Surface Soil Changes during Twelve Years of Pasture Management in the Southern Piedmont USA

Alan J. Franzluebbers*
John A. Stuedemann
USDA-ARS
1420 Experiment Station Road
Watkinsville GA 30677

Surface soil characteristics are of key importance in assessing the sustainability of agricultural management systems. We evaluated the factorial combination of nutrient source (inorganic, mixed organic + inorganic, and organic as broiler litter) and forage utilization (unharvested, low and high cattle grazing pressure, and hayed) on soil organic matter during 12 yr of pasture management on a Typic Kanhapludult in Georgia. Nutrient source had very little effect on bulk density, soil organic C (SOC), and total soil N (TSN). Forage utilization greatly affected all soil properties, more so nearest the surface. For example, SOC at a depth of 0 to 3 cm under low grazing pressure was 47.6 g kg^{-1} and under haying was 28.8 g kg^{-1} ($P < 0.001$), while at 3 to 6 cm it was 20.1 and 14.9 g kg^{-1}, respectively ($P = 0.04$), and at 6 to 12 cm it was 12.7 and 11.0 g kg^{-1}, respectively ($P = 0.59$). Soil bulk density was inversely related to SOC. Total SOC (0–20 cm) plus surface residue C was 3.6 ± 3.6 Mg C ha^{-1} greater (mean ± standard deviation among six nutrient source × forage utilization comparisons) in the zone nearest shade and water sources than farther away. Sequestration of TSN in the surface 6 cm averaged 8 ± 8 kg N ha^{-1} yr^{-1} (mean ± standard deviation among three nutrient source comparisons) when hayed, 31 ± 15 kg N ha^{-1} yr^{-1} when left unharvested, and 74 ± 5 kg N ha^{-1} yr^{-1} when grazed by cattle with either low or high grazing pressure. These results indicate the large potential of well-managed grazing systems to improve the quality and functioning of soils in the southeastern United States.

Abbreviations: BD, bulk density; SOC, soil organic carbon; TSN, total soil nitrogen.

Changes in surface-soil bulk density (BD) and organic C and N contents are of particular importance in determining ecosystem functioning in management systems with frequent traffic and plant removal. As well, sequestration of SOC and conservation of N are of keen scientific and political interests for developing management strategies to help mitigate the emission of greenhouse gases (i.e., CO_2 and N_2O) and combat climate change (Follett et al., 2001; Lal, 2004). Total soil N is often closely associated with SOC and plays a key role in building soil fertility and enhancing soil productivity.

In the warm-humid region of the southeastern United States (Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia), pastures are recognized as an important land use (12.4 Mha or 32% of the total farmland [National Agricultural Statistics Service, 2010]), capable of storing a large quantity of SOC and TSN relative to other agricultural land uses (Franzluebbers, 2010). Only limited data are available, however, that describe how pasture management can influence the medium-term dynamics of SOC and TSN. Establishment of switchgrass (*Panicum virgatum* L.) for bioenergy production resulted in a SOC sequestration rate to a depth of 30 cm ranging from 0.5 Mg C ha^{-1} yr^{-1} during 10 yr in Alabama (Ma et al., 2000) to 2.9 Mg C ha^{-1} yr^{-1} during 5 yr at five locations in eastern Texas (Sanderson et al., 1999).

Soil Sci. Soc. Am. J. 74:2131–2141
Published online 14 Sept. 2010
doi:10.2136/sssaj2010.0034
Received 21 Jan. 2010.
*Corresponding author (alan.franzluebbers@ars.usda.gov).

Sequestration of SOC with pasture establishment has been increasingly estimated in recent years with land surveys (Potter et al., 1999; Franzluebbers et al., 2000b; Akala and Lal, 2001; Conant et al., 2004; Causarano et al., 2008). Such estimates are useful for determining coarse-resolution effects, since uniformity of initial conditions must be assumed (e.g., site history, soil texture, topography, etc.), as well as uniformity of management among selected fields (because fields are often owned by different landowners). Detailed pasture experiments with sufficient replication of a diversity of management systems conducted during a number of years to determine SOC and TSN sequestration are acutely lacking from North American literature. In a replicated 4-yr experiment in Manitoba, a trend for greater SOC and TSN was observed with fertilizer rather than without fertilizer and spatial redistribution effects on soil inorganic N were detected (Chen et al., 2001). In a replicated experiment in Georgia, SOC and TSN were greater with higher fertilization rate and with higher endophyte infection of tall fescue (*Lolium arundinaceum* [Schreb.] Darbysh.) at the end of 8 and 15 yr (Franzluebbers et al., 1999) and at the end of 20 yr (Franzluebbers and Stuedemann, 2005b). During the first 4 yr of a bermudagrass experiment in Georgia, SOC and TSN sequestration were greater when grazed than when ungrazed (Franzluebbers et al., 2001; Franzluebbers and Stuedemann, 2001). Deep soil-profile sampling of the experiment described here was conducted at 0, 5, and 12 yr and indicated significant sequestration of SOC only in the surface 15 cm (Franzluebbers and Stuedemann, 2009). More frequent sampling of shallower soil depth increments can reduce variation and allow detection of smaller changes in SOC (Franzluebbers and Stuedemann, 2005a).

We hypothesized that detailed sampling throughout at least a decade of management would be needed to obtain high-quality estimates of changes in surface soil organic matter under a variety of pasture management systems. Therefore, our objectives were to: (i) ascertain the effects of nutrient source, forage utilization, and their interactions on BD, SOC, TSN, and surface residue C and N contents during the latter course of a 12-yr pasture experiment, (ii) determine the rates of change in SOC and TSN in the surface 6 cm during 12 yr of evaluation (which was the deepest depth sampled from initiation to Year 4), and (iii) quantify the spatial distribution of BD, SOC, TSN, and surface residue C and N contents caused by cattle behavior within pastures managed with low and high grazing pressures.

MATERIALS AND METHODS

Site Characteristics

A 15-ha upland field (33°22′ N, 83°24′ W) in the Greenbrier Creek subwatershed of the Oconee River watershed near Farmington, GA, had previously been conventionally cultivated with various row crops for several decades before grassland establishment by sprigging of 'Coastal' bermudagrass [*Cynodon dactylon* (L.) Pers.] in 1991. From 1994 to the end of summer in 1998, bermudagrass was the dominant forage (Franzluebbers et al., 2004). 'Georgia 5' tall fescue was drilled (∼25 kg pure live seed ha^{-1}) directly into existing bermudagrass sod during November 1998, 1999, and 2000. Dry winter conditions prevented adequate establishment in 1998 and 1999 and created the need for repeated sowing. The long-term mean annual temperature is 16.5°C, rainfall is 1250 mm, and potential pan evaporation is 1560 mm. Dominant soils at the site are Madison, Cecil, and Pacolet sandy loam (fine, kaolinitic, thermic Typic Kanhapludults).

Experimental Design

The experimental design was a randomized, complete block with treatments in a split-plot arrangement in each of three blocks, which were delineated by landscape features (i.e., slight, moderate, and severe erosion classes). The main plots were nutrient source (n = 3) and split plots were forage utilization (n = 4) for a total of 36 experimental units. Grazed paddocks were 0.69 ± 0.03 ha. The spatial design of the paddocks minimized runoff contamination and facilitated handling of cattle (*Bos taurus*) through a central roadway. Each paddock contained a 3- by 4-m shade, a mineral feeder, and a water trough placed in a line 15 m long at the highest elevation. Unharvested and hayed exclosures (100 m^2) were randomly placed side by side in paired low- and high-grazing-pressure paddocks of each nutrient source.

Nutrient-source treatments were (i) inorganic only, (ii) organic + inorganic mixture, and (iii) organic only. From 1994 to 1998, nutrient source treatments were (i) inorganic fertilizer as NH_4NO_3 broadcast in May and July, (ii) crimson clover (*Trifolium incarnatum* L.) cover crop + inorganic fertilizer (half of N assumed fixed and released by the clover cover crop during spring and the other half as NH_4NO_3 broadcast in July), and (iii) chicken (*Gallus gallus*) broiler litter broadcast in May and July. Nutrient-source treatments were modified after the first 5 yr of management. Fertilizer application was targeted to supply 200 kg N ha^{-1} yr^{-1} during the first 5 yr and targeted to supply 270 kg N ha^{-1} yr^{-1} during the next 7 yr (for application details, see Franzluebbers and Stuedemann, 2005a, 2009). From 1999 to the end of summer 2005, the three nutrient source treatments were (i) inorganic fertilizer as NH_4NO_3 broadcast in three applications in February to April, May to July, and September to November, (ii) a single application of broiler litter broadcast in February to April and supplemented with inorganic fertilizer as NH_4NO_3 broadcast in May to July and September to November, and (iii) multiple application of broiler litter broadcast three times in February to April, May to July, and September to November.

