RESEARCH SECTION

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Soil carbon and bulk density distribution within 10 Southern Piedmont grazing systems

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Abstract: Sufficient and consistent distribution of carbon (C) across pastures can influence and improve production and sustainability in pasture-based grazing systems. The objective of this research was to determine spatial distribution of bulk density, soil C measured as loss-on-ignition (LOI) C, and permanganate oxidizable C (POXC), in continuously stocked Southern Piedmont pastures as affected by landscape position and management to enable producers to make better informed management decisions. Soil samples were collected from three depths (0 to 5, 5 to 10, and 10 to 20 cm), on a 50 m grid (matrix) and within areas of interest (AOIs, where cattle tended to frequent) from 10 pastures (ranging from 9.2 to 21.8 ha) fertilized with only mineral fertilizer. Mean soil bulk density was greatest ($\mu = 1.62$ g cm^{-3}) in the 5 to 10 cm soil layer. Median soil LOI and POXC were greatest in the 0 to 5 cm soil layer (medians = 6.16 g kg^{-1} and 776 mg kg^{-1}, respectively), and both were strongly correlated to soil organic C. Soil phosphorus (P) was lowest in the 10 to 20 cm samples (median = 2.12 mg kg^{-1}), regardless of sampling location. Multivariate analysis of variance (MANOVA) determined that bulk densities were lower closer to hay and water sources (usually within 0 to 39 m from sources) not located in areas vulnerable to erosion likely because of added C combined with the moderate hoof action to incorporate C into the soil. However, LOI values in the surface 0 to 5 cm soil layer associated with hay, water, and shade in areas vulnerable to erosion demonstrated relatively few differences in distance from a hay, water, or shade source, and these differences often did not occur until 200 m or greater from a pasture equipage. This research indicates that producers can more efficiently utilize nutrient resources and improve soil health measures with strategic placement of hay, waterers, or shade to facilitate best use of limited resources.

Key words: bulk density—carbon—equipage—grazing—spatial distribution

Uneven distribution of carbon (C) in grazing systems may negatively influence a producer's ability to manage nutrients efficiently for optimum forage production and rainfall infiltration. Beef cattle production is an important economic and cultural component of the Southern Piedmont region. In the Southeast, approximately 5.5 million ha of land is in pasture-based beef cattle production (USDA ERS 2013). With the realization of global climate change and an increase in extreme weather patterns, US agricultural systems are focusing on more sustainable production management by improving nutrient use and minimizing nutrient leaks from existing systems.

Beef cattle are usually managed using either a continuous or a rotationally stocked grazing system (Butler et al. 2010). In continuously stocked pastures, there are areas where cattle tend to frequent, and these sites have the potential to accumulate soil organic C (SOC) and associated nitrogen (N) (Dahal et al. 2018) and phosphorus (P) deposited by the cattle as feces or urine. Often, however, these sites are in shaded low-lying areas or near riparian areas that are sensitive to erosion and can be compacted due to the heavy traffic. The deposition or accumulation of nutrients in these areas may become point sources of pollution. Further, the poor uniformity of nutrients in these pastures can negatively influence a producer's ability to manage nutrients efficiently for optimum forage production. Overapplication of nutrients in areas of high nutrient build-up may result in environmental concerns through runoff to surface waters while underapplication of nutrients can limit a system's productivity and place the producer under financial constraints. If the variability of a grazing system is not well managed, the production system overall may suffer by reducing forage quality and productivity (Ball et al. 2007; Paine et al. 1999), increasing the need for feed supplementation, which may lead to unnecessary loss of nutrients thereby reducing the productivity, profit, and sustainability of the entire system.

Areas that animals frequent are often near grazing equipage such as shade, waterers, minerals, and hay-feeding locations. Location of equipage within a pasture may influence soil compaction, C and P concentrations and distributions, as well as loss of nutrients from the pastures. Therefore, it is imperative to understand if and at what distance from grazing equipage bulk density (BD), soil C, and soil P are affected in order to develop the most effective best management practices to efficiently utilize grazing system nutrients and improve system sustainability.

To make pasture-based beef cattle production systems more sustainable, producers are focusing on efficient forage use, maximizing nutritional quality of forages, and improving overall pasture quality while also maximizing animal gains. To do this, producers must first have some understanding of the concentrations and distribution of

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nutrients within their pastures. Best management practices and a strong grazing program can be used to make improvements to both the immediate pasture and the surrounding environment. Improved nutrient distribution across the pasture may result in improved forage productivity, improved infiltration rates of rainfall, and reduced nutrient concentrations in runoff. The amount, type, and distribution (horizontal and vertical) of nutrients critically influence biogeochemical measures of soil health.

A key component for sustainable grazing systems is the ability of the pasture soils to maintain plant and animal productivity and enhance water and air quality (Sharma et al. 2009). Several soil properties, including soil classification, BD, soil C, and topography, can affect the soil fertility, which is a major contributing factor in determining soil health. Each of the physical properties are interdependent, and one soil health factor often acts as an indicator of a different property.

Soil organic C is the C component of the soil organic matter (SOM). Soils with increased levels of SOM have been shown to have improved water retention and infiltration rates, increased nutrient availability (Dalzell et al. 2007) and microbial biomass (Sparling 1992), and decreased soil BD (Wander 2004). When building or banking SOC, it is often difficult to accurately quantify the rapid (annual) changes in SOC that may occur because of management decisions. Because C fractions are extremely dynamic and highly variable, precise and accurate estimates of SOC require a large number of samples (Weil et al. 2003). These samples are expensive and time-consuming to obtain and analyze. New, cost-effective, and rapid methods of measuring SOC and C fractions in real-time and in situ are needed.

Loss-on-ignition (LOI), an estimation of SOC, is frequently used because of its relative affordability and rapid turnaround time (De-Vos et al. 2005; Konen et al. 2002). Because LOI is an indiscriminate analysis method and routinely overestimates the presence of SOM (De-Vos et al. 2005), it must be calibrated to other methods of SOC determination.

Small changes in SOC may be difficult to measure using LOI. Some authors estimate that it may take up to 10 years to demonstrate measurable LOI differences following a change in management practice (Weil et al. 2003; Marriott and Wander 2006). Therefore, measuring soil C fractions that are dependent on microbial activity has been shown to accurately predict soil C changes following management changes over a shorter term (Weil et al. 2003; Marriott and Wander 2006). Unlike particulate organic C and microbial biomass C analysis methods, the permanganate oxidizable C (POXC) method of C determination is a rapid and relatively inexpensive method of C estimation. This, coupled with its ability to detect management-based changes in as little as 9 to 12 months (Weil et al. 2003; Culman et al. 2012; Hurisso et al. 2016), makes it a valuable tool for making management decisions to improve soil C.

A dual-method approach to determine soil C can be a valuable tool to create a calibration curve for subsequent soil C estimates. By analyzing soil samples using both the LOI and POXC methods, soil C concentrations in pasture soils can be determined rapidly, allowing for better grazing management decisions over time.

The objective of this research was to determine spatial distribution of BD and soil C (measured as LOI C and POXC) in continuously stocked Southern Piedmont pastures as affected by landscape position and management to enable producers to make better informed management decisions.

