Paul et al., 1997). In the Southern Piedmont USA, agricultural land is approximately divided between cropland that supports traditional grain/fiber production and grazingland that supports an increasing animal production industry (Census of Agriculture, 1992). Despite the abundance and importance of managed pastures in the eastern USA, relatively little information is available that quantitatively describes the effects of long-term pasture management on soil organic matter pools and dynamics (Schnabel et al., 2000). A variety of management decisions that might affect soil organic matter, including harvest technique, species composition, stand age and previous land use need to be better understood.

Although total organic C and N are important for long-term assessments of sustainable land management systems (Follett et al., 1987), particulate organic C and N and biologically active soil C and N pools have been shown to be equally and sometimes more, responsive to changes in soil management, which makes them excellent indicators of soil quality (Gregorich et al., 1994). Our objective was to evaluate the effect of various long-term pasture management strategies in the Southern Piedmont USA on surface residue C and

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* Corresponding author. Tel.: +1-706-769-5631, ext 223; fax: +1-706-769-8962.

E-mail address: afranz@arches.uga.edu (A.J. Franzluebbers).

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Table 1
Management characteristics and soil physical and chemical properties to a depth of 200 mm (mean ± standard deviation among four replicates)

System	Management	Clay (%)	Sand (%)	Bulk density (Mg m^{-3})	Soil Organic C (g m^{-2})	Soil Total N (g m^{-2})	Residue C (g m^{-2})	Residue N (g m^{-2})
Conversion of conventionally tilled cropland to pasture versus conversion to conservation-tillage cropland								
1 Cropped	24 yr conservation tillage after conventional tillage	15 ± 3	69 ± 7	1.57 ± 0.04	2447 ± 391	175 ± 28	205 ± 72	5 ± 2
2 Pasture	20 yr tall fescue/common bermudagrass pasture	22 ± 3	61 ± 2	1.48 ± 0.05	3212 ± 171	234 ± 20	108 ± 14	4 ± 1
Grazed versus hayed hybrid bermudagrass								
3 Grazed	19 yr Tifton 44 bermudagrass	29 ± 2	56 ± 2	1.48 ± 0.03	3837 ± 332	349 ± 52	105 ± 22	6 ± 2
4 Grazed	15 yr Tifton 44 bermudagrass after forest	23 ± 6	58 ± 6	1.39 ± 0.05	4642 ± 594	347 ± 43	176 ± 41	6 ± 2
5 Grazed	15 yr Tifton 44 bermudagrass after cropping	12 ± 1	73 ± 4	1.60 ± 0.02	2921 ± 455	185 ± 22	253 ± 13	12 ± 1
6 Hayed	19 yr Tifton 44 bermudagrass	19 ± 6	56 ± 17	1.42 ± 0.07	3721 ± 931	276 ± 72	137 ± 11	4 ± 1
7 Hayed	15 yr Coastal bermudagrass after forest	28 ± 2	57 ± 2	1.50 ± 0.04	2742 ± 219	173 ± 16	81 ± 20	2 ± 1
8 Hayed	15 yr Coastal bermudagrass after cropping	23 ± 4	58 ± 3	1.50 ± 0.01	2875 ± 290	209 ± 29	129 ± 9	4 ± 1
Stand age of grazed tall fescue and hayed bermudagrass								
9 Bermuda	6 yr hayed Coastal bermudagrass after cropping	23 ± 13	59 ± 12	1.64 ± 0.12	2763 ± 258	198 ± 34	261 ± 92	12 ± 4
8 Hayed	15 yr Coastal bermudagrass after cropping	23 ± 4	58 ± 3	1.50 ± 0.01	2875 ± 290	209 ± 29	129 ± 9	4 ± 1
10 Bermuda	40 yr hayed Coastal bermuda after cropping	13 ± 2	69 ± 3	1.52 ± 0.02	3151 ± 332	216 ± 17	309 ± 73	12 ± 3
11 Fescue	10 yr grazed tall fescue	15 ± 3	69 ± 4	1.52 ± 0.04	3011 ± 420	193 ± 21	217 ± 21	13 ± 3
12 Fescue	17 yr grazed tall fescue	13 ± 4	67 ± 8	1.34 ± 0.12	4040 ± 266	320 ± 15	173 ± 14	8 ± 1
13 Fescue	50 yr grazed tall fescue	29 ± 5	54 ± 4	1.38 ± 0.02	3877 ± 188	341 ± 24	224 ± 58	10 ± 3
Bermudagrass following cropland versus following forestland								
5 Grazed	15 yr Tifton 44 bermudagrass after cropping	12 ± 1	73 ± 4	1.60 ± 0.02	2921 ± 455	185 ± 22	253 ± 13	12 ± 1
8 Hayed	15 yr Coastal bermudagrass after cropping	23 ± 4	58 ± 3	1.50 ± 0.01	2875 ± 290	209 ± 29	129 ± 9	4 ± 1
4 Grazed	15 yr Tifton 44 bermudagrass after forest	23 ± 6	58 ± 6	1.39 ± 0.05	4642 ± 594	347 ± 43	176 ± 41	6 ± 2
7 Hayed	15 yr Coastal bermudagrass after forest	28 ± 2	57 ± 2	1.50 ± 0.04	2742 ± 219	173 ± 16	81 ± 20	2 ± 1
Longest-term land management systems								
14 Forest	130 yr forest planted to pines	15 ± 4	70 ± 4	1.32 ± 0.05	2867 ± 436	104 ± 16	1943 ± 556	81 ± 30
1 Cropped	24 yr conservation tillage after conventional tillage	15 ± 3	69 ± 7	1.57 ± 0.04	2447 ± 391	175 ± 28	205 ± 72	5 ± 2
10 Bermuda	40 yr hayed Coastal bermuda after cropping	13 ± 2	69 ± 3	1.52 ± 0.02	3151 ± 332	216 ± 17	309 ± 73	12 ± 3
13 Fescue	50 yr grazed tall fescue	29 ± 5	54 ± 4	1.38 ± 0.02	3877 ± 188	341 ± 24	224 ± 58	10 ± 3

N and soil depth distribution of total, particulate and biologically active (i.e., soil microbial biomass and mineralizable) C and N pools.

