SOIL CARBON ACCUMULATION IN AN URBAN ECOSYSTEM: CANOPY COVER
AND MANAGEMENT EFFECTS

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Thesis Prepared for the Degree of
MASTER OF SCIENCE

UNIVERSITY OF NORTH TEXAS

May 2020

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Black carbon (BC), a stable form of organic carbon (OC), is a byproduct of the incomplete combustion of biomass, biofuels, and fossil fuel. The main objectives of this research are to examine the spatial distribution of OC and BC in urban soil and determine the influence of tree canopy cover and landscape maintenance on soil carbon accumulation. Soil sampling was conducted at 29 sites throughout the City of Denton, Texas, in May 2019. Samples were collected from underneath post oak canopies and in adjacent open areas and were analyzed for total carbon (TC), total organic carbon (TOC), total N (TN), C:N ratio, and BC. Although maintenance levels had no significant effect, TOC was greater underneath trees (5.47%, 5.30 kg/m²) than lawns (3.58%, 4.84 kg/m²) at the surface 0-10 cm. Total nitrogen concentration was also greater underneath trees (0.43%) than lawns (0.31%) at the surface 0-10 cm. Preliminary results for BC were closely correlated to TOC. The lack of difference in C:N ratio between cover types indicates that leaf litter quality may not be the primary driving factor in soil C and N accumulation. Instead, differences in soil properties may be best explained by manual C inputs and greater atmospheric deposition of C and N to soils with tree canopy cover. Identifying patterns and potential drivers of soil OC and BC accumulation is important because soil carbon sequestration not only reduces atmospheric CO₂, but also may provide additional pollution mitigation benefits, thereby contributing to a more sustainable urban environment.
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By

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ACKNOWLEDGMENTS

I would like to first express my deepest gratitude to my brilliant advisor, Dr. Alexandra Ponette-González, who continuously challenged me to go beyond my expectations and taught me the importance of taking everything in stride. Her dedication to my growth and research saw to the completion of this project. Thank you to Dr. Reid Ferring for always being available to answer all my questions and teaching me the ways of soil field work. I would also like to give my sincerest thanks to Dr. Erika Marín-Spiotta who helped me develop my methodology and allowed me to utilize her laboratory for my analysis. Thank you to my committee member Dr. Lu Liang for her support and advice throughout my research. Additionally, I would like to thank UNT and the City of Denton and its residents for providing sampling sites and allowing me to dig holes in their yards. I am also incredibly grateful to my friend Jenna Rindy for helping me dig said holes throughout the Texas summer heat. Finally, I would like to recognize the support and love of my family and friends throughout my research and their unending confidence in my ability to succeed. Thank you to everyone for your encouragement.
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CHAPTER 1
BLACK CARBON: SIGNIFICANCE AT GLOBAL AND LOCAL SCALES

Introduction: Environmental Effects of Black Carbon

The atmospheric pollutant black carbon (BC) is second only to CO₂ in terms of its contribution to climate warming (Bond et al. 2013). There are also health risks associated with atmospheric BC pollution (Davidson et al. 2007). Due to its small size, BC falls within the category of PM₂.₅ pollutants, defined as particulate matter smaller than 2.5 microns in diameter. Inhalation of these particles has been shown to cause cardiovascular, lung, and other respiratory diseases (Wu et al. 2018a). Long term exposure to high levels of PM₂.₅ in urban areas has also been linked to age-specific mortality risk (Wu et al. 2018a). Children, the elderly, and individuals with predisposed respiratory diseases are most susceptible to greater health impacts (Davidson et al. 2007).

Compared to the detrimental effects of BC in the atmosphere, BC in soil may have environmental and agricultural benefits (Ding et al. 2010, Hearth et al. 2013, Schifman et al. 2018). Due to its characteristics, BC acts as a strong sorbent material, capturing and filtering pollutants such as heavy metals, polycyclic aromatic hydrocarbons, and polychlorinated biphenyls. Soils and sediments can accumulate these adsorbed contaminants, preventing pollutant leaching into waterways (Ding et al. 2010). Soil BC also has the potential to mitigate soil greenhouse gas emissions resulting from soil respiration. For example, a study conducted by Maucieri et al. (2017) found that arid and semi-arid soils amended with BC produced ~10% less CO₂ and N₂O emissions. Thus, once in the soil, there is evidence that BC decreases
pollutant leaching into surface and ground waters while also reducing pollutant emissions into the atmosphere.

In urban ecosystems, human activities likely affect soil BC accumulation, potentially limiting the regulating ecosystem service benefits observed in some studies (e.g., Schifman et al. 2018). Therefore, this thesis aims to better understand canopy cover and management effects on BC accumulation in soils, with a view to expanding our knowledge of the benefits of soil BC sequestration in urban environments.

Defining Black Carbon

Black carbon is the byproduct of incomplete combustion of fossil fuel, biofuel, and biomass burning (Goldberg 1985). Three significant characteristics of BC are its high carbon content, aromatic structure, and chemical heterogeneity (Masiello 2004). Black carbon is commonly coated with a mixture of both organic and inorganic byproducts such as nitrate, sulfate, ammonium and organic carbon (Cui et al. 2016). In terms of physical properties, BC is dark in color and highly porous on a microscopic level. It is also composed of a highly aromatic hydrocarbon ring structure, thereby functioning as one of the most refractory and hydrophobic pollutants, highly resistant to weathering and decomposition (Goldberg 1985). In a comprehensive examination of BC, Goldberg (1985) addressed these fundamental attributes and spearheaded research on the importance of BC in the environment.