The forage utilization regimes consisted of (i) unharvested biomass (cut and left in place at the end of growing season during Years 1–5 and left unmanaged during Years 6–12, except for an occasional woody plant removal), (ii) low grazing pressure targeted to maintain 3.0 Mg ha^{-1} of forage, (iii) high grazing pressure targeted to maintain 1.5 Mg ha^{-1} of forage, and (iv) hayed monthly to remove aboveground biomass at 5-cm height. Yearling Angus steers grazed paddocks during a 140-d period from mid-May until early October during Years 1 to 5 (mean body weight of 212 kg and mean stocking density of 5.8 and 8.7 steers ha^{-1} in low- and high-grazing-pressure treatments, respectively). Grazing was extended into spring (March–May) and autumn (mid-October–early January) during Years 6 to 12 with the presence of tall fescue. Grazing did not typically occur from mid-January to mid-March.

Sampling and Analyses

Soil (0–2-, 2–4-, and 4–6-cm depths) and surface residue were sampled in Years 1 to 4, and organic C and N results were reported in Franzluebbers et al. (2001). Soil and surface residue were sampled in January to February 1999, February to March 2000, January 2001, January 2002, and January to February 2006. Surface residue was collected from a composite of eight 0.04-m^2 areas randomly selected within each of three zones within grazed paddocks (i.e., 0–30-, 30–70-, and 70–100-m distances from livestock shades) and from one zone in each exclosure. Following removal of vegetation at a height of ~4 cm, surface residue, including plant stubble, was cut to the mineral surface with battery-powered hand shears, bagged, and dried at 55°C for several days. A single 4-cm-diam. soil core was collected from each of the eight residue sampling sites and composited. Soil was collected at depths of 0 to 3, 3 to 6, 6 to 12, and 12 to 20 cm, oven dried (55°C for 72 h), and gently crushed to pass a 4.75-mm screen.

Soil BD was calculated from the oven-dried soil weight and pooled-core volume (302, 302, 603, and 804 cm^3 from depths of 0–3, 3–6, 6–12, and 12–20 cm, respectively). Surface residue was ground to <1 mm and a 20- to 30-g soil subsample from each composite sample was ground to a fine powder in a ball mill for 3 min before analysis of total C and N by dry combustion. The soil pH was near 6 so total C was assumed to be organic C.

Several levels of statistical analysis were available due to repeated samplings in space (vertical and horizontal) and time. Because the surface soil during Years 1 to 4 was only to a depth of 6 cm, regression analysis of changes in soil C and N during 12 yr was only for a depth of 0 to 6 cm. To assess nutrient source and forage utilization effects, data from zonal samples within an experimental unit were averaged and not considered a source of variation using the general linear models procedure (SAS Institute, 2003). The effects of nutrient source and forage utilization were analyzed for SOC and N concentrations in each individual soil depth and for cumulative stocks of SOC and N across various depth increments. Stocks were calculated as the product of concentration, BD, and soil depth. Analysis of variance with zonal samples was conducted separately as a repeated measure within a paddock, and means were separated with two orthogonal contrasts (i.e., shade vs. mid + far zones and mid vs. far zones).

Within-depth, across-depth, within-year, and across-year analyses were conducted according to the split-plot design with three blocks. Across-depth and across-year analyses resulted in better mean values but did not change the statistical structure focused on fixed effects (3 nutrient sources × 4 forage utilization regimes) and random effects (three replications). Effects were considered significant at $P \leq 0.05$.

RESULTS AND DISCUSSION

Environmental Conditions

Precipitation during this 12-yr study was variable (Fig. 1). The mean yearly precipitation of 1280 mm for the 12 yr was very close to the long-term mean yearly precipitation of 1250 mm for the area. On average, seasonal accumulations were also close to normal. There were several periods, however, in which precipitation was outside 75 to 125% of normal precipitation. Winter precipitation (January–March) had the lowest relative variation and was greater than normal in Years 3 and 5 but below normal in Years 7 and 11. Spring precipitation (April–June) was greater than normal in Years 2, 10, and 12 but below normal in Years 7 and 9. Summer precipitation (July–September) was greater than normal in Years 1, 4, 10, and 11 but below normal only in Year 5. Autumn precipitation (October–December) had the highest relative variation and was greater than normal in Years 2, 4, and 9 but below normal in Years 3, 5, 6, 8, and 10. These variations in precipitation certainly affected plant production (Franzluebbers et al., 2004) and may have affected soil properties, as described below.

Soil Bulk Density

Soil BD averaged across treatments and years was 1.01, 1.45, 1.54, and 1.55 Mg m^{-3} at depths of 0 to 3, 3 to 6, 6 to 12, and 12 to 20 cm. Nutrient source did not affect BD at any depth. Very strong effects of forage utilization were evident on BD, particularly in the surface 6 cm of the soil, and the effects were strong enough to affect cumulative BD at a depth of 0 to 20 cm (Table 1). At a depth of 0 to 3 cm, soil BD was lower when pastures were grazed (0.99 Mg m^{-3}) than when ungrazed (1.07 Mg m^{-3}). At a depth of 3 to 6 cm, however, the soil BD was greater when pastures were grazed (1.46 Mg m^{-3}) than when ungrazed (1.42 Mg m^{-3}). This interaction between grazing and depth of sampling was consistent with that reported during the first 4 yr of this study (Franzluebbers et al., 2001) and was explainable based on greater surface accumulation of organic matter that mitigated compaction at the surface but that compressed the soil immediately below the zone of organic matter accumulation. No difference occurred between forage utilization systems at a depth of 6 to 12 cm, but BD was lower when pastures were grazed (1.54 Mg m^{-3}) than ungrazed (1.58 Mg m^{-3}) at a depth

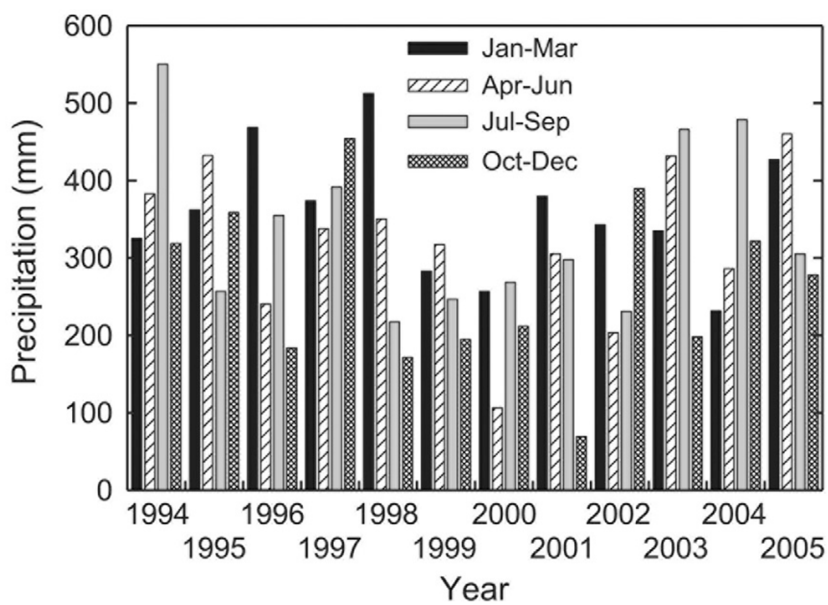

Fig. 1. Seasonal precipitation during the 12 years of pasture management.

Table 1. Soil bulk density at various depth increments as affected by fertilization, forage utilization, sampling zone, and their interactions averaged across nutrient sources (inorganic, organic + inorganic, and organic) and five sampling dates (end of 5, 6, 7, 8, and 12 yr of management).

