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Influence of aboveground tree biomass, home age, and yard maintenance on soil carbon levels in residential yards

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Abstract With the rapid urbanization of natural lands, researchers have begun to examine the capacity of urban soils to store carbon (C), with recent attention to residential yards. We performed a case study to examine four potential influences on soil C levels in residential yards. In 67 yards containing trees, we examined the relationship of soil C (kg m^{-2}) to tree aboveground biomass, home age (3–87 years), yard maintenance (fertilization, irrigation, mulching or bagging lawn clippings), and soil texture (% clay, % sand, % silt), at three depths (0–15 cm, 15–30 cm, and 30–50 cm). Six tree aboveground biomass data sets were developed: 1) biomass, 2) biomass*(1/distance from tree), 3) biomass$\leq$15 m from sample site, 4) biomass$\leq$10 m, 5) biomass$\leq$5 m, and 6) biomass$\leq$4 m. Biomass$\leq$5 m and biomass$\leq$4 m had the greatest explanatory power for soil C at 30–50 cm depth (P=0.001, R^2=0.28; P=0.05 R^2=0.39, respectively). The relationship between soil C and home age was positive at 0–15 cm (P=0.0003, R^2=0.19), but constant at the two lower depths. Yard maintenance had no significant influence on soil C levels across home age. At 0–15 cm, soil C increased with % silt (P=0.006, R^2=0.12). Overall, trees in turfgrass yards may have a stabilizing effect on soil C levels below 15 cm but minimal influence above 15 cm.

Keywords Soil carbon · Residential yards · Aboveground tree biomass · Home age · Yard maintenance

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Introduction

Metropolitan populations and urban land area in the United States are rapidly increasing (Alig et al. 2004; Auch et al. 2004). Trees within urban green spaces are either remnants from prior non-urban lands or have been established since urbanization. These trees and their associated resources comprise urban forests and are located along streets and within residential yards, business and institution lawns, golf courses, parks, and cemeteries (Nowak et al. 2001). The importance of urban forests can be expressed in the wide range of ecosystem services they provide. Urban forests can filter out air pollution (Freer-Smith et al. 2004; Fuller et al. 2009), improve water drainage (Sanders 1986; Bartens et al. 2008), provide shade and reduce energy use (Rudie and Dewers 1984; Pandit and Laband 2010), and store atmospheric carbon (Jo and McPherson 1995; Escobedo et al. 2010). Zhang et al. (2012) estimated that 1.72 Pg C was stored in the urbanized lands of the southern U.S. in 2007, with 64 % of the C in the soil. Urban forests have accumulated higher soil organic carbon (SOC) levels than neighboring rural forests in Baltimore, MD (Pouyat et al. 2009; Raciti et al. 2011), and also greater SOC levels than neighboring agricultural systems (Kaye et al. 2005) and shortgrass steppe (Golubiewski 2006) in Colorado. In urban areas, residential land occupies the largest area, approximately 41 % (Nowak 1996), and by 2005, urban plus rural residential lands covered 7 % of all U.S. land area (Lubowski et al. 2006).

In residential yards with turfgrass, detritus from aboveground tree biomass would mostly be removed from the lawns, and thus, unlike natural forests, the addition of tree organic matter to soil would come primarily from belowground biomass. Belowground biomass is often estimated from aboveground biomass by application of a root:shoot (R:S) ratio which is developed by measuring the above- and below-ground biomass of harvested trees, typically from plantations or natural forests (Ritson and Sochacki 2003; Peichl and Arain 2007). Because roots are a major contributor to the soil C pool (Fahey and Hughes 1994; Russell et al. 2007), data are needed to discern the influence of tree roots on soil C levels, especially in urban forests.

The time span of soil C accumulation in residential yards is often represented as the period since home construction, or home age (Scharenbroch et al. 2005). At present, research involving continuous annual measurements of soil C levels for a decade or more in the same urban areas has not been conducted. Chronosequences are a collection of land based experimental units that contain a range of ages and are used when the time span under investigation is greater than the time the researchers can spend on the project (Walker et al. 2010). Chronosequences are well suited to provide information on well-known ecological processes, such as the soil C cycle (Amundson 2001). Chronosequences of urban areas, such as golf courses (Qian and Follett 2002; Huh et al. 2008; Selhorst and Lal 2011) and residential yards (Golubiewski 2006; Smetak et al. 2007; Pouyat et al. 2009; Raciti et al. 2011), have been used to assess soil C levels across different time spans after construction. In Chicago, IL, residences>40 years old had significantly higher SOC levels than those<35 years old (Pouyat et al. 2009). In Colorado's Front Range, lawns<7 years old had significantly lower SOC concentrations at 0–10 cm depth than older lawns, and SOC concentrations at 10–20 cm and 20–30 cm depths were significantly lower in yards younger than 25 years compared to yards older than 25 years (Golubiewski 2006).

The accumulation of SOC in urban lawns may be amplified by yard maintenance practices such as fertilization and irrigation (Milesi et al. 2005; Smetak et al. 2007; Huh et al. 2008; Selhorst and Lal 2011) and the return of mowed turfgrass clippings into the lawn (Qian et al. 2003). In Baltimore, MD, land uses that typified more intensive yard maintenance regimes, i.e. institutional and low-density residential zones, had the greatest SOC levels (Pouyat et al.

2002). Fertilization and irrigation practices were proposed as a factor that increased SOC levels in Colorado lawns over nearby grassland levels (Golubiewski 2006) and increased SOC levels in lawns in Baltimore, MD, over nearby forest levels (Raciti et al. 2011).