Beyond the three properties mentioned above (i.e., high carbon content, aromaticity, chemical heterogeneity), BC exists in diverse forms along a continuum from slightly charred biomass to soot and graphitic BC (Masiello 2004). Variations along this continuum are dependent upon initial combustion temperatures. These forms are also differentiated by
particle size, chemical reactivity, optical properties, and combustion sources (Masiello 2004). As seen in Figure 1, movement along the continuum (from left to right) results in a decrease in the size of BC particles with greater combustion temperature. Lower temperatures produce slightly charred biomass, char and charcoal, which retain enough of their physical and chemical properties that the original organic source can be identified. These BC products have larger particle sizes, greater chemical reactivity, more heterogeneous composition, and remain in the soil after combustion (Masiello 2004). Given their larger sizes, char and charcoal travel shorter distances in the atmosphere and have been used to reconstruct historical levels of BC pollution from biomass and fossil fuel combustion (He & Zhang 2009).

Black carbon produced at higher combustion temperatures, such as soot and graphitic BC (GBC), retain little to no evidence of their original carbohydrate and lignin composition sources. Instead, the level of combustion almost completely decomposes and oxidizes the product into polycyclic aromatic hydrocarbons (PAH). This acts as a precursor to further ring formation that condenses itself into what is known as soot (Nam et al. 2008). Soot is different from charcoal and charred products due to its smaller size, greater aromaticity and refractivity (Masiello 2004). It is produced from both liquid and biological sources of combustion which are initially emitted into the atmosphere. Soot BC is usually the dominant type of BC within urban areas due to high combustion temperatures of fossil fuels (Bond et al. 2013). Within the polluted urban atmosphere, BC particles present a bimodal distribution with peaks at ~0.1 µm and 1 µm (Seinfeld and Pandis, 1998).

The BC continuum provides a universal framework for understanding BC in the environment and how definitions differ among disciplines. Atmospheric research on BC focuses
on soot and graphitic BC, components of PM$_{2.5}$ that can travel long distances in the atmosphere before being deposited to the Earth’s surface. On the other end of the spectrum, soil science focuses on slightly charred biomass, char and charcoal (Fig. 1). Research on these forms of soil BC has predominantly been conducted in remote forested and agricultural areas, focusing on either natural or anthropogenic biomass burning as a BC source (Glaser et al. 2000, Hearth et al. 2013, Hal & Lobada 2018, Santos et al. 2014). While biomass burning results in both low and high combustion temperatures, burning has a greater chance of producing partially charred BC, which can be deposited closer to the combustion source. These soil BC studies usually focus on the contribution of BC to soil organic matter (SOM) and soil organic carbon (SOC) pools and show that BC additions do not just influence the chemical composition of a soil profile, but also regulate nutrient composition, microbial activity, and soil and vegetation fertility (Lehman et al. 2011, Shrestha & Lal, 2010, Ding et al. 2010, Glaser et al. 2000, Cheng et al. 2006, Nguyen & Lehman 2009). Compared to soil BC studies in remote or agricultural areas, only a few studies have quantified soot in soils of urbanized areas, referring to this as ‘soot BC’ (Lehmann & Stahr 2007, Hamilton & Harnett 2013).

The way in which BC is identified and understood is also dependent upon the methodology used to quantify its concentration. The methodology used is specific to the fraction on the continuum that is being targeted. For example, lower temperature BC samples rely upon more optical and absorption analysis due to its larger particle size. Higher temperature BC, such as soot, is often analyzed using chemothermal oxidation analysis (CTO-375), which is more efficient for highly condensed submicron particle sizes (Masiello 2004).
Differences among these forms of BC also affect the transport, accumulation, and cycling of BC in the global environment.

Figure 1: Black carbon continuum, showing diverse forms of BC that differ in formation temperature, size, plant structures, reactivity, initial reservoir, and range of distribution (after Masiello 2005).

The Global Black Carbon Cycle: Pools and Fluxes

Compared to CO$_2$, the global BC cycle remains less well understood, with the size of major pools and magnitude of fluxes poorly constrained (Fig. 1). Variables such as initial combustion source and transport determine the movement, or flux, of BC among accumulation areas, or pools, until its eventual integration into marine sediments. In 2000, total BC emissions from industrial and biomass sources were estimated to be around 7500 Gg/year (Bond et al. 2013). Of this total, diesel and residential fossil fuel combustion contributed ~60% of emissions while open biomass burning contributed ~40% (Bond et al. 2013). While fossil fuel combustion emits BC directly into the atmosphere, biomass burning adds BC directly to atmospheric or soil pools. The majority of BC produced from natural combustion (char and charcoal) is deposited
and incorporated into nearby soils or transported by water as runoff, especially in sloping terrain (Berhe et al. 2014). In contrast, materials resulting from higher temperature combustion, such as soot, are small enough to be transported by wind (Masiello 2004). Soot BC produced from both biomass and fossil fuel combustion may remain suspended for less than a day to more than one month, eventually depositing onto terrestrial and aquatic systems, or directly into the open ocean (Ogren & Charlson 1983). Deposition occurs through wet or dry deposition. Dry BC deposition is the direct delivery of particles onto surfaces by turbulent impaction. Wet deposition is the deposition of particles incorporated into precipitation (Barrett et al. 2019). The atmosphere itself is the smallest pool of BC in the global cycle, retaining only a small fraction of all BC in the environment and for a short period of time. However, the atmosphere transports BC around the world and contributes to deposition in remote areas (Masiello 2004).

