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

by

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Abstract

Urban land area is expanding worldwide; however, little is known about the dynamics of urban soil C. In natural forests and grasslands, soil C levels increase after disturbances in part due to organic C contributions from roots and possible protection from oxidation by the binding of organic matter to clay particles. In urban areas, home lawns can provide stable chronosequences for studying the response of urban soil C to environmental variables. Residential yards experience the passage of time since home construction, contain roots from turfgrasses and trees, and encompass a range of soil textures. Homeowners may also apply fertilizers, irrigation, and mulched turfgrass clippings to lawns, which may influence soil C levels over time. An observational case study was performed in 102 residential yards in Auburn, AL, and examined the linear regression relationships of soil C to home age, aboveground tree biomass, soil texture, and yard maintenance, within 0-15 cm, 15-30 cm, and 30-50 cm soil depths. The yards were divided into three vegetation categories. Twenty-three 'pure lawns' (PL) contained only turfgrass with home ages 1-51 yrs. Sixty-seven 'lawns with trees' (LwT) had a mix of turfgrass and trees with home ages 3-87 yrs, and twelve yards composed of 'unmanaged forest stands ' (pure woods, PW) contained trees with forest floor instead of turfgrass. Home age was not obtained for PW given that the home was built within a preexisting forest stand and the history of recent forest disturbance was unknown.

In PL and LwT, soil C levels at 0-15 cm increased slightly across home age, with greater accumulation in the first three decades for LwT. When compared across a 50 yr home age range, soil C at 15-30 cm had a significantly more positive slope in LwT than PL. Yard maintenance and % clay had no significant influence on soil C levels. In LwT, the explanatory power of significant positive relationships between aboveground tree biomass and soil C increased with the closeness of the trees to the sample site and was greatest at the two lower soil depths, though the R^2 values were consistently less than 41%. Further analyses of mean soil C levels across groups of home age and tree biomass showed prevalence for soil C stabilities before and after a significant change in mean soil C levels. Overall, the results indicate that most of the increases in soil C levels occur in the initial few decades and in the top soil layer. The low explanatory power of aboveground tree biomass suggests that measurement of belowground biomass, including fine roots, may provide a better biomass variable to analyze the influence of trees on soil C levels over time.

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Table of Contents

List of Tables

Chapter 2

Chapter 3

Chapter 4

List of Figures

Chapter 2

Chapter 3

CHAPTER 1

Dissertation Introduction

Agriculturalists have long known that decaying plant leaves or waste from ruminant livestock added to the soil can improve soil fertility and crop productivity (Allison 1973, Weil and Magdoff 2004). Plant detritus is the dominant source of soil organic matter (SOM) and is composed of 50-58% organic (OC) carbon (Allison 1973, Post and Kwon 2000) obtained from atmospheric carbon dioxide (CO_2) which is used in photosynthesis. The capacity of soil to accumulate OC, and therefore slow the rate of increase in atmospheric CO_2 concentrations, is of great interest to governments who have signed the Kyoto Protocol (Bolin 1998) and also for the U.S. government which recently set a target for the Federal Government to reduce greenhouse gas pollution by 28% by 2020 (Office of the Press Secretary 2010). Soil maintains the second largest bank of carbon in the world, second only to the oceans (Lal 2004), and information on the environmental variables affecting the change in soil organic carbon (SOC) levels over time (Parton et al. 1995, Bellamy et al. 2005, Jastrow et al. 2005) is important for estimating past and present SOC levels and for predicting the effects of future altered climate patterns on SOC pools (Post and Kwon 2000, Falloon and Smith 2003, Davidson and Janssens 2006). This information is critical because if climate change induced 10% of the global SOC to be emitted to the atmosphere, the amount would be equivalent to 30 years of anthropogenic CO_2 emissions (Kirschbaum 2000).

Much of the information on SOC has been obtained in forests, shrublands, grasslands, and wetlands (Armentano and Menges 1986, Raich and Schlesinger 1992, Conant et al. 2001, Goodale et al. 2002, Emmett et al. 2004). The connection between the rapid expansion of urban populations and land area (Lubowski et al. 2006, United Nations 2008) and the lack of comprehensive information on urban forest and soil characteristics has propelled new research on the capacity of urban vegetation and soils to store organic carbon (Nowak and Crane 2002, Pouyat et al. 2010).

Every day urban citizens rely upon the ecosystem services provided by urban forests and soils. Urban soils support vegetation can reduce storm water runoff (Sanders 1986), provide shade and energy savings (Escobedo et al. 2009), filter airborne particles and pollutants (Nowak 1994) and store atmospheric C (Nowak and Crane 2002). High quality urban soils can capture, store, and filter water, minimize erosion, and regulate soil nutrient and mineral cycles, such as the C cycle, and, thus, influence gaseous exchanges between soil and atmosphere (Costanza et al. 1987).

The capacity of an ecosystem to provide benefits to people depends upon the quality of the soil, which is directly affected by SOC biogeochemical activity. SOC is the main fuel for microorganisms which regulate the availability of soil nutrients and improve soil structure by facilitating root and mycorrhizal growth. Activity of soil microorganisms enhances the soil organism food web, including populations of soil meso- and macro-organisms, and can promote net primary productivity (NPP), which can increase the amount of plant litter deposited into the soil. Soil C levels stabilize when the accumulation of SOC balances the loss of SOC over time (Lardy et al. 2011).

Soil carbon

Understanding the importance of SOC requires knowledge of its components. Soil C is separated into organic carbon and inorganic carbon. Soil inorganic carbon (SIC) is a carbonate mineral, such as $CaCO_3$, whose original C source comes from the parent material. In arid and semi-arid regions, the SIC pool can be the dominant source of soil C (Schlesinger 1982). SOC is composed mostly of plant material, but also of animal, fungal, bacterial and other micro-organisms, either alive or in varying stages of decomposition (Allison 1973). The amount of SOC measured in mineral soil is the total SOC input minus SOC lost through mineralization, erosion, and leaching (Post and Kwon 2000).

The SOC pool can be roughly separated into active, slow, and passive pools, each defined by their mean residence time (MRT) in the soil. Three mechanisms are responsible for the stabilization of SOC: biochemical, chemical, and physical (Six et al. 2002). Biochemical stabilization results from having inherent physiochemical resistance to decomposition processes, e.g. lignin compounds, and from undergoing reactions that alter more labile SOC into more resistant biochemical complexes (Six et al. 2002). Chemical stabilization is the binding of SOC to mineral soil surfaces, typically clay particles, and thus the longevity of SOC can be strongly influenced by the texture of the soil. Physical stabilization arises from the shielding effects of soil micro- and macro-aggregates upon the SOC interred within them (Six et al. 2002). Organic compounds entering mineral soil can experience any number of biochemical, chemical, and physical stabilizations or be mineralized immediately.

Active SOC pools are composed of labile carbon compounds, such as water-soluble simple carbohydrates and polysaccharides (Allison 1973, Weil and Magdoff 2004), which are metabolized within a season to several years. In temperate climates, 50-70% of carbon from original crop residues decomposes within a single year (Collins et al. 1997). The active carbon pool can also be generally interpreted as containing SOC compounds which are not adsorbed onto mineral or organic matter (OM) surfaces or bound within mineral aggregates (Post and

Kwon 2000). The bulk of biochemical activity in soils results from the active SOC pool. The active SOC pool spurs nutrient mineralization, provides a quick fuel source for the soil food web and also directly affects the formation of soil organo-mineral complexes, micro- and macro-aggregates which protect organic carbon compounds from oxidation (Weil and Magdoff 2004).

SOC compounds in the passive SOC pool are either physio-chemically recalcitrant or have been modified by a gauntlet of decomposition processes to become highly resistant to decay (Allison 1973, Parton et al. 1987). Passive SOC compounds include suberans, cutans, lignins, and charcoal (Wander 2004). This recalcitrant pool can take over a century to several millennia to decompose and in certain environments, such as volcanic soils, the majority of SOC can come from the passive SOC pool (Torn et al. 1997).

The slow pool is composed of SOC compounds whose decay rate is slower than the active pool and faster than the passive pool, either due to their physiochemical structure, e.g. cellulose, or due to protection by soil aggregates and organo-mineral complexes (Collins et al. 1997). Depending upon how researchers measure the decomposition rate of the slow pool compounds, their MRT in the soil can span years to decades (Wander 2004) or decades to centuries (Trumbore 2000). In temperate soils, within a depth of 100 cm or less, the slow SOC pool comprises the majority of total SOC pool (Collins et al. 2000, Trumbore 2000).

Belowground tree biomass

Belowground biomass is a major source of SOC (Fahey and Hughes 1994, Ruess et al.1996, Helmisaari et al. 2002, Russell et al. 2007), and, for trees, belowground biomass is roughly separated into coarse and fine roots, with coarse root biomass dominating belowground biomass (Keyes and Grier 1981, Misra et al. 1998, Xiao et al. 2003, Peichl and Arain 2007). Coarse roots are characterized by development of woody fibers, suberized bark and secondary thickening (Chaffey 2002), and, in research, coarse roots are often defined as having diameters either > 2 mm (Ruess et al. 1996, Millikin and Bledsoe 1999, Helmisaari et al. 2002, Raz-Yaseef et al. 2013) or > 5 mm (Joslin and Henderson 1987, Comeau and Kimmins 1989, Xiao et al. 2003). Coarse roots have a longer lifespan than fine roots (Joslin and Henderson 1987, Gill and Jackson 2000, Janssens et al. 2002, Matamala et al. 2003) and a lower decomposition rate (Fahey et al. 1988, Olajuyigbe et al. 2012).

Fine roots have a more extensive distribution (Roberts 1976, Millikin and Bledsoe 1999, Raz-Yaseef et al. 2013), greater NPP (Keyes and Grier 1981, Janssens et al. 2002, Chen et al. 2003, Xiao et al. 2003), greater biomass production (Helmisaari et al. 2002), and higher annual turnover (Gholz et al. 1986, Joslin and Henderson 1987, Gill and Jackson 2000) than coarse roots. The greater productivity, turnover rate, and extensive distribution of fine roots makes them major sources of SOM (McClaugherty et al. 1982, Steele et al. 1997, Gale and Cambardella 2000, Persson 2012) and fine roots have been associated with changes in soil C levels within less than a decade (Lichter et al. 2005).

In residential yards, turfgrass inputs OC to the soil from both above- and belowground tissues. In contrast, the main contribution of tree C to the soil would come from belowground biomass because tree leaf litter, limb and branch detritus are typically removed from a lawn. Estimations of belowground tree biomass originally come from harvesting of multiple trees of a single species and weighing the dry mass of aboveground tissues, i.e. stem, limb and branches and belowground tissues, i.e. coarse roots, to calculate a root:shoot (R:S) biomass ratio (Cairns et al. 1997). The R:S ratio can be used to estimate belowground biomass from aboveground biomass measurements (Kurz et al. 1996) for either a single species or groups of species, e.g. softwoods, when harvesting is impractical. In residential lawns, where obtaining permission to harvest trees from multiple homeowners can be difficult, the relationship between belowground biomass and soil C may be investigated by using measurements of aboveground tree biomass as a substitute for belowground biomass.

Soil Texture

Once OM is input into the soil, the amount of SOC that accumulates is largely dependent upon its resistance to decomposition. Soil texture is the % composition of sand, silt, and clay, and can influence the MRT of SOC. The surface area of mineral particles (m^2 g^{-1}) can decrease the rate of SOC oxidation (Chenu and Plante 2006) by providing binding opportunities for SOM; clay particles have the largest surface areas and sand grains have the smallest surface areas (Fisher and Binkley 2000). Soils with a high sand content have greater amounts of pore space than silt- and clay-dominated soils and the larger pore space decreases soil water retention (Gupta and Larson 1979) and permits higher mineralization rates of OC (Hassink 1992, Weil and Magdoff 2004). In general, SOC levels are negatively associated with % sand content (Burke et al. 1989, Jobbágy and Jackson 2000) and positively associated with clay content (Anderson et al. 1981, Sorensen 1981, Nichols 1984) or with a combination of silt and clay content (Burke et al. 1989, Homann et al. 2007).

Soil microaggregates are composed of SOM bound to clay particles with the clay particles adhering together by attraction between polyvalent metal cations (Fe, Ca, Al) (Six et al. 2004). The small pore space of microaggregates impedes access of decomposers to SOC. The mineralogy of clays may affect the relationship of SOC to clay particles. For example, 2:1 clays, e.g. smectite, are expected to bind with and stabilize higher levels of SOC than 1:1 clays, e.g. kaolinite, because 2:1 clays have greater surface area and greater interlayer space (Six et al. 2002). However, in 1:1 clay soils high levels of oxides may reduce the observed strength of the relationship between clay particles and SOC because the oxides can usurp the role of SOM in building soil aggregates (Six et al. 2004).

Microaggregates can be bound together by roots and hyphae to form macroaggregates (Elliott 1986) or macroaggregates can originate from the decay of fresh coarse particulate organic matter (cPOM). During the decomposition of cPOM into fine particulate organic matter (fPOM), mucilage from decomposers and exudates from fine roots coats fPOM which then becomes encrusted with clay particles (Six et al. 2004). Further binding by roots and hyphae enclose the clay particles and SOM compounds, forming macroaggregates, with older, more decomposed SOC on the inside, and newer SOC on the outside. Soil disturbance or death of roots or hyphae break apart macroaggregates and seed the soil with microaggregates (Six et al. 2000).

Land use change

Strong soil disturbances typically lead to immediate reductions in SOC levels partially by breaking up macroaggregates and exposing SOC to oxidation (Tiessen and Stewart 1983, Cambardella and Elliott 1994). After a disturbance, the time needed to accumulate SOC to past levels or to equilibrium levels varies depending upon environmental variables, such as climate characteristics and the successive vegetation establishment. SOC accumulation rates may be reduced by high mean annual temperature (MAT) (Burke et al. 1989, Trumbore et al. 2003, Garten 2011) and may be increased by high mean annual precipitation (MAP) (Sun et al. 2004, Homann et al. 2007) with SOC levels in surface soils (< 20 cm) more affected by climate than SOC levels in deeper soils (Jobbágy and Jackson 2000). In U.S. Central Plains Grasslands, SOM levels generally increase from south to north (Texas to North Dakota) and from west to east (eastern Colorado to eastern Missouri) (Burke et al. 1989) as higher MAT (especially when associated with coarse textured soils) increases the SOC decomposition rate (Kirschbaum 1995, Raich et al. 2006).

A change in vegetation type after land use can also influence future SOC levels. Pasture converted to pine plantation typically corresponds with a long term reduction in SOC levels (Guo and Gifford 2002, Paul et al. 2002). On the other hand, increased SOC levels arise from development of pasture on previous crop land (Gebhert et al. 1994, Guo and Gifford 2002) and when native forest is changed to pasture (Guo and Gifford 2002). Grasslands have 2-fold or 3-fold the total fine root biomass of temperate evergreen or temperate deciduous forests, respectively (Jackson et al. 1997), and with a higher R:S ratio than forests or plantations (Mokany et al. 2006), the bulk of the OC in grasses is allocated to fine roots which increases the opportunity of OM becoming incorporated and stabilized into the soil.