2. Materials and methods

2.1. Site characteristics

Fourteen fields located on the J. Phil Campbell Sr. Natural Resource Conservation Center (33° 52′ N, 83° 25′ W) were sampled in early May 1997 (Table 1). The location is characterized by mean annual temperature of 16.5°C, mean annual precipitation of 1250 mm and mean annual potential evaporation of 1560 mm.

2.2. Management systems

An assumption was made that differences in soil C and N pools due to inherent soil characteristics were minimal compared with differences due to management. Soils types were similar down to the family level (fine, kaolinitic, thermic Typic Kanhapludults). Soil series were Cecil, Madison and Pacolet with sandy loam, loam, or sandy clay loam texture. Generally, surface soils were once low in clay content (< 15%), but now commonly have greater clay content due to erosion that has exposed clayey subsoil. Fields were selected to contrast:

1. Conversion of conventionally tilled cropland to conservation tillage versus conversion to tall fescue (*Festuca arundinacea* Schreb. cv. 'Kentucky 31')-common bermudagrass (*Cynodon dactylon* L.) pasture. Prior to 1974, a single field 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 'Kentucky-31' tall fescue 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 4.7–3.5–10.8 g N–P–K m^{-2} yr^{-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 224 g m^{-2}. The tall fescue pasture was grazed with Angus cattle (*Bos taurus*) and with time was invaded by common bermudagrass because of armyworm (*Pseudaletia unipuncta* Haworth) damage to tall fescue. Fertilization averaged 4.7–1.4–4.2 g N–P–K m^{-2} yr^{-1} during the past seven years. Dolomitic limestone (224 g m^{-2}) was applied once during the past seven years.
2. Grazing versus haying of hybrid bermudagrass (cv. 'Coastal' or 'Tifton 44'). Grazed pastures were two 15-year-old and one 19-year-old stands of 'Tifton 44'. Hayed fields were two 15-year-old stands of 'Coastal' and one 19-year-old stand of 'Tifton 44'. Grazing was with Angus cattle periodically and haying was 3 to 4 times annually. During the past seven years, grazed pastures received an average of 9.3–2.3–6.3 g N–P–K m^{-2} yr^{-1} and hayed fields received an average of 16.2–4.5–13.4 g N–P–K m^{-2} yr^{-1}.
3. Stand age of grazed 'Kentucky-31' tall fescue (i.e., 10, 17 and 50 yr) and of hayed 'Coastal' bermudagrass (i.e., 6, 15 and 40 years). The 10- and 17-year-old pastures were replicated field experiments receiving 33.6–3.7–13.9 g N–P–K m^{-2} yr^{-1}. Two of the replications sampled were with high endophyte infection and two were with low endophyte infection. The 50-year-old pasture was endophyte infected and received fertilizer sporadically with only one application of 4.5–2.0–3.7 g N–P–K m^{-2} during the past seven years. The 6-year-old bermudagrass field was fertilized with an average of 14.9–3.5–10.5 g N–P–K m^{-2} yr^{-1}. The 15- and 40-year-old bermudagrass fields received an average of 16.2–4.5–13.4 g N–P–K m^{-2} yr^{-1} during the past seven years.
4. Hybrid bermudagrass following cropping versus following forest clearing. The four 15-year-old bermudagrass fields described in Contrast 2 were the source of this comparison. Comparison of previous land use, therefore, was blocked according to grazing and haying.
5. Longest-term continuous land management systems of forestland, cropland, hayland and grazingland. Forestland was a planted 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. Cropland was the 24-year-old conservation tillage system described in Contrast 1. Hayland and pastureland were the 40- and 50-year-old bermudagrass and tall fescue systems, respectively, described in Contrast 3.

2.3. Soil sampling

Soil samples were collected from each field (3 ± 2 ha) in four zones, which served as pseudoreplicates for analyses. 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 ~10 m. At each site, plant material above 40 mm from the soil surface was removed from within a 0.3 m diam ring. Surface residue (all organic material at 0–40 mm 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 (41 mm diam) within each ring was divided into 0–50, 50–125 and 125–200 mm increments. A second core to a depth of 0–50 mm within the ring was added to the first core. Samples from the six sites within each zone were composited, resulting in estimates of surface residue from 0.42 m^2, soil bulk density at 0–50 mm depth from 792 cm^3 and soil bulk density at 50–125 and 125–200 mm depths from 990 cm^3. Surface residue and soil were dried at 55°C for 48 h and weighed. Soil was gently crushed to pass a 4.75 mm screen prior to biological analyses. Stones > 4.75 mm were removed from soil samples.

2.4. Soil biological analyses

Potential C mineralization was determined from subsamples (20, 52 and 65 g for 0–50, 50–125 and 125–200 mm depths, respectively) of soil under the following set of standard conditions. Duplicate soil subsamples were moistened to 50% water-filled pore space and incubated at 25 ± 1°C in 1 l canning jars containing vials with 10 ml of 1.0 M NaOH to absorb CO_2 and water to maintain humidity. Alkali traps were replaced at 3 and 10 d and removed at 24 d. Carbon dioxide evolved was determined by titration of alkali with 1.0 M HCl (Anderson, 1982). At 10 d, one subsample was removed, fumigated with chloroform and incubated separately under the same conditions to determine the flush of CO_2–C representing microbial biomass C using a k_C factor of 0.41 (Voroney and Paul, 1984). Determination of soil microbial biomass C following rewetting of dried soil with 10 d of pre-incubation has been shown to yield equivalent estimates compared with those from field-moist soil (Franzluebbers et al., 1996; Franzluebbers, 1999).