Materials and Methods

Study Site. This study was conducted at University of Georgia's J. Phil Campbell Research and Education Center's North and West Units (33°53′14.95″ N, 83°25′15.48″ W and 33°51′47.66″ N, 83°27′27.36″ W, respectively) in Watkinsville, Georgia, and at the Animal and Dairy Science Department's Beef Research Unit (33°25′14.73″ N, 83°28′35.60″ W) near Eatonton, Georgia. Average annual rainfalls and minimum and maximum temperatures are 123 cm, 10.40°C, and 22.5°C, respectively, in Watkinsville and 119 cm, 11.1°C, and 25.6°C, respectively, in Eatonton. There were four pastures on the North Unit (14.3 to 17.8 ha), two on the West Unit (9.2 to 9.3 ha), and four in Eatonton (18.0 to 21.6 ha). Each of these pastures was an experimental unit, and locations of hay feeding, waterers, and shade were predominantly downhill in Watkinsville and uphill in Eatonton (figure 1). The North and West unit pastures in Watkinsville are characterized by Cecil sandy loam (2% to 6% slope) and Pacolet sandy clay loam (6% to 10% slope) soils that are eroded or severely eroded (table 1). Eatonton pastures are primarily characterized by Davidson clay loam (6% to 10% slope), Davidson loam (2% to 6% slope), and Wilkes sandy loam (2% to 10% slope) soils, although Iredell loam, Enon, Congaree, and Toccoa soils were also reported.

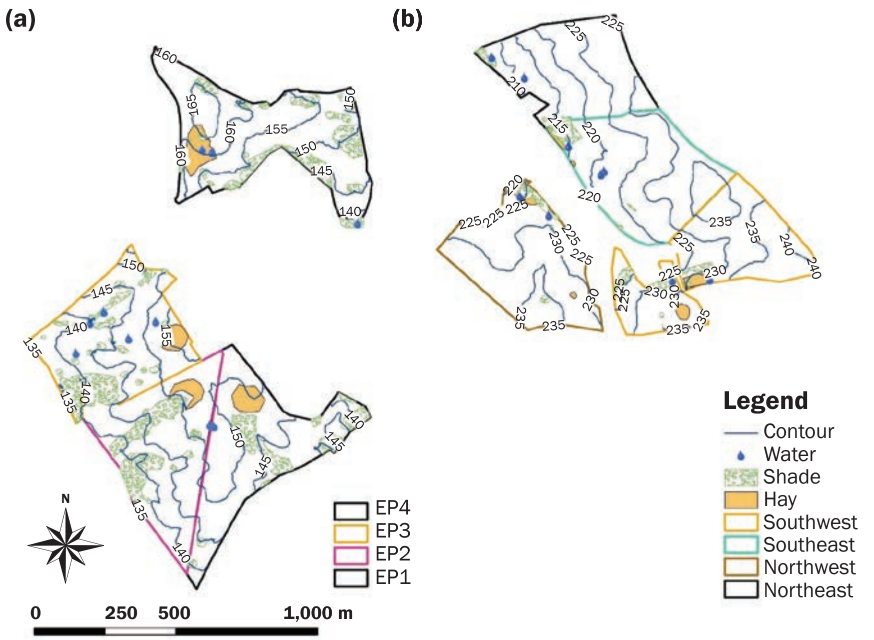
The pastures in Watkinsville have been managed over at least 10 years, with approximately 40 head per stocking herd. The pastures in Eatonton were also managed for at least 10 years grazing in continuously stocked pastures with 20 to 30 head per stocking herd depending on available grass. Aerial imagery (from Google Earth Pro) shows that the approximate hay feeding locations have remained the same for both Eatonton and Watkinsville since 1993. Eatonton used primarily hay rings and Watkinsville used hay rings from 2000 to 2006, heavy use areas from 2006 to 2013, and a hay unroller from 2013 to present.

Soil Sampling. Soil samples were taken on a 50 m grid pattern within the pastures and are referred to as the matrix samples throughout the manuscript. Additional soil samples were taken from areas within each of the 10 pastures where cattle frequented (referred to as areas of interest [AOIs]). All samples were taken using a 5 cm core diameter Giddings hydraulic soil probe (Giddings Machine Corporation, Inc., Windsor, Colorado) with three replications per point within a 1 m sampling radius. Soil cores were taken and separated into three depths: 0 to 5 cm, 5 to 10 cm, and 10 to 20 cm. The AOIs were determined based on historical observations and evidence (e.g., fecal deposits, trampled or overgrazed forage, etc.) of cattle camping activity near shade or grazing equipage (water and feed sources). Pastures contained 3 to 8 AOIs depending on pasture area and distribution of pasture features that attracted cattle (i.e., shade, water, food, hay sources, etc.).

Determination of Distances from Equipage. The Euclidean distances (straight line) from each sampling point to closest edge of shade or grazing equipage (hay, water, and manmade or natural shades) were determined using geographic information system (GIS) technology (Trimble RTK R10 GNSS; Trimble, Inc., Sunnyvale, California), and ArcGIS 10.3.2 software (ESRI, Redlands, California). The analysis was completed by creating shapefiles with GPS coordinates of each sampling point and

Figure 1

Pasture delineations for (a) Eatonton and (b) Watkinsville. Maps indicate elevation with contour lines every 5 m and locations of hay feeding stations, waterers, and shade. Note that most hay feeding and waterers are uphill in Eatonton and downhill in Watkinsville. Maps created by sustainable Ag Lab, University of Georgia, Subash Dahal.



hay, water, and shade features in the pasture. A "near tool" analysis was run through an ArcGIS model builder to measure the distance from each unique sampling point to the nearest hay, water, and shade source. Distance zones (m): 0 to 39, 40 to 99, 100 to 199, and >200 were selected based on recursive partitioning analysis conduction in JMP 11 (SAS, Cary, North Carolina).

Soil Analysis. Soil samples were air-dried and ground (<2 mm), and moisture and soil BD were calculated using the *USDA Soil Survey Laboratory Methods Manual* (USDA 2004) for a sample from a known volume soil core. Additionally, samples were analyzed for LOI C using the method in the *USDA Soil Survey Laboratory Methods Manual* (USDA 2004) where organic matter was combusted at 550°C for 8 to 10 hours. POXC analyses were based on the procedure set by Weil et al. (2003). Sample POXC extracts were analyzed using a Biotek ELx800 absorbance reader at 550 nm (Biotek Instruments, Inc., Winooski, Vermont) using a standard curve ranging from 0.005 to 0.025 mg L^{-1} of 0.2 M $KMnO_4$.

Relationships among LOI, POXC, and BD were determined through recursive partitioning and partial least square regression (PLSR) statistical analyses in JMP 11 statistical software to determine which, if any, BD, LOI, or POXC levels were related to one another. Differences in BD between depths and soil types were determined using the Tukey's test for significance ($\alpha = 0.05$), while differences in LOI and POXC were analyzed using Wilcoxon rank sum test for nonparametric statistical hypotheses.

Soil sampling points were grouped into 0 to 39 m, 40 to 99 m, 100 to 199 m, and greater than 200 m from hay, water, and shade sources. The relationships of BD, LOI, and POXC to pasture equipage were determined using multivariate analysis of variance (MANOVA) in JMP 11. Additionally, the relationships of soil BD and C to topographic features, soil type, and soil family were determined through recursive partitioning and MANOVA.