Figure 2: Global cycle of black carbon (after Kuhlbusch 1999). Fluxes are in petagrams/year.
In terrestrial systems, BC deposits to vegetation, soil, snow, and ice. Vegetation surfaces may capture a significant amount of atmospheric BC (Rindy et al. 2019) but still act only as an intermediate pool before BC is transported to the soil. Soil is the second largest pool of BC in the global environment (Kuhlbusch 1998). Flux of BC out of soil occurs through wind erosion and surface runoff (Schmidt & Noack 2000). Black carbon in rivers and streams continues its migration into the ocean where it eventually integrates into the largest and slowest cycling oceanic sedimentary pool (Druffel 2004).

The Urban Black Carbon Cycle: Pools and Fluxes

There are important similarities and differences in BC pools and fluxes between the global and urban BC cycles. In urban environments the dominant BC source is fossil fuel combustion while biomass burning is much less important (Bond et al. 2013). Fossil fuel combustion produces high concentrations of soot BC, which is emitted into the atmosphere and deposited by wet and dry deposition onto vegetation, soil, and impervious surfaces. However, the atmosphere is still the smallest pool of BC within the urban ecosystem. Figure 3 illustrates the movement of BC from atmosphere to and through soils in an urban environment. Black carbon can settle onto vegetation surfaces and adhere to the waxy outer layer of leaves, acting as a temporary sink (Mo et al. 2015, Valesco et al. 2016, Liu et al. 2016, Rindy et al. 2019). From the canopy, BC may then be delivered to soil either by throughfall or litterfall. Throughfall is the water that falls through and drips from the canopy, while litterfall is organic material that falls from vegetation to the ground. After deposition onto soil, BC can be reemitted back into the atmosphere through wind erosion, especially in areas cleared of vegetation, under excavation, or under construction. Black carbon deposited to impervious and other surfaces can be
transported by surface runoff into rivers and streams (Kuhlbusch 1998). Black carbon can also become incorporated into the soil profile through mixing processes or with water that infiltrates into the soil, and either be retained in the soil profile or lost through hydrologic flow paths. In urban ecosystems, soil may be the largest BC pool with vegetation serving as an intermediate sink for BC.

Figure 3: Conceptual model illustrating the movement of BC from atmosphere to and through soil (after Ponette-González, In prep).

Spatial Variability in Soil Black Carbon in Urban Ecosystems

There are several factors that influence the spatial distribution of soil BC across and within the urban soil profile: emissions sources, soil type, soil management practices, and land use and land cover (He & Zhang 2009, Hamilton & Hartnett 2013, Edmondson et al 2015,
Land use, such as industrial versus agriculture, affects BC emission sources and strength. One study found that soot BC concentrations decreased from urban to agricultural to rural land uses, reflecting differences in levels of fossil fuel combustion (Hamilton & Hartnett 2013). Within urban environments, soot BC concentrations in soil typically decrease with distance from production sources, such as roadways and industrial sites (Liu et al. 2011, Schifman et al. 2018, Hamilton & Hartnett 2013, He & Zhang 2009). Soil BC accumulation within the urban environment has also been associated with historical land use. For example, soil BC concentration was found to be higher in industrial and commercial perimeter zones compared to the central historical palace and residential zone in the ancient city of Nanjing, China (He & Zhang 2009). Varying levels of BC accumulation within the soil profile due to historical land use, referred to as “cultural layers”, have also been identified (Vasenev & Kuzyakov 2018, He & Zhang 2009). He & Zhang (2009) sampled to almost 7 m depth and identified modern BC contribution to only 50 cm depth. Other studies indicate a general decrease in soil BC concentration with depth, but an increase in its contribution to total organic carbon (TOC) (Edmondson et al. 2015, Lorenz & Kandeler 2005).

Black carbon accumulation varies by soil textural composition as well (Masiello 2004, Schmidt et al. 2002, Schifman et al. 2018, Edmondson et al. 2015). In particular, soil samples with higher clay content tend to have higher BC accumulation (Schifman et al. 2018). Clay is a strong sorbent of hydrophobic materials and can bind BC particles within soil aggregates (Schifman et al. 2018). Therefore, finer soil textures tend to have higher levels of BC accumulation in comparison to areas with coarser textured soils.
Construction and direct soil modification, such as introduction of non-natural soil, yard waste management, and soil sealing are activities that can increase or decrease BC accumulation (Vasenev & Kuzyakov 2018). Industrial construction, which involves the excavation or sealing of topsoil, can potentially decrease SOC and BC accumulation (Raciti et al. 2012, Vasenev & Kuzyakov 2018). However, industrialization can also introduce more BC sources such as asphalt layers and backfill material (Vasenev & Kuzyakov 2018, Schifman et al. 2018). Leaf litter and vegetation clippings with BC adhered to surfaces (e.g., Rindy et al. 2019) can be exported to landfills (Templer et al. 2015). Soil sealing—the process of covering the soil surface with impermeable artificial materials—isolates subsoil BC, reducing BC degradation and oxidation (Vasenev & Kuzyakov 2018, Edmonson et al. 2012). Therefore, areas such as greenspaces, landfills, and asphalt or concrete-covered topsoil may have higher or lower BC accumulation compared to neighboring areas.

The presence of vegetation canopies has been shown to affect BC accumulation in urban soils (Edmondson et al. 2015, Schifman et al. 2018). In a study conducted by Edmondson et al. (2015), researchers sampled soil from multiple regional parks in a historically industrial area. Data obtained from the samples indicated significantly greater BC/total organic carbon (TOC) concentrations in soil underneath canopies versus soils in open grasslands. However, in another study, Schifman et al. (2018) found a negative correlation between vegetative canopy density and soil BC concentrations across 11 US cities.

