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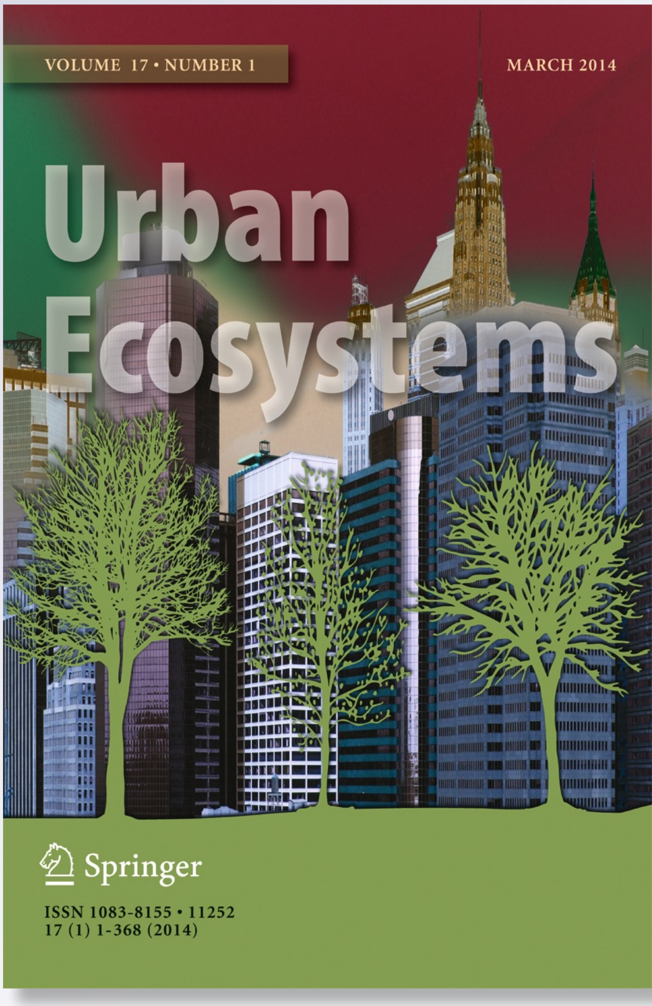

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Drivers of soil carbon in residential 'pure lawns' in Auburn, Alabama

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Abstract Urban land area is expanding worldwide and may contribute to long-term carbon (C) storage; however, little is known about potential drivers of soil C in urban areas. Residential areas are one of the largest urban land use zones and lawns can provide stable chronosequences for studying soil C dynamics. In residential lawns containing no trees (n=23), the relationships between soil C and four potential drivers [home age (1–51 years), yard maintenance practices (fertilization, irrigation, and bagging or mulching lawn clippings), soil nitrogen (N) and soil texture] were investigated. Soil C increased with home age at 0–15 cm depth by 0.026 kg C m^{-2} yr^{-1}, declined by −0.011 kg C $m^{-2} yr^{-1}$ at 15–30 cm depth, and was stable at 30–50 cm depth. Soil C had a positive relationship with soil N (R^2=0.55) at the 0–15 cm depth. Soil C and N were not related to yard maintenance practices or soil texture. The low soil C sequestration rate and limited relationships between soil C and home age, yard maintenance, soil N and soil texture may have resulted from the positive influence of Auburn's humid, subtropical climate on residue decomposition.

Keywords Urban soil carbon · Yard maintenance · Home age · Residential lawns

Introduction

The year 2008 marked the first time that a greater number of people lived on urban rather than rural soils. Models predict the continued expansion of urban populations and subsequent land area into the future (UNFPA 2007). Urban soils are natural soils that have undergone anthropogenic alterations (Effland and Pouyat 1997), are quite diverse (Schleuß et al. 1998; Lorenz and Kandeler 2005; Scharenbroch et al. 2005; Pouyat et al. 2007), and can be dissimilar to natural soil series that are native to the site (Blume 1989). Despite their anthropogenic origins,

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urban soils support a range of ecosystems services including the ability to store atmospheric carbon (Jo and McPherson 1995; Pouyat et al. 2006). In the past decade, soil C dynamics were examined in urban areas such as golf courses (Qian and Follett 2002; Huh et al. 2008; Selhorst and Lal 2011) and residential lawns (Pouyat et al. 2002; Kaye et al. 2005; Golubiewski 2006; Smetak et al. 2007; Raciti et al. 2011). Results from these studies indicated a strong capacity for these urban areas to sequester C in soil, but little is known about the singular contribution of turfgrass to soil C dynamics.

Turfgrass is a dominant vegetative cover of urban soils and the expansion of municipal areas subsequently increases turfgrass coverage (Robbins and Birkenholtz 2003). Milesi et al. (2005) calculated total turfgrass coverage of the continental USA to be roughly 16 million ha while Vinlove and Torla (1995) estimated residential lawn area to be 5.7–7.3 million ha. In Colorado, Kaye et al. (2005) and Golubiewski (2006) found higher soil C sequestration in residential lawns than nearby short grass steppes, and in Baltimore, MD, residential turfgrass lawns had a greater soil C sequestration rate than nearby rural forests (Pouyat et al. 2009; Raciti et al. 2011).