Forage utilization and zone		Bulk density						
		Incremental depth, cm				Cumulative depth, cm		
		0–3	3–6	6–12	12–20	0–6	0–12	0–20
		——— Mg m^{-3} ———				—— Mg ha^{-1} ——		
Unharvested		1.00	1.39	1.52	1.56	1.20	1.36	1.44
Low grazing pressure, shade		0.94	1.41	1.54	1.55	1.18	1.36	1.44
Low grazing pressure, mid		0.97	1.44	1.54	1.54	1.21	1.37	1.44
Low grazing pressure, far		0.99	1.45	1.55	1.54	1.22	1.39	1.45
High grazing pressure, shade		0.95	1.46	1.52	1.51	1.20	1.36	1.42
High grazing pressure, mid		1.03	1.51	1.56	1.54	1.27	1.41	1.46
High grazing pressure, far		1.05	1.51	1.57	1.56	1.28	1.43	1.48
Hayed		1.14	1.45	1.54	1.59	1.30	1.42	1.49
LSD (P = 0.05)		0.06	0.04	0.03	0.04	0.04	0.03	0.03
Source of variation†	df				Pr > F			
Nutrient source	2,4	0.50	0.10	0.96	0.72	0.63	0.84	0.96
FUZ1	1,42	<0.001	<0.001	0.12	0.004	0.10	0.83	0.08
FUZ2	1,42	<0.001	0.005	0.31	0.18	<0.001	<0.001	0.006
FUZ3	1,42	0.01	<0.001	0.80	0.55	<0.001	0.006	0.18
FUZ4	1,42	<0.001	0.002	0.04	0.32	<0.001	<0.001	0.007
FUZ5	1,42	0.31	0.57	0.34	0.65	0.32	0.25	0.36
FUZ6	1,42	0.13	0.54	0.06	0.10	0.18	0.06	0.05
FUZ7	1,42	0.85	0.79	0.94	0.36	0.99	0.97	0.60
Nutrient source × FUZ	14,42	0.85	0.22	0.29	0.88	0.41	0.23	0.47
Year	4,192	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Year × nutrient source × FUZ	92,192	0.005	0.52	0.21	0.25	0.05	0.07	0.14

† Forage utilization zone: FUZ1, grazed vs. ungrazed; FUZ2, unharvested vs. hayed; FUZ3, low vs. high grazing pressure; FUZ4, shade vs. others; FUZ5, mid vs. far; FUZ6, shade vs. others × low vs. high grazing pressure; FUZ7, mid vs. far × low vs. high grazing pressure.

of 12 to 20 cm. Taken to a cumulative depth of 20 cm, BD was lower in grazed pastures (1.45 Mg m^{-3}) than when hayed (1.48 Mg m^{-3}), suggesting overall that animal traffic had little negative influence on compaction of the "plow layer" of the soil.

Soil BD was significantly greater when pastures were hayed than when left unharvested at depths of 0 to 3 cm (1.14 vs. 1.00 Mg m^{-3}) and 3 to 6 cm (1.45 vs. 1.39 Mg m^{-3}), as well as cumulatively to depths of 0 to 6 cm (1.30 vs. 1.20 Mg m^{-3}), 0 to 12 cm (1.42 vs. 1.36 Mg m^{-3}), and 0 to 20 cm (1.49 vs. 1.44 Mg m^{-3}). Soil BD was also significantly greater with high grazing pressure than with low grazing pressure at depths of 0 to 3 cm (1.01 vs. 0.97 Mg m^{-3}), 3 to 6 cm (1.49 vs. 1.43 Mg m^{-3}), 0 to 6 cm (1.25 vs. 1.20 Mg m^{-3}), and 0 to 12 cm (1.40 vs. 1.37 Mg m^{-3}). Lastly, BD was lower nearest shade and water sources compared with other zones in grazed paddocks at depths of 0 to 3 cm (0.95 vs. 1.01 Mg m^{-3}), 3 to 6 cm (1.44 vs. 1.48 Mg m^{-3}), and 6 to 12 cm (1.53 vs. 1.56 Mg m^{-3}), and the effect was stronger with high grazing pressure than with low grazing pressure at a depth of 0 to 20 cm.

Low surface BD at 0 to 3 cm was expected, based on results from earlier in this experiment, as well as other previous pasture experiments in the region (Franzluebbers et al., 2000a, 2001; Franzluebbers and Stuedemann, 2008). A strong inverse relationship occurred between BD and SOC (Fig. 2). Therefore, the major reason for low BD at the soil surface was due to a large accumulation of soil organic matter. Similarly strong inverse relationships between BD and soil organic matter have been reported for different soil types around the world (Manrique and Jones, 1991; Kätterer et al., 2006; Benites et al., 2007). Such studies have often found soil organic matter to be the most dominating influence on BD, but soil texture also has had some influence. The soils in our study varied somewhat (75% sandy loam, 12% sandy clay loam, 8% loamy sand, and 4% loam [Franzluebbers et al., 2001]), but the range of texture was narrow in a global context. Coarse-textured soils tend to have greater BD than fine-textured soils.

Greater BD in our study with high than with low grazing pressure and grazed compared with unharvested management was consistent with previous studies. Although the high grazing pressure in our study could not be considered overgrazed, grazing pressure results were similar in magnitude and effect to the results from two different soils (clay and sandy loam) in Finland, where a poached part of pastures had greater BD than the nominally grazed portion of the pastures (Pietola et al., 2005). Increasing the stocking rate on a silty clay soil in Texas also resulted in increasing BD at a depth of 0 to 5 cm (Warren et al., 1986). In a review of grazing effects on soil BD, Greenwood and McKenzie (2001) summarized the difference between grazed and ungrazed treatments as 0.12 ± 0.12 Mg m^{-3} (n = 46).

Soil Organic Carbon and Nitrogen with Time

Soil organic C at a depth of 0 to 6 cm increased nonlinearly with time (Fig. 3). The rate of SOC sequestration during the 12-yr period was not different among nutrient source treatments and averaged 0.39 Mg C ha^{-1} yr^{-1}. From Years 5 to 8, there was a downward trend in SOC content that we believe could be attributed to the dry conditions in 1999, 2000, and 2001, which may have shifted the balance between soil organic matter decomposition and C input from plant growth. The 12 seasons during this

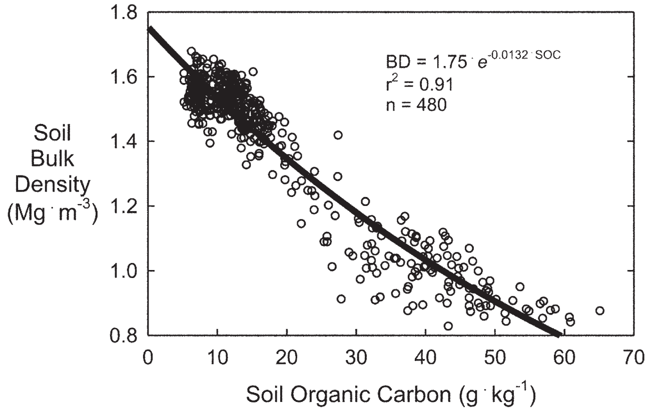

Fig. 2. Relationship of soil bulk density (BD) to soil organic C. Values are means from three replicate samples of 8 forage utilization zones (low and high grazing pressure × shade, mid, and far zones) × 3 nutrient sources (inorganic, organic + inorganic, and organic) × 4 depths (0–3, 3–6, 6–12, and 12–20 cm) × 5 yr (1999, 2000, 2001, 2002, and 2006).

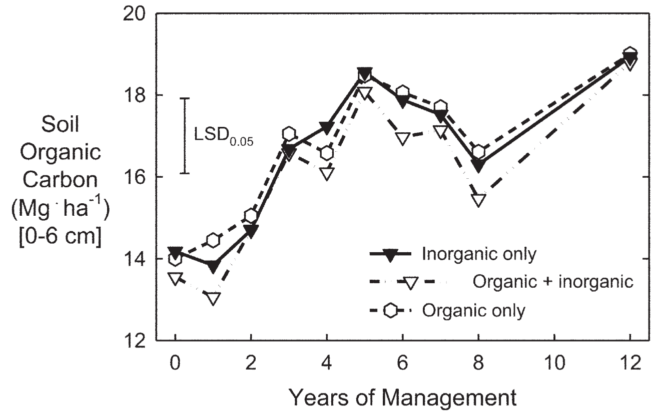

Fig. 3. Soil organic C content at a depth of 0 to 6 cm as affected by nutrient source and years of management (LSD is among all nutrient source × year combinations).

3-yr period had 77 ± 25% of normal precipitation (Fig. 1). There was also a management change from bermudagrass only to bermudagrass + tall fescue beginning in 1999 and continuing to the end of the study; however, the temporary decline in SOC soon after the initiation of this management change did not appear to be linked to this management change because the SOC content reached its highest value at the end of 12 yr of management. Despite the brief decline during the middle of this study, the fit of nonlinear equations to the actual data was still reasonable, ranging from r^2 = 0.71 to 0.81. The decline in SOC coinciding with the period of low precipitation in our study could be supported by similar observations of drought-induced declines in SOC from a northern, mixed-grass prairie in Wyoming (Derner and Schuman, 2007).