While vegetation may be significant in influencing BC accumulation, natural landscape factors such as relief and curvature do not appear to influence BC in artificially modified urban soils (Vasenev & Kuzyakov 2018, Schifman et al. 2018). In addition, rain and temperature
differences have been shown to not have a major effect on the distribution of BC in the urban environment (Schifman et al. 2018, Vasenev & Kuzyakov 2018).

Controls on Soil Black Carbon Accumulation

Czimczik and Masiello (2007) identify five processes that control BC accumulation within a soil profile: 1) frequency of combustion; 2) mixing to depth; 3) abundance of reactive soil minerals; 4) presence of BC-degrading microbes; and 5) human activity. First, frequent fires tend to increase soil BC concentrations, but the extent to which this happens is dependent upon the level of fire energy and the ratio of lignin to cellulose. High fire energy and greater lignin/cellulose ratios in biomass result in higher BC production. Second, integration of BC into the soil profile protects it from further oxidation and surface erosion. Mixing can occur through bioturbation by earthworms and other burrowing species or through physical mixing by shrink-swell movement. Third, BC can be stabilized through bonding with Ca$^{2+}$ ions and with Al and Fe oxyhydroxides which can protect BC from UV oxidation. Black carbon can also avoid enzymatic decomposition through sequestration within micropores of <1 µm found within high clay content soils and stable soil aggregates. Fourth, microbes with the capacity to degrade BC must be present for decomposition to occur. Finally, human activities add or remove BC or organic carbon (OC), influencing the overall ratio of BC/OC composition in a soil profile.

Within this study, Czimczik and Masiello (2007) provide a conceptual model displaying BC accumulation in different soil types. However, there is no reference to the degree to which these variables affect urban soils. First, BC in urban ecosystems likely originates more from fossil fuel than from open biomass combustion (Hamilton and Hartnett 2013). This combustion source leads to higher atmospheric BC production, and is also sourced from a highly aromatic
diesel precursor which produces much more aromatic and refractory BC products. Second, lower soil biodiversity and greater soil compaction in urban soils may result in less mixing of BC to depth (Vasenev and Kuzyakov 2018). Third, urban soils are amended with fertilizers and have greater presence of metal oxides and pollutants (Yesilonis et al. 2008). These additions may influence the presence of Ca ions, metal oxides and clay particles which can either increase or decrease BC stabilization. Fourth, BC degradation by microbes may well occur within the urban context, but its presence is correlated with concentration of organic matter and carbon storage (Lange et al. 2015). Greater vegetation diversity and richness produce higher levels of microbial activity. Urban areas which affect organic matter content in soils disrupt natural levels of microbial degradation (Lange et al. 2015). Finally, human activities such as lawn management, construction, and high foot traffic disturb topsoil and redistribute soil BC. While all these processes contribute to the stability and accumulation of BC in soils, human activity is likely one of the most influential factors affecting soil BC accumulation in urban areas.

**Conclusion**

Soil BC accumulation in urban ecosystems is an area of increasing research interest (Edmondson et al. 2018, Hamilton & Hartnett 2013, Vasenev & Kuzyakov 2018, Lorenz & Kandeler 2004, Schifman et al. 2018, Liu et al. 2011). However, there are still gaps in knowledge about BC accumulation within urban soils. While aboveground vegetation is an important carbon sink within the urban ecosystem, understanding the specific conditions that promote BC sequestration in soils remains limited. This thesis provides an opportunity to analyze the influence of canopy cover and management effects on soil BC accumulation.
CHAPTER 2
INFLUENCE OF CANOPY COVER AND MANAGEMENT ON SOIL CARBON ACCUMULATION IN AN URBAN AREA

Introduction

Black carbon (BC), commonly referred to as soot, is a human health and environmental hazard in urban areas (Davidson et al. 2007). Black carbon is emitted to the atmosphere as a result of fossil fuel and biomass combustion (Masiello 2004). Black carbon has strong warming potential: one kilogram of BC is estimated to cause 680 times more warming than one kilogram of CO₂ over a 100-year period (Bond and Sun 2005). A component of fine particulate matter (PM₂.₅), BC also contributes to poor air quality. Inhalation of BC is associated with increased risk of cardiovascular and respiratory diseases and increased cardiovascular mortality in young children (Wu et al. 2018a).

Research shows that urban vegetation, especially trees, may be effective at removing BC from the atmosphere (Rindy et al. 2019) and sequestering BC in soils (Edmondson et al. 2015). Although a large amount of carbon can be stored in aboveground biomass in urban ecosystems (Davies et al. 2011), the majority of carbon in urban ecosystems is stored in soils (Edmondson et al. 2012, Livesley et al. 2015), mostly in the form of organic carbon (OC). Organic carbon represents all carbon derived from decomposed soil organic matter (SOM). Black carbon, a relatively stable form of organic carbon that enters the soil as a result of fossil fuel and biomass burning, can comprise as much as 28-39% of total organic carbon (TOC: OC + BC) up to 1 m depth (Edmondson et al. 2015). Soil BC has a high sorption capacity which contributes to the
regulation of pollutants and excess nutrients, especially within urban ecosystems (Schifman et al. 2018).