The LOI data were validated by identifying a subset of soils from each pasture that were sent to the University of Georgia Soil, Plant, and Water Test Lab and analyzed for SOC to determine relationship of SOC to LOI and POXC. Relationships among the three C analyses (SOC, LOI, and POXC) were determined using linear or logarithmic regression curves where appropriate.

Results and Discussion

Bulk Density. Bulk densities were variable across all 10 pastures (figures 2 and 3) and soil classifications (table 1). When soil BD data were pooled by sampling depths, the data were normally distributed and ranged from 0.69 to 2.61 g cm^{-3}. The mean BD for Watkinsville and Eatonton pastures (1.43 and 1.51 g cm^{-3}, respectively) were significantly different ($p < 0.0001$). In both locations, BDs were significantly greater ($p < 0.0001$) in the 5 to 10 cm (1.62 g cm^{-3}) depth than in either the 0 to 5 cm (1.31 g cm^{-3}) or 10 to 20 cm (1.44 g cm^{-3}) depth (figure 4). Soil classification had a significant effect on BD at the 0 to 5 cm and 10 to 20 cm depths ($p < 0.0001$ and $p = 0.0064$, respectively), not in the 5 to 10 cm layer. This suggests that management is influencing BD in the 5 to 10 cm soil depth. Details of soil BD by classification and depth can be found in table 1. Greater BD in the 5 to 10 cm soil layer were often above 1.6 g cm^{-3} indicating likely root penetration limitations, restricted infiltration, and the capacity of these pastures to capture rainfall (Reynolds et al. 2009). Management practices that help to reduce compaction in this layer could have a significant impact on the amount of water received and banked during rainfall events in the Southern Piedmont. Because BDs were significantly different between Watkinsville and Eatonton, results will be presented for the two locations separately.

Bulk Density Relationship to Pasture Management or Equipage. In Watkinsville, BD was significantly greater within 200 m of a waterer in the surface (0 to 5 cm) soil ($p = 0.0017$), while in Eatonton, the 0 to 5 cm soil layer within the 40 to 99 m distance zone from a waterer had significantly lower BDs ($p < 0.001$). Also in Eatonton, BD for all depths was lower within 40 to 99 m distance zone from shade and within the 100 to 199 m distance zone from hay. Although cattle are likely to congregate in the areas closest to hay feeding sources, the BD may be lowered in these areas as cattle drop hay they are fed and that hay is incorporated into the soil profile, increasing the organic matter content of the area, especially when hay is fed away from concentrated flow pathways as in the case of Eatonton (figure 1). This is further discussed in the section below (Distance from Hay/Feeding Areas: Permanganate Oxidizable Carbon).

Table 1

Location, surface area, and mean (upper) and median (lower) bulk density values in three soil depths for each soil type sampled. E, ME, and SE represent erosion classification according to USDA Natural Resources Conservation Service soil survey classes "eroded," "moderately eroded," and "severely eroded," respectively.

		Bulk density (g cm^{-3})		
Soil type	**Location**	**0 to 5 cm**	**5 to 10 cm**	**10 to 20 cm**
Cecil soils, (Slope 0 to 2); overwash	Watkinsville	1.22	1.65	1.10
Fine kaolinitic thermic Typic Kanhapludults		1.21	1.66	1.29
Cecil Sandy Loam (Slope 2 to 6); E	Watkinsville	1.14	1.66	1.40
Fine kaolinitic thermic Typic Kanhapludults		1.13	1.67	1.42
Cecil Sandy Clay Loam; (Slope 2 to 6); SE	Watkinsville	1.23	1.66	1.41
Fine kaolinitic thermic Typic Kanhapludults		1.20	1.67	1.42
Conagree and Toccoa Soils	Eatonton	1.33	1.50	1.45
Loamy, mixed, active, nonacid, thermic Oxyaquic Udifluvents		1.40	1.50	1.46
Davidson Loam (Slope 2 to 6); ME	Eatonton	1.17	1.59	1.39
Fine, kaolinitic, thermic Rhodic Kandiudults		1.21	1.39	1.51
Davidson Clay Loam (Slope 6 to 10); ME	Eatonton	1.30	1.67	1.36
Fine, kaolinitic, thermic Rhodic Kandiudults		1.40	1.53	1.36
Davidson Clay Loam (Slope 10 to 25); ME	Eatonton	1.14	1.55	1.57
Fine, kaolinitic, thermic Rhodic Kandiudults		1.14	1.67	1.54
Enon soils; E	Eatonton	1.00	1.45	1.52
Fine, mixed, active, thermic Ultic Hapludalfs		0.99	1.52	1.45
Iredell Loam (Slope 2 to 6)	Eatonton	1.68	1.53	1.21
Fine, mixed, active, thermic, Oxyaquic Vertic Hapludalfs		1.73	1.31	1.53
Pacolet Sandy Clay Loam (Slope 6 to 10); SE	Watkinsville	1.12	1.65	1.39
Fine, kaolinitic, thermic Typic Kanhapludults		1.14	1.41	1.67
Pacolet Sandy Clay Loam (Slope 10 to 15); SE	Watkinsville	1.33	1.57	1.28
Fine, kaolinitic, thermic Typic Kanhapludults		1.21	1.39	1.59
Wilkes Sandy Loam (Slope 2 to 10); E	Eatonton	1.44	1.58	1.40
Loamy, mixed, active, thermic shallow Typic Hapludalfs		1.41	1.40	1.60

Carbon: Loss-on-Ignition—Soil Carbon Relationships. A strong linear relationship ($y = 0.469x - 0.629$; $r^2 = 0.8971$) was found between LOI and SOC concentrations (figure 5). This ratio was comparable to the findings of De-Vos et al. (2005) that showed a LOI to SOC ratio of 0.42 before clay content was included in the equation. The results from that study mirrored the LOI to SOC ratios found in Bhatti and Bauer (2002) after clay content was considered in the equation (0.57 and 0.58, respectively).

Carbon: Permanganate Oxidizable Carbon—Soil Carbon Relationships. Relationships of POXC to both LOI and SOC were also found. Regression equations for these relationships were both expressed through second order polynomial equations with r^2 values of 0.44 and 0.51 for LOI and SOC, respectively (figures 6 and 7). Outliers in these relationships may be due to saturation of manganese (Mn) from soil samples that inhibited the reduction of the permanganate from Mn^{7+} to Mn^{4+}. Each of the samples that provided a POXC outlier were taken in a low-lying area that remained moist throughout most of the sampling period and therefore susceptible to the presence of Mn concretions in the soil. These samples were removed from all POXC analysis and are not part of presented results.

Soil Carbon Distribution. Soil C, measured as LOI and POXC were not evenly distributed across pastures (figures 1 to 3) nor were they normally distributed. When all depths and locations were combined, LOI ranged from 0.1 to 35.6 g kg^{-1}; median LOI was significantly lower ($p < 0.0001$) in Watkinsville than in Eatonton (5.35 g kg^{-1} and 6.54 g kg^{-1}, respectively). In contrast, median POXC values were higher in Watkinsville than in Eatonton (372 mg kg^{-1} and 326 mg kg^{-1}, respectively; $p < 0.0001$) and POXC for pooled depths and locations ranged from 0 to 1,822 mg kg^{-1}. The range in POXC reported is in line with other analysis done in these types of soils (Culman et al. 2012).