Rural - urban soil gradient

Differences between urban land uses and non-urban landscapes prevent automatic transfer of knowledge of soil dynamics from non-urban to urban sites. Research into urban soils has revealed that urban soils experience unique atmospheric conditions compared to natural and agricultural environments (Blume 1989, Schleuß et al. 1998, Lorenz and Kandeler 2005) and that urban soils operate within strongly heterogenic environments (Pickett and Cadenasso 2009). Urban soil features can vary widely across urban land uses with differences in microbial biomass and activity, elemental C, total organic C and total N (Lorenz and Kandeler 2005), and soil origins, soil structure, total soil C and N, and base cation holding capacity (Schleuß et al. 1998). These differences can manifest highly varying levels of SOC. In New York City, NY, SOC density was highest at a golf course, 28.5 kg m^{-2}, and lowest in clean fill and dredge, 2.9 - 6.9 kg m^{-2} (Pouyat et al. 2002).

The urban-rural land use gradient has been used to investigate the dynamics of soils subject to different intensities of urban land use. Compared to rural soils, urban soils experience elevated soil (Ziska et al. 2004) and atmospheric temperatures (Bornstein 1968, Oke 1973, Tapper 1989, Philandras et al. 1999), altered precipitation patterns (Huff and Changnon 1972, Rosenfeld 2000, Shepherd et al. 2002, Dixon and Mote 2003), increased atmospheric concentrations of CO_2 (Idso et al. 2001, Grimmond et al. 2002), and higher levels of nitrogen oxides (Nikula et al. 2010, Power and Collins 2010) and sulfur oxides (Nikula et al. 2010). Compared with rural soils, urban soils tend to have increased concentrations of heavy metals (Pouyat and McDonnell 1991, Watmough et al. 1998, Yuangen et al. 2006), polycyclic aromatic hydrocarbons (Van Metre et al. 2000, Wong et al. 2004), and polychlorinated compounds (Lovett et al. 2000, Krauss and Wilcke 2003). Urban soils are reported to have higher net N mineralization rates (Pouyat et al. 1997, Pouyat and Turechek 2001, Pavao-Zuckerman and Coleman 2005) and also have greater native and non-native earthworm abundance and biomass than rural soils (Steinberg et al. 1997). As yet, much research is still required on urban soil characteristics. Compared to rural forest stands, urban soils are reported to have higher net N nitrification rates (Pouyat et al. 1997, Pouyat and Turecheck 2001) or similar soil net N nitrification rates (Pavao-Zuckerman and Coleman 2005). Litter decomposition rates in urban sites have been reported as being faster (Pouyat et al. 1997, Nikula et al. 2010), slower (Carreiro et al. 1999), or similar (Pavao-Zuckerman and Coleman 2005) to rural sites.

Chronosequences and home age

Because ascertaining the rate of change in SOC levels may take a decade or more, a chronosequence, or a collection of similar land based experimental units with a range of ages, is often used as a surrogate to provide information on how environmental variables influence SOC levels over time (Amundson 2001, Walker et al. 2010). Soil C research commonly uses chronosequences due to the length of time needed to discern the environmental variables that induce significant changes in SOC levels (Torn et al. 1997, Huggett 1998). Chronosequences have been used to investigate soil C dynamics in forests in Pacific Northwest states (Sun et al. 2004) and Rhode Island, USA (Hooker and Compton 2003), and in grasslands in Minnesota, USA (McLauchlan et al. 2006), and in Belgium (Accoe et al. 2004). Chronosequences of urban forests and soils, as in natural areas, can provide information on SOC dynamics but usually begin with time after a chosen anthropogenic disturbance, e.g. house construction. In Baltimore, MD, residences > 40 years home age had significantly higher SOC, at 0-20 cm and 0-100 cm, than those < 35 years in home age (Pouyat et al. 2009). Soil organic carbon levels also differed according to home age in the Front Range of Colorado (Golubiewski 2006). At depth 0-10 cm, lawns 7 years and younger had significantly lower SOC concentrations than older lawns. At depths 10-20 cm and 20-30 cm, 25 years was needed to produce a significant difference in SOC concentrations. Concentrations of soil N over time differed slightly with soil C; 25 years was needed at all soil depths to show a difference in N concentrations (Golubiewski 2006).

Influence of lawn maintenance

Recent studies on SOC pools in urban landscapes have indicated that urban soils may have a similar or greater capacity to accumulate SOC than nearby agricultural or native soils. Nagy et al. (2013) measured SOC along the Gulf Coast in Franklin County, FL, and reported that mean SOC levels of urban lawns was similar to urban forests and greater than pine plantations and natural pine forests. In residential yards, SOC levels can be greater than nearby grasslands (Golubiewski 2006) and greater than nearby rural forests (Pouyat et al. 2009). Residential yards in Baltimore, MD, had greater soil C and soil N densities than nearby reference forest soils

(Raciti et al. 2011). Kaye et al. (2005) found that SOC and total nitrogen (N) densities, and total belowground C allocation in urban soils in Fort Collins, CO, were significantly greater than surrounding wheat and corn crops and native shortgrass steppe. While the high productivity of urban turfgrass from early spring into mid-summer may contribute to greater SOC levels (Kaye et al. 2005), potentially, applications of fertilizer, irrigation, and/or mulched turfgrass clippings to lawns may also influence the accumulation of soil C over time.

Unlike natural soils, the dominant vegetation covering urban soils is turfgrass (Milesi et al. 2003, Robbins and Birkenholtz 2003). As the U.S. population grows and suburbs extend into rural or native areas, turfgrass landscapes, as represented by residential, industrial, institutional and commercial lawns, city parks, athletic fields, and golf courses, expand into natural ecosystems. Vinlove and Torla (1994) estimated lawn land area to be 14 - 18 million acres (5.6 - 7.3 million hectares) and almost a decade later, Milesi et al. (2003) estimated total turfgrass land area to cover 31 - 49 million acres (12.5 - 20 million hectares). Presently, turfgrass has become America’s largest irrigated crop (Milesi et al. 2003), and researchers have investigated the soil C sequestration rate of turfgrass species under different irrigation regimes (Qian et al. 2010), and the soil C sequestration rate between managed ornamental and athletic turfgrass lawns (Townsend-Small and Czimczik 2010).

Soils rarely exist in N-saturation conditions and plant growth is usually limited by soil N availability. Additions of N-fertilizer are known to increase NPP which can lead to greater detritus production and thus greater input of OM into mineral soil (Russell et al. 2009). Paustian et al. (1992) and Graham et al. (2002) reported increased SOM levels with N-fertilizer applications to crops. In Colorado agricultural soils, SOC levels were positively related to levels of N-fertilizer applications when combined with the retention of crop residue in the soil

(Halvorson et al. 1999). Alvarez (2005) reviewed paired data from 137 agriculture sites and also found a positive relationship between the size of the SOC pool and levels of N-fertilizer application. However, grassland studies have shown positive relationships between SOC levels and N-fertilization (Conant et al. 2001) and also have shown a lack of relationship between SOC levels and N-fertilization (Hassink 1994). In a long-term study in Iowa, increased decomposition rates with additions of N-fertilizer resulted in no increase in SOC levels (Russell et al. 2009). Mulching turfgrass clippings back into the lawn supplements available N and increases turfgrass productivity (Kopp and Guillard 2002) and can stimulate the rate of SOC sequestration in turfgrass lawns (Qian et al. 2003). Irrigation has been shown to increase SOC levels in the Nebraska Sandhills region (Lueking and Schepers 1985), and in cropland in semi-desert southern Idaho (Entry et al. 2007).

Together, fertilization and irrigation have the potential to enhance SOC pools over time (Milesi et al. 2005, Qian et al. 2010). Fertilization and irrigation of residential yards in the Front Range of Colorado was credited with higher rates of SOC accumulation than the surrounding grassland areas, increasing yard SOC levels past grassland SOC levels after two decades (Golubiewski 2006). In Moscow, ID, Smetak et al. (2007) measured total SOC density in an old urban park receiving high maintenance (frequent fertilization and irrigation), an old residential area receiving low maintenance (no fertilizer and infrequent irrigation), and a young residential area receiving high maintenance (frequent fertilizer and irrigation). The levels of SOC density and total soil N followed the pattern of highest with ‘time + maintenance’ (urban park), intermediate with ‘time’ (old residential units), and lowest with just ‘maintenance’ (young residential units) (Smetak et al. 2007). Qian and Follett (2002) analyzed SOM levels in a chronosequence of 11 golf courses in Colorado and 1 in Wyoming, spanning ~45 yrs in age. In the fairways and putting greens, the high SOM accumulation rate of 0.082 – 0.091 kg C m^{-2} yr^{-1} was attributed to high levels of management, including irrigation at 75% to 100% of the local potential evapotranspiration (Qian and Follett 2002).

Urban SOC dynamics in residential soils are an expanding topic for investigation that is still relatively new. In the US, residential SOC data have been collected in Maryland (Pouyat et al. 2002, Raciti et al. 2011), Illinois (Jo and McPherson 1995), Idaho (Smetak et al. 2007) and Colorado (Kaye et al. 2005, Golubiewski 2006). As yet, residential yard soil C dynamics have not been investigated in the southeastern US nor in relationship to yard aboveground tree biomass, home age, turfgrass maintenance, and soil texture. Given the rapid urbanization of the southeast U.S. (Godschalk 2007), residential SOC data from the southeast would advance the knowledge of urban SOC dynamics and the environmental variables that affect the rate of SOC change over time.

Objectives and hypotheses

The overall goal of this dissertation was to provide information on the influence of belowground tree biomass, home age, soil texture, and yard maintenance on soil C levels within the southeastern U.S. To obtain this goal, we sampled soil in 102 yards across a range of aboveground tree biomass (from 0 kg to 36,956 kg), home ages (from 1-87 yrs), yard maintenance practices (from low to high maintenance), and soil textures (from sandy to clayey).

The main hypotheses were: (1) Soil C levels would be positively related to home age because longer time periods would allow for more SOC to accumulate; (2) Soil C levels would be positively related to aboveground tree biomass because of the addition of SOC from tree belowground biomass; (3) Soil C levels in lawns with trees (LwT) would have a more positive relationship with home age compared to lawns without trees (pure lawns, PL) due to the additional SOC input over time from tree belowground biomass; (4) SOC levels would be more positively related to home age in yards that were fertilized, irrigated, and mulched, as these practices would facilitate greater NPP and thus higher levels of OC deposited into the soil; and (5) SOC levels would be positively related to % clay content as higher % clay content would provide more mineral surface area for binding SOM and more construction material for the formation of soil aggregates to protect SOC from oxidation.

To test these hypotheses, a single meter square plot was placed on the front lawn and soil was sampled at each of the 4 corners. Front lawns were selected for ease of access since back lawns were more often used by owners and pets. The location of the meter square plot had to avoid irrigation/gas/water/sewer pipes, home security and electric lines, rocks, areas devoid of turfgrass, and areas with belowground foundations such as sidewalks, walkways, driveways, roads, and the home. Within structural and use limitations, a meter square was placed on the lawn "arbitrarily but without preconceived bias" (McCune and Grace 2002).

At each corner of the plot, two soil cores were taken at three depths: 0-15 cm, 15-30 cm, 30-50 cm. In one soil core, we took samples of soil C and soil N. In the second soil core, we took samples for soil texture and bulk density. The yards were categorized as to the levels of aboveground tree biomass and the presence of turfgrass. Pure lawns (PL) were lawns with trees > 20 meters away and separated by roads from the center of the meter square plot. Twenty-three PL with home ages of 1-51 yrs were sampled. LwT were lawns that had turfgrass and at least a single tree intercepted by a 45 angle from the center of the plot and also within 1.5 × height of the tree from the center of the plot. Sixty-seven LwT with home ages of 3-87 yrs were sampled. The yards of homes that were built within preexisting, unmanaged forest stands with a forest floor instead of a turfgrass lawn were labeled 'pure woods' (PW). We sampled 12 PW yards.

The yard maintenance categories were: ‘fertilized’ if fertilized regularly every year or multiple times in a year and ‘not fertilized’ if fertilized less than once a year, ‘irrigated’ if irrigated every two weeks or more, and ‘not irrigated’ if infrequently or never irrigated, and ‘mulched’ if lawn clippings were mulched into the lawn and ‘bagged’ if lawn clippings were removed from the lawn. If the lawn clippings were mulched every other mowing, the yard was designated as ‘mulched’.

Statistical analysis

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 in PL and all LwT. Using data from PL and LwT, we conducted regression analysis of soil C and soil N values against home age and soil texture. Regression analysis was used to determine the relationship of soil C:N to home age and to the relationship of soil C to soil N. In addition, the soil C and soil N values of the yards separated into individual maintenance categories were regressed against home age to ascertain whether the relationship of soil C and soil N to home age differed between contrasting yard maintenance practices, i.e. fertilized and not fertilized yards, irrigated and not irrigated yards, mulched and bagged yards. A likelihood ratio test was used to ascertain whether the intercept and slope of two regression relationships differed significantly from each other. 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 and to see if differences in regression led to differences in the mean soil C and N levels.

Using data from LwT, we performed regression analyses on soil C and soil N values against aboveground tree biomass. Also we separated home ages into young (< 36 yrs) and old

(> 36 yrs) home age categories to assess whether the relationship of soil C to home age differed between young and old homes. Within a single age category, we separated the yards into individual yard maintenance practices and compared the regression relationship of soil C to home age across contrasting yard maintenances, e.g. fertilized yards < 36 yrs vs. non-fertilized yards < 36 yrs. In all regression and ANOVA analyses, the number of yards in an analysis may be less than total number of yards due to removal of yards containing outliers. Differences and relationships were considered significant when $\alpha = 0.10$. We used 0.10 because this was an observational case study where the soil, vegetation and yard maintenance history of the yards was largely unknown and the variability of soil C and N values in yards was expected to be high.

Chapters

The dissertation is arranged by chapters according to yard vegetation categories. PL are the focus in Chapter 2, where the relationships of soil C to home age and soil texture were discussed, and the relationship of soil C to home age was compared across contrasting yard maintenance practices. In Chapter 3, LwT (3-87 yrs) were the focus and the relationship of soil C to aboveground tree biomass, home age, and soil texture was examined and the relationships between soil C and home age across contrasting yard maintenance practices were compared. In Chapter 4, the results of two investigations were assessed. One investigation involved the comparison of soil C dynamics between PL (1-51 yrs) and LwT (3-51 yrs). In this investigation, the differences in the relationships of soil C to home age and to soil texture between the two yard types were compared, as well as any differences in the relationship of soil C to home age in response to yard maintenance. Within LwT (3-51 yrs), the relationship of soil C to three aboveground tree biomass data sets was analyzed as well as the relationship of soil C to home age within each biomass data set. The second investigation encompasses PL, LwT (66 yards, 3-

87 yrs), and PW and involves the comparison of mean soil C levels within four ascending categories of aboveground tree biomass starting with 0 kg biomass and ending with > 36,956 kg and also involves comparison of mean soil C levels within five ascending groups of home age beginning with the first decade and ending with > eight decades.