In recent decades, rapid urbanization has contributed to increasing atmospheric pollution (Liu et al. 2016a), as well as major changes in ecosystem structure and function. Activities such as deforestation, soil compaction, and vegetation management alter the potential for soils to sequester organic and black carbon (Setala et al. 2016, Raciti et al. 2011). Furthermore, variation in management across the urban landscape creates a mosaic of conditions that make it difficult to identify the variables that control organic carbon and BC accumulation (Pouyat et al. 2006). Compared to organic carbon, few studies examine the effects of urban canopy cover and management on the spatial distribution and accumulation of BC throughout the urban ecosystem (Edmondson et al. 2015, Golubiewski, 2006).

Research Question and Objectives

This study sought to investigate the influence of canopy cover and management level on soil organic carbon and BC accumulation within an urban ecosystem. The main objectives of the study were to: (1) quantify soil OC and BC concentrations and mass under trees and adjacent lawns; and (2) examine whether OC and BC differed between trees and lawns under differing levels of management.

Study Area

Overview

This study was conducted within the City of Denton (33.1991 N, 97.1049 W), Texas, located within the Dallas Fort Worth (DFW) Metropolitan area. Denton was first established in
1857 as a county seat a little over 64 km north of Dallas off of Interstate 35. Interstate 35E
connects Denton to Dallas while Interstate 35W connects Denton to Fort Worth. With a
population of 136,268 (U.S. Census Bureau 2017), Denton is significantly smaller in population
compared to either the Dallas population of 1,241,075 (U.S. Census Bureau 2017) or Fort
Worth's 874,168 (U.S. Census Bureau 2017). However, Denton has experienced an exponential
population growth of 17.1% in the last few years from April 2010 to July 2017 (U.S. Census
Bureau 2017). This has resulted in increasing population density, economic growth and
urbanization.

Climate

Denton is set within a humid subtropical climate, with fluctuations in seasonal
precipitation and temperatures (National Weather Service 2019). Highest temperatures are
usually during June to September with an average daily high above 31°C. Lower temperatures
occur between December and February with the average daily high temperature below 17°C.
Denton receives an average of 914 mm of rain per year, with higher rainfall in mid to late May
and October. Wind direction is predominantly from south to north throughout the year
(National Weather Service 2019).

Vegetation

The City of Denton lies within the Eastern Cross Timbers landscape. This ecoregion is a
transitional area between prairie and irregular plains, composed of a mosaic of forest,
woodland, savanna, and prairies (Hoagland et al. 1999). In terms of land cover, 14% of the
cityscape is covered by impervious surfaces, 45% by non-canopy vegetation (turfgrass/lawns),
and 30% by tree canopy (State of Denton Urban Forest 2016). Some of the most common grass species found within North Texas are Bermuda grass, St. Augustine grass, and Zoysia grass (Chalmers & McAfee 2009). Common Bermudagrass has an average root length of 21.18 cm and a root mass of 0.38 g per 10 individual plants (Wadekar et al. 2018). St. Augustine grass has a root length of 12.31 cm and a root mass of 0.45 g per 10 individual plants (Wadekar et al. 2018). In comparison, Zoysiagrass has a significantly smaller root length density of 9.0 cm/cm³ and a smaller root mass density of 0.74 mg/cm³ when compared against La Paloma and Princess Bermudagrass which held an average root length density of 12.95 cm/cm³ and a mass density of 1.21 mg/cm³ (Rimi et al. 2012). While some of these species are more adapted to the North Texas region, other species such as St. Augustine require greater maintenance (Chalmers & McAfee 2009).

Post oak (*Quercus stellata*) is the third most abundant native tree species found within Denton’s urban forest and will be the focal species of this research study. Post oaks are a deciduous species that grow in coarse sandy soils, most commonly in soils with sandy loam texture (Hoagland et al. 1999). Although they comprise ~9% of the tree population, post oaks are estimated to store 24% of the total carbon stored in above and belowground biomass in the City of Denton (State of Denton Urban Forest 2016). Post oaks have an especially thick taproot but undergo less extensive root development compared to other oak species such as white, red, and blackjack oak (Stransky 1990). Post oaks commonly establish on sites with thick clay subsoils, thereby limiting root depth to above underlying clay horizons, and instead extensively developing outward (Stransky 1990). Although post oaks may be ideally suited for carbon storage, post oaks are also highly sensitive to soil disturbance and cannot be transplanted or
propagated. Along with increased urban development and tree cutting and inappropriate yard maintenance practices, post oak populations in the Easter Cross Timbers have declined rapidly in recent years (McBride & Appel 2016).

Soil

The City of Denton has low relief with slopes ranging from 0-5% traversed by multiple streams. Dominant soil orders in the area are Alfisols, Mollisols, and Vertosols, developed through the weathering of Cretaceous sandstones, shales and limestones (USDA NRCS soil survey 2008). Of the Alfisols, the most prominent soil series are Birome, Gasil, Calisburg, Navo and Wilson (USDA NRCS soil survey 2008). The Birome, Gasil, Calisburg, and Navo soil series are classified within the great group Paleustalfs which are defined as highly developed soils with a distinct argillic and eluvial horizon (USDA Soil Classification). The Wilson series is classified within the great group Ochraqualfs which is defined by its highly saturated surface and greater clay content compared to the Paleustalfs (Ford & Pauls 1980, USDA Soil Classification). The Birome, Gasil, and Calisburg series can all be found within the upland savannas and have a more sandy loam texture compared to the Navo and Wilson series which is found within the upland prairies with a clay loam texture (Ford & Pauls 1980). While small differences can be seen in textural composition and moisture conditions, typical Alfisols soils have a sandier A horizon from 0-15 cm and finer textured soils such as clay loam or sandy clay loam below. The Somervell series is found within the Mollisol order and is classified within the great group Calciustolls defined by its calcic horizon and limited moisture conditions (USDA Soil Classification). The Somervell series is calcareous in all parts of the profile and is characterized with a deep, rich organic matter surface which extends to 40 cm in depth (Ford & Pauls 1980).
Finally, Vertisols in the area comprise the Sanger soil series and are classified in the great group Chromusterts, characterized by its high clay content and low moisture regimen which causes it’s characteristic cracking during the summer (Ford & Pauls 1980). Typical soil profiles within this taxonomic group are underdeveloped with no distinct horizons (USDA Soil Classification).