Soil C levels may also be influenced by the percent composition of clay, sand, and silt particles (Oades 1988). The high surface area of clays and silts provide more area for chemical binding than sand and these chemical bindings can protect organic C compounds from oxidation (Saggar et al. 1996; Six et al. 2002). Also, soil microaggregates formed from interactions between clay and silt particles, roots, mico-organisms, cations, and organic matter can limit access of decomposers to the organic matter shielded within (Oades 1988). Clay content in particular has been linked to greater levels of SOC (Nichols 1984; Jobbágy and Jackson 2000; Homann et al. 2007). In addition to providing information about potential influences on soil C levels, soil texture analysis also provides information on the basic soil particle composition for each yard, which is necessary given the varying and often unknown yard construction techniques.

Our goal was to examine four variables located within or attributed to residential yards that may influence soil C levels: tree aboveground biomass, home age, yard maintenance practices, and soil texture. We performed a case study using a chronosequence of 67 lawns containing trees, with home ages from 3 to 87 years, with a range of lawn maintenance regimes and soil textures. Information about the relationship of soil C to these four variables would enhance our present knowledge of urban soil C dynamics.

We tested four hypotheses:

1) Soil C levels would be positively related to tree aboveground biomass
2) Soil C levels would increase with home age
3) Soil C would have a more positive relationship with home age in lawns that were fertilized, irrigated, or mulched compared to lawns absent supplements
4) Soil C would increase with % clay.

Methodology

Site

Our study was performed within the city of Auburn, located in east central Alabama, in Lee County abutting the Georgia border (latitude 32.6°N longitude 85.5°) (U.S. Census Bureau 2009) at an altitude of 210 m (689 ft) (U.S. Climate Data 2011). The soils of Alabama are dominated by Udults, a well-drained Ultisol with base saturation greatest at surface soil layers though still less than 35 % (USDA NRCS 2009). Auburn straddles the fall line between the Piedmont Plateau and Coastal Plains soils (McNutt 1981). Piedmont Plateau soils have a sandy loam or clay loam surface layer and a red clayey subsoil and Coastal Plain soils have a sandy loam or loam surface layer with either a loamy or clayey subsoil (Mitchell 2008). The climate is humid, subtropical (Chaney 2007) with a mean low temperature of 11.6 °C (52.8 °F), mean high temperature of 23.3 °C (74 °F), and mean annual temperature (MAT) of 17.4 °C (63.4 °F) (U.S. Climate Data 2011). From 1976 to 2011, the mean annual precipitation (MAP) was 127.8±21.8 cm (50.3±8.6″) (Rodger R. Getz, AWIS Weather Services, Inc., personal communication).

Yard selection and characteristics

Soil was sampled in 67 single family homes and U.S. Department of Housing and Urban Development duplexes in spring/summer 2009 and 2010. The requests for permission to sample soils in yards were delivered to various individuals and organizations either in person, by email, or by placing the request on their front door.

All 67 homes contained 1 to 25 trees, located within tree distance requirements. In the residential yards, zoysia grass (*Zoysia spp.*) and Bermuda grass (*Cynodon dactylon*) were the most common turfgrass species. Home age data were obtained from the city of Auburn Planning Commission (Justin Steinmann, personal communication) and the Lee County Courthouse, Opelika, AL.

Soil sampling and processing

Front lawns were selected for ease of access because back yards were more often used by owners and pets. Within the front yard, we avoided sampling near sidewalks, driveways, roads, buildings and other buried construction objects as well as pipes and cables (i.e., irrigation, gas, water, sewer, home security, electric), protruding woody roots and rocks, and within areas devoid of grass (i.e., heavy use). Within the sampling constraints of each yard, a single meter square plot was placed on the front lawn in an “arbitrary but without preconceived bias” manner (McCune and Grace 2002). Two soil cores were removed from each corner of the meter square plot. One core provided soil samples for soil C and nitrogen (N) analysis and the second core, collected<8 cm away from the first core, was used to determine both bulk density and soil texture. For every core, we sampled at 3 depths: 0–15 cm, 15–30 cm, and 30–50 cm, thus producing a total of 4 C, 4 N, and 4 soil texture samples per depth. The soil probe was a 2.9 cm×61 cm (1 1/8″ x 24″) slotted chrome plated AMS soil recovery probe (AMS, Inc., American Falls, ID) with a diameter of 2.2 cm (7/8″). The soil samples for soil C and N analysis were dried in an oven 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. The soil texture samples were oven-dried at 100 °C for 3 days to remove all moisture.

Carbon and nitrogen analysis

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

Bulk density

Bulk density was calculated by dividing the mass (g) of the fine soil (< 2 mm) by its volume (cm^3). The mass and volume of roots and rocks removed by the 2 mm mesh were subtracted from the mass and volume of the total soil core. The volume of the rocks/roots was obtained by suspending them in water and recording the weight of the water displaced. Soil C and N content (g cm^{-2}) was the product of bulk density and soil C or N concentration.

Soil texture

Soil texture was analyzed by using 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 ($NaPO_3$) x Na_2O and sodium carbonate (Na_2CO_3) dissolved in 1 L distilled water. A small amount of water was added to the soil solution to provide sufficient liquid to disperse soil clods. The soil solution was mixed by a commercial mixer for 5 min and then the solution was placed in a 1 L glass cylinder and brought to volume. The cylinder was corked and the solution shaken for 1 min. Immediately afterwards, a hydrometer was placed in the solution and read after 40 s of settling time. The 1 min shaking of the cylinder solution was repeated and followed by a second hydrometer reading and a recording of the solution temperature. After 24 h, hydrometer and temperature readings were repeated on the resting solution.