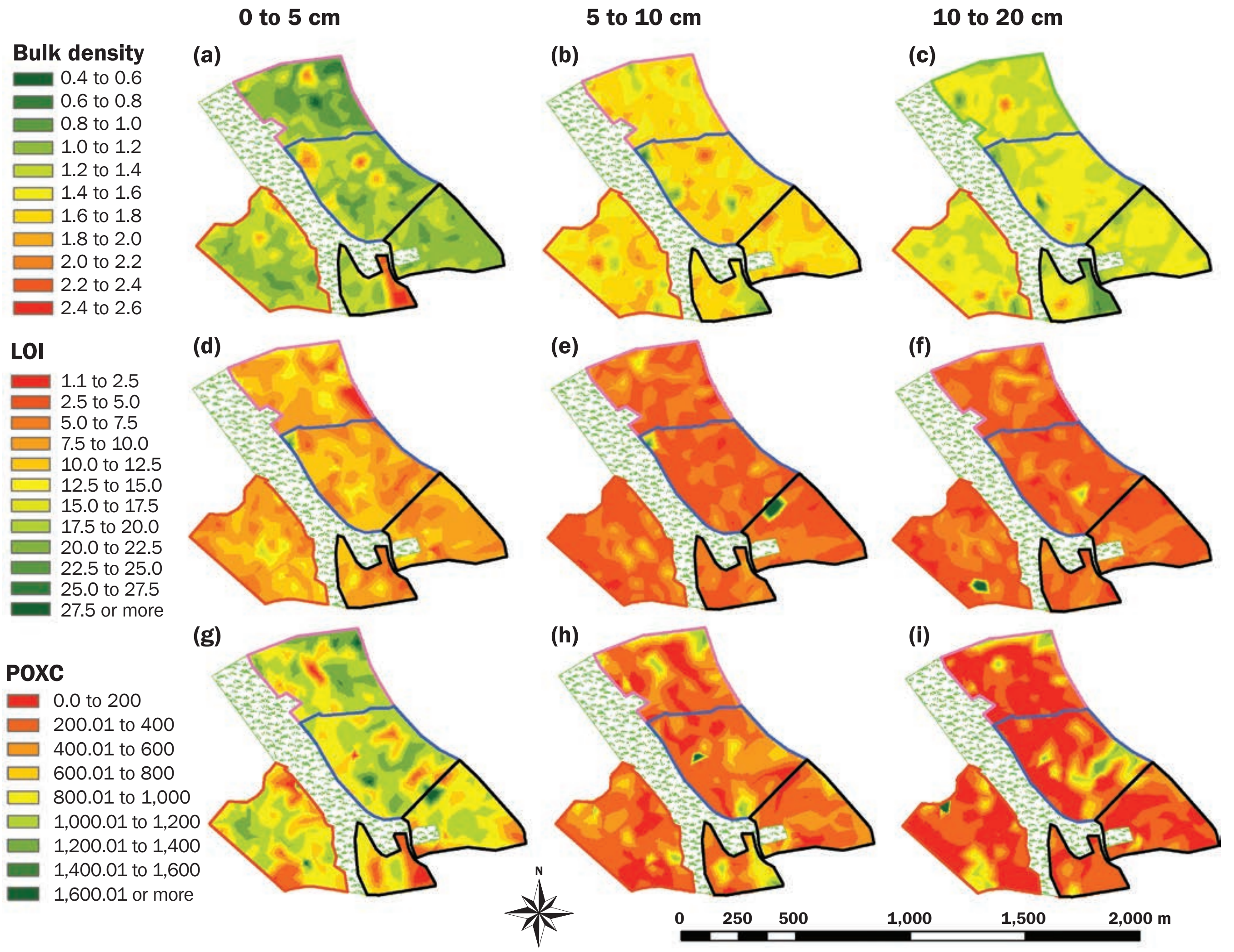
Regardless of depth or location, POXC showed the greatest range and variability among measured soil variables. This is to be expected because of the sensitive nature of this analysis method and its capacity to measure "active" or labile soil C compared to LOI analysis method, which measures recalcitrant C.

When LOI was analyzed by depth, significant differences among soil classifications were found in the 5 to 10 cm and 10 to 20 cm depths ($p = 0.0141$ and 0.0096, respectively; table 2, medians in parentheses below). As could be expected with greater clay content, in the 5 to 10 cm depth, moderately eroded Davidson loam (2% to 6%) had significantly greater LOI C (5.9 g kg^{-1}) than the eroded Cecil sandy loam (2% to 6%; 4.2 g kg^{-1}; $p = 0.04$) (table 3).

Similar to LOI C, POXC showed significant differences ($\alpha = 0.05$) when soil classifications were analyzed by depth. However, significant differences found in the 0 to 5 cm depth ($p < 0.0001$) did not appear to relate directly to texture classifications. For example, the severely eroded Pacolet sandy clay loam (6% to 10%; 1,035 mg kg^{-1}) had significantly greater POXC than both the moderately eroded Davidson clay loam (6% to 10%; 555 mg kg^{-1}) and the eroded Wilkes sandy loam (2% to 10%; 633 mg kg^{-1}) ($p < 0.0001$ and $p = 0.03$). In addition, the severely eroded Cecil sandy clay loam (2%

Figure 2

(a, b, c) Bulk density, (d, e, f) loss-on-ignition carbon (LOI), and (g, h, i) permanganate oxidizable carbon (POXC) for each sampling depth (0 to 5, 5 to 10, and 10 to 20 cm, respectively) for the Watkinsville North Unit. Soil bulk density is displayed in g cm^{-3}, with low bulk densities displayed in green (0.6 to 1.2 g cm^{-3}) and high bulk densities (2.21 to 2.6 g cm^{-3}) shown in red. LOI values are displayed in g kg^{-1}, with low LOI values displayed in red (1 to 5) and high LOI values (20 to 30) displayed in green. POXC values are displayed in mg kg^{-1}, with low POXC values (75 to 400) displayed in red and high POXC values (1,400 to 1,800) in green. Speckled area in the middle of each map is a riparian area. Maps created by sustainable Ag Lab, University of Georgia, Subash Dahal.



to 6%; 992 mg kg^{-1}) and the eroded Cecil sandy loam (2% to 6%; 953 mg kg^{-1}) showed significantly greater POXC in the 0 to 5 cm depth than the eroded Davidson clay loam (6% to 10%; 555 mg kg^{-1}) (p = 0.0004 and 0.002, respectively). We speculate that the greater active C (POXC) is a product of management practices such as placement of hay, water, and shade.

Carbon: Relationship to Pasture Management or Equipage, Hay Feeding, Watering Points, and to Shade. When data were sorted by location and depth, distance to grazing equipage had an impact on soil concentrations of LOI and/or POXC. Distance zones were 0 to 39, 40 to 99, 100 to 199, and greater than 200 m from equipage such as hay/feeding areas, watering points, and to shade.