**Table 1: Soil orders in the study area in Denton, Texas, and characteristics pertinent to black carbon accumulation.**

<table>
<thead>
<tr>
<th>Soil Order</th>
<th>Clay Content</th>
<th>Organic Matter Content</th>
<th>Cation Content (Ca(^+), Al(^{3+}), Fe(^{2+}))</th>
<th>Bioturbation</th>
<th>Shrink Swell Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfisols</td>
<td>Variable</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Mollisols</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Vertisols</td>
<td>High</td>
<td>Moderate</td>
<td>Variable</td>
<td>Moderate</td>
<td>High</td>
</tr>
</tbody>
</table>

The three soil orders also vary by soil texture as well as organic matter and cation content, factors that influence soil BC accumulation (Table 1). Black carbon can be stabilized in the mineral matrix by binding with organic matter and cations such as Ca\(^{2+}\), aluminum (Al\(^{3+}\)) oxyhydroxides, and iron (Fe\(^{2+}\)) oxyhydroxides (Czimczik et al. 2007). As discussed by Czimczik et al. (2007), BC accumulation also depends on the degree of soil mixing. Soil mixing includes pedoturbation either through bioturbation or through shrink and swell.

**Materials and Methods**

**Site Selection**

To assess the influence of canopy cover and management practices on soil C accumulation, soils were sampled below post oak trees and in adjacent lawns. Sites were selected using three criteria: 1) presence of a post oak tree, 2) presence of a BC emissions source, and 3) soil order. Information on each of these criteria was incorporated into a Geographic Information System (GIS) and used to select sampling sites.
First, a dataset of potential sampling sites with post oak trees was obtained from a previous study in the area where BC in throughfall and litterfall were measured. Second, a Euclidean distance map was created to calculate distances from post oak trees to BC emissions sources, including primary and secondary highways, inner-city streets, and areas of developed urban landcover. Layers were compositied using a weighted sum, producing an approximate distance map from BC sources. Third, sampling sites were overlain onto a soil survey map to identify variability in soil type across the area. Based on this analysis, 13 paired sites were selected for sampling. Where a post oak tree was not adjacent to a lawn, a lawn no more than 30 meters from the tree was selected for sampling, resulting in 3 unpaired tree sites ($n=16$ trees, $n=13$ lawns). All sites were located in areas near BC emissions sources and classified as Alfisols and Mollisols.

Preliminary Site Survey

A preliminary site survey was conducted at each site. Key features, such as roads, vegetation, and water were mapped. Four parameters were surveyed: ground cover, maintenance level, soil cover, and slope. Ground cover was described as presence of grass, weeds, mulch, and leaves. Maintenance levels were categorized as high, moderate, or low maintenance. High maintenance levels demonstrated evidence of human activities such as mowing, leaf raking, and/or trimming. Areas of low maintenance were categorized by the lack of human interference, presence of native growth, and natural leaf mulching. Soil cover was categorized as bare soil, patchy cover, or fully covered. This categorization was based on coverage by leaf litter, mulch, and grass. Finally, the slope of the area was measured using a compass. Once the survey was completed, a 1-inch diameter soil core was used to sample soil
to 20 cm depth. The depth, color, and soil texture of each horizon were described for each soil core. Data on home age (date of construction) was obtained from the Denton central appraisal district and aerial photographs. Distance was measured from each sample location to primary and secondary highways in meters using GIS proximity analysis. Primary highways are defined as limited-access highways classified in the interstate highway system while secondary highways are main roads within the county and city highway system.

Figure 4: Map of soil sampling sites across the City of Denton. Soil samples were collected from underneath 16 post oaks and 13 lawns from May through June 2019.

Soil Sampling

A composite soil sample was collected at each of the 29 locations (n=16 trees, n=13 lawns) during May and June 2019 (Table 2). Before sampling, leaf litter was removed from the
surface of the sampling point and placed in bags for potential future analysis. Using a thin probing wire, the ground was tested to identify the most accessible point for core sampling. Samples were extracted with a 1-inch diameter soil corer to 20 centimeters depth and the depth, color, and soil texture of each horizon were described. The core was then divided into two intervals of 0-10 cm and 10-20 cm, producing a total of 58 samples. Four cores were extracted at each location—all within three meters of each other—and combined in a plastic bag. Samples were transported to the Geoarchaeology Laboratory at UNT and were left open to air dry until preparation.

Soil Preparation

Samples were air dried for one week within the laboratory. Samples were weighed and ground using a rubber pestle. Soils were then passed through a 2 mm sieve to remove any large roots and gravel. A 10 g subsample was split and dried at 105°C for 12 hours, measured for moisture percentage, and tested for carbonates using a hydrochloric acid (HCl) drop test. The remaining sample was ground further using a porcelain pestle and passed through a 63 µm sieve which fully removes the sand fraction and isolates the clay and silt particles.