Contrary to the lack of response to nutrient source, SOC accumulation at a depth of 0 to 6 cm was highly affected by forage utilization regime (Fig. 4). The rate of SOC sequestration during the 0- to 12-yr period was 0.32 Mg C ha^{-1} yr^{-1} (r^2 = 0.67) when unharvested, 0.62 Mg C ha^{-1} yr^{-1} (r^2 = 0.85) with low grazing pressure, 0.59 Mg C ha^{-1} yr^{-1} (r^2 = 0.86) with high grazing pressure, and 0.07 Mg C ha^{-1} yr^{-1} (r^2 = 0.08) when hayed (when calculated as the difference in values at initiation and the end of 12 yr from a nonlinear regression equation). These average rates of SOC sequestration were modified slightly by interactive trends with nutrient source treatments at various depth increments at the end of 12 yr (Table 2) and as derived from linear regression slopes across years (Table 3), most notably the greater rate of SOC sequestration when unharvested with organic nutrient source (0.43 Mg C ha^{-1} yr^{-1}) than with other nutrient sources (0.08–0.18 Mg C ha^{-1} yr^{-1}). Sequestration of TSN was affected by treatments in a similar manner as sequestration of SOC (Table 3). Temporal responses at a depth of 0 to 6 cm illustrated the superiority of grazed compared with ungrazed management systems in sequestering SOC and TSN, as well as unharvested compared with hayed management. An exception occurred with the mixed nutrient source (i.e., organic + inorganic), in which SOC and TSN sequestration rates were not different between unharvested and hayed management.

Rates of SOC and TSN sequestration during the 12-yr period were considerably lower than those reported previously for the first 4 yr (Franzluebbers et al., 2001; Franzluebbers and Stuedemann, 2001). The dry period during the middle of the study, therefore, appeared to have negatively affected overall rates of sequestration. To help understand the impact of significant and repeated drought periods from the second half of Year 5 to the first half of Year 9, we derived regression slopes for data in three periods: Years 0 to 5 (Period 1), Years 5 to 8 (Period 2), and Years 8 to 12 (Period 3). The mean rate of change in SOC followed the order of Period 1 (0.94 Mg C ha^{-1} yr^{-1}) > Period 3 (0.70 Mg C ha^{-1} yr^{-1}) > Period 2 (−0.69 Mg C ha^{-1} yr^{-1}). The mean rate of change in TSN followed the order of Period 1 (104 kg N ha^{-1} yr^{-1}) > Period 3 (−1 kg N ha^{-1} yr^{-1}) > Period 2 (−53 kg N ha^{-1} yr^{-1}). Rates of SOC and TSN sequestration during Period 3 were lower than during Period 1, but at least for SOC sequestration were significantly positive and still much higher than during the drought in Period 2. Mean yearly precipitation was 1409 mm in Period 1, 1047 mm in Period 2, and 1288 mm in Period 3.

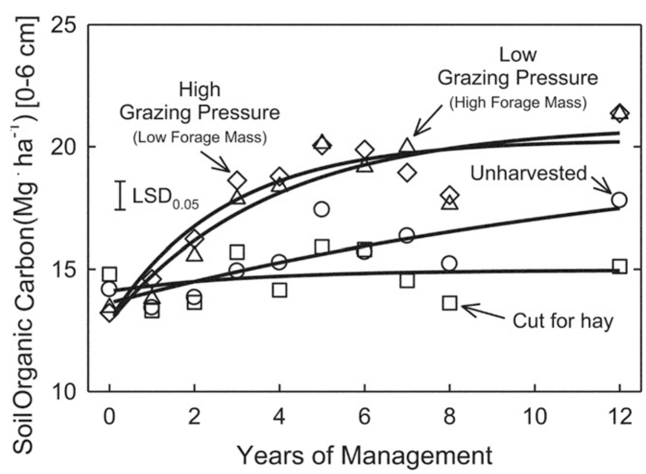

Fig. 4. Soil organic C content at a depth of 0 to 6 cm as affected by forage utilization regime and years of management (LSD is among all forage utilization × year combinations).

Table 2. Soil organic C (SOC) concentration and stock at various depth increments as affected by nutrient source, forage utilization, and their interactions at the end of 12 yr of management.

Forage utilization	Nutrient source	Incremental SOC conc.				Cumulative SOC stock				
		0–3 cm	3–6 cm	6–12 cm	12–20 cm	0–6 cm	0–12 cm	0–20 cm	Residue	Total
		g kg^{-1}				Mg ha^{-1}				
Unharvested	inorganic	32.3	14.8	10.7	5.8	16.6	26.5	33.6	4.6	38.2
Low grazing pressure	inorganic	48.3	18.2	12.0	7.0	21.6	32.7	41.2	2.6	43.7
High grazing pressure	inorganic	56.3	16.2	10.9	7.5	22.2	31.9	40.7	1.6	42.3
Hayed	inorganic	31.5	13.9	10.5	6.1	15.3	24.6	32.0	1.5	33.5
Unharvested	organic + inorganic	34.2	18.0	10.9	7.6	17.3	27.0	36.1	4.6	40.6
Low grazing pressure	organic + inorganic	49.9	20.8	12.7	8.1	21.3	33.0	42.4	2.8	45.3
High grazing pressure	organic + inorganic	48.8	16.8	11.7	6.8	21.5	32.2	40.2	1.8	42.1
Hayed	organic + inorganic	29.0	14.9	10.9	7.6	15.1	24.9	34.1	2.2	36.3
Unharvested	organic	33.0	22.2	15.5	8.4	19.5	33.4	43.6	2.9	46.5
Low grazing pressure	organic	44.6	21.3	13.4	8.8	21.1	33.3	43.8	2.0	45.8
High grazing pressure	organic	45.5	18.8	11.5	6.8	20.4	30.9	38.9	1.6	40.5
Hayed	organic	25.9	16.0	11.5	5.2	15.0	25.4	32.1	2.0	34.1
LSD (P = 0.05)		12.7	4.8	3.2	3.4	2.7	3.9	6.7	1.8	7.3
Source of variation†	df					Pr > F				
NS1	1,4	0.18	0.11	0.50	0.50	0.96	0.58	0.53	0.82	0.53
NS2	1,4	0.23	0.28	0.50	0.88	0.81	0.52	0.70	0.10	0.85
FU1	1,18	<0.001	0.01	0.51	0.20	<0.001	<0.001	<0.001	0.004	<0.001
FU2	1,18	0.23	0.02	0.13	0.29	0.002	0.001	0.01	<0.001	0.002
FU3	1,18	0.21	0.001	0.02	0.09	0.97	0.04	0.03	0.01	0.01
NS1 × FU1	1,18	0.40	0.46	0.48	0.47	0.10	0.13	0.17	0.91	0.22
NS1 × FU2	1,18	0.48	0.20	0.35	0.36	0.19	0.18	0.20	0.19	0.39
NS1 × FU3	1,18	0.08	0.46	0.77	0.07	0.40	0.55	0.19	0.62	0.28
NS2 × FU1	1,18	0.67	0.44	0.07	0.41	0.11	0.02	0.31	0.62	0.41
NS2 × FU2	1,18	0.82	0.36	0.08	0.18	0.21	0.04	0.05	0.23	0.12
NS2 × FU3	1,18	0.68	0.46	0.46	0.56	0.40	0.32	0.32	0.40	0.48

† Nutrient source: NS1, inorganic vs. others; NS2, organic + inorganic vs. organic only. Forage utilization: FU1, grazed vs. ungrazed; FU2, unharvested vs. hayed; FU3, low vs. high grazing pressure.

Evidence for the accumulation of SOC and TSN with pasture age is abundant from many chronosequence reports around the world. In Western Australia with 960 mm of precipitation, SOC and TSN sequestration were estimated at 0.44 Mg C ha^{-1} yr^{-1} and 38 kg N ha^{-1} yr^{-1}, respectively, from 11 *Trifolium subterraneum* L. pastures up to 40 yr of age (Barrow, 1969). In Rondônia, Brazil, with >2000 mm of precipitation and 25°C temperature, five pasture chronosequences established after forest clearing resulted in mean SOC and TSN sequestration rates of 0.17 Mg C ha^{-1} yr^{-1} and 12 kg N ha^{-1} yr^{-1}, respectively (Neill et al., 1997). In Texas with 860 mm of precipitation and 19°C temperature, SOC sequestration was estimated at 0.45 Mg C ha^{-1} yr^{-1} in a tall-grass prairie chronosequence (Potter et al., 1999). In Georgia with 1250 mm of precipitation and 16.5°C temperature, SOC and TSN sequestration rates during a 30-yr period from a chronosequence of hayed bermudagrass were 0.21 Mg C ha^{-1} yr^{-1} and 9 kg N ha^{-1} yr^{-1}, respectively, while from grazed tall fescue were 0.51 Mg C ha^{-1} yr^{-1} and 47 kg N ha^{-1} yr^{-1}, respectively (Franzluebbers et al., 2000b). In Ohio with 1020 mm of precipitation and 11°C temperature, SOC sequestration to a depth of 30 cm from a pasture chronosequence on reclaimed mine soils was 3.0 Mg C ha^{-1} yr^{-1} (Akala and Lal, 2001).