In residential areas, the accumulation of soil C over time is often referenced in regards to the age of the home (Scharenbroch et al. 2005). In Chicago, IL, USA, residential homes > 40 years old had more soil C than homes < 35 years old (Pouyat et al. 2009). In Colorado's Front Range, lawns > 7 years in age had greater soil C concentration at the 0–10 cm depth than lawns < 7 years old, and homes > 25 years in age had more soil C concentrations at the 10–20 cm and 20–30 cm depths than homes < 25 years in age (Golubiewski 2006). The increase in soil C over time may be influenced by turfgrass maintenance practices (e.g., fertilization, irrigation, mulching lawn clippings).

Qian and Follett (2002) and Selhorst and Lal (2011) suggested that the high level of fertilization and irrigation applied to golf courses boosted the soil C sequestration rate. In addition, nitrogen (N) supplements from turfgrass clippings mulched into lawns have improved turfgrass productivity (Kopp and Guillard 2002) and soil C sequestration (Qian et al. 2003). Milesi et al. (2005) modeled turfgrass growth across the continental USA under different yard maintenance regimes and projected that without fertilization and irrigation, the majority of turfgrass covered urban soils would become a C source. Past investigations of soil C dynamics in residential areas have credited yard maintenance supplements for high soil C sequestration rates but none have directly compared contrasting yard maintenance practices e.g. fertilization vs. not fertilization, to assess whether a distinct difference occurs.

The need for information on urban soil C dynamics increases with expansion of urban land area. In the southern USA, urbanization is increasing dramatically with escalating population growth (Lubowski et al. 2006; Alig et al. 2004). Urban soil C dynamics in the southern USA have received little attention at present, and no research has investigated soil C storage in purely turfgrass residential lawns. Our overall goal was to measure soil C in Auburn's residential 'pure lawns' (absent tree biomass) and to examine the relationships between soil C and home age and across yard maintenance practices (fertilization, irrigation, mulching or bagging lawn clippings). In addition, we examined the relationship of soil C with soil N, as a parameter for soil fertility, and with soil texture, i.e. % clay, % sand, % silt. Soil texture has been linked with soil C storage capacity (Sorensen 1981; Burke et al. 1989) and analysis of soil texture provided basic soil characteristics for each lawn. Within our study objectives we tested four hypotheses:

1) soil C levels would increase with home age;
2) lawns that were either fertilized, irrigated, or mulched would exhibit greater soil C levels over home age than lawns not receiving supplements;
3) soil C levels would be positively related to soil N;
4) soil C levels would be positively related to % clay.

Methods and materials

Location

The city of Auburn is located in east central Alabama, in Lee County abutting the Georgia border (latitude 32.6°N longitude 85.5°W) (U.S. Census Bureau) at an altitude of 210 m (U.S. Climate Data ©). The city is located on the fall line between the Coastal Plain and the Piedmont Plateau (McNutt 1981). Piedmont Plateau soils "have red, clayey subsoil and a sandy loam or clay loam surface layer" and Coastal Plain soils "have either loamy or clayey subsoil with a sandy loam or loam surface layer" (Mitchell 2008). Auburn's climate is humid, subtropical (Chaney 2007) with a mean annual temperature (MAT) of 17.4 °C (63.4 °F) and mean annual precipitation (MAP) of 133.6 cm (52.6″) (U.S. Climate Data ©).

Yard selection

Soil was sampled from 23 'pure lawn' yards of single family homes within the city limits in spring/summer 2009 and 2010. Yards designated as 'pure lawns' had trees located > 20 m away and separated by roads from the sample site to minimize the influence of tree roots on soil C and N. The 'pure lawns' were located through visual inspection of neighborhoods using Google Earth© aerial photos and by driving through neighborhoods. Samples were obtained through agreement with home owners via a written or verbal request for permission to sample. Zoysiagrass (*Zoysia spp*.) and bermudagrass (*Cynodon dactylon*) were the prevalent lawn turfgrass species. Home age spanned 1 to 51 years, and these data were obtained from the city of Auburn Planning Commission and Lee County Courthouse, Opelika, Al.

Soil sampling and processing

Sample sites were selected to avoid irrigation/gas/water/sewer pipes, home security and electric lines, rocks, areas devoid of grass, and away from sidewalks, walkways, driveways, roads, and the home. Front lawns were selected for ease of access since back lawns were more often used by owners and pets. Within structural and use limitations, a meter square was placed on the lawn "arbitrarily but without preconceived bias" (McCune and Grace 2002) and two soil samples were taken at each corner at three depths per core: 0–15 cm, 15–30 cm, and 30–50 cm. The soil probe used was a 2.9 cm×61 cm (1 1/8″×24″) slotted chrome plated AMS soil recovery probe (AMS, Inc., American Falls, ID) with a diameter of 2.2 cm (7/8″). At each meter square corner, one core provided a soil sample for C and N, and the second core, collected 2–8 cm from the first core (depending on soil conditions), was used to determine bulk density and soil texture. The soil samples for C and N were oven-dried at 45 °C for 3 days, sieved (2 mm mesh) to remove residue fragments, and ground with a roller grinder (Kelley 1994) to pass a 1 mm mesh. Soil texture samples were dried at 100 °C for 3 days and sieved (2 mm mesh) to remove residue fragments. For each yard there were 4 soil C, 4 soil N, and 4 soil texture samples per depth.