Bulk density, the mass of soil per unit volume, was measured by dividing air-dried sample weight by bulk volume (202.68 cm³). Moisture percentage, the amount of water in the soil, was calculated by measuring the weight of the 10 g subsample before and after drying. Inorganic carbonates within soil can be detected by applying a drop of 1 M HCL which causes the carbonates to effervesce. Carbonates can then be removed from the identified samples before being analyzed for total organic carbon.
Table 2: Characteristics of sample locations in the City of Denton, Texas, where soils were sampled to 20 cm depth from May to June 2019.

<table>
<thead>
<tr>
<th>Site ID</th>
<th>Cover Type</th>
<th>Maintenance Level</th>
<th>Soil Order</th>
<th>Soil Series</th>
<th>Home Age</th>
<th>Domestic or Non-Domestic</th>
<th>Distance to Primary Highways (m)</th>
<th>Distance to Secondary Highways (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1721C</td>
<td>Tree</td>
<td>Low</td>
<td>Vertisols-Mollisols</td>
<td>Sanger-Somervell</td>
<td>45</td>
<td>Domestic</td>
<td>905</td>
<td>894</td>
</tr>
<tr>
<td>1721O</td>
<td>Lawn</td>
<td>High</td>
<td>Vertisols-Mollisols</td>
<td>Sanger-Somervell</td>
<td>55</td>
<td>Domestic</td>
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<td>878</td>
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<tr>
<td>1600C</td>
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<td>Vertisols-Mollisols</td>
<td>Sanger-Somervell</td>
<td>58</td>
<td>Domestic</td>
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<td>700</td>
</tr>
<tr>
<td>1600O</td>
<td>Lawn</td>
<td>Low</td>
<td>Vertisols-Mollisols</td>
<td>Sanger-Somervell</td>
<td>58</td>
<td>Domestic</td>
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<td>1712C</td>
<td>Tree</td>
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<td>Vertisols-Mollisols</td>
<td>Sanger-Somervell</td>
<td>55</td>
<td>Domestic</td>
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<td>864</td>
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<td>1223C</td>
<td>Tree</td>
<td>Low</td>
<td>Vertisols-Mollisols</td>
<td>Sanger-Somervell</td>
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<td>Domestic</td>
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<td>301</td>
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<td>Vertisols-Mollisols</td>
<td>Sanger-Somervell</td>
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<td>Non-Domestic</td>
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<td>2211C</td>
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<td>High</td>
<td>Alfisols</td>
<td>Birome-Gasil-Callisburg</td>
<td>62</td>
<td>Non-Domestic</td>
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<tr>
<td>2211O</td>
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<td>High</td>
<td>Alfisols</td>
<td>Birome-Gasil-Callisburg</td>
<td>62</td>
<td>Non-Domestic</td>
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<td>150</td>
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<tr>
<td>2100C</td>
<td>Tree</td>
<td>Moderate</td>
<td>Vertisols-Mollisols</td>
<td>Sanger-Somervell</td>
<td>60</td>
<td>Non-Domestic</td>
<td>42</td>
<td>13</td>
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<td>2100O</td>
<td>Lawn</td>
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<td>Vertisols-Mollisols</td>
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<td>Non-Domestic</td>
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<td>Site ID</td>
<td>Cover Type</td>
<td>Maintenance Level</td>
<td>Soil Order</td>
<td>Soil Series</td>
<td>Home Age</td>
<td>Domestic or Non-Domestic</td>
<td>Distance to Primary Highways (m)</td>
<td>Distance to Secondary Highways (m)</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
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<td>High</td>
<td>Alfisols</td>
<td>Birome-Gasil-Callisburg</td>
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<td>Non-Domestic</td>
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<td>0308C</td>
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<td>Alfisols</td>
<td>Birome-Gasil-Callisburg</td>
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<td>Domestic</td>
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<td>Domestic</td>
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<td>Alfisols</td>
<td>Birome-Gasil-Callisburg</td>
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<td>Domestic</td>
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<tr>
<td>2330C</td>
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<td>Low</td>
<td>Alfisols</td>
<td>Navo-Wilson</td>
<td>56</td>
<td>Domestic</td>
<td>116</td>
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<td>2330O</td>
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<td>Low</td>
<td>Alfisols</td>
<td>Navo-Wilson</td>
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<td>Domestic</td>
<td>107</td>
<td>559</td>
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<td>2403C</td>
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<td>High</td>
<td>Vertisols-Mollisols</td>
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<td>Non-Domestic</td>
<td>944</td>
<td>77</td>
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<td>2403O</td>
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<td>Vertisols-Mollisols</td>
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<td>3201C</td>
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<td>Alfisols</td>
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<td>High</td>
<td>Alfisols</td>
<td>Birome-Gasil-Callisburg</td>
<td>64</td>
<td>Non-Domestic</td>
<td>494</td>
<td>459</td>
</tr>
</tbody>
</table>
Elemental Analysis

Samples were analyzed for total nitrogen (TN), total carbon (TC), total organic carbon (TOC), and BC using an elemental analyzer (EA). Total carbon includes both inorganic and organic carbon while TOC consists of pyrogenic and non-pyrogenic carbon. It is important to distinguish between TC and TOC to estimate TOC within the soil and the contribution of BC to TOC.

Thirty mg of the <63 µm fraction were weighed and packed into 5x9 mm silver capsules in duplicates and analyzed for TC and TOC. For samples with no evidence of carbonate, TC equals TOC. Samples with evidence of carbonates were acid fumigated first to remove inorganic carbon.