Distance from Hay/Feeding Areas: Loss-on-Ignition. In Watkinsville, hay was primarily fed in lower lying areas and at times evidence of erosion was obvious, which may explain why there was little difference in the 0 to 5 cm LOI between zones. In the 5 to 10 cm depth, LOI was significantly greater in samples occurring in the 0 to 39 m zone and lowest in the >200 m zone away from the nearest hay/feeding area (p = 0.03 and 0.0086, respectively). In the 10 to 20 cm samples, LOI was greatest in the 100 to 199 m zone compared to <200 zone (p = 0.002; table 3).

In Eatonton, most hay feeding was near the top of the hill. The LOI C in the 0 to 5 cm depth was significantly (p = 0.005) greater in the samples occurring 0 to 39 m from the nearest hay source than samples falling 40 m or more away. The 5 to 10 and 10 to 20 cm sample depths did not appear to be influenced by distance to hay (table 3).

Figure 3

(a, b, c) Bulk density, (d, e, f) loss-on-ignition carbon (LOI), and (g, h, i) permanganate oxidizable carbon (POXC) for each sampling depth (0 to 5, 5 to 10, and 10 to 20 cm, respectively) for the Eatonton Unit. Maps created by sustainable Ag Lab, University of Georgia, Subash Dahal.

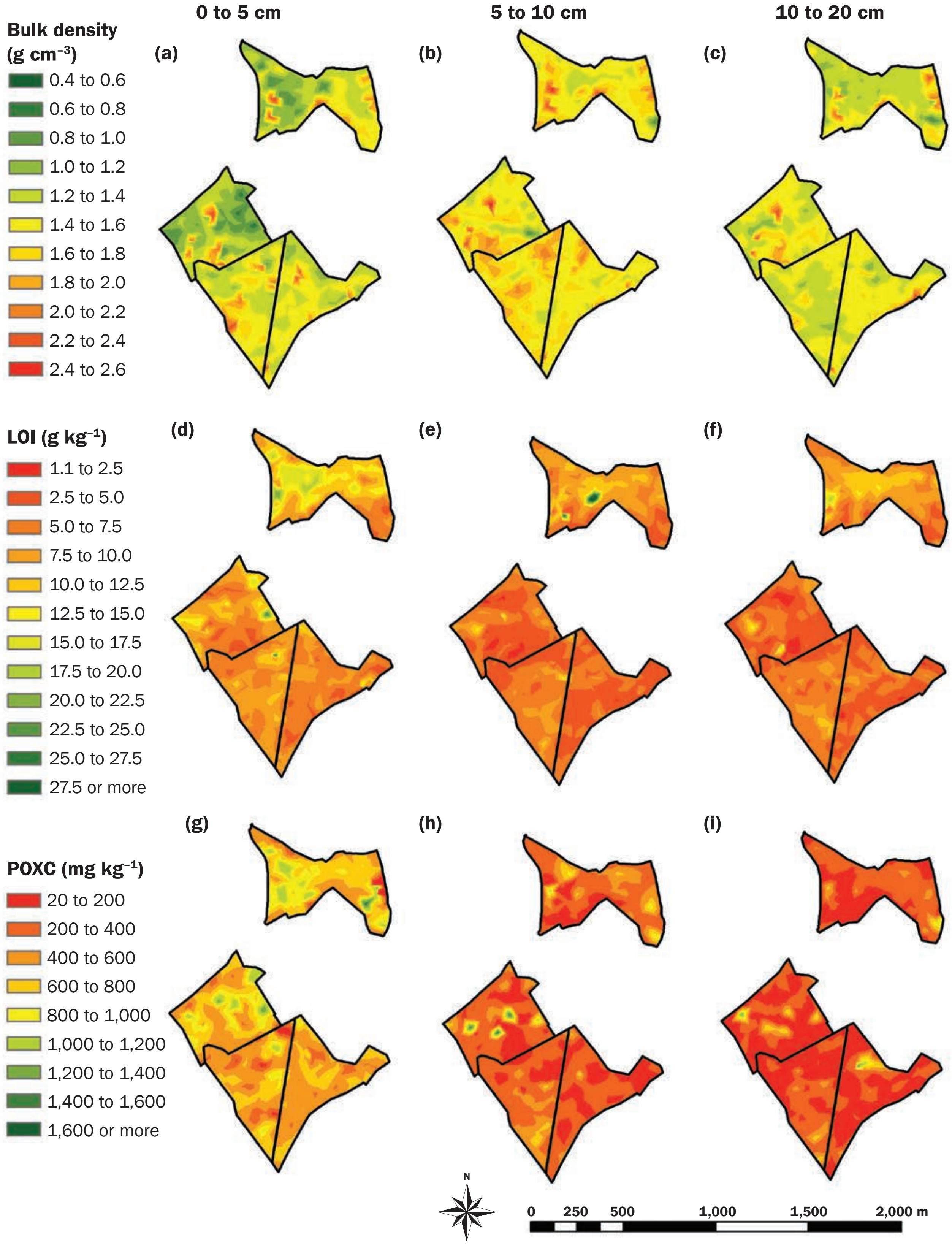


Figure 4

Minimum and maximum (mean bold line and median fine line) bulk density (g cm^{-3}, *y*-axis) for Watkinsville pastures (left) and Eatonton (right). Within each location different letters indicate significant differences between mean bulk density according to pairwise comparisons using Tukey's test ($p = 0.05$) between depths.

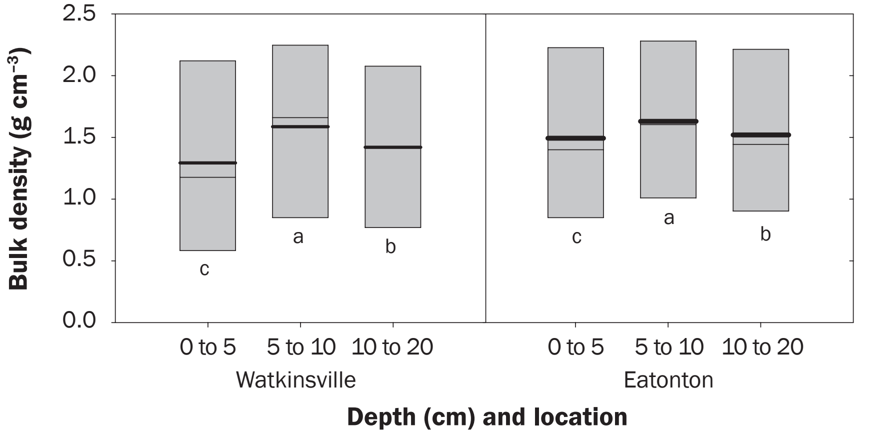
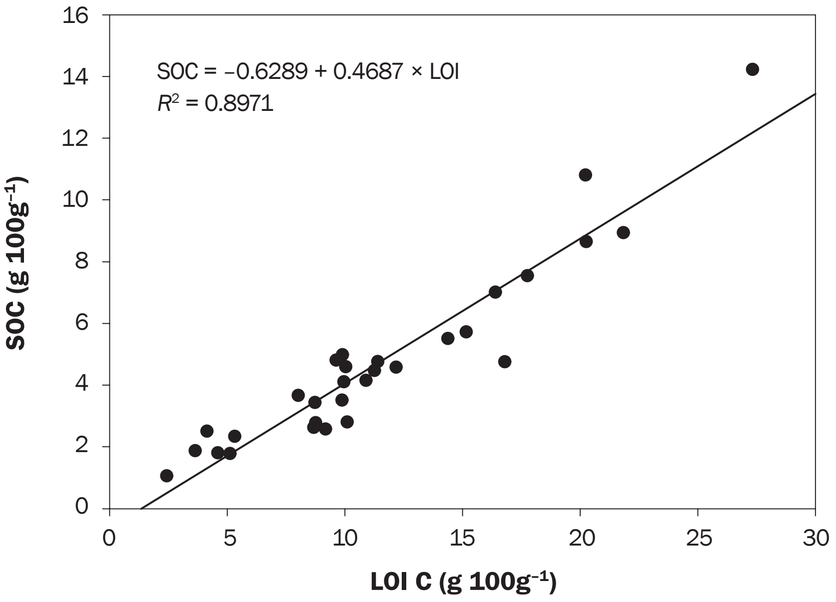


Figure 5

Relationship between soil organic carbon (measured by combustion, SOC) and loss on ignition carbon (LOI).