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CHAPTER 2

Drivers of soil carbon in residential ‘pure lawns’ in Auburn, Alabama

Abstract

Urban land area is expanding worldwide and may play a significant role in long-term carbon (C) storage; however, little is known about potential drivers of soil C storage 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 yrs), 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.

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, urban soils provide a range of ecosystem 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 Baltimore, MD, USA, residential homes > 40 yrs old had more soil C than homes < 35 yrs old (Pouyat et al. 2009). In Colorado’s Front Range, lawns > 7 yrs in age had greater soil C concentration at the 0-10 cm depth than lawns < 7 yrs old, and homes > 25 yrs in age had more soil C concentrations at the 10-20 and 20-30 cm depths than homes < 25 yrs old (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 would increase with home age; 2) Lawns that were either fertilized, irrigated, or mulched would exhibit greater soil C over home age than lawns not receiving supplements; 3) Soil C would be positively related to soil N; and 4) Soil C would be positively related to % clay content.

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°) (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 and 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") (http://www.idcide.com/weather/al/auburn.htm).

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' (PL) had trees located > 20 meters away and separated by roads from the sample site to minimize the influence of tree roots on soil C and N. PL 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 x 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”). 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.

Soil 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 or 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 35.7g of sodium metaphosphate ($NaPO_3$) x Na_2O and sodium carbonate (Na_2CO_3) dissolved in 1L distilled water. The soil solution was mixed for five minutes with a commercial mixer. After mixing, the solution was placed in a 1L glass cylinder and brought to volume. The solution was shaken for one minute and a hydrometer reading was taken after 40 seconds of settling time. The one minute 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 hours, 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 two 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 were less than 14 yrs home age. Twelve yards were mulched and 11 yards bagged.

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 soil C and home age, soil N, and soil texture. Regression analyses were also used to calculate the relationship between soil N and home age and soil texture. A stepwise procedure was used, with soil C as the dependent value and home age, soil N, % sand, % clay, % silt as 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. In all regression and ANOVA analyses, differences and relationships were considered significant at $\alpha = 0.10$, and for appropriate analyses, all p-values were reported.

Results

Soil Characteristics

Both soil C and N significantly decreased with depth (Table 2). Soil C levels were roughly 2× to 4× greater at 0-15 cm than at the 15-30 cm and 30-50 cm depths, respectfully. 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 and 30-50 cm depths while % sand was significantly greater at 0-15 cm than 30-50 cm depth. The percent clay, sand, or silt did not affect soil C and N at any depth (data not shown). The soil C:N ratio significantly declined by over half from the first two depths to the lowest depth.

Home Age

Soil C levels were positively related to home age at 0-15 cm depth (Fig. 1a). However, at 15-30 cm depth, soil C was negatively related to home age, and at 30-50 cm depth, soil C levels did not change across home age (Fig. 1b and 1c). Soil N levels were 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, 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 levels increased with soil N in the 0-15 cm depth, but did not change 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 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, at the 15-30 cm depth, soil C levels did not change 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, at the 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. For the 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 depths, the relationship between soil C and home age was not significantly different between bagged and mulched yards ($P = 0.38$, $P = 0.74$, respectively). 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 (kg m^{-2}) 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 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 fertilized and non-fertilized yards, irrigated and non-irrigated yards, and mulched and bagged yards (data not shown).

Discussion

Soil C Sequestration Rates

In Auburn's lawns, soil C accumulated at 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 this 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 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 the diminished or absent soil C accumulation over home age. One explanation could be the absence of tree biomass in our turfgrass dominated yards. Organic matter derived from roots, especially fine roots, contribute to soil C pools (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 that found in grasslands (Jackson et al. 1997). However, Jobbágy and Jackson (2000) showed that forests have a greater percentage of SOC at the 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 for golf courses, studies such as Qian and Follett (2002), Huh et al. (2008), and Selhorst and Lal (2011). Thus, the evaluation of how soil C levels in Auburn's yards would have responded to additions of tree root biomass would be difficult.

In this study, a possible decline in turfgrass root biomass below 15 cm depth may have played a role in the absence of soil C accumulation. Zoysiagrass and bermudagrass were the most common turfgrass species found in Auburn 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 Auburn's yards, 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 growth and transport of SOC to produce measureable 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 can stimulate 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 a positive relationship between soil C and MAP. Burke et al. (1989) stated that the negative relationship with MAT may be due to the decomposition rate increasing faster than accumulation of soil C as MAT increased to 17°C. In contrast, as MAP increased, both the rate of decomposition and accumulation increased until MAP reached 80 cm; afterwards, the decomposition rate increased faster than the accumulation rate. 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 Auburn's 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 were too low compared to turfgrass maintenance in golf courses and other residential yard studies. In this study, 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 per month (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 increase 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 yrs 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 levels did not change (in all depths) across the 13 yrs of home age for irrigated yards (data not shown). Consequently, the greater soil C at 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 across Soil N

A similarity between this study and studies by 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 for soil C was with soil N at 0-15 cm depth. The strength of the relationship between soil C and N may depend upon the accumulation of new organic matter, as shown by the absence of this relationship at the 15-30 and 30-50 cm depths and the lack of accumulation of soil C and N at these depths.

Soil C across Soil Texture

In our study, soil C and soil N had no significant 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 negatively associated with MAT and MAP but was not influenced by soil texture (Conant et al. 2001). In general, the humid, subtropical climate of Auburn may have amplified the decomposition rate 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 lawn vegetation compositions.

Table 1 Number of yards (total 23) subdivided by home age (1-51 yrs) and yard maintenance practices.

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**

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

	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 (kg m^{-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

± (bound) is the amount to give for upper and lower boundary intervals for 90% CI for the mean. Significant differences between depths and within a category occur at $\alpha = 0.10$ and are marked with different lowercase letters.

N = number of yards sampled.

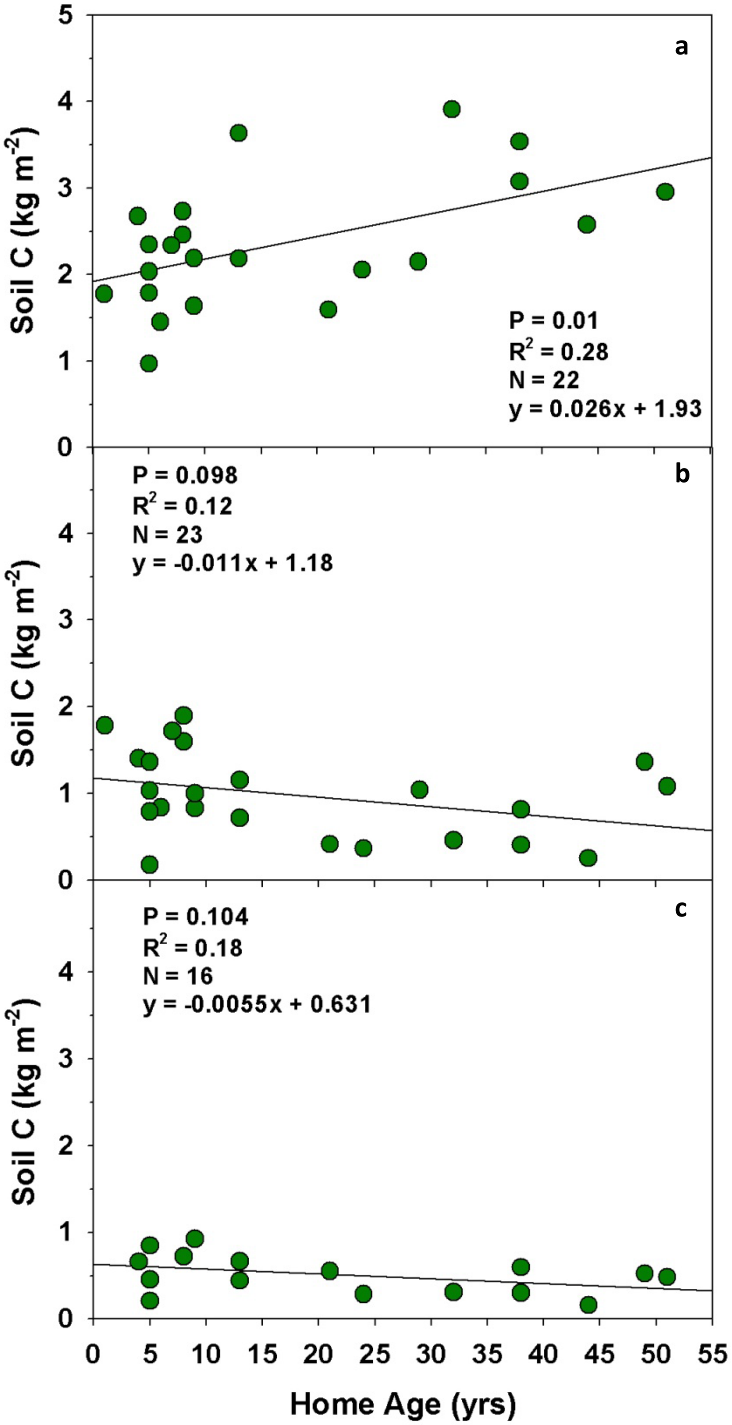

Fig. 1 Relationship of mean soil C (kg m^{-2}) over home age (1-51 yrs) at depths: a) 0-15 cm, b) 15-30 cm, and c) 30-50 cm.

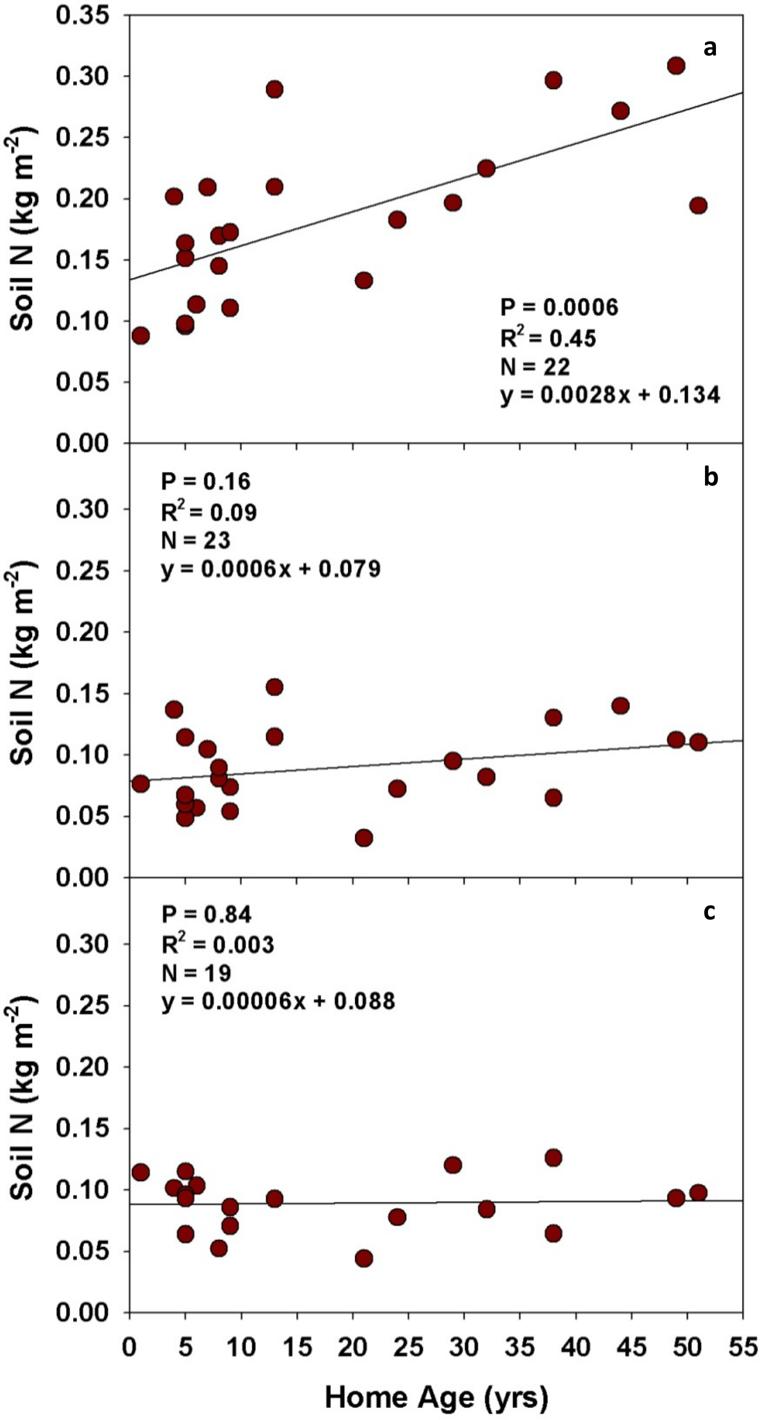

Fig. 2 Relationship of mean soil N (kg m^{-2}) to home age (1-51 yrs) at depths: a) 0-15 cm, b) 15-30 cm, and c) 30-50 cm.

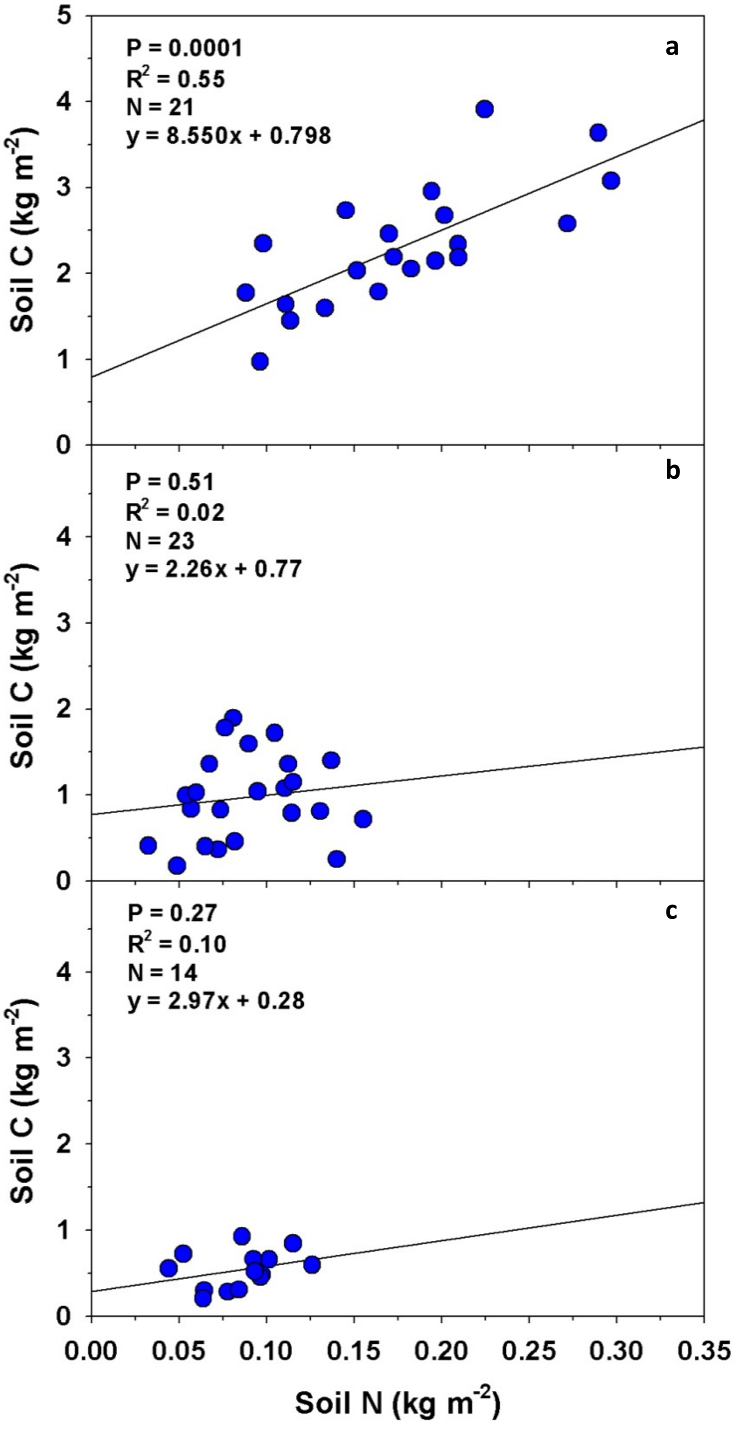

Fig. 3 Relationship of mean soil C (kg m^{-2}) to mean soil N (kg m^{-2}) at depths: a) 0-15 cm, b) 15-30 cm, and c) 30-50 cm.