Carbon and nitrogen analysis

Each sample was analyzed for soil C and N using a LECO TruSpec CN 2003 model, (LECO Corporation, St. Joseph, Missouri) at the USDA-ARS National Soil Dynamics Laboratory in Auburn, AL. The LECO TruSpec CN 2003 model had an Infrared Gas Analyzer to measure C and a thermoelectric conductivity analyzer to measure N.

Bulk density

Bulk density was obtained using a modified method of Culley (1993). Soil C and N content (kg m^{-2}) was determined as the product of bulk density (g cm^{-3}) and C or N concentration.

Soil texture

Soil texture was analyzed with a modified hydrometer method of Gee and Bauder (1986). Forty grams of oven-dried soil was mixed with 50 ml dispersing agent in a metal mixing cup. The dispersing agent was a solution of 35.7 g of sodium metaphosphate ($NaPO_3$) × Na_2O and sodium carbonate (Na_2CO_3) dissolved in 1 L distilled water. The soil solution was mixed for 5 min with a commercial mixer. After mixing, the solution was placed in a 1 L glass cylinder and brought to volume. The solution was shaken for 1 min and a hydrometer reading was taken after 40 s of settling time. The 1 min shaking of the cylinder solution was repeated followed by a second hydrometer reading. Immediately following the second reading, the solution temperature was recorded. After 24 h, hydrometer and temperature readings were repeated on the resting solution.

Yard maintenance

Home owners were interviewed to determine yard maintenance history (i.e., fertilization, irrigation, and mulching or bagging clippings). As most residents did not remember the exact frequency of fertilization or watering, fertilization was categorized as 'yes' if they consistently fertilized at least once a year and watering as a 'yes' if they consistently watered the lawns at least once every 2 weeks. If the owners equally alternated bagging and mulching, the yards were recorded as 'mulched'.

A total of 23 yards were sampled with home ages spanning 1–51 years (Table 1). Sixteen yards were fertilized and 7 yards were non-fertilized. All 7 of the irrigated yards were also fertilized and all less than 14 years home age. Twelve yards were mulched and 11 yards bagged.

Table 1 Number of yards by home age (1–51 years) and yard maintenance practice

Home age (years)	Fertilized (# yards)	Non- fertilized (# yards)	Irrigated (# yards)	Non-irrigated (# yards)	Mulched (# yards)	Bagged (# yards)
0–2	1		1		1	
3–7	6	1	3	4	4	3
8–12	2	2	2	2	1	3
13–17	2		1	1	1	1
18–22	1			1		1
23–27	1			1	1	
28–32	1	1		2	1	1
33–37						
38–42	2			2	1	1
43–47		1		1	1	
48–52		2		2	1	1
Total	16	7	7	16	12	11

Statistical analysis

For each yard, we obtained mean soil C, soil N, bulk density, and percent clay, sand, and silt measurement for the 0–15 cm, 15–30 cm, and 30–50 cm depths. Regression analyses (SAS 9.1, SAS Institute Inc., Cary, NC, USA) were used to calculate the relationship between the soil C and home age, soil N, and soil texture. Regression analyses were also used to calculate the relationship between the soil N and home age and soil texture. A stepwise procedure was run with soil C as the dependent value and home age, soil N, % sand, % clay, % silt as the independent values. Because results from stepwise regression added complexity without improving the explanatory power of the model, we used simple linear regression models to analyze the data sets. We utilized the R^2 value instead of AIC in order to facilitate comparison with other research. A likelihood ratio F-test was used to establish whether the relationships between soil C and home age, and between soil N and home age, differed between fertilized and non-fertilized yards, between irrigated and non-irrigated yards, and between mulched and bagged yards. A Tukey's Studentized Range Test was performed using ANOVA (SAS 9.1, SAS Institute Inc., Cary, NC, USA) to determine if mean soil C, soil N, soil C:N ratio, bulk density, and soil texture differed by depth. We used ANOVA to examine whether soil C and N differed between the main effects of fertilized and non-fertilized yards, irrigated and non-irrigated yards, and mulched and bagged yards.

Results

Soil depth

Both soil C and N significantly decreased with depth (Table 2). In respect, soil C was roughly 2× to 4× greater at 0–15 cm than at the 15–30 cm and 30–50 cm depths. Soil N at 0–15 cm was 2× the values of the lower two depths. Bulk density was significantly less at 0–15 cm than the two lower depths. Additionally, % clay was significantly lower at 0–15 cm than at 15–30 cm and 30–50 cm depths while % sand was significantly greater at 0–15 cm than 30–50 cm depth. The soil C:N ratio significantly declined by over half from the first two depths to the lowest depth.