Tree aboveground biomass

Because tree roots may have extended into our sample yard from trees in neighboring lawns, we used distance to determine which trees to measure. As tree root presence has been approximated to extend at least 1.5×height of tree (Sudmeyer et al. 2004), we measured only those whose location from the meter square plot was<1.5×height of tree and whose location was unobstructed by roads and buildings. All trees were identified to species and measured for diameter at breast height (dbh, 1.37 m), total height, and distance from center of the plot. The most populous tree species was loblolly pine (*Pinus taeda*) at 28 % of the total number of trees, followed by sweetgum (*Liquidambar styraciflua*) at 10 %, red maple (*Acer rubrum*) at 9 %, and water oak (*Quercus nigra*) at 7 %. Of the individual trees, 34 % were *Pinus* spp., 14 % were *Acer* spp. and 13 % were *Quercus* spp. The remainder encompassed various native and ornamental tree species.

Brantley (2008) provided the biomass algorithms for Chinese privet (*Ligustrum sinense*), $y = 0.1214x^{2.4919}$, with 'x' as dbh (cm) and 'y' as biomass (kg). We applied the Chinese privet algorithm to crape myrtle (*Lagerstroemia spp.*): one yard contained crape myrtle. All remaining tree biomass algorithms were obtained from Jenkins et al. (2003) and used the equation: $total\ aboveground\ biomass = Exp(\beta_0 + \beta_1\ ln\ dbh)$, with β_0 and β_1 as parameters for each species group. Individual tree biomass, for each yard, was multiplied by 0.8 because "open-grown" urban trees develop less biomass than non-urban forest trees (Nowak 1994). Out of all the tree species in our yards, only loblolly pines had a relatively comprehensive set of R:S ratios developed for a range of tree dbhs (Monk 1966; Bongarten and Teskey 1987; Naidu et al. 1998). However, neither loblolly pines nor the other tree species had R:S ratios developed specifically for urban settings. Because estimating belowground biomass from aboveground biomass would therefore have necessitated using a general R:S ratio constant, we retained our aboveground biomass measurements as a surrogate variable to assess the relationship between tree belowground biomass and soil C.

Five tree aboveground biomass data sets were developed in case the relationship between biomass and soil C changed in accordance with distance from the bole of the tree. One biomass data set was developed by multiplying the biomass of individual trees by the reciprocal of the tree's distance from the center of the meter square plot (1/distance). This had the effect of decreasing the biomass as distance increased from the stem. Four additional biomass data sets were constructed using only trees that were$\leq$15 m, $\leq$ 10 m, $\leq$ 5 m, and$\leq$4 m from center of meter square plot. The biomass$\leq$4 m data set was created to determine if a difference of 1 m would be observable in the relationship of biomass with soil C and N. Further analysis at distances≤3 m could not be performed due to sample size limitations. A total of six tree aboveground biomass data sets were developed: biomass, biomass*(1/distance), biomass≤15 m, biomass≤10 m, biomass≤5 m, and biomass≤4 m.

Yard maintenance

Home owners were asked about their yard maintenance practices (i.e., fertilization, irrigation, and the bagging or mulching of lawn clippings). As most residents did not remember the exact frequency or amount of fertilization or irrigation, fertilization was categorized as 'yes' if they fertilized at least once a year and irrigation as a 'yes' if they watered the lawns regularly at least once every 2 weeks. If the owners equally alternated bagging and mulching, the yards were recorded as 'mulched'; two yards were consistently bagged or mulched every other mowing. The majority of yards older than 20 years were non-fertilized, non-irrigated, and the mown clippings were mulched into the lawn (Fig. 1a, b and c). Overall, 47 % the yards were fertilized, 22 % of the yards were irrigated, and 61 % were mulched.

Statistical analysis

For each yard, we obtained tree aboveground biomass and mean soil C, soil N, bulk density, % clay, % sand, and % silt for 0–15 cm, 15–30 cm, and 30–50 cm depths. A Tukey's Studentized Range test was performed using Analysis of Variance (ANOVA, SAS 9.1, SAS Institute Inc., Cary, NC, USA) to determine if mean soil C and N, soil C:N, bulk density, and soil texture differed by depth. Regression analyses (SAS 9.1, SAS Institute Inc., Cary, NC, USA) were conducted to calculate the relationship between soil C and tree aboveground biomass data sets, home age, soil texture, and soil N and also between soil N and tree aboveground biomass data sets, home age and soil texture.

Regression analyses were used to assess the relationship of soil C to home age within a series of paired younger and older home age classes. All "young" home age classes began with the youngest home age of 3 years, and the first home age class was 3–16 years, the earliest "young" age group to contain≥10 yards. The 3–16 years age group was paired with the first "old" age group, 17–87 years. All "old" age classes would end with the oldest home age of 87 years. The "young" home age class then progressed by adding 5 years to the group, from 3–20 years to 3–55 years while the paired "old" home age class simultaneously reduced 5 years from its group, from 21–87 years to 56–87 years, ending with 56–87 years because that was the last "old" home age group to contain≥10 yards. The 5 years interval, after 3–20 years, was chosen because it was the smallest repeatable home age span that fit between 3 years and 87 years and had all home age groups containing≥10 yards.