The SOC and TSN results obtained during the 5- to 12-yr period of this pasture management study complemented and were consistent on a relative treatment basis with the results reported during the 0- to 4-yr period (Franzluebbers et al., 2001; Franzluebbers and Stuedemann, 2001). Furthermore, the stock of SOC to a depth of 30 cm was 10.1 to 10.4 Mg ha^{-1} greater with light or heavy stocking rates at the end of 12 yr of grazing on a northern mixed-grass prairie in Wyoming than the long-term previously managed condition of prairie without grazing and without fire for >40 yr (Schuman et al., 1999). The stock of TSN was 1.24 Mg ha^{-1} greater with a light stocking rate and was 0.53 Mg ha^{-1} greater with a heaving stocking rate than the ungrazed exclosure. At the end of 56 yr of grazing of a short-grass prairie in Colorado, SOC to a depth of 30 cm was 5 Mg ha^{-1} greater with a heavy stocking rate than an ungrazed exclosure, but there was no difference in SOC between the light stocking rate and the ungrazed exclosure (Reeder and Schuman, 2002). Derner et al. (1997) reported that SOC and TSN in the surface 5 cm of soil beneath plants were lower with grazing than under ungrazed exclosures (but had no effect at 5–15- and 15–30-cm depths) in both tall-grass and mid-grass prairies in Kansas; however, SOC and TSN were greater in the surface 15 cm of soil beneath grazed compared with ungrazed plants in a short-grass prairie in Colorado. In *Bromus* pastures in Alberta, Canada, SOC was not affected by grazing intensity treatments during a 3-yr period (Mapfumo et al., 2000). In Oklahoma, SOC declined with increasing stocking rate on a loam soil but increased slightly with increasing stocking rate on a silt loam soil (Potter et al., 2001). This body of literature suggests that several plant- or environment-specific effects on SOC and TSN sequestration can be expected. Our results of greater SOC and TSN sequestration with grazing are an example from introduced forages in a wet environment compared with the drier native prairies of the western United States.

Soil Organic Carbon and Nitrogen Depth Distribution

At the end of 12 yr, SOC was highly stratified with depth under all management systems, averaging 39.9 ± 10.0 g kg^{-1} at 0- to 3-cm depth, 17.7 ± 2.7 g kg^{-1} at 3- to 6-cm depth, 11.9 ± 1.4 g kg^{-1} at 6- to 12-cm depth, and 7.1 ± 1.1 g kg^{-1} at 12- to 20-cm depth (Table 2). Nutrient source did not have a significant effect on SOC at any depth. At a depth of 0 to 3 cm, SOC was significantly greater in grazed treatments (48.9 ± 4.2 g kg^{-1}) than in ungrazed treatments (31.0 ± 3.0 g kg^{-1}). At a depth of 3 to 6 cm, the largest effect on SOC was between grazing pressure treatments, in which high grazing pressure had a 14% lower concentration than with low grazing pressure. Other significant effects at this depth were greater SOC in grazed treatments (18.7 ± 2.1 g kg^{-1}) than in ungrazed treatments (16.6 ± 3.1 g kg^{-1}) and 19% lower SOC with haying than with unharvested management. At the 6- to 12- and 12- to 20-cm depths, SOC was also 10 ± 10% lower under high than under low grazing pressure. There were no significant differences among forage utilization regimes at a depth of 12 to 20 cm. Summed to a depth of 0 to 20 cm, SOC was significantly greater in grazed treatments (41.2 ± 1.7 Mg ha^{-1}) than in ungrazed treatments (35.3 ± 4.4 Mg ha^{-1}). Soil organic C was also greater when unharvested (37.8 ± 5.2 Mg ha^{-1}) than when hayed (32.7 ± 1.2 Mg ha^{-1}) and greater under low grazing pressure (42.5 ± 1.3 Mg ha^{-1}) than under high grazing pressure (39.9 ± 0.9 Mg ha^{-1}).

The lack of difference in SOC and TSN between organic and inorganic nutrient sources at any of the sampling depths was a bit surprising considering the broiler litter input of 2.44 ± 0.60 Mg C ha^{-1} yr^{-1} with organic and 0.62 ± 0.56 Mg C ha^{-1} yr^{-1} with organic + inorganic fertilization (Franzluebbers and Stuedemann, 2009); however, the results were consistent with those found at deeper soil depths in this same study (Franzluebbers and Stuedemann, 2009) and suggest that decomposition of broiler litter C is rapid and not readily transformed into stable soil organic matter. At the end of 12 yr, the stock of SOC plus surface residue C averaged 41.7 Mg C ha^{-1} with organic fertilization and 39.4 Mg C ha^{-1} with inorganic fertilization (Table 2). Although not significant, the calculated rate of SOC sequestration with broiler litter would have been 0.21 ± 0.43 Mg C ha^{-1} yr^{-1} among the four forage utilization regimes. This average rate of SOC accumulation would have been near the LSD value of 0.17 Mg C ha^{-1} yr^{-1} among nutrient sources and forage utilization rates for SOC at a depth of 0 to 6 cm (Table 3) and would have translated into 9% retention of the C applied in broiler litter, certainly well within the range of 7 ± 5% reported for studies in thermic regions and 23 ± 15% reported for studies in temperate or frigid regions (Franzluebbers and Doraiswamy, 2007). The difference in SOC between broiler litter and inorganic fertilization at the end of 12 yr with unharvested management was, in fact, statistically significant at the 0- to 6-, 0- to 12-, and 0- to 20-cm depths (Table 2). A few other studies in the southeastern United States have documented greater SOC with broiler litter fertilization of pastures than without, including 5.8 Mg C ha^{-1} on tall fescue pastures in Alabama (Kingery et al., 1994) and 5.7 Mg C ha^{-1} on bermudagrass hayfields in Oklahoma (Sharpley et al., 1993).

Table 3. Sequestration rate of soil organic C and total soil N at a depth of 0 to 6 cm during 12 yr of pasture management, derived as a linear rate among 12 management systems with a common intercept. Regression fit of the model was 58% with 11% coefficient of variation for soil organic C, and 60% with 16% coefficient of variation for total soil N sequestration.

Forage utilization	Nutrient source	Soil organic C sequestration	Total soil N sequestration
		Mg C ha^{-1} yr^{1}	kg N ha^{-1} yr^{1}
Unharvested	inorganic	0.18	34
Low grazing pressure	inorganic	0.70	75
High grazing pressure	inorganic	0.72	79
Hayed	inorganic	0.07	13
Unharvested	organic + inorganic	0.08	14
Low grazing pressure	organic + inorganic	0.67	73
High grazing pressure	organic + inorganic	0.64	74
Hayed	organic + inorganic	−0.01	−2
Unharvested	organic	0.43	44
Low grazing pressure	organic	0.60	64
High grazing pressure	organic	0.66	76
Hayed	organic	0.05	12
LSD (P = 0.05)		0.17	19

When averaged across years (the end of 5, 6, 7, 8, and 12 yr), TSN concentration was also highly stratified with depth, averaging 3.42 ± 0.95 g kg^{-1} at 0- to 3-cm depth, 1.04 ± 0.26 g kg^{-1} at 3- to 6-cm depth, 0.70 ± 0.15 g kg^{-1} at 6- to 12-cm depth, and 0.33 ± 0.06 g kg^{-1} at 12- to 20-cm depth (Table 4). Similar to that of SOC, TSN was highly affected by whether forage was grazed or not and between unharvested and hayed management at all soil depths. The concentration of TSN was not different between low and high grazing pressures at cumulative soil depths to 6, 12, or 20 cm but was significantly greater with low grazing pressure (1.18 ± 0.16 g kg^{-1}) than with high grazing pressure (1.04 ± 0.20 g kg^{-1}) at a depth of 3 to 6 cm.