Home age

Soil C was positively related to home age in 0–15 cm depth (Fig. 1a). However, in 15–30 cm depth, soil C was negatively related to home age, and at 30–50 cm depth, soil C was stable across home age (Fig. 1b, c). Soil N was positively related to home age at the 0–15 cm depth, but had no relationship with home age at the 15–30 and 30–50 cm depths (Fig. 2). At 0–15 cm and 30–50 cm depths, the soil C:N ratio did not change with home age (P=0.43, P=0.42, respectively) while in the 15–30 cm depth, the soil C:N ratio declined slightly over home age (P=0.019, R^2=0.25, N=22, y=−0.20x+15.09). Soil C increased with soil N in the 0–15 cm depth, but remained stable across soil N levels in the two lower depths (Fig. 3).

Yard maintenance

The relationship between soil C and home age was not significantly different between fertilized and non-fertilized yards at 0–15 cm (P=0.30), 15–30 cm (P=0.19) and 30–50 cm (P=0.59) depths. Between irrigated and non-irrigated yards, the relationship between soil C and home age

Table 2 Mean soil C, soil N, soil C:N, bulk density, % sand, % clay, % silt are shown by depth. ± bound is the amount to give upper and lower boundary intervals for 90 % CI for the mean

	N	Mean ± (bound)
Soil C (kg m^{-2})		
0–15 cm	22	2.37 (0.27) a
15–30 cm	23	0.98 (0.11) b
30–50 cm	16	0.51 (0.10) c
Soil N (kgm^{-2})		
0–15 cm	22	0.18 (0.02) a
15–30 cm	23	0.09 (0.01) b
30–50 cm	19	0.09 (0.01) b
Soil C:N		
0–15 cm	20	13.12 (1.12) a
15–30 cm	22	11.40 (2.36) a
30–50 cm	11	5.16 (0.71) b
Bulk density (g m^{-3})		
0–15 cm	22	1.36 (0.42) a
15–30 cm	22	1.53 (0.04) b
30–50 cm	22	1.52 (0.05) b
% Sand		
0–15 cm	23	48.02 (3.84) a
15–30 cm	23	39.66 (5.52) ab
30–50 cm	23	37.18 (5.43) b
% Clay		
0–15 cm	23	23.74 (1.58) a
15–30 cm	23	32.50 (4.93) b
30–50 cm	23	34.43 (5.30) b
% Silt		
0–15 cm	23	28.17 (1.88) a
15–30 cm	21	26.46 (1.93) a
30–50 cm	23	28.41 (2.05) a

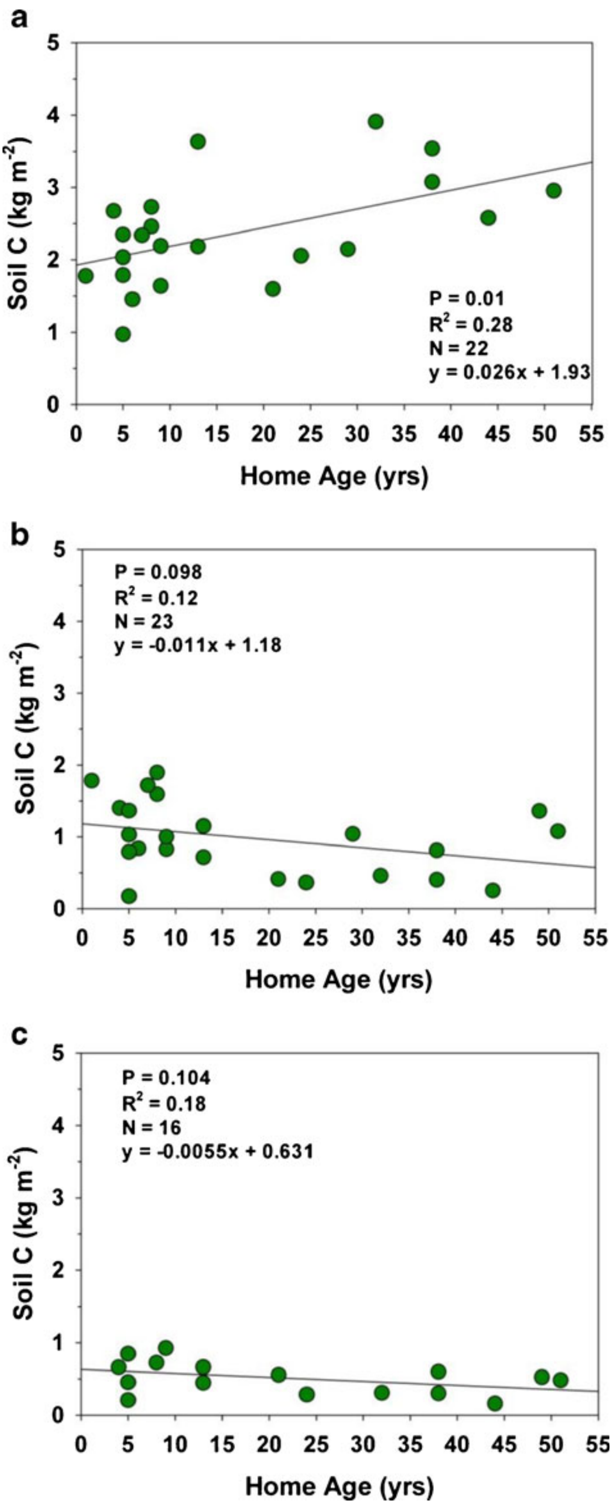
Different letters within a category indicate significant differences between depths at $\alpha \leq 0.10$. N = number of yards