2.5. Soil physical and chemical analyses

Particulate organic fraction was collected from the dried (55°C, 72 h) sample previously used for microbial biomass determination by shaking in 100 ml of 0.1 M $Na_4P_2O_7$ for 16 h, diluting suspension to 1 l with distilled water, allowing to settle for 5 h and catching material on a 0.06 mm screen (Franzluebbers et al., 1999). Sand-sized material retained on the screen was transferred to a drying bottle and weighed after oven-drying (55°C, 72 h). Clay content was determined with a hydrometer at the end of the 5 h settling period (Gee and Bauder, 1986).

Subsamples of whole soil and particulate organic fraction (ground in a ball mill for 5 min) and surface residue (ground to < 1 mm) were analyzed for total C and N using dry combustion. Under forest, separate analyses were conducted for Oi and Oa horizons. Organic C was assumed to be equivalent to total C, because soils had pH < 6.5. Organic N was assumed to be equivalent to total N, although total N was composed of $1.3 \pm 0.5\%$ inorganic N.

2.6. Statistical analyzes

Soil properties from each depth and from the weighted mean of the 0–200 mm depth were analyzed for variance using the general linear models procedure of SAS (SAS Institute Inc., 1990). Differences among treatments were considered significant at $P \leq 0.1$.

3. Results and discussion

3.1. Conversion of conventionally tilled cropland to pasture versus conversion to conservation-tillage cropland

Soil bulk density was lower under tall fescue-common bermudagrass pasture than under conservation-tillage cropland at depths of 0–50 mm (1.12 vs. 1.31 Mg m^{-3}, $P \leq 0.01$) and 50–125 mm (1.54 vs. 1.63 Mg m^{-3}, $P \leq 0.01$), but not at 125–200 mm (1.65 vs. 1.69 Mg m^{-3}, $P = 0.59$).

Soil organic C to a depth of 200 mm was greater under pasture than under conservation-tillage cropland (3212 vs. 2447 g m^{-2}, $P = 0.01$) (Table 1). Surface residue C, however, was lower under pasture than under conservation-tillage cropland (108 vs. 205 g m^{-2}, $P = 0.04$). Soil organic C-to-N ratio averaged 14 and was not affected by land use. Surface residue C-to-N ratio was lower under pasture than under conservation-tillage cropping (28 vs. 38, $P < 0.01$).

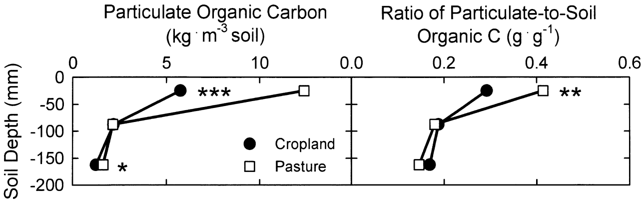

Fig. 1. Depth distribution of particulate organic C and the ratio of particulate-to-soil organic C under 20-year-old tall fescue-common bermudagrass pasture compared with 24-year-old conservation-tillage cropping (significance within a soil depth at $^{*}P \leq 0.1$, $^{**}P \leq 0.01$ and $^{***}P \leq 0.001$).

Depth distribution of particulate organic C was similar to that of total soil organic C with pasture containing greater levels at 0–50 mm and 125–200 mm compared with conservation-tillage cropland (Fig. 1). Particulate organic N was greater under pasture than under conservation-tillage cropland only at a depth of 0–50 mm (data not shown). Similar to surface residue C-to-N ratio, particulate organic C-to-N ratio at a depth of 0–50 mm was lower under pasture than under conservation-tillage cropland (21 vs. 32, $P = 0.01$), but was unaffected by land use at lower depths. Lower surface residue and particulate organic C-to-N ratios, but greater soil organic C under tall fescue-common bermudagrass pasture suggests much greater quantities of organic input that decomposed more rapidly because of higher quality (i.e., lower C-to-N ratio) than conservation-tillage cropland. Ruminant processing of forage and deposition of dung and urine may contribute considerably to this difference in residue quality between these two land management systems.

Ratio of potential C mineralization-to-soil organic C was unaffected by land management, averaging 39, 22 and 10 mg CO_2–C g^{-1} SOC 24 d^{-1} at depths of 0–50, 50–125 and 125–200 mm, respectively. When all data collected in this study were combined, potential C mineralization was highly related to soil organic C ($r = 0.85$, $P < 0.001$, $n = 168$). Soil microbial biomass C to a depth of 200 mm was greater under pasture than under conservation-tillage cropland (124 vs. 97 g m^{-2}, $P = 0.05$).

Although animal traffic can cause localized soil compaction and disturbance of vegetation with heavy grazing pressure (Trimble and Mendel, 1995), our comparison at the end of 20 years of a typical pasture in the Southern Piedmont USA (seeded to tall fescue with gradual invasion of common bermudagrass) with that of conservation-tillage cropland indicates that cattle grazing may compact soil less than machine traffic in conservation-tillage cropping. Lower bulk density was probably the result of more organic C input under pasture, which lessened the effect of animal traffic and led to greater storage of total and particulate organic C and N and soil microbial biomass C. When all data collected in this study were combined, 87% of the variation in soil bulk density could be explained by soil organic C concentration (Fig. 2). By itself, clay content explained only 4% of the variation in bulk density.

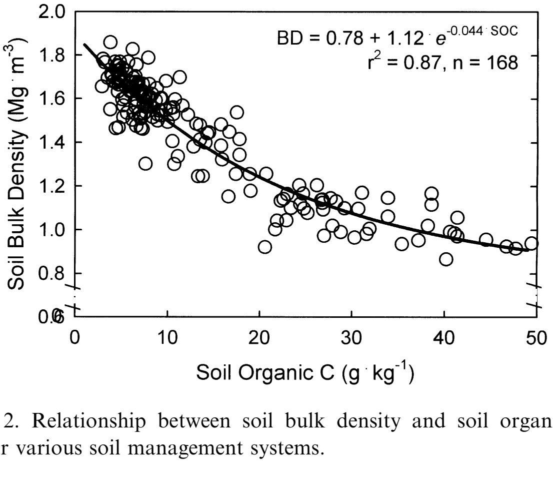

Fig. 2. Relationship between soil bulk density and soil organic C under various soil management systems.