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.

Depth	N	Soil C ± (bound)	N	Soil C ±(bound)	P-value
		Fertilized		***Not 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		***Not 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*

± (bound) is the amount to give for lower and upper boundary intervals for 90% CI for the mean. Significant differences between contrasting yard maintenance practices at the specified depth occur at $\alpha = 0.10$ and are marked with an '*'.

N = number of yards.

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CHAPTER 3

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

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 ≤ 15 m from sample site, 4) biomass ≤ 10 m, 5) biomass ≤ 5 m, and 6) biomass ≤ 4 m. Biomass ≤ 5 m and biomass ≤ 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.

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 than neighboring agricultural systems (Kaye et al. 2005) and shortgrass steppe (Golubiewski 2006) in Colorado. In urban areas, residential land occupies the greatest 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 Baltimore, MD, residences > 40 yrs old had significantly higher SOC levels than those < 35 yrs 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 yrs than yards older than 25 yrs (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 clay and silt particles provides more area for chemical binding than sand particles 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, microorganisms, 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: aboveground tree biomass, home age, yard maintenance practices, and soil texture. We performed a case study using a chronosequence of 67 lawns containing trees, with home age ranging from 3 to 87 yrs, with a range of lawn maintenance regimes and soil textures. Information about the relationship of soil C to these four variables would improve our present knowledge of urban soil C dynamics.

We tested four hypotheses: 1) Soil C levels would be positively related to aboveground tree 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; and 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) at an altitude of 210 m (689 ft) (U.S. Climate Data). 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). 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). 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. Requests for permission to sample soils in yards were delivered to various individuals and organizations either in person, by email, or by placing a written request on the home’s 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"). 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. 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 the 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 35.7g of sodium metaphosphate ($NaPO_3$) x Na_2O and sodium carbonate (Na_2CO_3) dissolved in 1L 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 minutes and then the solution was placed in a 1L glass cylinder and brought to volume. The cylinder was corked and the solution shaken for one minute. Immediately afterwards, a hydrometer was placed in the solution and the value read after 40 seconds of settling time. The one minute shaking of the cylinder solution was repeated and followed by a second hydrometer reading and a recording of the solution temperature. After 24 hours, hydrometer and temperature readings were repeated on the resting solution.

Aboveground Tree 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 pine 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 with soil C.

Five aboveground tree 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 ≤ 15 m, ≤ 10 m, ≤ 5 m, and ≤ 4 m from center of meter square plot. The biomass ≤ 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 aboveground tree 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 irrigating, fertilization was categorized as 'yes' if they fertilized at least once a year and irrigating as a 'yes' if they watered the lawns regularly at least once every two 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 yrs were not fertilized, non-irrigated, and the mown clippings were mulched into the lawn (Fig 1a, 1b, 1c). Overall, 47% of the yards were fertilized, 22% of the yards were irrigated, and 61% were mulched.

Statistical Analysis

For each yard, we obtained aboveground tree 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 aboveground tree biomass data sets, home age, soil texture, and soil N and also between soil N and aboveground tree 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 yrs, and the first home age class was 3-16 yrs, the earliest "young" age group to contain ≥ 10 yards. The 3-16 yr age group was paired with the first "old" age group, 17-87 yrs. All "old" age classes would end with the oldest home age of 87 yrs. The "young" home age class then progressed by adding 5 yrs to the group, from 3-20 yrs to 3-55 yrs while the paired "old" home age class simultaneously reduced 5 yrs from its group, from 21-87 yrs to 56-87 yrs, ending with 56-87 yrs because that was the last "old" home age group to contain ≥ 10 yards. The 5 yr interval, after 3-20 yrs, was chosen because it was the smallest repeatable home age span that fit between 3 yrs and 87 yrs 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 yrs) home age class and an older (37-87 yrs) 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 yrs home age and across 37-87 yrs home age differed between contrasting yard maintenance practices, e.g. soil C in mulched vs. bagged yards across 3-36 yrs. Only soil C at 0-15 cm depth was analyzed due the surface soil layer receiving the greatest influence from yard maintenance practices. The 3-36 yrs home age class was used because that age group was the youngest to contain $\geq$ 10 yards within all yard maintenance practices. Within the 37-87 yrs 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 at $\alpha = 0.10$ and for appropriate analyses, all p-values were reported.

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 4). 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). At 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 levels did not change across % silt for 15-30 cm and 30-50 cm depths (data not shown).

Soil C and Soil N across Aboveground Tree Biomass

Relationships between soil C and the biomass, biomass*(1/distance), and biomass ≤ 10 m variables had similar patterns across depths: constant soil C levels 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 5). 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 ≤ 4m 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 5a) but exhibited no relationship with home age at 15-30 cm and 30-50 cm depths (Fig 5b and Fig 5c). Soil N levels remained constant across home age at all depths (Fig 6) 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 at 0-15 cm depth across the “young” home age groups, except for the 3-16 yrs and 3-30 yrs groups (Table 6). The slope declined by approximately 50% between 3-25 yrs and 3-35 yrs. For the corresponding paired “old” home age groups that started with 17-87 yrs and progressed to 56-87 yrs, 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 at 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 7). Both mean soil C and N were greater at 0-15 cm in mulched compared to bagged yards (Tables 7 and 8). 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 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 $\leq$ 36 yrs old and at 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 levels increased with home age ($P = 0.02$, $N = 11$, $R^2 = 0.46$, $y = 0.080x + 1.23$) while in bagged yards, soil C levels did not change across home age ($P = 0.67$, $N = 14$, $R^2 = 0.02$, $y = 0.006x + 2.45$). In mulched and bagged yards $\geq$ 37 yrs 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 $\leq$ 36 yrs old or $\geq$ 37 yrs old (data not shown). Likewise, in yards $\leq$ 36 yrs old, the relationship between soil C and home age at 0-15 cm depth did not differ between irrigated yards and non-irrigated yards. Due to limited sample size for irrigated yards, no comparative analysis could be performed for yards $\geq$ 37 yrs old.

Discussion

In our turfgrass lawns, the relationship between aboveground tree 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 aboveground tree biomass. However, the explanatory power of the 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 a 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 aboveground tree biomass and soil C but, at that depth, the amount of soil C input matched the amount of soil C output for 84 yrs. The constant soil C levels and low C:N 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 lack of change in soil C levels below 15 cm depth suggest that aboveground tree 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 for estimated belowground biomass, estimated belowground biomass may be a poor predictor for changes in soil C levels within the 87 yr time frame of the Auburn homes. Coarse root biomass composes 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 aboveground biomass values of softwoods and hardwoods have 79.9% and 56.2% explanatory power for their associated belowground biomass (respectively), 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.

For the second hypothesis, soil C would have a strong positive relationship with home age; however, soil C accumulated slowly (0.021kg C m^{-2} yr^{-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 an accumulation of soil C over home age, in contrast to the yards from prior forested land which showed constant soil C levels across home age. We did not ascertain the soil legacy of Auburn 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 this study, the legacy of Auburn 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} yr^{-1}) but the home age spanned a younger age range of 1-51 yrs (Huyler et al. 2013). Comparably, in the current study's lawns, the addition of trees did not appear to promote soil C accumulation, but the addition of homes within the 52-87 yrs age range may have lowered the slope. In the Auburn home age class of 3-50 yrs, the slope was 0.038 kg C m^{-2} yr^{-1} which suggests that the addition of trees in lawns may have fostered a more positive relationship between soil C and home age, even at 0-15 cm depth. However, results from this 3-87 yr study are not directly comparable to the 1-51 yr study and any interpretation remains speculative.

The rate of soil C accumulation was low in Auburn's study compared to work performed by Selhorst and Lal (2011) who measured a sequestration rate of 0.264 – 0.355 kg C m^{-2} yr^{-1} at 0-15 cm depth, but in the younger Auburn home age classes, the rate was similar to Qian and Follett (2002) who reported a soil C sequestration rate of 0.082 – 0.091 kg C m^{-2} yr^{-1} at 0-11.4 cm depth in Colorado and Wyoming golf courses. Across young Auburn home age groups, 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} yr^{-1} at 0-20 cm depth. In this study, the decline in slope between 3-25 yrs and 3-35 yrs, and further to 3-87 yrs, suggests greater positive relationships between soil C and home age in the younger yards.

For the third hypothesis, lawns that were fertilized, irrigated, or mulched would exhibit greater soil C levels across home age; however, 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 the Auburn 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 regard to the lack of response of soil C to mulched clippings, the addition of turfgrass trimmings may increase the input of organic C to the soil but the low C:N ratio for clippings may facilitate 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 yrs, 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 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 regard to irrigation may be difficult to make.

The fourth hypothesis, that soil C would increase with % clay, was not supported. In grasslands converted from agriculture across the past 40 yrs, 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, this study's results may be similarly explained. The positive relationship with % silt may be due to the greater percentage of silt compared to clay at 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 this 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 Auburn's case study, aboveground tree biomass was a poor representative of soil C levels. Even though the explanatory power of aboveground tree biomass increased with depth, soil C levels below 15 cm remained constant 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.

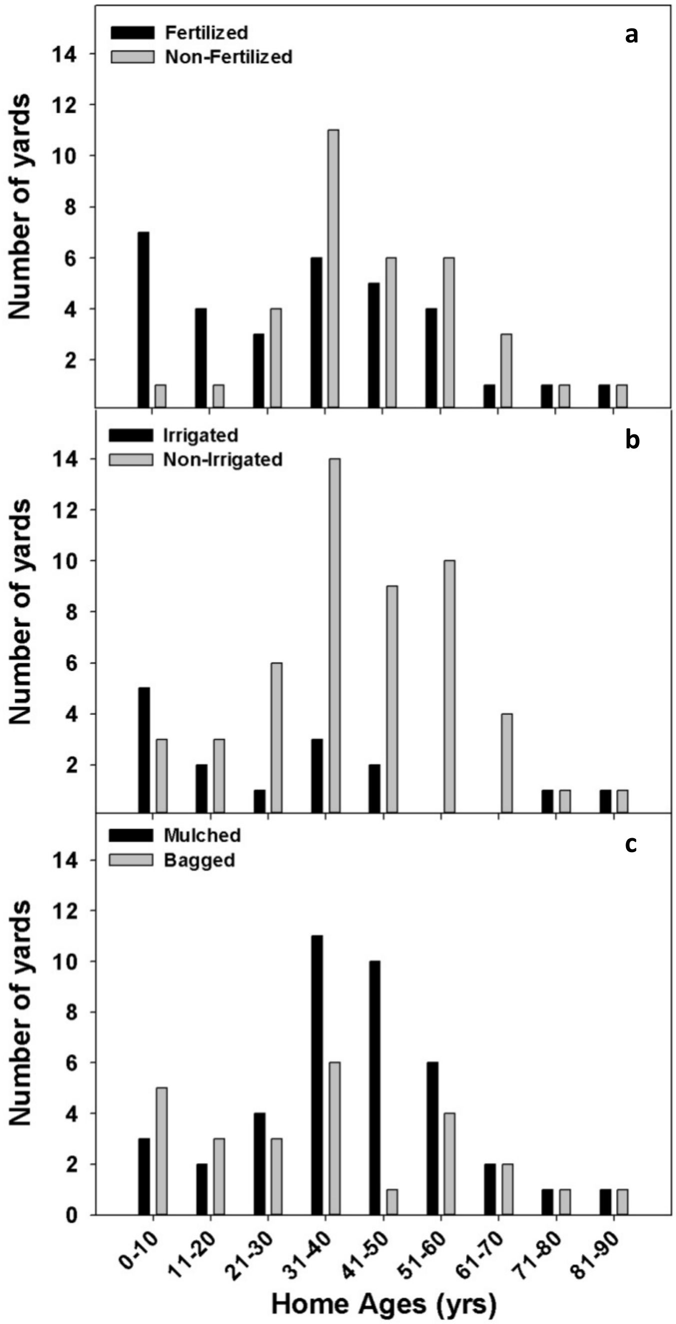

Fig. 4 The number of yards subdivided by maintenance practices across home ages (3-87 yrs): a) fertilized and non-fertilized, b) irrigated and non-irrigated, and c) mulched and bagged.

Table 4 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 differences within a category and between depths occur at $\alpha = 0.10$ and are marked different lowercase letters.

N = number of yards.

Table 5 Linear regression analysis of soil C (kg m^{-2}) to aboveground tree biomass (kg) data sets across depths with corresponding median values for aboveground tree biomass, # trees, dbh, and distance from trees.

Biomass	**P-value**	**R^2**	**N**	**Slope (×10^{-4})**	**Median Biomass (kg)**	**Median # Trees**	**Median Dbh (cm)**	**Median Distance (m)**
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

Significant relationships occur at α = 0.10 and are marked with an ‘*’.
N = number of yards.