Distance from Hay/Feeding Areas: Permanganate Oxidizable Carbon. In Watkinsville, POXC in the 0 to 5 cm soil samples was lowest in the 0 to 39 m distance to hay sampling zone. Going into further detail from above, hay feeding areas in Watkinsville are either in concentrated flow paths, in areas which are vulnerable to erosion, such as side slopes, or in areas that alternated between erosional and depositional depending of duration and intensity of rainfall event (toeslope, figure 1). Because hay had historically been fed in these more erosive areas, labile C (POXC) may have been more easily lost in solution as runoff waters moved through these locations. In the 5 to 10 cm soil samples, the highest POXC occurred within 0 to 39 m of a hay/feeding area ($p = 0.082$; table 3), suggesting that active C within this soil layer was not as influenced by erosion. Samples occurring 200 m or more from the nearest hay source were also significantly greater than samples 40 to 199 m from the nearest hay source ($p = 0.035$). Samples over 200 m from the nearest hay/feeder were often in landscapes that were more level with thicker topsoil, and forage roots were less likely to be disturbed by foot traffic than those located closer to a hay feeder. No differences were seen in between POXC and distance to hay in the 10 to 20 cm soil samples.

In Eatonton, as was the case with LOI, the 0 to 5 cm samples within 39 m of the nearest hay source had the greatest ($p = 0.005$) POXC. Hay feeding areas in Eatonton are most often located in upper landscape areas not in concentrated flow areas. In 5 to 10 and 10 to 20 cm samples, POXC in >100 m zone from hay/feeders was found to have the greatest concentration (table 3). Jones (1983) and later in a review Unger and Kasper (1994) associated root restrictions at BDs between 1.4 and 1.85 g cm^{-3}, depending on texture. Reynolds et al. (2009) considered BDs of 0.9 to 1.2 g cm^{-3} critical values for optimal maximum agronomic production in fine to medium textured soils, and values above 1.25 to 1.30 g cm^{-3} were considered to limit yield. In our study, LOI and POXC averaged 9.36 g kg^{-1} and 920 mg kg^{-1} for soils with BD less than 1.28 g cm^{-3} while soils with greater BD averaged 5.10 g kg^{-1} LOI and 379 mg kg^{-1} POXC. Often the areas of highest LOI C occurred in cattle camping areas positioned in the upland field positions. This could be the result of a general buildup of organic matter through fecal depositions in these camping areas and redistribution of associated nutrients within the pasture via runoff during high-precipitation weather events.

Distance from Waterer: Loss-on-Ignition. In both Watkinsville and Eatonton, LOI in the 0 to 5 cm depth was significantly greater than in either the 5 to 10 or 10 to 20 cm depths (each $p < 0.05$), and no differences between distance-zones in the 0 to 5 cm soil layer (table 4) were indicated. However, in the 5 to 10 cm depth, samples falling within 0 to 39 m from the nearest water source had significantly greater LOI than samples within the 40 to 200 m ($p = 0.0011$; table 4). This is important because it strongly suggests that placement of water for cattle can help renovate pastures in the 5 to 10 cm soil layer by increasing soil C with the expectation of reducing compaction.

Distance from Waterer: Permanganate Oxidizable Carbon. In Watkinsville pastures, POXC was only affected by the distance to water in the 0 to 5 cm samples (table 4). Samples taken 200 m or more from a waterer had greater POXC (p = 0.0989) than samples taken closer to waterers. As most watering stations in the Watkinsville pastures are located in the lower portion of the pastures where soils are vulnerable to erosion, it is likely that added C from cattle activity did not remain in the surface layer. Further away from waterers, pastures are more level. However, greater soil POXC concentrations further away from waterers may also be attributed to less animal presence, thereby leaving more undisturbed forage in these areas, allowing fine roots to contribute more to the POXC values in these >200 m zones. In Eatonton, distance to water affected POXC at each sampling depth. In the 0 to 5 cm samples, POXC was highest (p = 0.0002) within 100 m of a water source.

Distance from Shade: Loss-on-Ignition. In Watkinsville, LOI was only affected by the distance to shade in the 5 to 10 cm soil depth (table 5). Samples that occurred 200 m or more from the nearest natural shade source had significantly lower LOI than samples occurring within 200 m (p = 0.09). No differences in LOI were seen in Eatonton

Distance from Shade: Permanganate Oxidizable Carbon. In Watkinsville, POXC was affected by the distance to shade sources for 0 to 5 cm and 5 to 10 cm soil depths (table 5). In both soil depths, POXC in samples 200 m or more from a shade source had the greatest POXC (p < 0.02 for distance to shade). In the 0 to 5 cm samples, POXC was significantly lower (p = 0.016) in the samples 40 to 99 m from shade than in any other shade distance zone (table 5). In Eatonton, no significant differences in POXC with distance were identified.

Figure 6

Relationship between permanganate oxidizable carbon (POXC) and loss-on-ignition C (LOI). Grey points represent outliers probably caused by the presence of manganese (Mn) concretions.