An ANOVA procedure was used to determine if mean soil C and soil N levels differed between yards with contrasting yard maintenance practices, i.e. fertilized vs. non-fertilized, irrigated vs. non-irrigated, mulched vs. bagged. Regression analyses were performed to discern the influence of each yard maintenance practice across all soil depths on the relationships between soil C and home age, between soil N and home age, between soil C:N and home age, and between soil C and soil N. A likelihood ratio test was used to determine whether those relationships differed between contrasting yard maintenance practices. In case the influence of yard maintenance on soil C may differ depending upon whether the yard is 'young' or 'old', regression analyses were used to ascertain the relationships of soil C at 0–15 cm depth to home age within a younger (3–36 years) home age class and an older (37–87 years) home age class within each yard maintenance practice. A likelihood ratio test was then used to discern whether the relationship of soil C at 0–15 cm depth to home age across 3–36 years home age and across

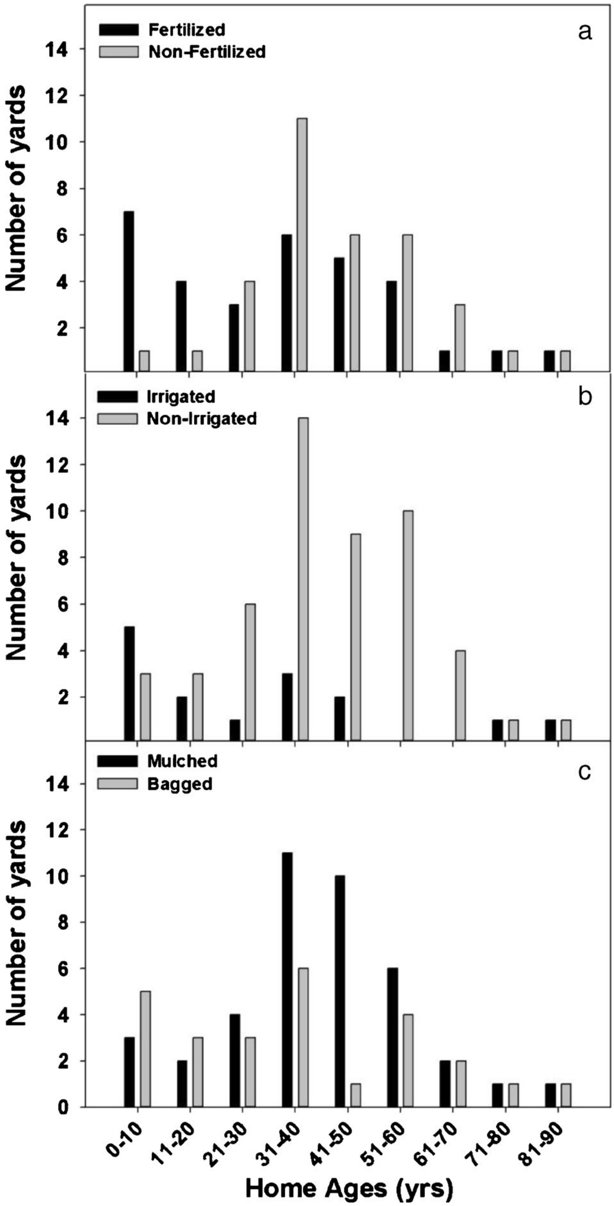

Fig. 1 The number of yards by maintenance practices across home ages (3–87 years): (**a**) fertilized and non-fertilized, (**b**) irrigated and non-irrigated, and (**c**) mulched and bagged

37–87 years home age differed between contrasting yard maintenance practices, e.g. soil C in mulched vs. bagged yards across 3–36 years. Only soil C at 0–15 cm depth was analyzed due the surface soil layer receiving the prevalence of influence from yard maintenance. The 3–36 years home age class was used because that age group was the youngest to contain≥ 10 yards within all yard maintenance practices. Within the 37–87 years home age class, irrigated yards had< 10 yards, and as such, regression analyses were not performed on irrigated or non-irrigated yards within that age class. In all regression and ANOVA analyses, the number of yards may be <67 due to removal of yards containing outliers, and differences and relationships were considered significant when $\alpha=0.10$.

Results

Soil characteristics

Soil C and the soil C:N ratio declined with each successive depth and soil N declined from 0–15 cm depth to the two lower depths (Table 1). The two lower depths had greater bulk density than the 0–15 cm depth. Percent sand declined from 0–15 cm depth to the two lower depths, % clay increased with each successive depth, and % silt did not differ significantly between depths. The % clay or % sand did not influence soil C at any depth (data not shown). In

Table 1 Mean ± (bound) for soil C (kg m^{-2}), soil N (kg m^{-2}), soil C:N ratio, bulk density (g m^{-3}), % sand, % clay, and % silt by depth

	N	Mean ± (bound)
Soil C (kg m^{-2})		
0–15 cm	66	3.25 (0.21) a
15–30 cm	63	1.03 (0.10) b
30–50 cm	60	0.74 (0.08) c
Soil N (kg m^{-2})		
0–15 cm	63	0.20 (0.01) a
15–30 cm	67	0.08 (0.007) b
30–50 cm	64	0.08 (0.007) b
Soil C:N		
0–15 cm	62	16.68 (0.82) a
15–30 cm	60	13.94 (1.31) b
30–50 cm	53	9.79 (1.11) c
Bulk Density (g m^{-3})		
0–15 cm	67	1.33 (0.02) a
15–30 cm	67	1.53 (0.02) b
30–50 cm	67	1.53 (0.03) b
% Sand		
0–15 cm	67	50.3 (2.32) a
15–30 cm	67	43.5 (2.96) b
30–50 cm	67	38.8 (3.22) b
% Clay		
0–15 cm	67	20.8 (1.64) a
15–30 cm	67	28.1 (2.43) b
30–50 cm	67	32.2 (2.78) c
% Silt		
0–15 cm	62	28.6 (0.85) a
15–30 cm	66	28.2 (1.02) a
30–50 cm	63	28.5 (0.90) a

± (bound) is the amount to give upper and lower boundary intervals for 90 % confidence intervals for the mean

Statistical difference within a category and between depths is indicated by different lowercase letters

N number of yards

0–15 cm, soil C increased with % silt ($P=0.006$, $N=61$, $R^2=0.12$, $y=0.085x+0.79$) but soil C was stable across % silt in 15–30 cm and 30–50 cm (data not shown).