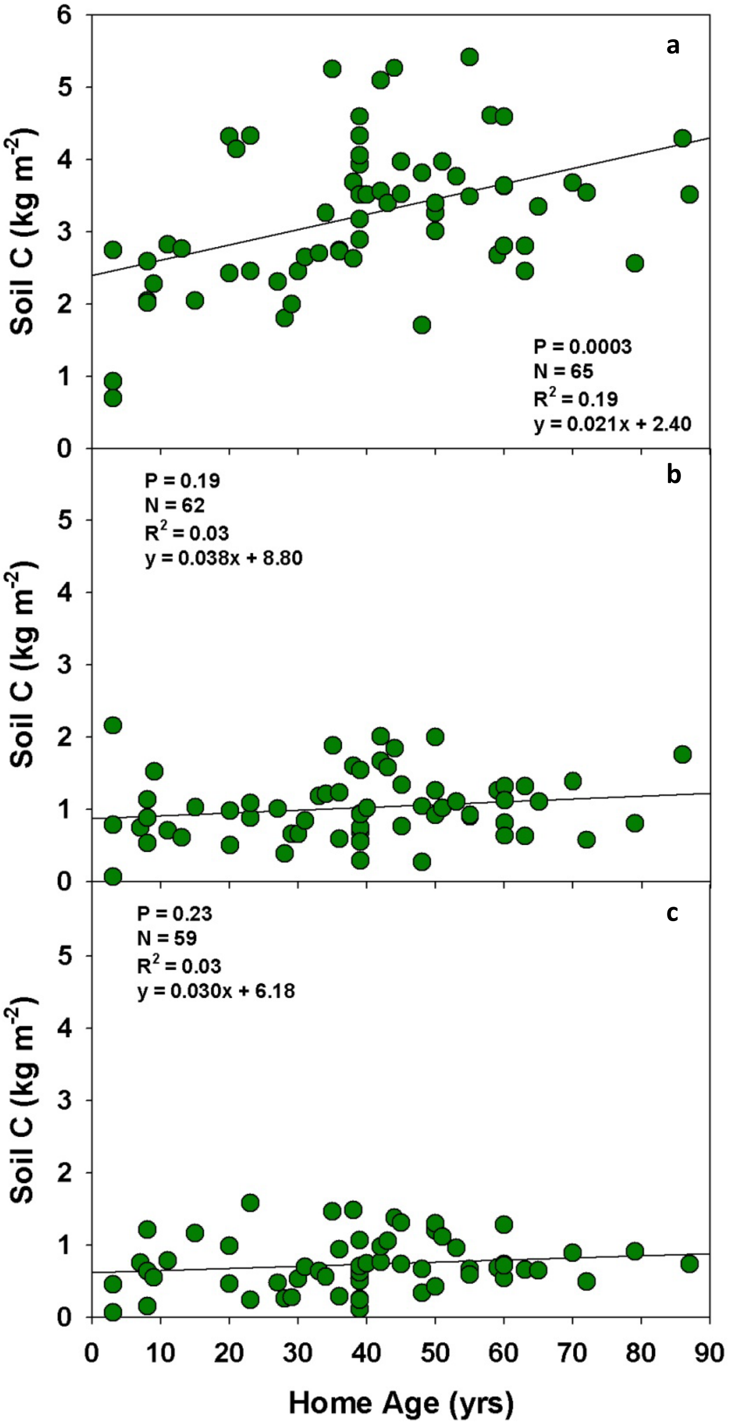

Fig. 5 Relationship of soil C (kg m^{-2}) to home age (3-87 yrs) at depths: a) 0-15 cm, b) 15-30 cm, c) 30-50 cm.

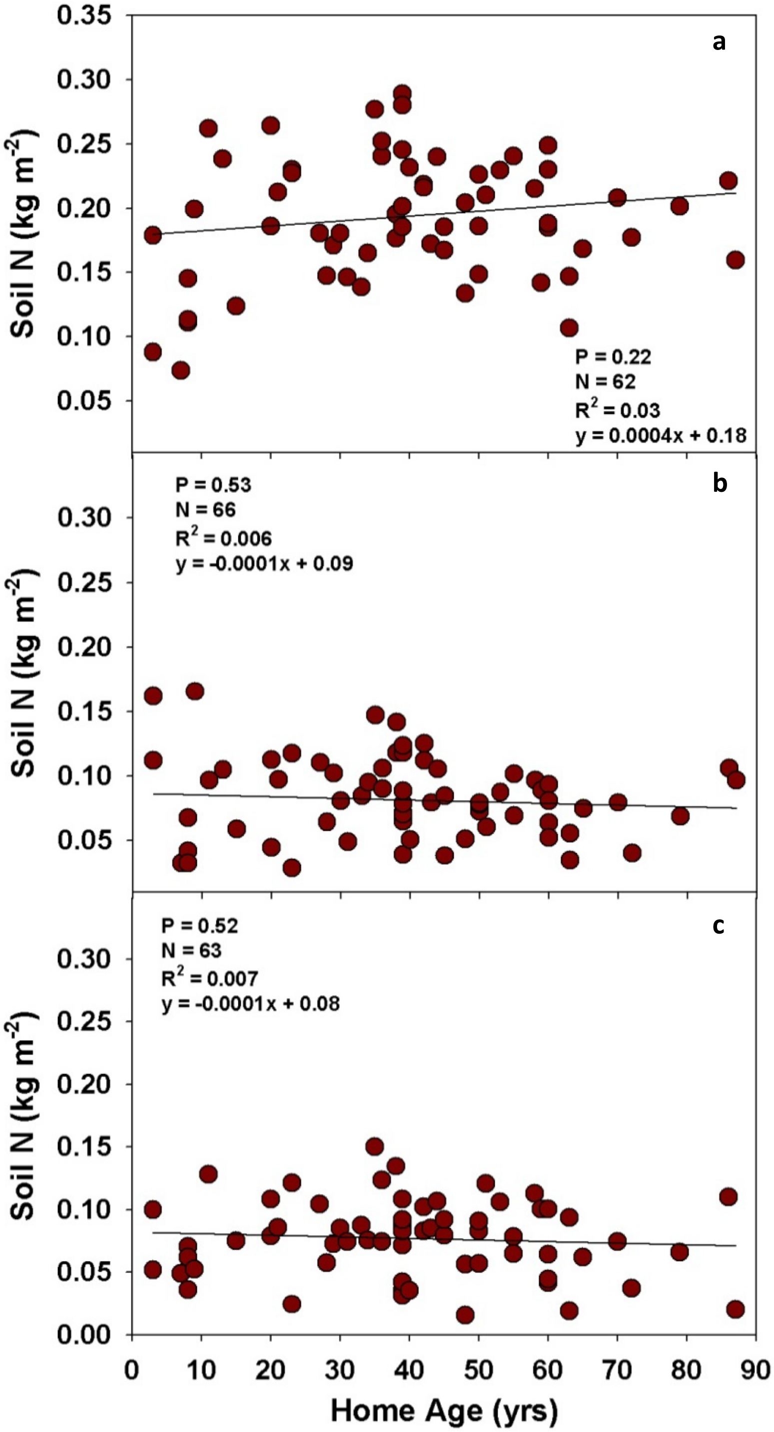

Fig 6. Relationship of soil N (kg m^{-2}) to home age (3-87 yrs) at depths: a) 0-15 cm, b) 15-30 cm, c) 30-50 cm.

Table 6 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 occur at $\alpha = 0.10$ and are marked with an '*'.
N = number of yards.
All "young" home age groups begin with the youngest home age of 3 yrs.

Table 7 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 occur at $\alpha = 0.10$ and are marked with an '*'.

N = number of yards.

Table 8 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 occur at $\alpha = 0.10$ and are marked with an ‘*’.

N = number of yards.

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CHAPTER 4

Soil C dynamics in residential lawns with and without trees in Auburn, AL

Abstract

Soil in residential yards can contain substantial amounts of organic carbon (C); thus research is needed to discern the environmental variables that may stimulate soil C accumulation in yards. In a case study in Auburn, AL, the relationship of soil C to home age was compared between 44 lawns with trees (LwT) and 23 lawns without trees (pure lawns, PL) across similar home age ranges (≤ 51 yrs) and at 3 depths: 0-15 cm, 15-30 cm, and 30-50 cm. In addition, the relationships between soil C and three aboveground tree biomass data sets were analyzed; 1) biomass, 2) biomass ≤ 10 m, and 3) biomass ≤ 5 m data set. The latter two biomass data sets used only trees within ≤ 10 m and ≤ 5 m from the sample site. With the inclusion of 12 yards of unmanaged forest stands, designated 'pure woods' (PW), we compared mean soil C levels in PL, LwT (3-87 yrs), and PW, across four categories of aboveground tree biomass [median values: 1) 0 kg; 2) 47 kg; 3) 3257 kg; 4) 12386 kg] and also across five groups of home age [median values: 1) 7 yrs; 2) 29 yrs; 3) 39 yrs; 4) 55 yrs; 5) 79 yrs + PW]. At 15-30 cm depth, soil C had a significantly more positive relationship with home age ($P = 0.03$) in LwT ($P = 0.033$, $R^2 = 0.11$, $N = 41$, $y = 0.011x + 0.62$) than in PL ($P = 0.097$, $R^2 = 0.13$, $N = 23$, $y = -0.011x + 1.18$). The biomass ≤ 5 m data set had the highest explanatory power for soil C across all depths, with a R^2 value of 0.40 at 15-30 cm. Compared to aboveground tree biomass category 1, mean soil C in both 0-15 cm and 30-50 cm depths significantly increased in category 3, by 30% and 45% respectively, whereas soil C at 15-30 cm depth increased by 30% in category 4. Compared to home age group 1, mean soil C at 0-15 cm depth increased by 73% in group 3, whereas soil C at 15-30 depth remained unchanged across all successive groups, and at 30-50 cm depth, mean soil C significantly decreased by 46% in group 2. Overall, the relationship between soil C and aboveground tree biomass was poorly associated with soil C levels over 50 yrs home age. Tree fine roots may be a more effective biomass variable to discern the influence of trees upon soil C levels in residential yards.

Introduction

Rising concentrations of atmospheric carbon (C) are contributing to climate change worldwide (IPCC 2008). Soil contains the second largest amount of organic C on the planet (Watson et al. 1990), with most of it developed under forest and grassland biomes (Jobbágy and Jackson 2000). Thus, much research has been focused on the capacity of forests (Goodale et al. 2002, Hooker and Compton 2003, Sun et al. 2004, Sartori et al. 2007) and grasslands (Gebhert et al. 1994, Potter el al. 1999, Conant et al. 2001) to accumulate soil organic carbon (SOC). However, the continued expansion of urban lands (Seto et al. 2012) has provided impetus for research on urban forests and their potential for significant SOC storage. Residential areas are a rapidly growing component of the urban landscape (Overman et al. 2008) and residential yards have not only provided a series of chronosequences of urban forests to examine SOC dynamics, but residential yards can also contain greater SOC levels than nearby grasslands (Kaye et al. 2005) and rural forests (Raciti et al. 2011, Nagy et al. 2013). In Colorado residential yards, SOC levels significantly increased at 0-10 cm and 10-20 cm depths after only 7 yrs and 25 yrs, respectively, and the homes built in the 1980s had greater SOC levels at 0-100 cm depth than the nearby shortgrass steppe (Golubiewski 2006).

Grasses and trees have differing C allocation patterns and the relationship between above- and belowground biomass can be represented by the root:shoot ratio (R:S) (Jackson et al. 1996). For grasses, fine roots receive the majority of the allocated C (Jackson et al. 1996, Mokany et al. 2006) and are responsible for the majority of organic C input to the soil (Kelly et al. 1996), though aboveground tissues also contribute to the SOC pool (Burke et al. 1998). In contrast, trees have a greater C allocation to aboveground tissues, such as stems and foliage (Jackson et al. 1996, Cairns et al. 1997, Levy et al. 2004, Mokany et al. 2006, Wang et al. 2008), despite trees having more root biomass than grasses (Jackson et al. 1996). The net primary productivity of tree leaves and fine roots can comprise a major portion of total annual NPP (Keyes and Grier 1981, Comeau and Kimmins 1989, Malhi et al. 2011) and both tree leaf litter in the forest floor (Liski et al. 2002, Ngao et al. 2005, Kalbitz and Kaiser 2007, Uselman et al. 2007) and fine roots (Gill et al. 1999, Lichter et al. 2005, Trumbore et al. 2006, Bird et al. 2008) contribute to the SOC pool. While SOC in native forests comes from both above- and belowground tissues, in residential yards the organic C from trees would mainly derive from belowground biomass because tree leaf litter and woody debris are typically removed from lawns. In lawns, the high productivity of turfgrass can last from early spring to mid-summer and may play a role in promoting increased SOC densities (Kaye et al. 2005), and as such, lawn maintenance practices may also influence soil C levels.

Over time, fertilization and irrigation may enhance the accumulation of soil C (Milesi et al. 2005, Qian et al. 2010). Fertilization and irrigation of residential yards in the Front Range of Colorado was credited with higher rates of SOC accumulation than the surrounding grassland areas, thereby increasing yard SOC levels past grassland levels after two decades (Golubiewski 2006). Qian and Follett (2002) analyzed SOM levels in a chronosequence of 12 golf courses that spanned ~45 yrs in age, and the high SOM accumulation rate of 0.082 – 0.091 kg C m^{-2} yr^{-1} in the fairways and putting greens was attributed to high levels of management. Moreover, the addition of mowed and mulched turfgrass clippings to the lawn provides supplemental nitrogen and increases turfgrass productivity and quality (Kopp and Guillard 2002) and can stimulate the rate of SOC sequestration in turfgrass lawns (Qian et al. 2003).

Once organic C is deposited into mineral soil, the amount of SOC that accumulates is largely dependent upon its resistance to decomposition. Soil texture is the % composition of sand, silt, and clay, and can influence the mean residence time of SOC. The surface area of mineral particles (m^2 g^{-1}) can decrease the rate of SOC oxidation (Chenu and Plante 2006) by providing binding opportunities for SOM; clay particles have the largest surface area and sand has the smallest (Fisher and Binkley 2000). In addition, clay particles, SOM, and polyvalent metal cations (Fe, Ca, Al) can bind together to form soil microaggregates which inhibit decomposition of SOC (Six et al. 2000). In general, SOC levels are positively associated with clay content (Anderson et al. 1981, Sorensen 1981, Nichols 1984) or with a combination of silt and clay content (Burke et al. 1989, Homann et al. 2007).

The vegetation cover of residential yards (i.e. turfgrass and trees), home age, yard maintenance (i.e. fertilization, irrigation, mulching) and soil texture may influence soil C levels. As yet, the relationships of soil C levels to the aforementioned yard characteristics have not been investigated. Thus, a case study was performed in Auburn, AL, to compare the relationship of soil C to home age, yard maintenance, and soil texture between pure lawns (PL, lawns absent trees) at 1-51 yrs home age and lawns with trees (LwT) at 3-51 yrs home age. The relationship of soil C in LwT to three aboveground tree biomass data sets was also examined; including analyses of the relationship of soil C to home age within each biomass data set.

Aboveground tree biomass instead of belowground biomass was used to assess the influence of trees upon soil C levels for several reasons: 1) direct measurement of belowground biomass in residential yards was unfeasible, 2) species specific allometric equations or R:S ratios did not exist for the urban trees within the regional and environmental conditions of Auburn's residential yards, and 3) the estimation of belowground biomass would involve a general R:S ratio for temperate forests, which implied that aboveground biomass could substitute for belowground biomass. The addition of soil C derived from belowground biomass was expected to supplement soil C levels such that an association between greater soil C levels and greater aboveground tree biomass levels could be observed.