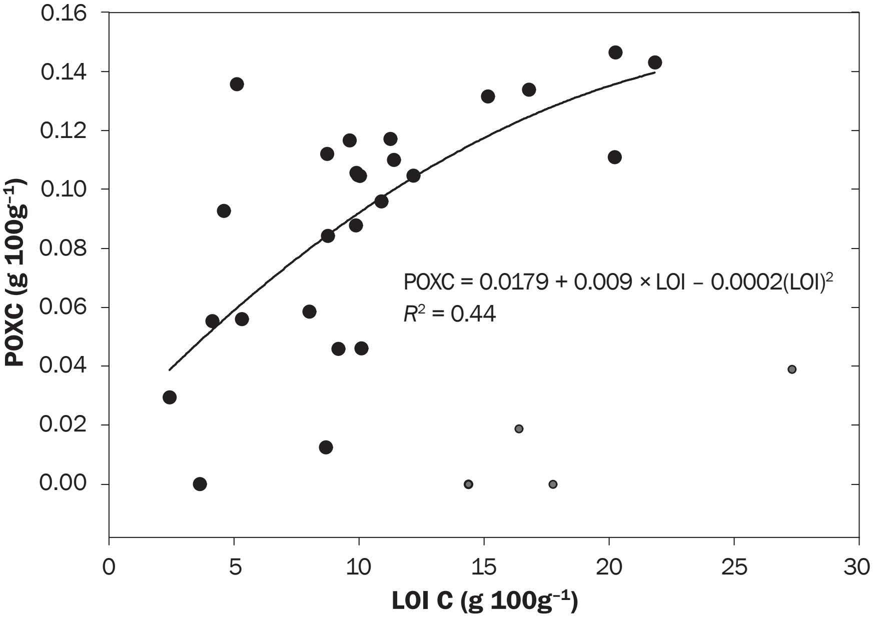
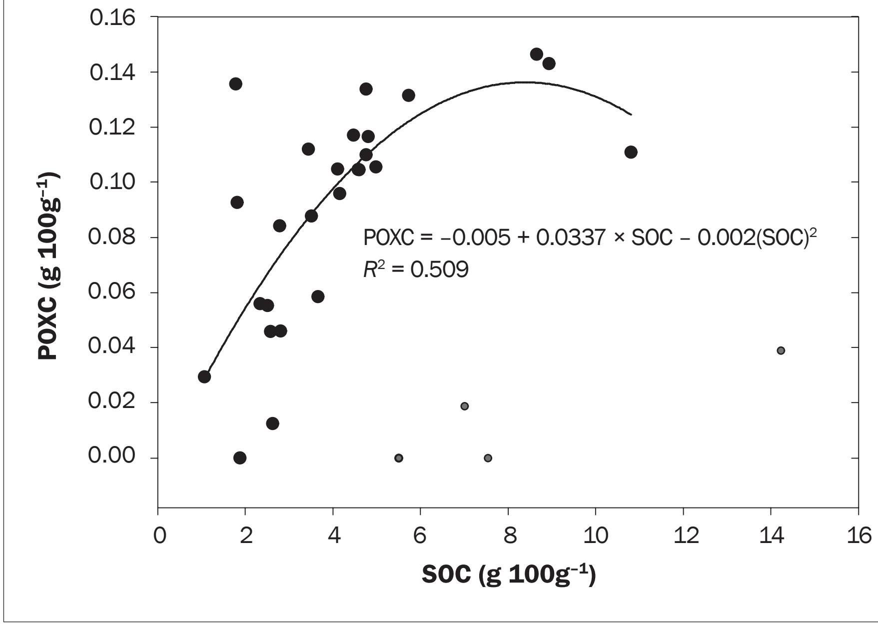


Figure 7

Relationship between permanganate oxidizable carbon (POXC) and soil organic carbon (SOC). Grey points represent outliers probably caused by the presence of manganese (Mn) concretions.



Summary and Conclusions

Regardless of location, soil BD was greater in the 5 to 10 cm depth. High BD values in this layer may be due, in part, to a legacy plow pan layer at this depth. The 10 to 20 cm samples were also likely affected by deep-rooted forages that lowered BD values. The BD values at the 5 to 10 cm sampling depth may create a restrictive layer for both rainfall infiltration and forage root development. More research is needed to determine the influence of these BD values on N mineralization and other soil health measures. Because this restrictive layer is so close to the surface, it could be mitigated through grazing management strategies.

A strong linear relationship ($y = 0.469x - 0.629$; $r^2 = 0.8971$) was found between LOI and SOC concentrations. Therefore, using LOI values may be an effective and inexpensive way to continue to monitor pasture soil C. In view of spatial distribution patterns

Table 2

Location, surface area, and mean (upper) and median (lower) loss-on-ignition (LOI) and permanganate oxidizable carbon (POXC) values in three soil depths for each soil type sampled. E, ME, and SE represent erosion classification according to Natural Resources Conservation Service soil survey classes "eroded," "moderately eroded," and "severely eroded," respectively.

			Sample depth (cm)					
			0 to 5		5 to 10		10 to 20	
Soil type	Location	Area (ha)	LOI (g C kg^{-1})	POXC mg C kg^{-1})	LOI (g C kg^{-1})	POXC (mg C kg^{-1})	LOI (g C kg^{-1})	POXC (mg C kg^{-1})
Cecil soils (slope 0 to 2); overwash; fine kaolinitic thermic Typic Kanhapludults	Watkinsville	0.5	9.63 9.06	944.4 919.5	6.07 5.74	384.5 380.5	5.83 5.74	225.4 228.4
Cecil Sandy Loam (slope 2 to 6); E; fine kaolinitic thermic Typic Kanhapludults	Watkinsville	21.9	8.97 9.19	901.6 953.4	4.43 4.19	348.7 302.0	4.75 4.00	360.6 226.4
Cecil Sandy Clay Loam (slope 2 to 6); SE; fine kaolinitic thermic Typic Kanhapludults	Watkinsville	28.1	9.42 9.53	931.5 992.1	5.00 4.47	342.7 299.0	5.04 4.23	342.7 224.4
Conagree and Toccoa Soils; loamy, mixed, active, nonacid, thermic Oxyaquic Udifluvents	Eatonton	1.2	5.37 4.98	944.4 483.0	4.07 4.07	163.7 197.5	4.28 4.23	4.6 21.5
Davidson Loam (slope 2 to 6); ME; fine, kaolinitic, thermic Rhodic Kandiudults	Eatonton	23.0	9.94 8.97	732.6 788.3	6.17 5.93	336.8 334.8	5.85 5.74	233.3 213.4
Davidson Clay Loam (slope 6 to 10); ME; fine, kaolinitic, thermic Rhodic Kandiudults	Eatonton	20.0	8.72 8.58	584.4 555.6	5.83 5.36	448.2 339.8	7.49 7.41	263.2 213.4
Davidson Clay Loam (slope 10 to 25); ME; fine, kaolinitic, thermic Rhodic Kandiudults	Eatonton	6.6	8.38 8.09	592.4 614.2	4.94 4.91	421.3 434.2	4.03 4.10	186.6 168.7
Enon soils; E; fine, mixed, active, thermic Ultic Hapludalfs	Eatonton	9.0	5.74 5.74	601.3 601.3	4.98 4.98	158.8 158.8	2.01 2.01	76.2 76.2
Iredell Loam (slope 2 to 6); fine, mixed, active, thermic, Oxyaquic Vertic Hapludalfs	Eatonton	10.1	9.33 7.62	700.8 642.1	6.45 6.46	303.9 332.8	6.68 6.64	191.6 170.7
Pacolet Sandy Clay Loam (slope 6 to 10); SE; fine, kaolinitic, thermic Typic Kanhapludults	Watkinsville	30.6	9.45 9.33	957.3 1,034.9	4.97 4.55	374.6 331.8	4.77 4.31	283.1 199.5
Pacolet Sandy Clay Loam (slope 10 to 15); SE; fine, kaolinitic, thermic Typic Kanhapludults	Watkinsville	3.7	8.26 8.28	833.0 923.5	5.78 4.89	393.5 345.7	4.48 4.17	154.8 209.5
Wilkes Sandy Loam (slope 2 to 10); E; loamy, mixed, active, thermic shallow Typic Hapludalfs	Eatonton	14.0	7.13 7.44	614.2 633.1	5.24 4.56	269.1 251.2	5.90 6.41	181.6 149.8

of LOI and POXC, the POXC distribution maps showed the most spatial variation, likely because POXC measures more of the active soil C than does LOI C and is more indicative of changes in management (Culman et al. 2012). Because of the rapid and inexpensive nature of the POXC method, it will be a valuable tool to determine soil C changes due to a change in management practice, although the presence of Mn concretions in the monitored soil must be considered.