was not significantly different at 0–15 cm depth (P=0.90) but was significantly different in 15–30 cm (P=0.08) and 30–50 cm (P=0.06) depths. However, in 15–30 cm depth, soil C was stable across home age in both irrigated (P=0.18, R^2=0.33, N=7, y=−0.07x+1.82) and non-irrigated (P=0.64, R^2=0.02, N=16, y=−0.003x+0.90) yards. Likewise, in 30–50 cm depth, soil C remained constant across home age in irrigated (P=0.39, R^2=0.25, N=5, y=−0.03x+0.92) and non-irrigated (P=0.97, R^2=0.0001, N=11, y=−0.0001x+0.42) yards. In 30–50 cm depth, soil C had a significantly different relationship with home age (P=0.04) between bagged yards, (P=0.02, R^2=0.62, N=8, y=−0.01x+0.85) and mulched yards, (P=0.79, R^2=0.01, N=8, y=−0.001x+0.44). At 0–15 cm and 15–30 cm depth, the relationship between soil C and home age was not significantly different between bagged and mulched yards (P=0.38, P=0.74, respectfully).

In addition, the relationship of soil N to home age was similar between fertilized and non-fertilized yards, irrigated and non-irrigated yards, and between mulched and bagged yards across all depths (data not shown).

Across all depths, mean soil C was similar between fertilized and non-fertilized yards and between mulched and bagged yards (Table 3). At 0–15 cm depth, mean soil C was similar

Fig. 1 Relationship of soil C (kg m^{-2}) to home age (1–51 years) at **a** 0–15 cm depth, **b** 15–30 cm depth, and **c** 30–50 cm depth



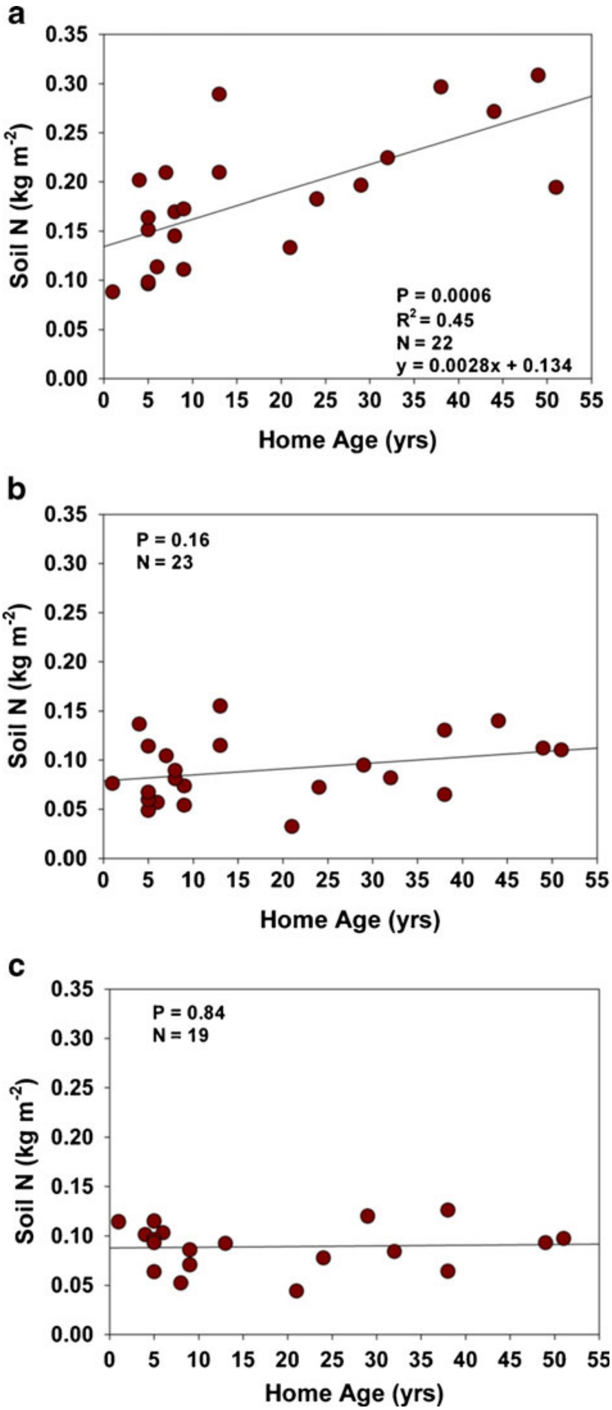


Fig. 2 Relationship of soil N (kg m^{-2}) to home age (1–51 years) at **a** 0–15 cm depth, **b** 15–30 cm depth, and **c** 30–50 cm depth

between irrigated and non-irrigated yards, but, at 15–30 cm and 30–50 cm depths, irrigated yards had greater mean soil C than non-irrigated yards. Mean soil N was similar between