Management effects on SOC and TSN were most dominant nearest the soil surface and declined with depth. The variation in TSN concentration among 24 treatment means (i.e., treatment variation) declined from 22% at a depth of 0 to 3 cm to 19% at 3 to 6 cm, to 15% at 6 to 12 cm, and to 12% at 12 to 20 cm (Table 4). In contrast, the percentage of mean TSN concentration represented by the LSD (i.e., random error variation) increased from 21% at 0 to 3 cm to 22% at 3 to 6 cm, to 29% at 6 to 12 cm, and to 33% at 12 to 20 cm. These results suggest that in medium-term evaluations such as this study, investigation of the near-surface effects with conservation management approaches will probably be the most discerning, although whole-profile estimation of changes is certainly needed to put these near-surface effects into proper context (Franzluebbers and Stuedemann, 2009). In Conservation Reserve Program lands in Indiana, SOC concentration was greater in 5- to 8-yr-old warm-season native grass plantations than neighboring cropland at a depth of 0 to 15 cm (four of 10 sites) and at a depth of 15 to 30 cm (four of nine sites) but was not different between land uses at 30 to 60 and 60 to 100 cm (Omonode and Vyn, 2006). Total soil N concentration was sensitive to land use change in two of 10 sites at the 0- to 15-cm depth and only in one site at the 15- to 30- and 30- to 60-cm depths.

Soil Organic Carbon and Nitrogen Pasture Distribution

Total soil N concentration was significantly redistributed within grazed paddocks, in which the shade zone had greater concentration than the mid and far zones at all soil depths except 12 to 20 cm (Table 4). There was also a significant interaction of this effect with the nutrient source at a depth of 0 to 3 cm, in which the shade zone contained 4.4 ± 0.2 g kg^{-1} with any of the nutrient sources, while the mid and far zones contained 4.0 ± 0.1 g kg^{-1} with inorganic fertilizer and 3.4 ± 0.2 g kg^{-1} with organic + inorganic and organic-only sources. At a cumulative depth of 0 to 20 cm, TSN was 2.7 ± 0.1 Mg ha^{-1} in all zones with inorganic fertilizer, while it was 3.1 ± 0.1 Mg ha^{-1} in the shade zone and 2.5 ± 0.1 Mg ha^{-1} in the mid and far zones with organic + inorganic and organic-only sources. Therefore, redistribution of TSN was relatively weak with inorganic fertilizer (i.e., 4% greater N content near shade than farther away at a depth of 0–6 cm) and much greater with organic + inorganic and organic-only sources (i.e., 23%).

Redistribution of SOC also occurred in most soil depths within grazed paddocks (Fig. 5). The effect was largest nearest the soil surface and declined with depth. At a cumulative depth of 0 to 20 cm, SOC was greater near the shade than at the far position only with low grazing pressure and was greater near the shade than at both mid and far positions with high grazing pressure. In New Zealand pastures grazed with sheep, SOC and various microbial activities were also greater in camp than in non-camp areas at depths of 0 to 5 and 5 to 10 cm but not below 10 cm (Haynes and Williams, 1999). In a bermudagrass pasture in North Carolina, cattle camping areas contained greater SOC and TSN, as well as microbial biomass and mineralizable components, than non-camping pasture areas, but consistently only at a depth of 0 to 5 cm and not at 5 to 15 cm (Iyyemperumal et al., 2007). In Florida, soil areas near shade had greater inorganic N than farther away as a consequence of more frequent cattle urination, and areas near mineral feeders and shades had greater total P (Sigua and Coleman, 2006).

Surface Residue Carbon and Nitrogen

Surface residue C content at the end of 12 yr of management was affected only by forage utilization and not by nutrient source (Table 2). Surface residue C at the end of 12 yr (Table 2) and averaged across years (the end of 5, 6, 7, 8, and 12 yr; Fig. 5) was greater under unharvested management than all other treatments. This result was reasonable because aboveground forage was not harvested but simply cut and left in place to decompose. Management of forage with a put-and-take animal stocking strategy also dictated that aboveground forage with low grazing pressure would always be greater at the end of the growing season than with high grazing pressure, a consequence that naturally led to greater surface residue C with low than with high grazing pressure. Surface residue C content illustrated the strong negative relationship between protective soil cover and the extent of forage utilization by grazing or haying.

Surface residue N content averaged across the 5- to 12-yr period was also mainly affected by forage utilization similar to that of surface residue C, except that the unharvested treatment did not have greater residue N content than the low grazing pressure treatment (Table 4). The mature forage with unharvested management was of poorer quality, similar to that reported during the first 5 yr (Franzluebbers et al., 2004). The C/N ratio of surface residue measured at the end of 0, 1, 2, 3, 4, 5, 6, 7, 8, and 12 yr of management was 22.9 ± 6.4 when unharvested, 21.0 ± 3.6 with low grazing pressure, 18.9 ± 2.3 with high grazing pressure, and 22.1 ± 2.1 with haying.

Surface residue C and N contents were also greater nearest shade and water sources in grazed paddocks than farther away, although the relative effect was not nearly as large as the spatially induced changes in SOC and TSN contents (Fig. 5; Table 4). Greater residue C and N contents near shade and water sources were probably a consequence of greater animal loafing in this region, which would have fouled forage and reduced its consumption by animals, as well as greater deposition of feces in this area (West et al., 1989; Franzluebbers et al., 2000a).

SUMMARY AND CONCLUSIONS

With 12 yr of pasture management on a previously eroded landscape in the Southern Piedmont region, surface-soil properties had achieved a relatively stable condition that could be considered of higher quality. Whether nutrient source was inorganic, organic with broiler litter, or a combination of the two strategies made relatively little difference on the temporal evolution of bulk density, soil organic C, total soil N, or surface residue C and N contents. The important fact was that nutrients were supplied to meet the demand by forage and subsequent animal intake.

Contrary to nutrient source, how forage was utilized had an enormous impact on the temporal development of soil properties. When forage was hayed continuously, surface residue was low, soil bulk density was high, and soil organic C and N remained relatively unchanged. When forage was grazed by cattle, surface residue was low to moderate, soil bulk density was low to moderate, and soil organic C and N were sequestered

Table 4. Total soil N concentration and stock at various depth increments as affected by nutrient source, forage utilization, sampling zone, and their interactions averaged across five sampling dates (end of 5, 6, 7, 8, and 12 yr of management).