Soil C and soil N across tree biomass

The relationships between soil C and the biomass, biomass*(1/distance), and biomass≤10 m variables had similar patterns across depths: stable soil C at 0–15 cm, significant increases at 15–30 cm and 30–50 cm, and the highest R^2 values at 30–50 cm (Table 2). Across all depths, soil C increased with the biomass≤5 m variable, with the explanatory power also increasing with depth. Despite having no significant relationship with soil C in the top two surface soil layers, the biomass≤4 m data set exhibited the greatest explanatory power for soil C at 30–50 cm compared to all other biomass data sets. Interpretation of the difference in R^2 values between biomass≤5 m and biomass≤4 m data sets for soil C at 30–50 cm must be made with caution, as the latter had only 10 yards compared with the 35 yards of the former. The only significant relationships soil N had with biomass variables were with biomass≤5 m in 15–30 cm depth ($P=0.07$, $N=39$, $R^2=0.09$, $y=0.000010x+0.08$) and with biomass≤4 m in 0–15 cm depth ($P=0.07$, $N=10$, $R^2=0.35$, $y=0.005x+0.15$).

Soil C and soil N across home age

Soil C demonstrated a significant positive relationship to home age at 0–15 cm depth (Fig. 2a) but exhibited no relationship with home age at 15–30 cm and 30–50 cm depths (Fig. 2b and c). Soil N remained stable across home age at all depths (Fig. 3) and across 0–30 cm ($P=0.42$) and 0–50 cm ($P=0.99$). The relationship between soil C:N and home age was significant and positive across all depths (P values<0.06) with R^2 values spanning 0.06–0.12. The relationship between soil C and soil N was also significant and positive across all depths (P values<0.0001) with R^2 values of 0.36, 0.41, and 0.26 with increasing depth.

Soil C across home age classes

Soil C had significant positive relationships with home age in 0–15 cm depth across the "young" home age groups, except for the 3–16 years and 3–30 years groups (Table 3). The slope declined by approximately 50 % between 3–25 years and 3–35 years. For the corresponding paired "old" home age groups that started with 17–87 years and progressed to 56–87 years, no significant relationship occurred between soil C and any "old" home age group, with P values ranging from 0.23 to 0.96 (data not shown). Soil C in 15–30 cm and 30–50 cm depths had no relationships with either "young" or "old" home age groups (data not shown).

Yard maintenance

Mean soil C was greater at 0–15 cm and 30–50 cm in non-irrigated compared to irrigated yards (Table 4). Both mean soil C and N were greater at 0–15 cm in mulched compared to bagged yards (Tables 4 and 5). However, the relationships of soil C with home age, soil N with home age, and soil C:N with home age, were not significantly different between fertilized and non-fertilized yards, between irrigated and non-irrigated yards, and between mulched and bagged yards across all depths (data not shown). The relationship of soil C with soil N was not significantly different between fertilized and non-fertilized yards or between irrigated and non-irrigated yards at any depth. Soil C did have a different relationship with soil N at 30–50 cm

Table 2 Linear regression analysis of soil C (kg m^{-2}) to tree aboveground biomass (kg) data sets across depths with corresponding median values for aboveground tree biomass, # trees, dbh, and distance from trees

	P value	R^2	N	Slope (×10^{-4})	Median Biomass (kg)	Median # Trees	Median Dbh (cm)	Median Distance (m)
Biomass								
0–15 cm	0.11	0.05	54	0.62	2113	3	5.57	7.54
15–30 cm	0.03*	0.09	52	0.38	2042	3	5.51	7.54
30–50 cm	0.02*	0.12	49	0.32	2050	3	5.54	7.92
Biomass*(1/distance)								
0–15 cm	0.22	0.03	56	4.09	287	3	5.66	8.00
15–30 cm	0.03*	0.09	54	3.50	210	3	5.54	8.00
30–50 cm	0.005*	0.15	51	3.35	248	3	5.63	8.46
Biomass≤15 m								
0–15 cm	0.05*	0.07	56	0.87	1696	2	5.27	7.10
15–30 cm	0.22	0.03	54	0.27	1390	2	5.23	7.10
30–50 cm	0.15	0.04	51	0.24	1456	2	5.24	7.10
Biomass≤10 m								
0–15 cm	0.20	0.03	53	1.10	927	2	5.16	6.00
15–30 cm	0.06*	0.07	51	0.81	773	2	5.00	6.00
30–50 cm	0.01*	0.13	48	0.80	850	2	5.11	6.00
Biomass≤5 m								
0–15 cm	0.04*	0.11	38	3.10	337	1	4.27	4.00
15–30 cm	0.04*	0.12	36	1.70	274	1	4.06	4.00
30–50 cm	0.001*	0.28	35	1.64	309	1	4.35	4.00
Biomass≤4 m								
0–15 cm	0.16	0.19	12	656.00	11	1	6.88	3.00
15–30 cm	0.91	0.001	12	27.60	11	1	6.88	3.00
30–50 cm	0.05*	0.39	10	276.60	11	1	6.88	3.00

A significant relationship is marked with an '*'

N number of yards

depth ($P=0.07$) between mulched yards ($P<0.0001$, $N=38$, $R^2=0.39$, $y=8.47x+0.12$) and bagged yards ($P=0.16$, $N=21$, $R^2=0.10$, $y=2.81x+0.46$).