When yards are composed of unmanaged forest stands with forest floor instead of turfgrass (pure woods, PW), linear regression cannot be used to analyze the relationship between soil C and home age because the forested yard age would not be represented by home age. In addition, linear regression analysis does not provide information on differences between mean soil C levels across home age, or even across aboveground tree biomass. However, mean soil C levels can be compared between ascending groups of home age and categories of aboveground tree biomass across PL (1-51 yrs), LwT (3-87 yrs), and PW.

The four hypotheses were: 1) The relationship between soil C and home age would be more positive in LwT compared to PL, 2) In LwT (3-51 yrs), soil C levels would be positively related to aboveground tree biomass levels, 3) Mean soil C levels would increase with aboveground tree biomass categories; and 4) Mean soil C levels would increase with home age groups.

Methodology

Site

The case study was performed in the city of Auburn, altitude of 210 m (689 ft) (U.S. Climate Data) and latitude 32.6°N longitude 85.5° (U.S. Census Bureau), located in east central Alabama, in Lee County abutting the Georgia border. The soils of Alabama are dominated by Udults, a well-drained Ultisol with base saturation greatest at surface soil layers but < 35% (USDA NRCS). 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 red, clayey subsoil and Coastal Plain soils have a sandy loam or loam surface layer and either 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 a mean annual temperature (MAT) of 17.4°C (63.4°F) (U.S. Climate Data). 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

Soil was sampled in 23 ‘pure lawns ‘(PL) of single family homes, where trees were located > 20 m away from the sample site. In addition, soil was sampled in 66 ‘lawns with trees’ (LwT) of single family homes and U.S. Department of Housing and Urban Development duplexes and in 12 PW yards. All yards were sampled in spring/summer 2009 and 2010. Because this was a case study of the influence of certain yard characteristics on soil C levels, and not an examination of the soils in Auburn’s residential yards, the priority was to achieve a large sample size of yards with a range of tree biomass and home ages. Requests for permission to sample soils in yards were sent to various individuals and organizations either by email or by placing a written request in the doorway of a home. Some yards were located through visual inspection of neighborhoods using Google Earth© aerial photos and by driving through neighborhoods. In the residential lawns, zoysia grass (*Zoysia* spp.) and Bermuda grass (*Cynodon dactylon*) were the most common turfgrass species.

The home age ranged 1-51 yrs for PL and 3-87 yrs for all LwT. When directly comparing PL to LwT, we used 44 LwT with a home age range of 3-51 yrs. Home age data were obtained from the city of Auburn Planning Commission (Justin Steinmann personal communication) and the Lee County Courthouse, Opelika, AL.

In the aboveground tree biomass categories and home age groups, we used 23 PL, 66 LwT and 12 PW yards. The parameters of the aboveground tree biomass categories and home age groups were developed in regards to two factors: the need to maintain similar numbers of yards within categories/groups and the utilization of the existing gaps in the range of home ages and levels of aboveground tree biomass. The median values for the four aboveground tree biomass categories were: 1) 0 kg; 2) 47 kg; 3) 3257 kg; and 4) 12386 kg. Of the 12 PW yards, four yards were in the 3rd biomass category and eight yards were in the 4th biomass category. The median values for the five home age groups were: 1) 7 yrs; 2) 29 yrs; 3) 39 yrs; 4) 55 yrs; and 5) 79 yrs including the 12 PW yards.

Soil sampling and processing

Front lawns were selected for ease of access and because back yards were more often used by owners and pets. Due to the potential for damage to home owner’s property and to the soil probe, we avoided sampling on irrigation/gas/water/sewer/home security/electric lines, and avoided sampling areas with protruding woody roots and rocks or exhibiting eroded soil, and near sidewalks, driveways, roads, and buildings where gravel, concrete, and other construction objects may have been buried. A single meter square plot was placed “arbitrarily without preconceived bias” in the front yard and within the yard’s sampling limitations (McCune and Grace 2002). At each corner of the meter square plot two soil cores were taken at three depth increments: 0-15 cm, 15-30 cm, and 30-50 cm. 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 composition. Within each yard we collected a total of four each C, N, and 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 moisture.

Carbon and Nitrogen Analysis

Measurement of the concentration of soil C and N was performed 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 calculated by dividing the mass of the fine soil (< 2 mm) by its volume. The mass and volume of roots and rocks removed by the 2 mm mesh were subtracted from the 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 the soil C or N concentration.

Soil Texture

Soil texture was analyzed with the 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 35.7g of sodium metaphosphate ($NaPO_3$) x Na_2O and sodium carbonate (Na_2CO_3) dissolved in 1L 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 minutes and then the solution was placed in a 1L glass cylinder and brought to volume. The cylinder was corked and the solution shaken for one minute. Immediately afterwards, a hydrometer was placed in the solution and read after 40 seconds of settling time. The one minute shaking of the cylinder solution was repeated and followed by a second hydrometer reading and a recording of the solution temperature. After 24 hours, hydrometer and temperature readings were repeated on the resting solution.

Pure Lawns and Lawns with Trees (3-51 yrs)

Yard Maintenance

Yard maintenance was quantified for all lawns with turfgrass (i.e. PL and all LwT). Home owners were interviewed to determine yard maintenance history (i.e., fertilization, irrigation, and turfgrass clipping removal or mulching). Because most residents did not recall the exact frequency or amount 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 two weeks. If the owners equally alternated bagging and mulching, the yards were recorded as ‘mulched’.

In PL, 70% of the yards were fertilized and roughly half the yards were mulched (Table 9, in **bold**). In PL, only 30% of the yards were irrigated, with all irrigated yards being younger than 15 yrs. In LwT (3-51 yrs), half of the home owners did not fertilize and none of the non-fertilized yards were younger than 20 yrs old (Table 9, in *italics*). In LwT, 73% of the yards were not irrigated and 61% of the yards were mulched. Home owners of PW did not fertilize or irrigate their yards.

Lawns with Trees (3-51 yrs)

Aboveground tree biomass

As the presence of tree roots has been approximated to extend at least 1.5 × height of tree (Sudmeyer et al. 2004), the trees used in this study had a distance from the center of the meter square plot that was $\leq 1.5 \times$ height of the tree and also were not separated by roads from the sample site. All trees were identified to species and measured for diameter at breast height (dbh, 1.37 m), total height, and distance from plot center.

Brantley (2008) provided biomass algorithms for Chinese Privet (*Ligustrum sinense*) and we applied the same algorithm to crape myrtle (*Lagerstroemia* spp.); two yards contained crape myrtle. All remaining tree biomass algorithms were obtained from Jenkins et al. (2003) and used the equation: $total\ aboveground\ biomass = Exp(\beta_0 + \beta_1\ ln\ dbh)$. Individual tree biomass, for each yard, was multiplied by 0.8 because 'open grown' urban trees develop less biomass than non-urban trees (Nowak 1994) and all the algorithms were derived from trees in wooded or forested environments. Because belowground biomass estimations would have involved multiplication of a R:S constant by aboveground biomass (Cairns et al. 1997), we retained aboveground biomass as the biomass variable to be used to investigate the influence of tree biomass on soil C levels. Two additional biomass data sets were developed in case root density decreased with increasing distance from the tree (Ammer and Wagner 2002, Sudmeyer et al. 2004); as such, the distance between trees and the sample site may affect the relationship between soil C and aboveground tree biomass. The two additional biomass data sets were biomass ≤ 10 m and biomass ≤ 5 m and incorporated only trees ≤ 10 m and ≤ 5 m from center of the meter square plot. Shorter distances were not possible due to sample size limitations. The range of values for the biomass, biomass ≤ 10 m, and biomass ≤ 5 m data sets were 0.07-12,386 kg, 0.07-4988 kg, and 0.07-2842 kg, respectively, with median biomass values of 1996 kg, 570 kg, and 230 kg, respectively (data not shown).

A maximum of 200 trees were identified to species and the most common tree species were loblolly pine (*Pinus taeda*) at 31%, followed by sweetgum (*Liquidambar styraciflua*) at 11%, red maple (*Acer rubrum*) at 10%, and water oak (*Quercus nigra*) at 8%. Overall, hardwoods encompassed 58.5% of all trees and the three dominant genera were *Pinus* at 39%, *Acer* at 16%, and *Quercus* at 13%.

Statistical Analysis

A Tukey's Studentized Range test was performed using ANOVA (SAS 9.1, SAS Institute Inc., Cary, NC, USA) for PL and LwT (3-51 yrs) to ascertain if mean soil C, soil N, soil C:N, bulk density, % sand, % clay, and % silt differed due to soil depth, and to determine if mean soil C, soil N, soil C:N ratio, bulk density, and % soil texture differed between PL and LwT at the same depth. Regression analyses (SAS 9.1, SAS Institute Inc., Cary, NC, USA) were performed on the relationship of soil C to % sand, % clay, and % silt within PL and LwT (3-51 yrs) and a likelihood ratio test (Neter et al. 1989) was conducted to determine if the relationships differed between PL and LwT (3-51 yrs).

Regression analyses were used to determine the relationship between soil C and soil N to home age within PL and LwT. A likelihood ratio test was performed to determine whether the relationships between soil C and home age, and between soil N and home age, differed between

PL and LwT (3-51 yrs). Within LwT, regression analyses were also used to assess the relationship of both soil C and N to the three biomass data sets as well as the relationship of soil C and N to home age within each biomass data set. For the aboveground tree biomass categories and home age groups, statistical differences in mean soil C levels were determined with the Tukey's Studentized Range test using ANOVA.

To ascertain the relationship of soil C to home age within individual yard maintenance practices within PL and LwT (3-51 yrs) regression analyses were used, and a likelihood ratio test was used to establish whether the relationships between soil C and home age and between soil N and home age differed between contrasting yard maintenance practices (e.g. between fertilized PL and non-fertilized PL). A likelihood ratio test was used to determine whether the relationship between soil C and home age differed between PL and LwT (3-51 yrs) within the same yard maintenance practice (e.g. fertilized PL and fertilized LwT). A Tukey's Studentized Range test was used to determine if mean soil C and mean soil N differed between contrasting yard maintenance practices within PL and LwT and also between PL and LwT within the same yard maintenance practice. Removal of yards with outliers, using the BOXPLOT procedure (SAS 9.1, SAS Institute Inc., Cary, NC, USA), reduced the number of yards in regression and ANOVA analyses. For this study, alpha was set at 0.10 for all analyses (Peterman 1990) due to the expectation of high soil C variability within yards and the lack of knowledge of home construction techniques and prior home owner activities regarding the front yard vegetation and soil conditions. All p-values were reported for appropriate analyses.

Results

Pure Lawns vs. Lawns with Trees (3-51 yrs)

Soil characteristics

In PL, soil C declined successively with depth, being roughly 4× greater at 0-15 cm than 30-50 cm depth and soil N declined from 0-15 cm to the two lower depths, being 2× greater at the surface soil layer (Table 10). In LwT, soil C and soil N declined from 0-15 cm to the two lower depths. Mean soil C in LwT was greater than PL at 0-15 cm and 30-50 cm depths, while soil N in PL was greater at the 30-50 cm depth compared to LwT. In PL, the soil C:N ratio was similar between 0-15 cm and 15-30 cm depths before declining by >50% at the 30-50 cm depth, whereas in LwT, the soil C:N ratio decreased with each soil depth interval. The soil C:N ratio at 0-15 cm and 30-50 cm depths in LwT was significantly greater than in PL.

In both PL and LwT, bulk density increased from 0-15 cm to the two deepest soil depths. In PL, % sand decreased from 0-15 cm to the deepest soil depth, whereas in LwT, % sand decreased successively with depth. In PL, % clay increased from 0-15 cm to the two deeper soil depths, while in LwT, % clay increased successively with depth. In both PL and LwT, % silt did not change across depths. There was no significant difference between PL and LwT in bulk density or % sand, % clay, and % silt. In both PL and LwT, soil C and soil N had no significant relationship with soil texture at any depth (data not shown).

Relationship of soil C and N across home age

At 15-30 cm, soil C exhibited a more positive relationship with home age in LwT than in PL (Table 11). In both PL and LwT, soil C at 0-15 cm depth increased significantly with home age, whereas at 30-50 cm, soil C had no significant relationship with home age. The relationship of soil N to home age was not significantly different between LwT and PL at any depth (data not shown).

Yard maintenance

Within PL, significant differences in the relationship between soil C and home age occurred between irrigated and non-irrigated yards at 15-30 cm ($P = 0.08$) and 30-50 cm ($P = 0.06$) depths. However, soil C had no relationship with home age at 15-30 cm depth in irrigated yards ($P = 0.18$) or non-irrigated yards ($P = 0.64$) or at 30-50 cm depth in irrigated ($P = 0.39$) or non-irrigated ($P = 0.97$) yards. A significantly different relationship between soil C and home age did occur at 30-50 cm depth ($P = 0.04$) between bagged yards ($P = 0.02$, $R^2 = 0.62$, $N = 8$, $y = -0.01x + 0.85$) and mulched yards ($P = 0.79$, $R^2 = 0.01$, $N = 0.8$, $y = -0.001x + 0.44$) but with sample sizes < 10, these results are tenuous. Within LwT, soil C at 0-15 cm had a significantly more positive response to home age ($P = 0.03$) in mulched yards ($P = 0.0009$, $R^2 = 0.36$, $N = 27$, $y = 0.05x + 1.83$) compared to bagged yards ($P =0.07$, $R^2 = 0.21$, $N = 17$, $y = 0.02x + 1.93$).

When comparing the relationship of soil C to home age between LwT and PL within the same yard maintenance practice, only mulched yards at 0-15 cm depth produced a meaningful comparison. In mulched yards, soil C had a slightly more positive increase over home age ($P = 0.097$) in LwT ($P = 0.0009$, $R^2 = 0.36$, $N = 27$, $y = 0.05x + 1.83$) than in PL ($P = 0.03$, $R^2 = 0.40$, $N = 12$, $y = 0.02x + 1.83$). When comparing the mean soil C levels between LwT and PL for the same yard maintenance practices, soil C at 0-15 cm depth in mulched yards was greater ($P = 0.003$) in LwT (3.36 kg m^{-2}) than in PL (2.27 kg m^{-2}). Mulching was the only yard maintenance practice that produced a significantly different relationship between soil C and home age between LwT and PL, but only at the 0-15 cm depth.

Lawns with Trees (3-51 yrs)

Soil C and soil N to aboveground tree biomass and home age

Soil C at 15-30 cm and 30-50 cm depths increased significantly with all three biomass data sets and soil C at 0-15 cm depth increased with biomass ≤ 5 m (Table 12). Explanatory power for soil C was greatest with the biomass ≤ 5 m data set, especially at 15-30 cm depth. Within the yards of the three biomass data sets, soil C had the strongest positive relationship with home age at 0-15 cm and no relationship with home age at 30-50 cm (Table 13). Soil N had a significant relationship only with the biomass ≤ 5 m data set at 15-30 cm and 30-50 cm depths ($P = 0.04$, $R^2 = 0.15$, $N = 29$, $y = 0.00002x + 0.08$ and $P = 0.02$, $R^2 = 0.20$, $N = 27$, $y = 0.00002x + 0.06$, respectively). However, in the yards of the biomass ≤ 5 m data set, soil N levels did not change across home age for the 15-30 cm ($P = 0.83$) and 30-50 cm depths ($P = 0.78$).