Forage utilization and position	Nutrient source	Incremental N conc.				Cumulative N stock				
		0–3 cm	3–6 cm	6–12 cm	12–20 cm	0–6 cm	0–12 cm	0–20 cm	Residue	Total
		g kg^{-1}				Mg ha^{-1}				
Unharvested	inorganic	3.14	0.96	0.70	0.33	1.30	1.94	2.35	0.19	2.54
Low grazing pressure, shade	inorganic	4.28	1.16	0.74	0.36	1.67	2.37	2.81	0.15	2.97
Low grazing pressure, mid	inorganic	4.01	1.09	0.76	0.34	1.62	2.33	2.75	0.13	2.88
Low grazing pressure, far	inorganic	3.94	1.02	0.75	0.35	1.60	2.29	2.72	0.17	2.89
High grazing pressure, shade	inorganic	4.49	0.95	0.72	0.29	1.67	2.33	2.68	0.11	2.79
High grazing pressure, mid	inorganic	4.02	0.94	0.66	0.35	1.61	2.22	2.64	0.11	2.75
High grazing pressure, far	inorganic	3.95	0.93	0.66	0.32	1.58	2.18	2.57	0.11	2.68
Hayed	inorganic	2.22	0.87	0.64	0.27	1.13	1.71	2.05	0.08	2.13
Unharvested	organic + inorganic	2.51	0.94	0.58	0.31	1.13	1.68	2.06	0.17	2.23
Low grazing pressure, shade	organic + inorganic	4.51	1.33	0.87	0.38	1.80	2.60	3.06	0.13	3.19
Low grazing pressure, mid	organic + inorganic	3.74	1.21	0.85	0.38	1.57	2.35	2.79	0.13	2.92
Low grazing pressure, far	organic + inorganic	3.37	1.19	0.69	0.37	1.47	2.10	2.54	0.11	2.66
High grazing pressure, shade	organic + inorganic	4.46	1.32	0.93	0.43	1.82	2.65	3.16	0.11	3.27
High grazing pressure, mid	organic + inorganic	3.55	0.93	0.63	0.31	1.56	2.15	2.53	0.07	2.61
High grazing pressure, far	organic + inorganic	3.27	0.86	0.62	0.30	1.45	2.05	2.42	0.09	2.51
Hayed	organic + inorganic	1.96	0.75	0.53	0.27	1.01	1.50	1.83	0.07	1.90
Unharvested	organic	2.92	1.32	0.91	0.35	1.39	2.20	2.64	0.12	2.76
Low grazing pressure, shade	organic	4.08	1.50	0.87	0.40	1.77	2.55	3.03	0.12	3.16
Low grazing pressure, mid	organic	3.05	1.19	0.70	0.36	1.41	2.06	2.50	0.08	2.58
Low grazing pressure, far	organic	3.51	0.95	0.66	0.33	1.43	2.05	2.45	0.09	2.54
High grazing pressure, shade	organic	4.81	1.45	0.84	0.34	1.91	2.67	3.07	0.11	3.18
High grazing pressure, mid	organic	3.55	1.02	0.71	0.30	1.52	2.18	2.54	0.06	2.61
High grazing pressure, far	organic	3.36	0.99	0.66	0.33	1.48	2.10	2.52	0.11	2.63
Hayed	organic	2.18	0.91	0.67	0.27	1.12	1.74	2.08	0.08	2.16
LSD (P = 0.05)		0.71	0.23	0.20	0.11	0.18	0.30	0.37	0.05	0.37
Source of variation†	df					Pr > F				
NS1	1,4	0.19	0.27	0.72	0.72	0.59	0.94	0.97	0.06	0.89
NS2	1,4	0.97	0.42	0.65	0.84	0.72	0.66	0.77	0.31	0.83
FUZ1	1,42	<0.001	<0.001	0.04	0.009	<0.001	<0.001	<0.001	0.32	<0.001
FUZ2	1,42	<0.001	<0.001	0.04	0.04	<0.001	0.002	0.001	<0.001	<0.001
FUZ3	1,42	0.35	<0.001	0.13	0.09	0.33	0.71	0.36	0.001	0.17
FUZ4	1,42	<0.001	<0.001	<0.001	0.14	<0.001	<0.001	<0.001	0.05	<0.001
FUZ5	1,42	0.54	0.11	0.24	0.85	0.23	0.17	0.24	0.09	0.34
FUZ6	1,42	0.26	0.33	0.25	0.86	0.55	0.39	0.51	0.81	0.45
FUZ7	1,42	0.52	0.48	0.52	0.83	0.76	0.84	0.78	0.73	0.79
NS1 × FUZ1	1,42	0.82	0.32	0.62	0.68	0.66	0.59	0.59	0.78	0.61
NS1 × FUZ2	1,42	0.51	0.12	0.49	0.97	0.84	0.62	0.68	0.16	0.83
NS1 × FUZ3	1,42	0.85	0.83	0.64	0.98	0.37	0.36	0.41	0.16	0.31
NS1 × FUZ4	1,42	0.02	<0.001	0.04	0.08	<0.001	0.001	0.002	0.24	0.001
NS1 × FUZ5	1,42	0.92	0.61	0.52	0.87	0.72	0.59	0.73	0.65	0.68
NS1 × FUZ6	1,42	0.81	0.16	0.93	0.19	0.79	0.89	0.60	0.99	0.60
NS1 × FUZ7	1,42	0.64	0.92	0.74	0.45	0.84	0.89	0.70	0.12	0.56
NS2 × FUZ1	1,42	0.16	0.02	0.002	0.35	0.006	0.001	0.003	0.54	0.003
NS2 × FUZ2	1,42	0.70	0.16	0.21	0.58	0.25	0.18	0.21	0.12	0.29
NS2 × FUZ3	1,42	0.11	0.11	0.37	0.82	0.15	0.18	0.33	0.21	0.26
NS2 × FUZ4	1,42	0.81	0.11	0.70	0.47	0.27	0.68	0.91	0.73	0.88
NS2 × FUZ5	1,42	0.20	0.42	0.63	0.80	0.30	0.37	0.43	0.28	0.35
NS2 × FUZ6	1,42	0.46	0.16	0.17	0.10	0.83	0.60	0.33	0.37	0.28
NS2 × FUZ7	1,42	0.29	0.26	0.38	0.54	0.75	0.48	0.75	0.93	0.76
Year	4192	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Year × NS × FUZ	92,192	0.61	0.23	0.77	0.55	0.13	0.17	0.25	0.43	0.32

† Nutrient source: NS1, inorganic vs. others; NS2, organic vs. organic + inorganic. Forage utilization zone: FUZ1, grazed vs. ungrazed; FUZ2, unharvested vs. hayed; FUZ3, low vs. high grazing pressure; FUZ4, shade vs. others; FUZ5, mid vs. far; FUZ6, shade vs. others × low vs. high grazing pressure; FUZ7, mid vs. far × low vs. high grazing pressure.

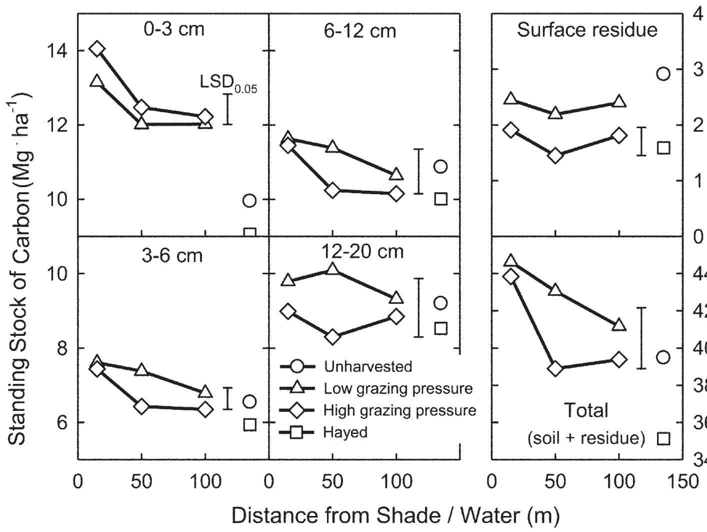

Fig. 5. Soil organic C content in different depth increments and surface residue C as affected by forage utilization regime and distance from shade and water (in grazed treatments). Estimates were derived from mean values across five sampling dates (the end of 5, 6, 7, 8, and 12 yr of management).

at high rates. We tested two grazing pressures and found that surface residue C and N contents declined, soil bulk density increased slightly, and soil organic C and N sequestration rates remained unchanged with high grazing pressure compared with low grazing pressure. When forage was unharvested (similar to a Conservation Reserve Program management scheme), surface residue was highest, soil bulk density was low (similar to low grazing pressure), and soil organic C and N sequestration rates were intermediate between haying and grazing. Soil organic C sequestration at a depth of 0 to 6 cm (linear regression across 12 yr) followed the order: haying (0.04 ± 0.04 Mg C ha^{-1} yr^{-1}) < unharvested (0.23 ± 0.18 Mg C ha^{-1} yr^{-1}) < low grazing pressure (0.65 ± 0.05 Mg C ha^{-1} yr^{-1}) = high grazing pressure (0.67 ± 0.04 Mg C ha^{-1} yr^{-1}). Rates were lower than reported earlier in this study due to a drought period that caused a temporary decline in soil organic C. Although broiler litter added significant organic C throughout the course of this study (2.4 ± 0.6 Mg C ha^{-1} yr^{-1}), its decomposition was high, resulting in statistically undetectable changes in soil organic C. Cattle grazing of mixed bermudagrass–tall fescue pastures can be considered a viable strategy to rehabilitate degraded cropland in the southeastern United States. Our data negate the perspective that only non-utilization of land will be the best strategy for rehabilitating degraded land.

ACKNOWLEDGMENTS

We appreciate the excellent technical support from Steve Knapp, Dwight Seman, and co-workers throughout the years (David Lovell, Robert Sheats, Fred Hale, Eric Elsner, Robert Martin, Devin Berry, Heather Hart, and Kim Lyness). This report is part of GRACEnet cross-location research (Greenhouse gas Reduction through Agricultural Carbon Enhancement network).

REFERENCES

Akala, V.A., and R. Lal. 2001. Soil organic carbon pools and sequestration rates in reclaimed minesoils in Ohio. J. Environ. Qual. 30:2098–2104.

Barrow, N.J. 1969. The accumulation of soil organic matter under pasture and its effect on soil properties. Aust. J. Exp. Agric. Anim. Husb. 9:437–444.

Benites, V.M., P.O.O.A. Machado, E.C.C. Fidalgo, M.R. Coelho, and B.E. Madari. 2007. Pedotransfer functions for estimating soil bulk density from existing soil survey reports in Brazil. Geoderma 139:90–97.

Causarano, H.J., A.J. Franzluebbers, J.N. Shaw, D.W. Reeves, R.L. Raper, and C.W. Wood. 2008. Soil organic carbon fractions and aggregation in the Southern Piedmont and Coastal Plain. Soil Sci. Soc. Am. J. 72:221–230.

Chen, W., W.P. McCaughey, C.A. Grant, and L.D. Bailey. 2001. Pasture type and fertilization effects on soil chemical properties and nutrient redistribution. Can. J. Soil Sci. 81:395–404.