Fig. 3 Relationship of soil C (kg m^{-2}) to soil N (kg m^{-2}) at **a** 0–15 cm depth, **b** 15–30 cm depth, and **c** 30–50 cm depth

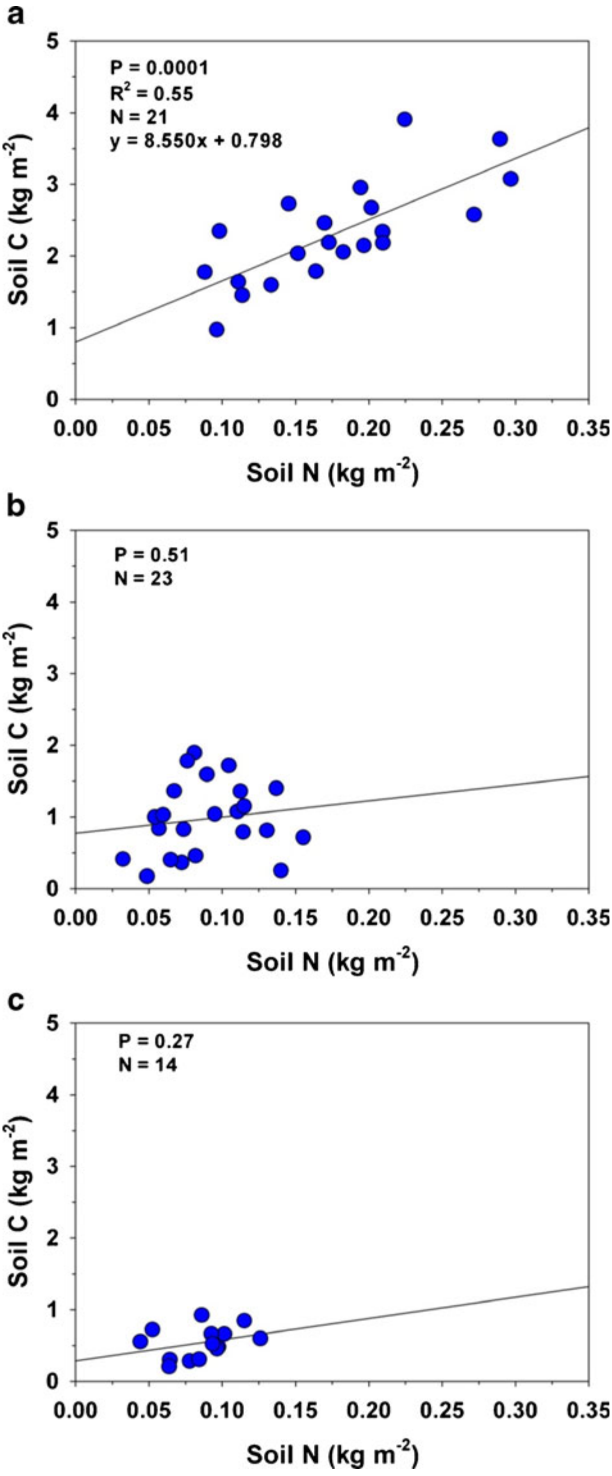


Table 3 Mean soil C (kg m^{-2}) ± (bound) across depths between fertilized and non-fertilized yards, irrigated and non-irrigated yards, and mulched and bagged yards. ± (bound) is the amount to give upper and lower boundary intervals for 90 % CI for the mean

Depth	N	Soil C ± (bound)	N	Soil C ± (bound)	Pvalue
		Fertilized		Non-Fertilized	
0–15 cm	16	2.36 (0.358)	6	2.40 (0.302)	0.91
15–30 cm	16	0.96 (0.234)	7	1.02 (0.276)	0.81
30–50 cm	12	0.54 (0.116)	4	0.41 (0.142)	0.30
		Irrigated		Non-Irrigated	
0–15 cm	7	2.16 (0.240)	15	2.47 (0.376)	0.38
15–30 cm	7	1.34 (0.313)	16	0.82 (0.187)	0.02*
30–50 cm	5	0.72 (0.143)	11	0.41 (0.087)	0.006*
		Mulched		Bagged	
0–15 cm	12	2.27 (0.319)	10	2.49 (0.463)	0.50
15–30 cm	12	0.90 (0.240)	11	1.06 (0.275)	0.44
30–50 cm	8	0.41 (0.109)	8	0.61 (0.139)	0.08*

Significant differences at $\alpha \leq 0.10$ between contrasting yard maintenance practices at the specified depth are indicated with an '*'. N = number of yards

fertilized and non-fertilized yards, irrigated and non-irrigated yards, and mulched and bagged yards (data not shown).

The percent clay, sand, or silt did not affect soil C and N at any depth (data not shown).