Conversion of conventional-tillage cropland to pasture has been shown to improve SOC in a variety of environments, including Argentina (Studdert et al., 1997), Australia (Robertson et al., 1993; Golchin et al., 1995; Chan, 1997), the Netherlands (Hassink, 1994), New Zealand (Ross et al., 1982; Hart et al., 1988; Fraser et al., 1994), the United Kingdom (Whitehead et al., 1975; McLaren and Swift, 1977) and the USA (Haas et al., 1957; Dodds et al., 1996). Our results also indicate that pastures have the ability to sequester more SOC than conservation-tillage cropland.

3.2. Grazed versus hayed hybrid bermudagrass

Soil bulk density was unaffected by management of hybrid bermudagrass, averaging 1.08, 1.60 and 1.64 Mg m^{-3} at 0–50, 50–125 and 125–200 mm depths, respectively. Any potential negative long-term impacts of animal traffic on soil compaction when grazed were matched equally with machine traffic when hayed.

Soil organic C to a depth of 200 mm averaged 22% greater under grazing than under haying (3800 vs. 3112 g m^{-2}, $P = 0.02$) (Table 1). Surface residue C was also greater under grazing than under haying (178 vs 116 g m^{-2}, $P \leq 0.01$). Soil organic C-to-N ratio was lower under grazing than under haying (13 vs 16, $P \leq 0.001$) at a depth of 0–50 mm, but not different at other depths. Surface residue C-to-N ratio was also lower under grazing than under haying (23 vs. 34, $P \leq 0.001$).

Particulate organic C and N were greater under grazing than under haying at a depth of 0–50 mm only (Fig. 3). Similar to surface residue C-to-N ratio, the particulate organic C-to-N ratio was lower at a depth of 0–50 mm under grazing than under haying. Surface

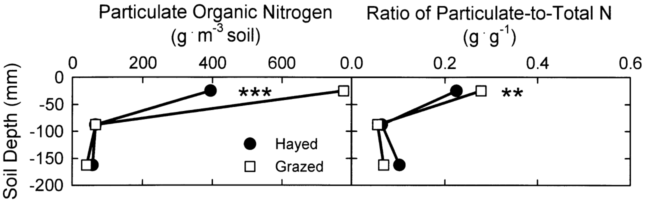

Fig. 3. Depth distribution of particulate organic N and the ratio of particulate organic-to-total N under 15–19-year-old grazed compared with hayed hybrid bermudagrass (significance within a soil depth at $^{*}P \leq 0.1$, $^{**}P \leq 0.01$ and $^{***}P \leq 0.001$).

soil tends to reflect many of the characteristics of the surface residue, which provides a majority of the input.

Ratio of potential C mineralization-to-soil organic C was unaffected by bermudagrass management, averaging 35, 7 and 11 mg CO_2–C g^{-1} SOC 24 d^{-1} at a depth of 0–50, 50–125 and 125–200 mm, respectively. Soil microbial biomass C was greater under grazing than under haying at depths of 0–50 mm (1133 vs 837 g m^{-3}; $P \leq 0.001$) and 125–200 mm (494 vs 405 g m^{-3}; $P = 0.09$), but not different at a depth of 50–125 mm (565 g m^{-3}). To a depth of 200 mm, soil microbial biomass C was 18% greater under grazing than under haying (136 vs. 115 g m^{-2}, $P = 0.01$).

Grazing of pastures in the southeastern USA appears to be beneficial to storage of soil C and N pools by recycling undigested forage in the pasture via excreta. More than two-thirds of ingested nutrients are returned to the pasture as excreta (Till and Kennedy, 1981). Hay harvest removes nutrients and reduces the amount of decomposable substrates added to the soil, which affect soil C and N pools and processes. Surprisingly, relatively little information is available in the literature that documents the effects of cattle grazing on soil C and N pools in the humid regions of the USA. There have been reports showing both positive and negative impacts of grazing compared with unharvested rangeland on soil C and N storage in the semi-arid regions of the USA (Bauer et al., 1987; Frank et al., 1995; Manley et al., 1995). Both positive and negative impacts of grazing compared with haying or unharvested grass on SOC have also been reported in western Canada (Dormaar et al., 1990; Naeth et al., 1991), the Netherlands (Hassink, 1994) and the United Kingdom (Marrs et al., 1989; Bardgett et al., 1997, 1993).

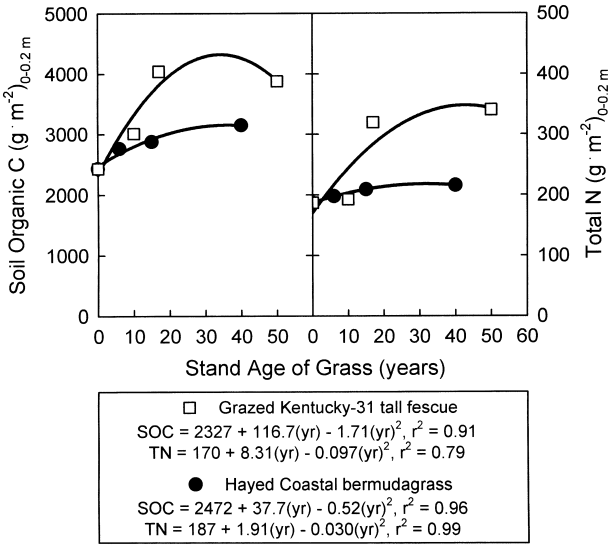

Fig. 4. Soil organic C and total N at a depth of 0–200 mm under grazed tall fescue and hayed bermudagrass as a function of stand age. [Note: Soil organic C and N, although not measured at initiation, were assumed to be 2430 and 187 g m^{-2}, respectively, based on data from tilled cropland on the same soil series (Franzluebbers et al., 1999)].