Conant, R.T., J. Six, and K. Paustian. 2004. Land use effects on soil carbon fractions in the southeastern United States: II. Changes in soil carbon fractions along a forest to pasture chronosequence. Biol. Fertil. Soils 40:194–200.

Derner, J.D., D.D. Briske, and T.W. Boutton. 1997. Does grazing mediate soil carbon and nitrogen accumulation beneath C4 perennial grasses along an environmental gradient? Plant Soil 191:147–156.

Derner, J.D., and G.E. Schuman. 2007. Carbon sequestration and rangelands: A synthesis of land management and precipitation effects. J. Soil Water Conserv. 62:77–85.

Follett, R.F., J.M. Kimble, and R. Lal (ed.). 2001. The potential of U.S. grazing lands to sequester carbon and mitigate the greenhouse effect. Lewis Publ., Boca Raton, FL.

Franzluebbers, A.J. 2010. Achieving soil organic carbon sequestration with conservation agricultural systems in the southeastern United States. Soil Sci. Soc. Am. J. 74:347–357.

Franzluebbers, A.J., and P.C. Doraiswamy. 2007. Carbon sequestration and land degradation. p. 339–354. *In* M.V.K. Sivakumar and N. Ndiangu'ui (ed.) Climate and land degradation. Springer-Verlag, New York.

Franzluebbers, A.J., N. Nazih, J.A. Stuedemann, J.J. Fuhrmann, H.H. Schomberg, and P.G. Hartel. 1999. Soil carbon and nitrogen pools under low- and high-endophyte-infected tall fescue. Soil Sci. Soc. Am. J. 63:1687–1694.

Franzluebbers, A.J., and J.A. Stuedemann. 2001. Bermudagrass management in the Southern Piedmont U.S.: IV. Soil-surface nitrogen pools. Sci. World 1(S2):673–681.

Franzluebbers, A.J., and J.A. Stuedemann. 2005a. Bermudagrass management in the Southern Piedmont USA: VII. Soil-profile organic carbon and total nitrogen. Soil Sci. Soc. Am. J. 69:1455–1462.

Franzluebbers, A.J., and J.A. Stuedemann. 2005b. Soil carbon and nitrogen pools in response to tall fescue endophyte infection, fertilization, and cultivar. Soil Sci. Soc. Am. J. 69:396–403.

Franzluebbers, A.J., and J.A. Stuedemann. 2008. Early response of soil organic fractions to tillage and integrated crop–livestock production. Soil Sci. Soc. Am. J. 72:613–625.

Franzluebbers, A.J., and J.A. Stuedemann. 2009. Soil-profile organic carbon and total nitrogen during 12 years of pasture management in the Southern Piedmont USA. Agric. Ecosyst. Environ. 129:28–36.

Franzluebbers, A.J., J.A. Stuedemann, and H.H. Schomberg. 2000a. Spatial distribution of soil carbon and nitrogen pools under grazed tall fescue. Soil Sci. Soc. Am. J. 64:635–639.

Franzluebbers, A.J., J.A. Stuedemann, H.H. Schomberg, and S.R. Wilkinson. 2000b. Soil organic C and N pools under long-term pasture management in the Southern Piedmont USA. Soil Biol. Biochem. 32:469–478.

Franzluebbers, A.J., J.A. Stuedemann, and S.R. Wilkinson. 2001. Bermudagrass management in the Southern Piedmont USA: I. Soil and surface residue carbon and sulfur. Soil Sci. Soc. Am. J. 65:834–841.

Franzluebbers, A.J., S.R. Wilkinson, and J.A. Stuedemann. 2004. Bermudagrass management in the Southern Piedmont USA: X. Coastal productivity and persistence in response to fertilization and defoliation regimes. Agron. J. 96:1400–1411.

Greenwood, K.L., and B.M. McKenzie. 2001. Grazing effects on soil physical properties and the consequences for pastures: A review. Aust. J. Exp. Agric. 41:1231–1250.

Haynes, R.J., and P.H. Williams. 1999. Influence of stock camping behaviour on the soil microbiological and biochemical properties of grazed pastoral soils. Biol. Fertil. Soils 28:253–258.

Iyyemperumal, K., D.W. Israel, and W. Shi. 2007. Soil microbial biomass, activity and potential nitrogen mineralization in a pasture: Impact of stock

camping activity. Soil Biol. Biochem. 39:149–157.
Kätterer, T., O. Andrén, and P.-E. Jansson. 2006. Pedotransfer functions for estimating plant available water and bulk density in Swedish agricultural soils. Acta Agric. Scand. B 56:263–276.
Kingery, W.L., C.W. Wood, D.P. Delaney, J.C. Williams, and G.L. Mullins. 1994. Impact of long-term land application of broiler litter on environmentally related soil properties. J. Environ. Qual. 23:139–147.
Lal, R. 2004. Soil carbon sequestration to mitigate climate change. Geoderma 123:1–22.
Ma, Z., C.W. Wood, and D.I. Bransby. 2000. Soil management impacts on soil carbon sequestration by switchgrass. Biomass Bioenergy 18:469–477.
Manrique, L.A., and C.A. Jones. 1991. Bulk density of soils in relation to soil physical and chemical properties. Soil Sci. Soc. Am. J. 55:476–481.
Mapfumo, E., D.S. Chanasyk, V.S. Baron, and M.A. Naeth. 2000. Grazing impacts on selected soil parameters under short-term forage sequences. J. Range Manage. 53:466–470.
National Agricultural Statistics Service. 2010. 2007 Census of agriculture. Vol. 1: U.S. summary and state reports. Available at www.agcensus.usda.gov/Publications/2007/Full_Report/index.asp (verified 25 Aug. 2010). NASS, Washington, DC.
Neill, C., J.M. Melillo, P.A. Steudler, C.C. Cerri, J.F.L. de Moraes, M.C. Piccolo, and M. Brito. 1997. Soil carbon and nitrogen stocks following forest clearing for pasture in the southwestern Brazilian Amazon. Ecol. Appl. 7:1216–1225.
Omonode, R.A., and T.J. Vyn. 2006. Vertical distribution of soil organic carbon and nitrogen under warm-season native grasses relative to croplands in west-central Indiana, USA. Agric. Ecosyst. Environ. 117:159–170.
Pietola, L., R. Horn, and M. Yli-Halla. 2005. Effects of trampling by cattle on the hydraulic and mechanical properties of soil. Soil Tillage Res. 82:99–108.
Potter, K.N., J.A. Daniel, W. Altom, and H.A. Torbert. 2001. Stocking rate effect on soil carbon and nitrogen in degraded soils. J. Soil Water Conserv. 56:233–236.
Potter, K.N., H.A. Torbert, H.B. Johnson, and C.R. Tischler. 1999. Carbon storage after long-term grass establishment on degraded soils. Soil Sci. 164:718–725.
Reeder, J.D., and G.E. Schuman. 2002. Influence of livestock grazing on C sequestration in semi-arid mixed grass and short-grass rangelands. Environ. Pollut. 116:457–463.
Sanderson, M.A., R.L. Reed, W.R. Ocumpaugh, M.A. Hussey, G. van Esbroeck, J.C. Read, C.R. Tischler, and F.M. Hons. 1999. Switchgrass cultivars and germplasm for biomass feedstock production in Texas. Bioresour. Technol. 67:209–219.
SAS Institute. 2003. SAS for Windows. Release 9.1. SAS Inst., Cary, NC.
Schuman, G.E., J.D. Reeder, J.T. Manley, R.H. Hart, and W.A. Manley. 1999. Impact of grazing management on the carbon and nitrogen balance of a mixed grass rangeland. Ecol. Appl. 9:65–71.
Sharpley, A.N., S.J. Smith, and W.R. Bain. 1993. Nitrogen and phosphorus fate from long-term poultry litter applications to Oklahoma soils. Soil Sci. Soc. Am. J. 57:1131–1137.
Sigua, G.C., and S.W. Coleman. 2006. Sustainable management of nutrients in forage-based pasture soils: Effect of animal congregation sites. J. Soils Sediments 6:249–253.
Warren, S.D., M.B. Nevill, W.H. Blackburn, and N.E. Garza. 1986. Soil response to trampling under intensive rotation grazing. Soil Sci. Soc. Am. J. 50:1336–1341.
West, C.P., A.P. Mallarino, W.F. Wedin, and D.B. Marx. 1989. Soil potassium distribution in grazed K-31 tall fescue pastures as affected by fertilization and endophytic fungus infection level. Agron. J. 81:508–512.