Soil C across home age classes

In yards≤36 years old and in 0–15 cm depth, the response of soil C to home age was significantly different ($P=0.06$) between mulched and bagged yards. In mulched yards, soil C increased with home age ($P=0.02$, $N=11$, $R^2=0.46$, $y=0.080x+1.23$) while in bagged yards, soil C remained stable across home age ($P=0.67$, $N=14$, $R^2=0.02$, $y=0.006x+2.45$). In mulched and bagged yards≥37 years old, the relationship of soil C to home age was not significantly different ($P=0.22$). No differences in soil C across home age in 0–15 cm depth were found between fertilized yards and non-fertilized yards when yards were≤36 years old or≥37 years old (data not shown). Likewise, in yards≤36 years old, the relationship between soil C and home age in 0–15 cm depth did not differ between irrigated yards and non-irrigated

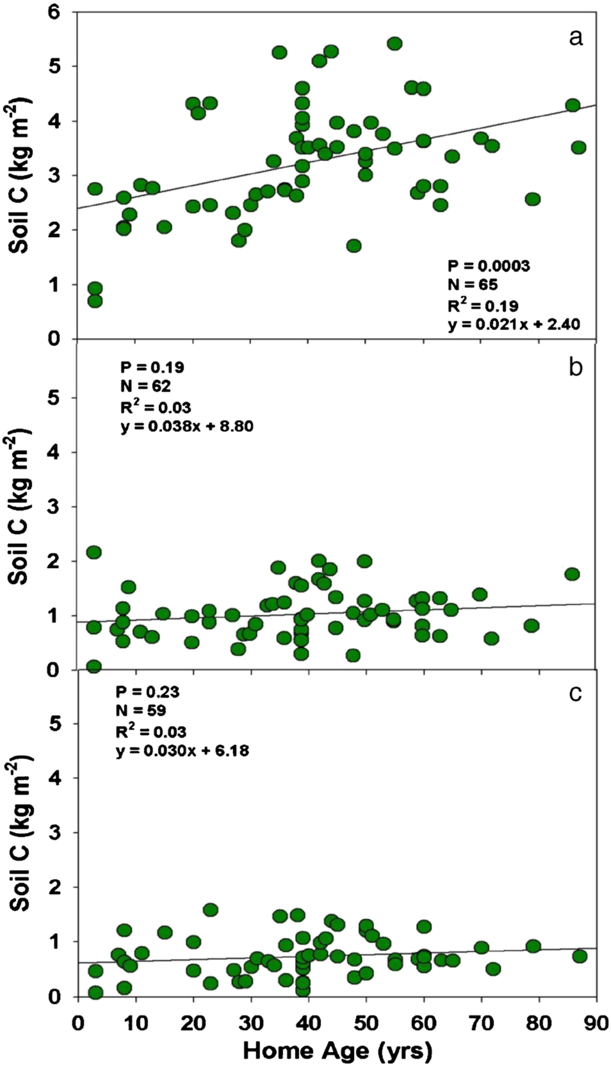

Fig. 2 Relationship of soil C (kg m^{-2}) to home age (3–87 years) at depths: (**a**) 0–15 cm, (**b**) 15–30 cm, (**c**) 30–50 cm

yards. Due to limited sample size for irrigated yards, no comparative analysis could be performed for yards≥37 years old.

Discussion

In our turfgrass lawns, the relationship between tree aboveground biomass and soil C levels would be connected directly through belowground biomass. Regarding our first hypothesis, we expected the connection to be direct enough to observe a substantial significant relationship between soil C levels and tree aboveground biomass. However, the explanatory power of the

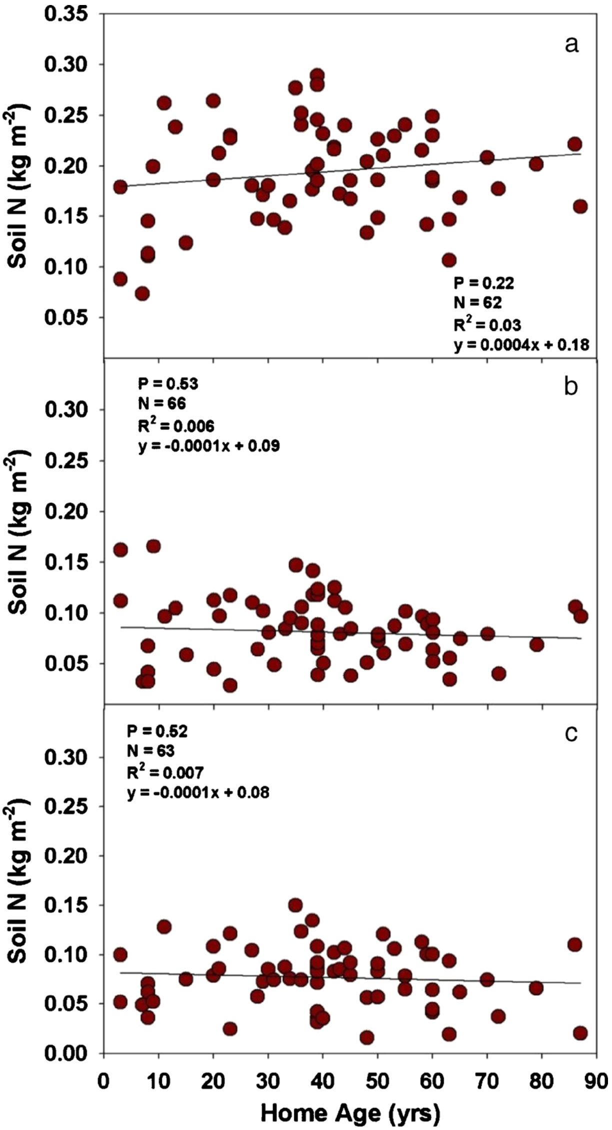

Fig. 3 Relationship of soil N (kg m^{-2}) to home age (3–87 years) at depths: (**a**) 0–15 cm, (**b**) 15–30 cm, (**c**) 30–50 cm

biomass data sets was relatively low, indicating a preponderance of influence from other factors affecting soil C levels. Given that biomass exhibited greater explanatory power and greater number of significant soil C relationships below 15 cm, while soil C increased with home age only at 0–15 cm, turfgrass may have a greater influence on soil C levels at 0–15 cm and tree root biomass may play more of a role in maintaining soil C levels below 15 cm. At 30–50 cm depth, distance between sample site and tree stem may influence the strength of the relationship between tree aboveground biomass and soil C, but at that depth, the amount of soil C input matched the amount of soil C output for 84 years. The stable soil C levels and low C:N