Soil C across Aboveground Tree Biomass Categories

Compared to aboveground tree biomass category 1 (median 0 kg), mean soil C levels at both 0-15 cm and 30-50 cm depths increased significantly in category 3 (median 3257 kg) by 30% and 45%, respectively (Table 14). In all categories with trees (categories 2-4), soil C levels at 0-15 cm depth remained constant. Mean soil C levels at 15-30 cm depth significantly increased by 30% in category 4 (median 12386 kg) when compared to category 1.

Soil C across Home Age Groups

Compared to home age group 1 (median 7 yrs), mean soil C levels at 0-15 cm was significantly greater by 73% in group 3 (median 39 yrs), with mean soil C then remaining constant to group 5 (median 79 yrs) (Table 15). The mean soil C in15-30 cm was not significantly different between group 1 and all successive groups (2-5); however, mean soil C had a significant 67% increase in group 5 compared to group 2 (median 29 yrs). Compared to group 1, mean soil C at 30-50 cm significantly decreased by 46% in group 2. Mean soil C levels then remained constant until a slight, significant increase in group 5 produced mean soil C levels statistically similar between group 1 and group 5.

Discussion

In our study, soil C at 15-30 cm depth had a more positive relationship with home age in LwT than in PL. In addition, all three biomass data sets had the greatest explanatory power for soil C at 15-30 cm depth, and soil C at 15-30 cm depth significantly increased with home age within each biomass data set. Considering these results, belowground tree biomass in LwT may enhance the accumulation of soil C at 15-30 cm depth across home age. However, mean soil C levels at 15-30 cm depth did not change from the 1st decade of home age group 1 to the 8th decade in group 5, which also contained all 12 PW yards. In addition, mean soil C at 15-30 cm depth only increased at the largest biomass category, whereas soil C at 0-15 cm and at 30-50 cm depths increased at lower biomass categories. Overall, mean soil C levels at 15-30 cm depth did not appear to reflect the positive linear regression relationships with home age and aboveground tree biomass. A partial explanation for the lack of change in mean soil C levels from home age group 1 (1st decade) to group 5 (8th decade), may be that a loss of vegetation C input to the soil from home/yard construction lowered soil C levels and more time was needed to observe a significant increase from the first decade. In home age group 2, mean soil C levels were less than group 1, though not significantly. Approximately 50 yrs after group 2, mean soil C levels had significantly increased, possibly representing new soil C input at 15-30 cm depth from tree roots.

Another premise may be that while soil C at 15-30 cm depth was influenced more by tree root biomass than the upper or lower depths, soil conditions at 15-30 cm depth may have fostered a greater loss of soil C in relation to soil C input. Gill et al. (1999) reported that the proportion of fine root biomass across depths did not match the proportion of soil organic C across the same depths, in part due to soil depths having different relative frequencies of high water potentials which can alter decomposition rates. Differences in decomposition rates across soil depths may change the explanatory power of aboveground tree biomass, as a representative of belowground biomass, for variability in soil C levels.

At 0-15 cm depth, a greater factor influencing soil C levels may be turfgrass instead of tree roots. PL and LwT had a similar positive relationship with home age, and in both lawn types turfgrass was the common vegetation cover at the surface soil layer. Possibly, tree fine roots may have relocated below turfgrass root level (Dawson et al. 2001, Mulia and Dupraz 2006) which may partially explain the more positive relationship between soil C and biomass at the two lower depths. At 30-50 cm, mean soil C appeared to have the most negative response to disturbance from home construction (i.e. with the significant decline in home age group 2), suggesting a direct connection with prior vegetation and supporting the positive relationships soil C had with all biomass data sets at that depth. However, soil C at 30-50 cm had no relationship with home age in LwT or PL or with home age within any of the three biomass data sets, and no significant increase occurred in mean soil C levels for 50 yrs after the decline in home age group 2. The reestablishment of root biomass and significant root C input at 30-50 cm depth may take longer than at 15-30 cm depth, where mean soil C levels significantly increased 50 yrs after home age group 2. At 30-50 cm depth, the low soil C:N values in both PL and LwT indicated a preponderance of humified SOM, suggesting a lack of substantive C input from the present vegetation (O’Brien and Stout 1978, Torn et al. 1997).

Overall, aboveground tree biomass was not a good predictor for soil C levels. Li et al. (2010) found weak associations between soil C levels and above- or belowground tree biomass in beech (*Fagus crenata*) and birch (*Betula ermanii*) forests in the mountains of Japan. While correlations values were significant and high between SOC levels and dbh (0.54 in 0-30 cm), mean tree height (0.65 in 0-30 cm), and leaf area index (0.56 in 0-30 cm), correlation values were not significant between SOC levels and tree biomass (Li et al. 2010). Vesterdal et al. (2002) suggested that accumulation of soil C may occur after ~30 yrs, when the decline in SOC from the decomposition of agricultural-related SOC becomes offset by increased above- and belowground C input from growing trees. In this study, a measurable impact of tree roots on soil C levels appears to require approximately 50 yrs in the 15-30 cm depth and > 50 in the 30-50 cm depth before significant increases in mean soil C levels occur.

Our hypothesis regarding the connection between soil C levels and aboveground tree biomass was dependent upon three "linked" assumptions. One assumption was that aboveground biomass in our residential yards could be accurately estimated from allometric equations developed from natural forests. The second assumption was that belowground biomass would be accurately estimated from multiplication of aboveground biomass by a constant R:S ratio, such that aboveground biomass could substitute for belowground biomass. The third assumption was that belowground biomass would have a significant and substantive influence on soil C levels over 50 yrs.

In regards to the first assumption, allometric equations are a common method to estimate aboveground tree biomass and are used extensively in managed forest stands and plantations. However, most timber species do not have a comprehensive list of biomass equations developed for specific site conditions, much less the non-timber species that populate residential yards. Loblolly pine is the most important timber species in the southeastern U.S. (Schultz 1999); however, estimations of aboveground loblolly pine biomass can differ widely, even between allometric equations developed within the same region as the loblolly pine stand. Using a loblolly pine stand in Arkansas, Bragg (2011) tested four allometric equations that estimated aboveground tree biomass. Three model equations were derived from Louisiana and Arkansas loblolly stands, and one model equation was a generalized pine equation from Jenkins et al. (2003). Bragg (2011) found disparity between all estimations for individual trees and for the entire stand, and the disparity widened greatly when dbh was greater than 50 cm. Similar to Bragg (2011), McHale et al. (2009) also found a wide disparity of aboveground tree biomass estimations but for urban trees. In Fort Collins, CO, McHale et al. (2009) determined the volume of 184 street trees, representing 11 species, and developed algorithms to estimate their aboveground biomass. The authors then compared their results to the aboveground biomass estimations predicted from sixteen equations from literature. For individual urban trees, the estimates from literature-based equations over-predicted by 169% and under-predicted by 97%, with only three equations producing estimates that fit within the 95% confidence intervals from the street tree algorithms. One of the equations was a general hardwoods equation for forests in Michigan, Minnesota, and Wisconsin and the other two equations were applied to different species than the equations were developed for. The wide range of over- and under estimations of aboveground biomass would produce uncertainty not only for the accuracy of studies involving urban tree biomass but also for the ability to compare results between studies. Possibly, the low explanatory power of aboveground tree biomass for soil C in this case study may partially be explained by inaccuracies in the estimations of aboveground tree biomass.

Our second assumption was that aboveground biomass could substitute for belowground biomass because the estimation of belowground biomass in the yards would have been a product of a constant R:S biomass ratio (developed for temperate forests) and estimated aboveground biomass. Cairns et al. (1997) estimated that the global mean R:S biomass ratio for temperate forests was 0.26. Neither the R:S ratio nor root biomass density were found to be influenced by forest age, latitude, soil texture, mean annual temperature, mean annual precipitation, the ratio of temperature:precipitation, or whether the trees were angiosperms or gymnosperms. However, Mokany et al. (2006) performed a meta-analysis of estimations of forest ecosystem R:S biomass ratios and found that R:S ratios declined with increasing annual precipitation, shoot biomass, forest stand age, and forest stand height and that the R:S ratio was significantly higher in sandy and sandy loam soils compared to clay soils. The carbon allocation patterns to roots and shoots were not constant, and instead, changed with forest and environmental conditions.

Research by Vogt et al. (1996) highlights the difficulty in predicting biomass C allocation patterns. Using 200 data sets, Vogt et al. (1996) grouped above- and belowground tree biomass within their specific forest climatic types plus soil orders, (e.g. subtropical needleleaf evergreen and Ultisol), in order to determine biomass patterns between forest climate and soil groupings. Because of the high variation in above- and belowground biomasses within groupings, no patterns could be discerned between groupings (Vogt et al. 1996). For the assessment of the R:S biomass ratio for a particular forest ecosystem, Cairns et al. (1997), Mokany et al. (2006), and Vogt et al. (1996) underscored using linear regression equations derived from that particular forest ecosystem, and at that particular scale (Vogt et al. 1996), in order to increase accuracy in predictions. Given the heterogeneity of urban environments, the aboveground tree biomass estimations in this study may not have accurately represented belowground tree biomass.

Tree roots have been shown to be a major contributor to soil C levels (Fahey and Hughes 1994, Ruess et al.1996, Helmisaari et al. 2002, Russell et al. 2007, Persson 2012), and as such, the third assumption was that belowground biomass would have a significant and substantive impact on soil C levels. An issue was the half century of Auburn’s home ages, which may have been too short a time span to discern a strong relationship of soil C to belowground biomass (as represented by aboveground biomass) with corresponding changes in soil C levels over time. Belowground biomass is dominated by coarse roots (Keyes and Grier 1981, Misra et al. 1998, Xiao et al. 2003, Peichl and Arain 2007), which, compared to fine roots, have a longer lifespan (Joslin and Henderson 1987, Gill and Jackson 2000, Janssens et al. 2002, Matamala et al. 2003) and a slower decomposition rate (Fahey et al. 1988, Olajuyigbe et al. 2012). Fine roots have been reported to have a more extensive distribution (Roberts 1976, Millikin and Bledsoe 1999, Raz-Yaseef et al. 2013), greater net primary productivity (Keyes and Grier 1981, Janssens et al. 2002, Chen et al. 2003, Xiao et al. 2003), greater biomass production (Helmisaari et al. 2002), and a higher annual turnover (Gholz et al. 1986, Joslin and Henderson 1987, Gill and Jackson 2000) than coarse roots. Thus, the C imported into soil from fine roots may have greater influence on soil C levels across ~50 years than coarse roots (Gaudinski et al. 2001, Lichter et al. 2005, Trumbore et al. 2006).

As yet, researchers have not discovered strong relationships between estimations of belowground biomass and fine root biomass. Kurz et al. (1996) and Li et al. (2003) produced allometric equations for the proportion of fine root biomass in belowground biomass for the Canadian forest sector. The former analysis had 16 data points with belowground biomass explaining 28% of fine root biomass variability, and the latter analysis had 91 data points, with belowground biomass explaining 36% of fine root biomass variability. The sensitivity of fine roots to numerous abiotic and biotic variables (Vogt et al. 1996) adds difficulty to the estimation of fine root biomass relative to belowground biomass, and yet, determination of the connection between soil C levels and trees in residential yards may necessitate analysis of fine root biomass.

Conclusions

In this case study, the relationship of soil C to home age was compared between PL and LwT and the relationship of soil C to three biomass data sets within LwT was also analyzed. Mean soil C levels were compared across separate home age groups and aboveground tree biomass categories. Soil C at 15-30 cm had a significantly more positive relationship with home age in LwT compared to PL. The 15-30 cm depth was the only depth where soil C had significant positive relationships with all aboveground biomass data sets and with home age in all three biomass data sets. However, compared to biomass category 1 (median 0 kg), mean soil C at 15-30 cm only increased in the highest biomass category (median 12386 kg), whereas soil C at 0-15 cm and 30-50 cm depths increased in category 3 (median 3257 kg). In addition, mean soil C at 15-30 cm did not change from home age group 1 (median 7 yrs) to group 5 (median 79 yrs). Possibly, a loss of vegetation C input to soil, from home/yard construction, and potentially higher decomposition rates at 15-30 cm depth may have obscured the relationship of aboveground tree biomass to soil C and changes in soil C levels over time.

Overall, aboveground tree biomass was not a strong predictor for soil C levels, possibly because the three assumptions that linked aboveground tree biomass to soil C levels were not strongly supported. First, estimations of aboveground biomass in residential yards from allometric equations derived from natural forest ecosystems may not have been accurate. Second, aboveground biomass would not be an accurate representative for belowground biomass because C allocation to roots and shoots would change in accordance to tree, climate, and soil conditions. Third, fine root biomass may be more related to changes in soil C across ~50 yrs than the coarse root biomass that dominates belowground biomass estimations.

Additional research is needed to develop urban tree allometric equations to accurately estimate above- and belowground biomass, including fine root biomass, and to assess the role of urban tree fine roots on soil C levels. The mean residence time of soil C also needs to be examined to determine the contribution of past and present vegetation on soil C levels. Knowledge of the soil legacy of residential yards is needed, not only in regards to the removal and addition of soil during home/yard construction, but also concerning the land uses prior to home construction, such as whether the home was built on crop land, grassland, or secondary forest. Past land use can influence future soil C dynamics. Knowledge of the soil and vegetation conditions that facilitate soil C accumulation is beneficial not only to enhance ecosystem services and benefit human society, but also to improve predictions about soil C levels in the future.

Table 9 The number of yards in ‘pure lawns’ (total 23) and ‘lawns with trees’ (total 44) subdivided by home age (1-51 yrs) and yard maintenance practice. Separated by a vertical line are ‘pure lawns’ in **bold** and ‘lawns with trees’ in *italics*.

Home Age (years)	**Fertilized (# yards)**	**Non-Fertilized (# yards)**	**Irrigated (# yards)**	**Non-Irrigated (# yards)**	**Mulched (# yards)**	**Bagged (# yards)**
0-3	**1**|*3*		**1**|*3*		**1**|*3*	
4-7	**6**|*1*	**1**	**3**	**4**|*1*	**4**	**3**|*1*
8-11	**2**|*4*	**2**	**2**|*3*	**2**|*1*	**1**	**3**|*4*
12-15	**2**|*2*		**1**|*1*	**1**|*1*	**1**|*1*	**1**|*1*
16-19						
20-23	**1**|*1*	*2*	*1*	**1**|*2*	*3*	**1**
24-27	**1**|*1*			**1**|*1*	**1**	*1*
28-31	*2*	**1**|*2*	*1*	**1**|*3*	**1**|*1*	*3*
32-35	**1**|*1*	*2*	*1*	**1**|*2*	*2*	**1**|*1*
36-39	**2**|*4*	*8*	*1*	**2**|*11*	**1**|*9*	**1**|*3*
40-43	*1*	*2*		*3*	*2*	*1*
44-47		**1**|*2*		**1**|*2*	**1**|*2*	
48-51	*2*	**2**|*4*	*1*	**2**|*5*	**1**|*4*	**1**|*2*
Total	**16**|*22*	**7**|*22*	**7**|*12*	**16**|*32*	**12**|*27*	**11**|*17*

Table 10 Mean ± (bound) for soil C, soil N, soil C:N, bulk density, % sand, % clay, and % silt by depth for 'pure lawns' and 'lawns with trees'.