Discussion

Soil C sequestration rates

In Auburn's lawns, soil C accumulated in 0–15 cm depth but at a low rate, 0.026 kg C m^{-2} yr^{-1}, compared to other turfgrass/residential yard studies. Qian and Follett (2002) reported a soil C sequestration rate of 0.082 kg C $m^{-2}yr^{-1}$ for fairways and 0.091 kg C $m^{-2}yr^{-1}$ for putting greens at 0–11.4 cm depth in Midwest golf courses. In Ohio golf courses, Selhorst and Lal (2011) had sequestration rates of 0.264 kg C $m^{-2}yr^{-1}$for rough areas and 0.355 kg C $m^{-2}yr^{-1}$ for fairways at 0–15 cm depth. Depending on turfgrass species and irrigation regimes, Qian et al. (2010) measured sequestration rates at 0–20 cm depth for fine fescue, non-irrigated at 0.052 kg C $m^{-2}yr^{-1}$ and irrigated at 0.074 kg C $m^{-2}yr^{-1}$, and also Kentucky bluegrass (*Poa pratensis*) and creeping bentgrass (*Agrostis palustris*), both irrigated, at 0.032 kg C $m^{-2}yr^{-1}$ and at 0.078 kg C $m^{-2}yr^{-1}$, respectively. Overall, other than the 0.032 kg C $m^{-2}yr^{-1}$ sequestration rate reported by Qian et al. (2010), the remaining sequestration rates were approximately 2× to 13× greater at similar depths.

Furthermore, soil C sequestration rates in our study either declined or remained stable at 15–30 cm and 30–50 cm depths, and rates were stable in the 0–30 cm (P=0.88) and the 0–50 cm (P=0.96) depths. This contrasts with soil C increases in Colorado residential yards in Golubiewski (2006) in 10–20 cm and 20–30 cm depths and in Pouyat et al. (2009) who calculated a soil C sequestration rate of 0.016 kg C $m^{-2}yr^{-1}$ in the 0–30 cm depth. In a New

Zealand golf course, Huh et al. (2008) calculated a sequestration rate of 0.069 kg C $m^{-2} yr^{-1}$ in the 0–25 cm depth. In addition, both Pouyat et al. (2009) and Raciti et al. (2011) measured soil C increases at the 0–100 cm depth in Baltimore, MD.

Several reasons can be posited to explain our diminished or absent C accumulation over home age. One explanation could be the absence of tree biomass in our turfgrass dominated yards. Soil C levels are enhanced by organic matter from decaying roots, especially fine roots (Rasse et al. 2005; Trumbore et al. 2006; Persson 2012) and the addition of tree roots could impart additional SOC, especially in deeper soils compared to turfgrass dominated lawns. In temperate climates, a greater percentage of deciduous and evergreen tree fine root biomass is located deeper than grasslands (Jackson et al. 1997). However, Jobbágy and Jackson (2000) showed that forests have a greater percentage of SOC in 0–20 cm depth than grasslands. In addition, in residential yards in Colorado, soil C levels were not significantly different between tree or turfgrass cover sites (Golubiewski 2006). The relationship between soil C levels and vegetation cover has not been investigated in other soil C studies involving residential lawns, including Pouyat et al. 2002; Kaye et al. 2005; Smetak et al. 2007; Raciti et al. 2011, or golf courses, such as Qian and Follett 2002; Huh et al. 2008; Selhorst and Lal 2011. Thus, we cannot evaluate how soil C levels in our lawns would have responded to additions of tree root biomass.

In our study, a possible decline in turfgrass root biomass below 15 cm depth may have contributed to the lack of soil C accumulation. Zoysiagrass and bermudagrass were the most common turfgrass species found in our lawns. Bowman et al. (2002) measured root length density in two zoysiagrass species and reported declines of 74 % to 85 % from 5 cm to the 18 cm soil depth. In a drought resistance study, Carrow (1996) reported that Meyer zoysiagrass and bermudagrass had 98 % and 78–94 % of their respective root length biomass within the 0–20 cm depth. Bowman et al. (2002) grew zoysiagrass species in pure sand and Carrow (1996) grew turfgrass species in 67 % sand, and, in sandy soils, native grasses import more C to greater soil depths as compared to loamy soils (Gebhert et al. 1994). In our study, the ~33–34 % clay content below 15 cm may have limited transport of SOC. Additionally, the high bulk density found in the clay loam soil below 15 cm could have impeded root penetration. Daddow and Warrington (1983) stated that a bulk density >1.45 $g cm^{-3}$ in clay loam soils could severely limit root growth. Overall, soil conditions below 15 cm may have impeded root biomass growth and transport of SOC and thus limited soil C accumulation over 50 years. Also, the low soil C:N ratio in the 15–30 cm and 30–50 cm depths implied that the SOM was well decomposed and humified (Allison 1973; Tan 2003). This suggested that the soil C in the two lower depths may not strongly represent new organic matter inputs from turfgrass.