Table 3 Linear regression analyses of soil C (kg m^{-2}) in 0–15 cm depth across a progression of "young" home age groups (yrs)

Home age group	*P* value	R^2	Slope	N
3–16	0.12	0.28	0.094	10
3–20	0.020*	0.43	0.102	12
3–25	0.0028*	0.51	0.104	15
3–30	0.14	0.12	0.036	19
3–35	0.02*	0.22	0.046	23
3–40	0.0003*	0.32	0.044	36
3–45	<0.0001*	0.39	0.049	42
3–50	0.0001*	0.28	0.038	47
3–55	<0.0001*	0.33	0.040	51

Significant relationships indicated with an '*'

N number of yards

All "young" home age groups begin with the youngest home age of 3 years

ratios indicated that the level of fresh organic matter input was negligible (Fontaine et al. 2007) and that the organic matter was mostly well-decomposed (Allison 1973), possibly representative of vegetation prior to home construction.

The conjunction of low explanatory power of biomass for soil C and the stable soil C levels below 15 cm depth suggest that tree aboveground biomass may be a poor surrogate for belowground biomass. The variable nature of urban soils may have altered estimated root growth patterns such as the relationship between horizontal root length and tree height (Day et al. 2010). However, even if estimated aboveground biomass was an accurate representative

Table 4 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

Depth	N	Soil C ± (bound)	N	Soil C ± (bound)	*P* value
		Fertilized		Non- Fertilized	
0–15 cm	31	3.08 (0.34)	35	3.40 (0.24)	0.21
15–30 cm	30	1.09 (0.16)	33	0.98 (0.12)	0.32
30–50 cm	27	0.74 (0.12)	33	0.74 (0.11)	0.96
		Irrigated		Non-Irrigated	
0–15 cm	15	2.74 (0.48)	51	3.40 (0.22)	0.02 *
15–30 cm	14	0.97 (0.28)	49	1.05 (0.10)	0.54
30–50 cm	11	0.55 (0.15)	49	0.78 (0.09)	0.06*
		Mulched		Bagged	
0–15 cm	41	3.43 (0.27)	25	2.96 (0.30)	0.06 *
15–30 cm	38	1.10 (0.14)	25	0.94 (0.13)	0.17
30–50 cm	38	0.77 (0.11)	22	0.70 (0.12)	0.47

± (bound) is the amount to give upper and lower boundary intervals for 90 % confidence intervals for the mean

Significant differences between contrasting yard maintenance practices at the specified depth are marked with an '*'

N number of yards

Table 5 Mean soil N ± (bound) across depths between fertilized and non-fertilized yards, irrigated and non-irrigated yards, and mulched and bagged yards

Depth	N	Soil N ± (bound)	N	Soil N ± (bound)	*P* value
		Fertilized		Non-Fertilized	
0–15 cm	30	0.19 (0.016)	33	0.20 (0.015)	0.19
15–30 cm	32	0.087 (0.012)	35	0.077 (0.008)	0.23
30–50 cm	29	0.080 (0.009)	35	0.075 (0.009)	0.52
		Irrigated		Non-Irrigated	
0–15 cm	14	0.18 (0.026)	49	0.20 (0.012)	0.17
15–30 cm	15	0.078 (0.019)	52	0.083 (0.007)	0.63
30–50 cm	13	0.075 (0.015)	51	0.078 (0.007)	0.75
		Mulched		Bagged	
0–15 cm	37	0.21 (0.013)	26	0.18 (0.018)	0.09*
15–30 cm	41	0.085 (0.009)	26	0.076 (0.012)	0.30
30–50 cm	40	0.078 (0.008)	24	0.076 (0.012)	0.79

± (bound) is the amount to give upper and lower boundary intervals for 90 % confidence intervals for the mean

Significant differences between contrasting yard maintenance practices at the specified depth are marked with an '*'

N number of yards

for estimated belowground biomass, estimated belowground biomass may be a poor predictor for changes in soil C levels within the 87 years time frame of our homes. Coarse root biomass comprises most of belowground biomass (Keyes and Grier 1981; Xiao et al. 2003), but fine roots have a higher net primary productivity (Janssens et al. 2002; Chen et al. 2003) and turnover rate (Gill and Jackson 2000; Norby et al. 2004), and fine roots have been associated with changes in soil C levels in less than a decade (Lichter et al. 2005). As such, estimated belowground biomass, as compared to fine root biomass, may have a weak relationship with soil C levels in residential yards.

However, accurate estimations of fine root biomass from belowground biomass cannot yet be relied upon. Li et al. (2003) determined that the aboveground biomass of softwoods and hardwoods have 79.9 % and 56.2 % explanatory power for their associated belowground biomass, but belowground biomass explained only 36.2 % of the proportion of fine root biomass. Vogt et al. (1996) found no predictable relationships between fine root biomass and climatic forest types in relation to soil orders, soil textures and nutrients, leaf phenology and nutrient use efficiency, litterfall nutrient content, or specific climate variables. As fine roots are major sources of soil organic matter (SOM) (Ares and Peinemann 1992; Persson 2012), and elevated levels of CO_2 have been shown to boost their productivity (Norby et al. 2004; Iversen et al. 2008) or have promoted fine root growth in deeper soil depths (Stover et al. 2010), fine root biomass measurements will be necessary for research into the relationship between urban trees and soil C levels.