3.3. Stand age of grazed tall fescue and hayed bermudagrass

Soil organic C and total N to a depth of 200 mm accumulated at greater rates under grazed tall fescue than under hayed hybrid bermudagrass (Fig. 4). Maximum soil organic C and total N contents were achieved under both grass management systems between 30 and 45 yr. Increasing stand age beyond 30 to 45 yr leads to shifts in vegetation composition. For example, the 50-year-old grazed tall fescue pasture was invaded with common bermudagrass and various cool-season annual and short-lived perennial species.

Calculated maximum soil organic C was 37% greater under grazed tall fescue than under hayed hybrid bermudagrass. This difference may have been, at least, partially due to grazing versus haying management as discussed earlier (i.e., an average of 22% under bermudagrass), but also partly due to a plant species effect. It may be that tall fescue offers greater potential to store soil organic C than hybrid bermudagrass, because of differences in plant architecture between grass species, including differences in root distribution. Tall fescue is a cool-season, bunch-type grass with more vertically oriented shoots and roots, whereas bermudagrass is a warm-season, rhizomatous-type grass with more lateral surface-occupying roots. Greater storage of soil organic C and N under tall fescue than bermudagrass does not support the hypothesis that more productive, warm-season (C4) grass leads to greater C input to the soil than less productive, cool-season (C3) grass. Water-use efficiency would generally be lower for C3 compared with C4 plants under the same conditions. However in the Southern Piedmont, winters are generally mild and wet, while summers are often hot and prone to periods of extended drought, which may actually increase water-use efficiency of C3 plants on a yearly basis.

Soil organic C and total N accumulated at an average rate of 100 and 7.3 g m^{-2} yr^{-1} during the first ten years under tall fescue pasture, 48 and 4.4 g m^{-2} yr^{-1} during 10–30 yr following establishment and −20 and 0.6 g m^{-2} yr^{-1} during 30–50 yr following establishment. Corresponding soil organic C and total N accumulation rates under bermudagrass were 33 and 1.6 during 0–10 yr, 17 and 0.7 during 10–30 yr and −4 and −0.5 g m^{-2} yr^{-1} during 30–50 yr, respectively. Total N sequestration in surface soil was likely met through a combination of factors, including historical fertilizer inputs, associative N-fixation, rainfall and plant uptake of deep-profile inorganic N (Giddens et al., 1971).

Particulate organic C and N at a depth of 0–200 mm increased with stand age under both tall fescue and bermudagrass (Table 2). However, particulate organic C-to-N ratio decreased with stand age under both systems (Table 2), mostly due to differences at a depth of 0–50 mm (data not shown). Particulate organic C-to-N ratio increased with soil depth, averaging 20, 36 and 40 under tall fescue and 27, 50 and 53 under bermudagrass at depths of 0–50, 50–125 and 125–200 mm, respectively. Quality of inputs (above- and below-ground) under bermudagrass were lower than under tall fescue based on the particulate organic fraction, which includes semi-decomposed above-ground litter inputs at a depth of 0–50 mm, but mostly root-derived inputs at lower soil depths.

Ratio of soil microbial biomass C-to-soil organic C at a depth of 0–200 mm decreased with time under tall fescue pasture from 43 mg g^{-1} at 10 yr to 38 mg g^{-1} at 17 yr to 35 mg g^{-1} at 50 yr [$\text{LSD}_{(P \leq 0.1)} = 5$]. This ratio also decreased with time under hayed bermudagrass from 46 mg g^{-1} at 6 yr to 39 mg g^{-1} at 15 yr to 36 mg g^{-1} at 40 yr [$\text{LSD}_{(P \leq 0.1)} = 6$]. A decrease in the ratio of soil microbial biomass C-to-soil organic C with time indicates accumulation of resistant organic matter that contributed relatively little as substrate for the microbial biomass pool.

Averaged across grass management systems, soil microbial biomass C decreased with depth from 1052 g m^{-3} at a depth of 0–50 mm to 576 g m^{-3} at a depth of 50–125 mm to 432 g m^{-3} at a depth of 125–200 mm. Ratio of potential C mineralization-to-soil microbial biomass C was 2 to 5 times higher in all grass management systems at a depth of 0–50 mm compared with lower depths (Fig. 5), suggesting more mineralizable C substrates were present at the soil surface than those leading to growth of microbial biomass. More extreme wetting/drying at the soil surface compared with lower depths may limit conversion of mineralizable C into soil microbial biomass. This ratio also decreased with length of time in grass at a depth of 0–50 mm, was relatively unaffected by time in grass at a depth of 50–125 mm and increased with time in grass at a depth of 125–200 mm. This shift in the ratio of potential C mineralization-to-soil microbial biomass C with time and soil depth suggests that less of the potentially mineralizable C substrates in older grass stands accumulated at the soil surface and more at lower soil depths, perhaps due to a shift in root proliferation from the soil surface early in establishment to lower depths in older grass stands. Further work is needed to test this hypothesis.

3.4. Bermudagrass following cropland versus following forestland

Soil organic C at a depth of 0–200 mm under 15- to 19-year-old stands of hybrid bermudagrass was greater when previous land use was forestland than cropland (3692 vs. 2898 g m^{-2}, $P = 0.03$). However, surface residue C was less when previous land use was forestland than cropland (129 vs. 191 g m^{-2}, $P < 0.001$). Total N in these two pools followed a similar pattern, with a total C-to-N ratio of 15 in surface residue + soil at a depth of 0–200 mm under both previous land uses.