Climate conditions in Auburn could be another factor in the low soil C sequestration rates in comparison with studies from other regions of the US. Auburn experiences a humid, subtropical climate with MAT of 17 °C and MAP of 134 cm. Higher temperatures foster increased organic matter degradation and emission of C (Allison 1973). Jobbágy and Jackson (2000) and Burke et al. (1989) found a negative relationship between soil C and MAT and Burke et al. (1989) stated that the negative relationship may be due to the decomposition rate increasing faster than accumulation of soil C. In fertilized grasslands, Conant et al. (2001) reported that soil C had negative relationships with both MAT and MAP. Auburn's hot humid summers, mild winters, and abundant, year-round precipitation may have increased the decomposition rate such that the sequestration rate was reduced compared to cooler and/or drier climates.

Yard maintenance

Another difference between our study and other turfgrass/residential yard studies was the lack of a positive influence by fertilization, irrigation, and mulching on soil C as suggested by others (Pouyat et al. 2009; Qian and Follett 2002; Golubiewski 2006; Milesi et al. 2005). Possibly, the fertilization applications in our study were too low compared to turfgrass maintenance in golf courses and other residential yard studies. Our yard maintenance practices were separated into 'yes' or 'no' categories, and the 11 yards receiving fertilizer annually were grouped with the 5 yards fertilized multiple times a year. In addition, N supplements may be lost from Auburn's lawns through the effect of climate enhancing ammonification, leaching, or denitrification (Baligar and Bennett 1986). Possibly, the zoysiagrass and bermudagrass in Auburn's lawns may require more than annual fertilization to augment soil C sequestration.

In Alabama, suggested minimum maintenance for zoysiagrass is 10–20 g of actual N per square meter per year, applied across April, June, and August (Higgins 1998); however, maximum maintenance would require monthly applications of 29–39 g from April to September. Basic bermudagrass maintenance requires 5 g actual N per square meter April through August (Han and Huckabay 2008). Auburn's turfgrass lawns can survive with little or no annual fertilizer, however, without intensive N-additions, turfgrass may not produce the biomass to facilitate greater soil C accumulation.

Similar to fertilization, we expected irrigation to stimulate soil C accumulation. All 7 of the irrigated yards were also fertilized and were < 14 years old and at 15–30 cm and 30–50 cm depths, mean soil C was greater in irrigated yards compared to non-irrigated yards. If irrigation plus fertilization positively influenced soil C sequestration, the response would show over time, but, soil C was stable, in all depths, across the 13 years of home age for irrigated yards (data not shown). Consequently, the greater soil C in 15–30 cm and 30–50 cm depths could not be attributed to irrigation plus fertilization but, possibly, to greater initial soil C levels. However, our interpretation of the relationship between soil C and irrigation was ultimately limited by the small sample size and restricted home age range and remains tenuous at best.

Surprisingly, soil C in bagged yards at 30–50 cm depth was greater than mulched yards. Given the significant decline in soil C and the low soil C:N ratio at 30–50 cm depth, the soil C in the bagged yards may be related to conditions occurring prior to, or during, home construction.

Soil C vs. soil N

A similarity between this study and those of Golubiewski (2006) and Raciti et al. (2011) was the strong positive relationship between soil C and soil N. In Auburn's lawns, the most positive relationship soil C had was with soil N and occurred in the 0–15 cm depth. The strength of the relationship between soil C and N may depend upon the accumulation of new organic matter, as seen in the absence of this relationship at the 15–30 and 30–50 cm depths and lack of accumulation of soil C and N at these depths.

Soil C vs. soil texture

In our study, soil C and soil N had no relationship with percent clay, sand, or silt. Climates with high MAT and MAP may have a greater effect on soil C storage than clay content (Homann et al. 2007; Six et al. 2002). In fertilized grasslands, the soil C sequestration rate was not influenced by soil texture but was negatively associated with MAT and MAP (Conant et al. 2001). In general, the humid, subtropical climate of Auburn may have enhanced decomposition to an extent that limited the protective effect of clay minerals on organic matter.

Conclusions

Four of the potential drivers for soil C investigated in this study were home age, yard maintenance, soil N, and soil texture. Soil C had a positive relationship with home age at the 0–15 cm depth, a negative relationship at 15–30 cm depth, and no relationship at 30–50 cm depth. The low sequestration rate at 0–15 cm depth may have resulted from a positive influence of climatic variables on decomposition. At the 15–30 and 30–50 cm depths, the absence of soil C accumulation may have resulted from shallow turfgrass rooting. Soil C had a positive relationship with soil N at 0–15 cm depth, but no relationship at lower depths. Yard maintenance did not influence soil C levels, possibly due to minimal fertilizer applications and small sample size for irrigated yards. Soil C had no relationship with soil texture, possibly due to stronger influence by climatic variables.

The influence of time, yard maintenance, soil N and soil texture on soil C was limited or insignificant. Climatic variables and the legacy of soil C were two potential drivers that were not measured and may have had a stronger influence on soil C levels. The lower than expected sequestration rates reported in this study highlight the complexity of mechanisms influencing accumulation of soil C in residential lawns and other turfgrass dominated landscapes. To validate soil C models, additional work is needed to explore soil C dynamics across climatic regions, soil legacies, and the potential influence of tree root biomass for augmenting soil C sequestration rates.

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