Our second hypothesis was that soil C would have a strong positive relationship with home age, but soil C accumulated slowly (0.021 kg C m^{-2} $year^{-1}$) and only at 0–15 cm depth. Raciti et al. (2011) reported that only residential yards that were developed on prior agricultural land showed increased soil C levels over home age, unlike the stable soil C in yards from prior forested land. We did not ascertain the soil legacy of our yards, but the city of Auburn was developed on prior cotton and agricultural lands, some that became afforested after abandonment (McNutt 1981). Given the variation in soil C levels across home age in our study, the legacy of our yards may have influenced the response of soil C to home age. In a study involving lawns without trees in Auburn, AL, soil C at 0–15 cm depth increased with home age by a similar amount (0.026 kg C m^{-2} $year^{-1}$) but the home age spanned a younger age range of 1–51 years (Huyler et al. 2013). Comparably, in the current study's lawns, the addition of trees did not appear to facilitate soil C accumulation, but the addition of homes within the 52–87 years age range may have lowered the slope. In our home age class of 3–50 years, the slope was 0.038 kg C m^{-2} $year^{-1}$which suggests that the addition of trees in lawns may have facilitated a more positive relationship between soil C and home age, even at 0–15 cm depth. However, results from this 3–87 years study are not directly comparable to the 1–51 years study and any interpretation remains speculative.

The rate of soil C accumulation was low in our study compared to work performed by Selhorst and Lal (2011) who measured a sequestration rate of 0.264 – 0.355 kg C m^{-2} $year^{-1}$ at 0–15 cm depth, but in our younger home age classes, our rate was similar to Qian and Follett (2002) who reported a soil C sequestration rate of 0.082 – 0.091 kg C m^{-2} $year^{-1}$ at 0–11.4 cm depth in Colorado and Wyoming golf courses. Across our young home age groups, our regression slopes were also roughly similar to soil C sequestration rates reported by Qian et al. (2010). Depending on turfgrass species and irrigation regimes, Qian et al. (2010) measured sequestration rates of 0.032, 0.052, 0.074, and 0.078 kg C m^{-2} $year^{-1}$ at 0–20 cm depth. In our study, the decline in slope between 3–25 years and 3–35 years, and further to 3–87 years, suggests greater positive relationships between soil C and home age in the younger yards.

We stated in our third hypothesis that lawns that were fertilized, irrigated, or mulched would exhibit greater soil C levels across home age but that hypothesis was not supported. Part of the problem in predicting a soil C response to N-fertilization comes from the assumption that the amount of fertilizer applied to lawns directly determines the amount of inorganic N available for growth. Raciti et al. (2008) measured NO_3^- in residential soils and reported that fertilization and irrigation practices could not predict the availability or production of NO_3^- in lawns. Another issue is the amount of fertilizer needed to stimulate turfgrass biomass production. In our study, annual fertilization was the dominant application frequency, lower than the recommended multiple fertilizer applications in spring and summer for maintenance of zoysia or Bermuda grass (Higgins 1998; Han and Huckabay 2008), and a single addition of fertilizer per year may not have a large enough impact on biomass production or rate of decomposition to produce discernible changes in SOC levels. In regards to the lack of response of soil C across home age to mulched clippings, the addition of turfgrass trimmings may contribute organic C to the soil but the low C:N ratio for clippings may foster rapid decomposition (Kopp and Guillard 2004), which may limit any increase in soil C levels.

The lack of response of soil C to irrigation may partially result from differing responses of turfgrass species to irrigation. Qian et al. (2010) measured the root density and net C sequestration of turfgrass species according to the presence or absence of irrigation. After establishment, non-irrigated fine fescue (*Festuca* spp.) had 1/3rd the root density of irrigated fine fescue at 10–20 cm depth, and yet, after 3 years, root density and net C sequestration did not differ significantly between irrigated and non-irrigated fine fescue. Responses to irrigation also differed between species. Irrigated creeping bentgrass (*Agrostis palustris*) had similar net C sequestration as both the irrigated and non-irrigated fine fescue plots but had 72 % less root density. Irrigated Kentucky bluegrass had similar levels of root density as irrigated creeping bentgrass, but significantly lower net C sequestration (−59 %). In our study, zoysia grass and Bermuda grass were the most common species, but some yards had St. Augustine or centipede grass. Given the inherent complexity of the response of turfgrass species to supplemental water, notwithstanding each yard having different soil characteristics and solar radiation interception, broad scale predictions of soil C levels in regards to irrigation may be difficult to make.

Our fourth hypothesis that soil C would increase with % clay was not supported. In grasslands converted from agriculture across the past 40 years, McLauchlan (2006) found no relationship between SOC content and % clay, though % clay was positively associated with soil aggregate size and negatively associated with potential net N mineralization. In the McLauchlan (2006) study, the authors suggested that the range of clay concentrations (mean 19.7±7.3 %) may have been too small to observe influence upon SOC content. If so, our results may be similarly explained. The positive relationship with % silt may be due to the greater percentage of silt compared to clay in 0–15 cm depth and thus a greater interaction between SOM and silt particles. In some studies, the interaction of SOC with silt particles provided greater resistance to mineralization than with sand or clay particles (Balesdent et al. 1987; Parfitt and Salt 2001). In our study, as depth increased, % clay increased to match % silt levels in the two lower depths, thus potentially obscuring any differences in their relationship with soil C.

Conclusions

In our case study, tree aboveground biomass was a poor representative of soil C levels. Even though the explanatory power of tree aboveground biomass increased with depth, soil C below 15 cm remained stable over home age. Measurement of fine root biomass in relation to soil C levels, and possibly to distance from the tree, would provide greater information on the role of trees in the accumulation of soil C in urban areas. The land use history prior to construction may also influence the capacity of urban soil to store soil C. Investigation of the age of the soil C in residential yards would highlight both the historical sources of and the time needed to develop the soil C pool.

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