Particulate organic C and N were 40 and 47% greater, respectively, when bermudagrass followed forestland than cropland at a depth of 50–125 mm (Fig. 6). To a depth of 200 mm, particulate organic C and N were 126 and 9 g m^{-2} greater following forestland than following cropland, respectively. It may be possible that these differences between previous land uses in total and particulate organic C are due to a portion of the large quantity of forest-floor residue

Table 2
Particulate organic C and N at a depth of 0–200 mm as affected by stand age under grazed 'Kentucky-31' tall fescue and hayed 'Coastal' bermudagrass

Stand age (yr)	Particulate organic fraction		
	C (g m^{-2})	N (g m^{-2})	C-to-N ratio
Grazed 'Kentucky-31' tall fescue			
10	1080	42	26
17	1274	56	23
50	1174	59	20
$\text{LSD}_{(P \leq 0.1)}$	180	11	4
Hayed 'Coastal' bermudagrass			
6	675	20	35
15	746	22	34
40	1012	35	29
$\text{LSD}_{(P \leq 0.1)}$	218	7	5

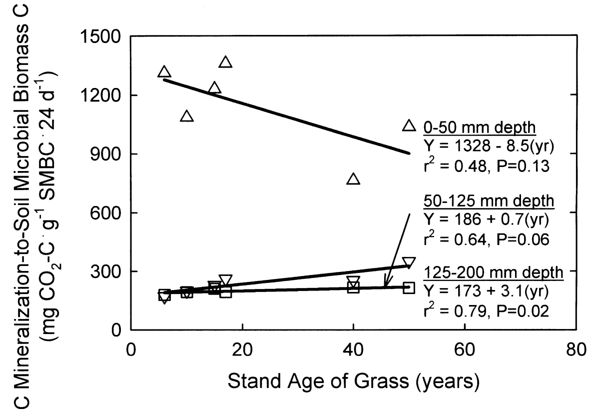

Fig. 5. Potential C mineralization-to-soil microbial biomass C ratio at three soil depths under grazed tall fescue and hayed bermudagrass as a function of stand age.

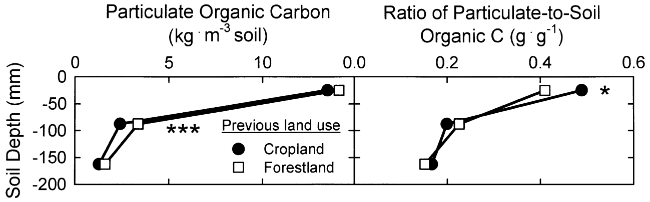

Fig. 6. Depth distribution of particulate organic C and the particulate-to-soil organic C ratio under 15-year-old hayed hybrid bermudagrass as affected by previous land use of forestland or cropland (significance within a soil depth at $^{*}P \leq 0.1$, $^{**}P \leq 0.01$ and $^{***}P \leq 0.001$).

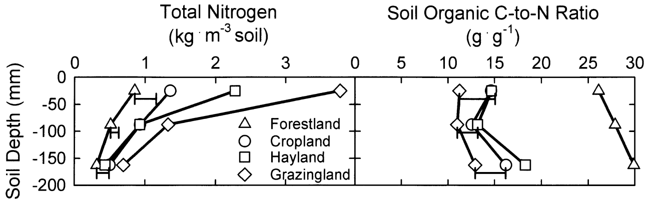

Fig. 8. Depth distribution of total N and the soil organic C-to-total N ratio under 130-year-old forestland, 24-year-old conservation-tillage cropland, 40-year-old bermudagrass hayland and 50-year-old tall fescue grazingland. (LSD bars are $P \leq 0.1$ within a soil depth).

remaining in the soil from forest clearing and land preparation for pasture establishment 15 to 19 yr earlier.

Soil microbial biomass C was greater under bermudagrass following forestland than following cropland only at a depth of 50–125 mm (Fig. 7). To a depth of 200 mm, soil microbial biomass C was not different between previous land uses, averaging 121 g m^{-2}. However, ratio of soil microbial biomass C-to-soil organic C was lower following forestland than following cropland at a depth of 0–50 mm (Fig. 7) and tended to be lower at a depth of 125–200 mm ($P = 0.14$). Although bermudagrass following forestland had more soil organic C than bermudagrass following cropland, the quality of the organic matter following forestland appears to have been poorer, sustaining a lower portion of it as soil microbial biomass.

3.5. *Longest-term land management systems*

Soil organic C and N at a depth of 0–200 mm were greater under grass-based management systems compared with forest or cropland (Table 1). Forestland contained less total N than all other management systems at depths of 0–50 and 50–125 mm (Fig. 8). Long-term grazed tall fescue had greater total N than all other management systems at all depths. When the sum of surface residue and soil organic C was considered, forestland had significantly greater standing stock of C than any other management system. However, since forestland had greater soil organic C-to-N ratio than all other management systems at all depths (Fig. 8), standing stock of residue + soil N under forestland was equivalent to that under cropland, was 18% lower ($P = 0.05$) than under hayland and 47% lower ($P < 0.001$) than under grazingland.

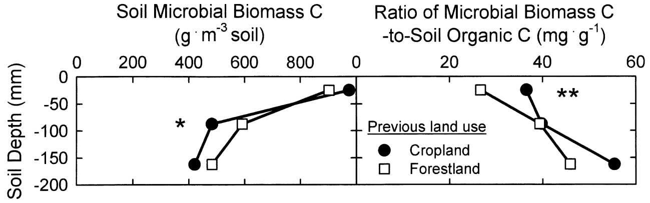

Fig. 7. Depth distribution of soil microbial biomass C and the soil microbial biomass C-to-soil organic C ratio under 15-year-old hayed hybrid bermudagrass as affected by previous land use of forestland or cropland (significance within a soil depth at $^{*}P \leq 0.1$, $^{**}P \leq 0.01$ and $^{***}P \leq 0.001$).