	Pure Lawns		**Lawns with Trees**	
Soil C (kg m^{-2})	***N***	***Mean ± (bound)***	***N***	***Mean ± (bound)***
0-15 cm	22	2.37 (0.27) aA	44	3.03 (0.27) aB
15-30 cm	23	0.98 (0.11) bA	41	0.96 (0.12) bA
30-50 cm	16	0.51 (0.10) cA	41	0.71 (0.11) bB
Soil N (kg m^{-2})				
0-15 cm	22	0.18 (0.02) aA	42	0.19 (0.02) aA
15-30 cm	23	0.09 (0.01) bA	44	0.08 (0.01) bA
30-50 cm	19	0.09 (0.009) bA	40	0.08 (0.008) bB
Soil C:N				
0-15 cm	20	13.12 (1.12) aA	42	15.7 (0.97) aB
15-30 cm	22	11.40 (2.36) aA	37	12.3 (1.45) bA
30-50 cm	11	5.16 (0.71) bA	37	9.1 (1.36) cB
Bulk density (g m^{-3})				
0-15 cm	22	1.36 (0.42) aA	41	1.36 (0.03) aA
15-30 cm	22	1.53 (0.04) bA	43	1.54 (0.03) bA
30-50 cm	22	1.52 (0.05) bA	43	1.51 (0.03) bA
% Sand				
0-15 cm	23	48.02 (3.84) aA	43	48.0 (2.29) aA
15-30 cm	23	39.66 (5.52) abA	44	42.0 (3.20) bA
30-50 cm	23	37.18 (5.43) bA	43	36.6 (3.77) cA
% Clay				
0-15 cm	23	23.74 (1.58) aA	44	21.7 (1.76) aA
15-30 cm	23	32.50 (4.93) bA	44	29.0 (2.53) bA
30-50 cm	23	34.43 (5.30) bA	44	33.9 (3.40) cA
% Silt				
0-15 cm	23	28.17 (1.88) aA	36	28.5 (0.88) aA
15-30 cm	21	26.46 (1.93) aA	43	28.7 (1.29) aA
30-50 cm	23	28.41 (2.05) aA	40	28.6 (1.14) aA

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

Significant differences between different depths and within a lawn type are indicated with different lowercase letters.

Significant differences between lawn types and within same depths are indicated with different upper case letters.

Significant differences occur at $\alpha = 0.10$

N = number of yards.

Table 11 Linear regression analyses of soil C (kg m^{-2}) with home age across three depths for pure lawns (PL) and lawns with trees (LwT).

	P-value	**R^2**	**N**	**Linear equation**	**Likelihood ratio test p-value**
Depth 0-15 cm					
PL	0.012	0.30	22	0.026x + 1.93	0.44
LwT	<0.0001	0.34	44	0.041x + 1.76	
Depth 15-30 cm					
PL	0.097	0.13	23	-0.011x + 1.18	0.03*
LwT	0.033	0.11	41	0.011x + 0.62	
Depth 30-50 cm					
PL	0.104	0.18	16	-0.006x + 0.63	0.08*
LwT	0.19	0.04	41	0.006x + 0.51	

Significant differences between regression equations occur at $\alpha = 0.10$ and are marked with an '*'.

N = number of yards.

Table 12 Linear regression analyses of soil C (kg m^{-2}) across three depths with biomass, biomass ≤ 10 m, and biomass ≤ 5 m data sets. Median yard biomass (kg) is shown for each depth and biomass data set.

	P-value	**R^2**	**N**	**Slope x10^5**	**Biomass (kg)**
Biomass					
Depth					
0-15 cm	0.96	0.0001	41	0.27	1996
15-30 cm	0.004*	0.21	38	5.47	1987
30-50 cm	0.006*	0.19	38	5.08	2023
Biomass ≤ 10 m					
Depth					
0-15 cm	0.23	0.04	42	12.35	570
15-30 cm	0.009*	0.17	39	12.34	478
30-50 cm	0.03*	0.13	39	9.60	662
Biomass ≤ 5 m					
Depth					
0-15 cm	0.07*	0.12	29	42.15	230
15-30 cm	0.0004*	0.40	27	38.75	230
30-50 cm	0.0004*	0.29	27	25.36	230

A significant relationship occurs at α = 0.10 and is marked with an '*'.
N = number of yards.

Table 13 Linear regression analysis of soil C (kg m^{-2}) across three depths with home age (yrs) within the biomass, biomass ≤ 10 m, and biomass ≤ 5 m data sets.

	P-value	R^2	N	Linear equation
Biomass				
Depth				
0-15 cm	< 0.0001*	0.38	41	0.042x + 1.72
15-30 cm	0.08*	0.08	38	0.0083x + 0.65
30-50 cm	0.30	0.03	38	0.0048x + 0.53
Biomass ≤ 10 m				
Depth				
0-15 cm	< 0.0001*	0.35	42	0.039x + 1.76
15-30 cm	0.03*	0.13	39	0.011x + 0.60
30-50 cm	0.20	0.04	39	0.0059x + 0.50
Biomass ≤ 5 m				
Depth				
0-15 cm	0.0004*	0.37	29	0.045x + 1.57
15-30 cm	0.07*	0.12	27	0.012x + 0.55
30-50 cm	0.34	0.04	27	0.0049x + 0.48

A significant relationship occurs at $\alpha = 0.10$ and is marked with an ‘*’.
N = number of yards.

Table 14 Four aboveground tree biomass categories and their corresponding range and median values for aboveground tree biomass, mean soil C ± (bound), number of sampled yards and the range and median of home ages.

	Category 1	**Category 2**	**Category 3**	**Category 4**
Tree biomass (kg)				
Median	0	47	3257	12386
Range	0	0.1-1487	1978-5064	5663-36956
Soil C (kg m^{-2})				
0-15 cm	2.37 ± 0.27 a	3.02 ± 0.40 ab	3.08 ± 0.31 b	3.63 ± 0.35 b
15-30 cm	0.98 ± 0.18 a	0.77 ± 0.098 a	1.00 ± 0.12 ab	1.27 ± 0.17 b
30-50 cm	0.51 ± 0.096 a	0.53 ± 0.11 a	0.74 ± 0.084 b	0.82 ± 0.13 b
Number of yards				
0-15 cm	23	23	22	27
15-30 cm	23	20	20	27
30-50 cm	16	21	20	24
Home Age (yrs)§				
Range	1-51	3-60	7-79	8-87
Median	9	39	39	45

'± (bound)' is the amount to give upper and lower boundary intervals for 90% CI for the mean. Significant differences between different categories and within a depth occur at $\alpha = 0.10$ and are indicated with different lowercase letters.

§ Range and median home age only for lawns that have turfgrass and not for pure woods.

Table 15 Five home age groups and their corresponding range and median of home age, mean soil C ± (bound), number of sampled yards and the range and median of aboveground tree biomass.

	Group 1	**Group 2**	**Group 3**	**Group 4**	**Group 5**
Home age (yrs)§					
Median	7	29	39	55	79
Range	1-13	15-36	38-45	48-65	70-87
Soil C (kg m^{-2})					
0-15 cm	2.08 ± 0.26 a	2.35 ± 0.20 a	3.60 ± 0.27 b	3.41 ± 0.31 b	3.83 ± 0.46 b
15-30 cm	1.06 ± 0.19 ab	0.78 ± 0.13 a	1.05 ± 0.26 ab	1.05 ± 0.093 ab	1.30 ± 0.22 b
30-50 cm	1.32 ± 0.44 a	0.72 ± 0.18 b	0.72 ± 0.19 b	0.75 ± 0.12 b	0.78 ± 0.12 ab
Number of yards					
0-15 cm	23	14	18	19	16
15-30 cm	23	16	18	17	17
30-50 cm	23	19	18	18	15
Tree biomass (kg)					
Range	0-5663	0-17672	0-11089	0-17416	2268-36956
Median	0	4336	127	2244	11310

'± (bound)' is the amount to give upper and lower boundary intervals for 90% CI for the mean. Significant differences between different groups and within a depth occur at $\alpha = 0.10$ and are indicated with different lowercase letters.

§ Range and median home age only for lawns that have turfgrass and not for PW.

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CHAPTER 5

Dissertation Summary

Study objectives

The question that instigated this project was, “What environmental conditions influence changes in soil C levels over time in residential yards?” The objectives of the project were to assess the relationship between soil C levels and 1) aboveground tree biomass, 2) home age, 3) yard maintenance, and 4) soil texture from samples and measurements taken in 102 residential front yards, along with other information gathered from those yards.

Synthesis

Soil C levels in the 23 PL increased slightly but significantly with home age (1-51 yrs) by 0.026 kg C m^{-2} yr^{-1} but only at 0-15 cm depth. Soil C declined significantly by -0.011 kg C m^{-2} yr^{-1} at 15-30 cm depth, and had no association with home age at 30-50 cm depth. Neither soil texture nor yard maintenance had a significant relationship with soil C, though sample size limitations occurred for irrigated yards. The rate of soil C accumulation at 0-15 cm depth was low in comparison to residential yard studies in Colorado and Maryland, possibly due to high local MAT amplifying the decomposition rate in conjunction with the low C:N ratio of turfgrass leaf litter.

In 67 LwT, soil C levels increased slightly with home age (3-87 yrs) by 0.021 kg C m^{-2} yr^{-1}, a similar rate as in PL, though soil C levels below 15 cm depth did not change across home age. At 0-15 cm depth, soil C had positive relationships with most of the young home age classes (from 3-16 yrs to 3-55 yrs) with the strength of the slope declining with increasing home age range. In none of the old home age classes (17-87 yrs to 56-87 yrs) did soil C have a significant relationship with the home age range, indicating that the greatest C accumulation occurred in the younger home ages. Similar to PL, yard maintenance in LwT had no significant influence on soil C levels across home age. At 0-15 cm, soil C increased slightly with % silt but had no relationship with % sand or % clay.

In LwT (3-87 yrs), the relationships between soil C and aboveground tree biomass variables appeared to be mediated by distance of trees to the sample site, with biomass ≤ 4 m having the greatest explanatory power for soil C at 30-50 cm. However, soil C levels remained constant across home age at 30-50 cm depth. In addition, the relationship between soil C and home was the most positive at 0-15 cm depth even though the relationships with aboveground tree biomass variables were either absent or negligible at that depth. These results show that the expectation that belowground tree biomass could be accurately represented by aboveground biomass was incorrect, or the supposition that belowground biomass would be strongly related to soil C levels was incorrect, or both. In other research, analyses of the relationship between above- and belowground biomass produced wide confidence intervals and a large range of predicted means for belowground biomass; thus, ascertaining the influence of trees on soil C levels may be more effective with direct measurement of root biomass. Belowground biomass is dominated by coarse roots but the large turnover rate and slow decomposition rate suggest that fine root biomass would be a better predictor for soil C levels within the home age range of century or less. Measurement of fine root biomass would provide a greater basis for inferring the association between trees and soil C levels in yards.

In the comparison between 23 PL and 44 LwT across ~50 yrs home age, soil C at 15-30 cm depth had a significantly more positive relationship with home age in LwT than in PL. In

LwT (3-51 yrs), the aboveground tree biomass ≤ 5 m data set had the strongest positive relationships with soil C across all depths, with the greatest explanatory power at 15-30 cm. 15-30 cm depth was the only depth where soil C had positive relationships with aboveground tree biomass and with home age within the biomass data sets. Compared to the 0 kg biomass category, soil C at 0-15 cm and 30-50 cm increased at category 3 (median 3257 kg) whereas soil C at 15-30 cm only increased in the largest biomass category (median 12386 kg). This result was unexpected given the more positive relationships between soil C and aboveground tree biomass at 15-30 cm depth and the weaker or missing relationships at the other two depths.

Within the home age groups, only at 0-15 cm depth was mean soil C significantly greater at the highest age group (median 79 yrs) compared to the 1st age group (median 7 yrs). At 15-30 cm depth, mean soil C levels were similar between the 1st age group and all higher home age groups. However, at the 15-30 cm depth, mean soil C in the 5th age group (median 79 yrs) was significantly greater than in the 2nd age group (median 29 yrs). At 30-50 cm depth, mean soil C significantly declined from the 1st age group to the 2nd age group, but a small, significant increase in the 5th age group produced mean soil C levels similar to the 1st age group. Home and yard construction may have halted the vegetation C input to soil and slowed the accumulation of soil C below 15 cm for decades after, especially at 30-50 cm depth. The lack of a decline at 0-15 cm depth may indicate rapid soil C replacement from turfgrass and/or the addition of new soil C in the newly deposited topsoil under the turfgrass sod.

Soil C had significant positive relationships with the aboveground tree biomass data sets and with home age in the biomass data sets. However, the disconnect between soil depths in the significance and explanatory power of the relationships of soil C to aboveground tree biomass and to home age underscored the assessment that aboveground tree biomass was not a substantive variable for discerning the influence of urban trees on soil C levels over time.

In conclusion, soil C accumulated mainly in the top soil layer and in the younger home ages. Possibly, climate factors such as high MAT and soil factors such as high water potentials and high bulk densities may impede the accumulation of soil C. Aboveground tree biomass, as a surrogate for belowground biomass, may have influenced soil C levels below 15 cm depth, but the effect was poorly associated with changes in soil C levels over home age. Soil C levels were not related to yard maintenance over time and soil texture had inconsequential significance. As the majority of SOM in temperate climates has a mean residence time of decades to centuries, discerning the environmental influences on soil C levels can be difficult with the strength of environmental variables changing across time, land uses, vegetation types, and disturbance impacts.

Future Directions

The benefits of urban ecosystem services are highly dependent upon the quality of urban soils, and to assess the strength and potential for improving these services, more urban soil research needs to occur across soil types, topographies, local climates, and vegetation categories. The relationship between soil C and the fine roots of vegetation cover types needs to be analyzed, with possible separation between certain tree types, such as angiosperm and gymnosperm. The influence of the seasonal productivity, mortality, and decomposition of roots on soil C levels needs to be investigated, though changes in soil C due to seasonal fine root dynamics may be negligible in relation to the large variability in soil C levels within yards.

Home construction techniques also need to be examined as to the effect of the removal and addition of soils on soil C accumulation over time. Furthermore, land use histories, such as types and longevity of agriculture and forestation, erosion events, and fire frequencies, need to be evaluated in relation to their role in influencing post-soil C dynamics. In addition, the mean residence time of soil C needs to be determined to understand the relationship of past and present day vegetation with soil C levels. Urbanization of natural lands will continue with our growing global population and understanding urban soil C dynamics is vital for the accuracy of long and short term climate change forecasts and for educating people on methods that may improve both urban and non-urban living conditions.