Table 3

The mean (upper) and median (lower) concentrations of loss-on-ignition (LOI) and permanganate oxidizable carbon (POXC) for each sampling depth in Euclidean distances 0 to 39, 40 to 99, 100 to 199, and >200 m from the nearest **hay source** at both the Watkinsville and Eatonton sites. Within columns, for each Watkinsville and Eatonton and within each depth, differences were compared between medians according to pairwise comparisons using Wilcoxon Rank Sum test at $p = 0.1$ (different letter indicate significant differences).

		Mean/median LOI values (g C kg^{-1})			Mean/median POXC (mg C kg^{-1})		
Location	**Distance to hay (m)**	**0 to 5 cm**	**5 to 10 cm**	**10 to 20 cm**	**0 to 5 cm**	**5 to 10 cm**	**10 to 20 cm**
Watkinsville	0 to 39	11.30	7.95	5.30	686.9	639.9	274.7
		8.52a	6.31a	4.74ab	723.2c	605.7a	257.9a
	40 to 99	9.31	4.86	5.69	889.3	358.7	228.1
		9.11a	4.69bc	4.01ab	898.5b	305.0c	170.2a
	100 to 199	9.81	5.37	7.55	857.2	367.7	365.1
		9.43a	5.10b	4.88a	932.0b	305.2c	199.2a
	200+	9.42	5.16	4.78	1,026.7	495.1	324.2
		9.50a	4.47c	4.01b	1,038.9a	377.1b	195.1a
Eatonton	0 to 39	10.71	6.90	6.51	750.5	261.3	205.5
		9.26a	5.65a	5.72a	718.8a	246.9b	137.9b
	40 to 99	8.79	5.97	6.22	596.9	212.1	126.5
		8.05b	5.34a	6.36a	593.5b	214.3c	144.9b
	100 to 199	8.64	6.42	6.14	631.2	316.6	216.4
		7.85b	5.49a	5.62a	586.0b	304.4ab	211.9a
	200+	8.45	6.14	6.21	604.9	341.6	235.4
		8.22b	6.17a	6.16a	588.3b	305.3a	208.7a

Table 4

The mean (upper) and median (lower) concentrations of loss-on-ignition (LOI) and permanganate oxidizable carbon (POXC) for each sampling depth in Euclidean distances 0 to 39, 40 to 99, 100 to 199, and >200 m from the nearest **water source** at both the Watkinsville and Eatonton sites. Within columns, for each Watkinsville and Eatonton and within each depth, differences were compared between medians according to pairwise comparisons using Wilcoxon Rank Sum test at $p = 0.1$ (different letters indicate significant differences).

		Mean/median LOI values (g C kg^{-1})			Mean/median POXC (mg C kg^{-1})		
Location	**Distance to water (m)**	**0 to 5 cm**	**5 to 10 cm**	**10 to 20 cm**	**0 to 5 cm**	**5 to 10 cm**	**10 to 20 cm**
Watkinsville	0 to 39	10.34	5.77	4.79	807.2	574.7	267.8
		10.59a	5.73a	4.04b	913.0b	393.3a	183.3a
	40 to 99	10.21	6.04	5.05	906.6	375.3	259.6
		9.78a	5.09b	3.36b	942.2ab	304.0a	176.3a
	100 to 199	9.64	5.93	5.39	917.0	510.0	252.8
		9.13a	5.08b	4.88a	941.0a	359.5a	201.2a
	200+	9.34	4.66	6.39	980.3	406.2	345.7
		9.22a	4.41c	4.02b	1,009.0a	360.9a	197.9a
Eatonton	0 to 39	10.48	6.86	6.15	765.1	379.1	201.9
		10.90a	6.04a	5.15a	775.1a	230.7b	173.4ab
	40 to 99	9.46	6.32	6.14	732.1	296.4	209.7
		8.89ab	5.43b	6.15a	718.2a	263.5b	165.8b
	100 to 199	8.89	6.12	6.03	620.9	243.3	176.9
		8.18b	5.48b	5.61a	601.6b	243.6b	165.8b
	200+	8.48	6.36	6.44	578.6	337.4	233.8
		8.06b	6.41a	6.29a	568.9b	325.7a	224.8a

Overall the greatest differences were for LOI C or POXC distributions between 0 to 39 and >200 m from a hay, water, or shade source. Bulk densities were lower closer to hay and water sources not located in areas vulnerable to erosion likely because of added C combined with the moderate hoof action to incorporate C into the soil. Bulk densities showed an increase in areas close to or within a shade source. LOI values in the surface 0 to 5 cm soil layer associated with hay, water, and shade in areas vulnerable to erosion demon-

Table 5

The mean (upper) and median (lower) concentrations of loss-on-ignition (LOI) and permanganate oxidizable carbon (POXC) for each sampling depth in Euclidean distances 0 to 39, 40 to 99, 100 to 199, and >200 m from the nearest **shade source** at both the Watkinsville and Eatonton sites. Within each column, for each Watkinsville and Eatonton and within each depth, differences were compared between medians according to pairwise comparisons using Wilcoxon Rank Sum test at $p = 0.1$ (different letters indicate significant differences).

		Mean/median LOI values (g C kg^{-1})			Mean/median POXC (mg C kg^{-1})		
Location	**Distance to shade (m)**	**0 to 5 cm**	**5 to 10 cm**	**10 to 20 cm**	**0 to 5 cm**	**5 to 10 cm**	**10 to 20 cm**
Watkinsville	0 to 39	10.41	6.03	5.81	890.0	438.9	256.8
		9.47a	5.2a	5.06a	932.4cb	347.2b	183.0a
	40 to 99	9.47	5.23	5.09	822.6	338.8	286.1
		9.55a	4.72a	4.59a	935.9c	275.8b	172.8a
	100 to 199	9.54	5.68	5.12	953.5	532.6	287.8
		9.21a	4.78a	4.38a	980.8b	345.9b	199.2a
	200+	9.31	4.59	4.69	1,047.8	453.1	351.2
		9.52a	4.41b	4.01a	1,080.8a	402.5a	215.8a
Eatonton	0 to 39	9.10	6.23	6.23	644.3	301.1	206.8
		8.49a	6.03a	5.94a	619.4a	282.1a	183.3a
	40 to 99	8.72	6.46	6.46	634.0	296.0	218.7
		7.91a	5.35a	6.18a	589.5a	282.8a	211.9a
	100 to 199	8.08	5.48	5.48	553.9	341.0	184.7
		7.73a	5.72a	4.57a	538.7a	303.4a	144.9a

strated relatively few differences in distance from a hay, water, or shade source, and these differences often did not occur until 200 m or greater from a pasture equipage. When water, hay, and shade were not located in areas susceptible to erosion, soils samples closer to each had significantly more LOI C, POXC, and P. This was likely due to cattle activity near water troughs as animals drank but did not camp in the immediate vicinity.

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