Particulate organic C was greater under grass management systems than under forestland at a depth of 0–50 mm, but was lower at depths of 50–125 and 125–200 mm (Fig. 9). Differences in particulate organic fractions among land management systems are likely a reflection of differences in root distribution. Particulate organic C-to-N ratio in forestland averaged 58, 94 and 76% greater than in other management systems at 0–50, 50–125 and 125–200 mm, respectively. Total and particulate organic C-to-N ratios indicate that available N was limited in this “unmanaged” forest ecosystem compared with the N-rich “managed” grass and crop ecosystems.

Soil microbial biomass C at a depth of 0–200 mm was not different between forestland and grazed tall fescue (138 g m^{-2}), but was greater ($P < 0.01$) in these two systems than in hayed bermudagrass (113 g m^{-2}) and conservation-tillage cropland (97 g m^{-2}).

Our results comparing long-term land management systems in the Southern Piedmont USA are consistent with those found in New Zealand (Haynes and Williams, 1992), where long-term, improved grazed pastures contained greater soil organic C, total N and soil microbial biomass C at a depth of 0–40 mm than a native “wilderness” grassland and arable cropland. In a companion study, it was shown that these differences in organic matter pools among land uses were limited

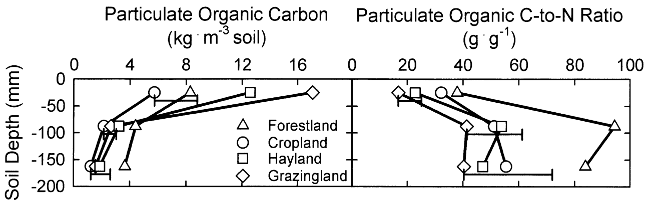

Fig. 9. Depth distribution of particulate organic C and the particulate organic C-to-N ratio under 130-year-old forestland, 24-year-old conservation-tillage cropland, 40-year-old bermudagrass hayland and 50-year-old tall fescue grazingland. (LSD bars are $P \leq 0.1$ within a soil depth).

to the soil surface and were not found at depths of 50–200 mm (Fraser et al., 1994). Ellert and Gregorich (1995) also reported greater soil microbial biomass C in grassland systems than in cropland at two locations in Ontario, but equivalent soil microbial biomass C in grassland and forestland at one site and less soil microbial biomass C in grassland than in forestland at another site.

Our estimates of C storage under forestland are in general agreement with those under a 55-year-old loblolly pine plantation in the South Carolina Piedmont, where soil organic C to a depth of 300 mm was 4000 g m^{-2} and surface residue C (Oi + Oe layers) was 1190 g m^{-2} (van Lear et al., 1995). At the Panola Mountain Research Watershed in the Georgia Piedmont (Huntington, 1995), which did not have Oa or Oe horizons (i.e., a mull soil), soil organic C at a depth of 0–200 mm (4820 g m^{-2}) was nearly identical to the combined soil organic C plus surface residue C that we measured.

4. Conclusions

We conclude that (1) typical tall fescue-common bermudagrass pastures in the Southern Piedmont USA can increase soil organic C and N storage more than conservation-tillage cropland, (2) grazing of pastures with cattle is beneficial to storage of soil organic C and N compared with haying, (3) storage of soil organic C occurs at a rate of ~65 g m^{-2} yr^{-1} during the first 30 years of establishment under grazed tall fescue and at a rate of ~22 g m^{-2} yr^{-1} under hayed bermudagrass, (4) pasture established following clearing of forestland has greater potential soil organic C and N storage than following cropland and (5) in the long-term, grass management systems have nearly equivalent potential to store soil organic C as forestland.

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References

Anderson, J.P.E., 1982. Soil respiration. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties, second ed. Society of Agronomy and Soil Science Society of America, Madison, WI, pp. 837–871.

Bardgett, R.D., Frankland, J.C., Whittaker, J.B., 1993. The effects of agricultural management on the soil biota of some upland grasslands. Agriculture, Ecosystems and Environment 45, 25–45.

Bardgett, R.D., Leemans, D.K., Cook, R., Hobbs, P.J., 1997. Seasonality of the soil biota of grazed and ungrazed hill grasslands. Soil Biology & Biochemistry 29, 1285–1294.

Bauer, A., Cole, C.V., Black, A.L., 1987. Soil property comparisons in virgin grasslands between grazed and nongrazed management systems. Soil Science Society of America Journal 51, 176–182.

Census of Agriculture. 1992. Geographic area series 1B: U.S. summary and county level data. US Department of Commerce, Economic and Statistics Administration, Bureau of the Census.

Chan, K.Y., 1997. Consequences of changes in particulate organic carbon in vertisols under pasture and cropping. Soil Science Society of America Journal 61, 1376–1382.

Dodds, W.K., Banks, M.K., Clenan, C.S., Rice, C.W., Sotomayor, D., Straus, E.A., Yu, W., 1996. Biological properties of soil and subsurface sediments under abandoned pasture and cropland. Soil Biology & Biochemistry 28, 837–846.

Dormaar, J.F., Smoliak, S., Willms, W.D., 1990. Distribution of nitrogen fractions in grazed and ungrazed fescue grasslands in Ah horizons. Journal of Range Management 43, 6–9.

Ellert, B.H., Gregorich, E.G., 1995. Management-induced changes in the actively cycling fractions of soil organic matter. In: McFee, W., Kelly, J.M. (Eds.), Carbon Forms and Functions in Forest Soils. Soil Science Society of America, Madison, WI, pp. 119–138.

Follett, R.F., Stewart, J.W.B., Cole, C.V., 1987. Soil Fertility and Organic Matter as Critical Components of Production Systems. Soil Science Society of America Special Publication 19, Madison, WI.

Frank, A.B., Tanaka, D.L., Hofmann, L., Follett, R.F., 1995. Soil carbon and nitrogen of Northern Great Plains grasslands as influenced by long-term grazing. Journal of Range Management 48, 470–474.

Franzluebbers, A.J., 1999. Potential C and N mineralization and microbial biomass from intact and increasingly disturbed soils of varying texture. Soil Biology & Biochemistry 31, 1083–1090.

Franzluebbers, A.J., Haney, R.L., Hons, F.M., Zuberer, D.A., 1996. Determination of microbial biomass and nitrogen mineralization following rewetting of dried soil. Soil Science Society of America Journal 60, 1133–1139.

Franzluebbers, A.J., Langdale, G.W., Schomberg, H.H., 1999. Soil carbon, nitrogen and aggregation in response to type and frequency of tillage. Soil Science Society of America Journal 63, 349–355.

Fraser, P.M., Haynes, R.J., Williams, P.H., 1994. Effects of pasture improvement and intensive cultivation on microbial biomass, enzyme activities and composition and size of earthworm populations. Biology and Fertility of Soils 17, 185–190.

Gee, G.W., Bauder, J.W., 1986. Particle-size analysis. In: Klute, A. (Ed.), Methods of Soil Analysis, Part 2: Physical and Mineralogical Methods, second ed. American Society of Agronomy and Soil Science Society of America, Madison, WI, pp. 383–411.

Giddens, J., Adams, W.E., Dawson, R.N., 1971. Nitrogen accumulation in fescuegrass sod. Agronomy Journal 63, 451–454.

Golchin, A., Clarke, P., Oades, J.M., Skjemstad, J.O., 1995. The effects of cultivation on the composition of organic matter and structural stability of soils. Australian Journal of Soil Research 33, 975–993.

Gregorich, E.G., Carter, M.R., Angers, D.A., Monreal, C.M., Ellert, B.H., 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Canadian Journal of Soil Science 74, 367–385.

Haas, H.J., Evans, C.E., Miles, E.F., 1957. Nitrogen and carbon changes in Great Plains soils as influenced by cropping and soil treatments. Technical Bulletin 1164, U.S. Department of Agriculture, Washington DC.

Hart, P.B.S., August, J.A., Ross, C.W., 1988. Some biochemical and physical properties of Tokomaru silt loam under pasture and after 10 years of cereal cropping. New Zealand Journal of Agricultural Research 31, 77–86.

Hassink, J., 1994. Effects of soil texture and grassland management on soil organic C and N and rates of C and N mineralization. Soil Biology & Biochemistry 26, 1221–1231.

Haynes, R.J., Williams, P.H., 1992. Accumulation of soil organic matter and the forms, mineralization potential and plant-availability of accumulated organic sulphur: Effects of pasture improvement and intensive cultivation. Soil Biology & Biochemistry 24, 209–217.

Huntington, T.G., 1995. Carbon sequestration in an aggrading forest ecosystem in the southeastern USA. Soil Science Society of America Journal 59, 1459–1467.

Manley, J.T., Schuman, G.E., Reeder, J.D., Hart, R.H., 1995. Rangeland soil carbon and nitrogen responses to grazing. Journal of Soil and Water Conservation 50, 294–298.

Marrs, R.H., Rizand, A., Harrison, A.F., 1989. The effects of removing sheep grazing on soil chemistry, above-ground nutrient distribution and selected aspects of soil fertility in long-term experiments at Moor House National Nature Reserve. Journal of Applied Ecology 26, 647–661.

McLaren, R.G., Swift, R.S., 1977. Changes in soil organic sulphur fractions due to the long-term cultivation of soils. Journal of Soil Science 28, 445–453.

Naeth, M.A., Bailey, A.W., Pluth, D.J., Chanasyk, D.S., Hardin, R.T., 1991. Grazing impacts on litter and soil organic matter in mixed prairie and fescue grassland ecosystems of Alberta. Journal of Range Management 44, 7–12.

Paul, E.A., Paustian, K., Elliott, E.T., Cole, C.V., 1997. Soil Organic Matter in Temperate Agroecosystems: Long-term Experiments in North America. Boca Raton, FL, 414 pp.

Robertson, F.A., Myers, R.J.K., Saffigna, P.G., 1993. Distribution of carbon and nitrogen in a long-term cropping system and permanent pasture system. Australian Journal of Agricultural Research 44, 1323–1336.

Ross, D.J., Tate, K.R., Cairns, A., 1982. Biochemical changes in a yellow-brown loam and a central gley soil converted from pasture to maize in the Waikato area. New Zealand Journal of Agricultural Research 25, 35–42.

SAS Institute Inc., 1990. SAS User's Guide: Statistics, Version 6 Edn. SAS Institute, Cary, NC.

Schnabel, R.R., Franzluebbers, A.J., Stout, W.L., Sanderson, M.A., Stuedemann, J.A., 2000. Pasture management effects on soil carbon sequestration. In: Follett, R.F., Kimble, J.M., Lal, R., Carbon Sequestration Potential of U.S. Grazinglands, CRC Press, Boca Raton, FL (in press).

Studdert, G.A., Echeveria, H.E., Cassanovas, E.M., 1997. Crop-pasture rotation for sustaining the quality and productivity of a Typic Argiudoll. Soil Science Society of America Journal 61, 1466–1472.

Till, A.R., Kennedy, A.P., 1981. The distribution in soil and plant of 35S sulfur isotope from sheep excreta. Australian Journal of Agricultural Research 32, 339–351.

Trimble, S.W., Mendel, A.C., 1995. The cow as a geomorphic agent: a critical review. Geomorphology 13, 233–253.

van Lear, D.H., Kapeluck, P.R., Parker, M.M., 1995. Distribution of carbon in a Piedmont soil as affected by loblolly pine management. In: McFee, W., Kelly, J.M. (Eds.), Carbon Forms and Functions in Forest Soils. Soil Science Society of America, Madison, WI, pp. 489–501.

Voroney, R.P., Paul, E.A., 1984. Determination of k_C and k_N in situ for calibration of the chloroform fumigation-incubation method. Soil Biology & Biochemistry 16, 9–14.

Whitehead, D.C., Buchan, H., Hartley, R.D., 1975. Components of soil organic matter under grass and arable cropping. Soil Biology & Biochemistry 7, 65–71.