Chemo-Thermo Oxidation Method

Black carbon was quantified in the Biogeo Lab at the University of Wisconsin-Madison using the chemo-thermal oxidation protocol (CTO-375; Gustafsson et al. 2001) followed by elemental analysis. CTO-375 is the most commonly used quantification method in soot BC analysis. Originating from Gustafsson et al. (2001), this protocol involves three steps for preparation and quantification of soil BC: 1) Removal of inorganic carbonates through acid fumigation; 2) removal of non-pyrogenic organic carbon (NPOC) through combustion; and 3) quantification of residual carbon, soot BC, by elemental analysis.

A preliminary analysis was conducted on six samples from three paired sites to determine BC concentrations within the samples. Sixty-five mg of the <63 µm fraction of each sample were weighed into 10x10 mm silver capsules in duplicates along with an additional 30 mg sample prepared for quality assurance. All samples were placed into a 24 grid well plate and
acid fumigated with 150 ml of 12M HCl within a desiccator for 12 hours to remove inorganic carbonates. Once completed, quality assurance samples were tested for carbonates using the HCl drop test. If no reaction was detected, samples were dried and transferred to an aluminum well plate and combusted at 375°C for 24 hours to remove non-pyrogenic organic carbon. After combustion, samples were packaged into a second silver capsule and quantified for the remaining BC using an elemental analyzer. Samples are currently being analyzed for BC and therefore these data are not reported here.

Statistical Analysis

Statistical analyses were performed using JMPv14 software. Dependent variables were tested for normality using the Shapiro-Wilk test. Distributions were examined by cover type (tree vs lawn) and soil depth (0-10 cm and 10-20 cm). Variables were log transformed where needed to meet standard assumptions of normality and homogeneity of variance. The effect of cover type and maintenance levels on soil physical and chemical properties were analyzed using a two-way ANOVA (cover type x maintenance level) and determines whether the effect of one variable depends on the other. Relationships between distance to road, bulk density, soil texture, and home age and dependent variables were analyzed using linear regression. Significance for all tests was set at \( p<0.1 \).

Results

Soil Physical Properties

Soil Moisture

Cover type had no effect on soil moisture at either 0-10 cm (\( p=0.56 \)) or 10-20 cm
(p=0.63) depth. Soil moisture also did not differ by maintenance level at either 0-10 cm (p=0.32) or 10-20 cm (p=0.82) depth. No interaction was detected between cover type and maintenance level (p=0.31, p=0.47). However, soil moisture was negatively correlated with bulk density (p<0.1) at 0-10 cm and positively correlated with home age (p<0.1) at 10-20 cm depth. Soil moisture also showed a positive correlation with percent clay at both depths, and a negative correlation with percent sand at 10-20 cm depth (p<0.1) (Fig. 5).

Soil Texture

Percentages of sand, silt, and clay in soil did not differ between cover type at either 0-10 cm (p=0.27, p=0.67, p=0.31) or 10-20 cm (p=0.21, p=0.88, p=0.46) depth. There was also no differences in soil texture among the different maintenance levels. There was no correlation between soil texture and bulk density at either depth. However, percent silt did decrease with home age at 0-10 cm depth, and percent clay increased with home age at 10-20 cm depth (Fig. 6)

Bulk Density

Soil bulk density was lower under trees than lawns at 0-10 cm (p=0.10), but not at 10-20 cm (p=0.32) depth. Maintenance level had no significant effect on bulk density at 0-10 cm (p=0.62) or 10-20 cm (p=0.99). There was no significant interaction between cover type and maintenance level. However, the greatest difference in bulk density between trees and lawns was found at 0-10 cm depth in areas classified as low maintenance. Bulk density had no clear relationship with home age at either 0-10 cm (p=0.74) or 10-20 cm (p=0.17) depth. Bulk density had no relationship with percent sand, silt, or clay at either sample depth (Fig. 7)
Soil Chemical Properties

Total Carbon

No significant difference in TC concentration was found between cover types at either 0-10 cm (p=0.14) or 10-20 cm (p=0.81) depth or among maintenance levels at 0-10 cm (p=0.74) or 10-20 cm (p=0.75) depth. Interactions between cover type and maintenance level were not detected. However, TC did differ by depth; TC was two times greater and more variable at 0-10 cm than at 10-20 cm depth. Total carbon concentration showed a negative linear relationship (p<0.1) with bulk density at both depths (Fig. 8).

Total carbon content did not differ by canopy cover (p=0.13, p=0.86) or by maintenance level (p=0.61, p=0.62) at 0-10 cm or 10-20 cm depth. There was also no significant interaction between the two variables at either depth (p=0.31, p=0.22). Total carbon content was negatively related to bulk density and positively related to percent sand (p<0.1) at 0-10 cm depth. Total carbon concentration and TC content were not related to home age at either depth. However, both TC concentration and content shared a positive linear relationship (p<0.1) with distance from primary roads at both depth but did not have any relationship with distance from secondary roads (Fig. 10).

Total Organic Carbon

Unlike TC, there was a significant effect of cover type (p=0.07) on TOC concentration at 0-10 cm depth where TOC was higher under trees compared to lawns. However, at 10-20 cm, this difference was not significant (p=0.77). Maintenance level at 0-10 cm (p=0.87) and 10-20 cm (p=0.93) depth had no effect on TOC. Although there was no interaction between cover type and maintenance level, there was a larger difference in TOC between trees and lawns.
under high maintenance within the 0-10 cm depth. Total organic carbon concentrations were also greater and more variable at 0-10 cm compared to 10-20 cm depth. A regression analysis showed a significant negative relationship ($p<0.1$) between bulk density and soil TOC concentrations at 0-10 cm depths (Fig. 9). No relationship between TOC concentration and home age was detected at either depth ($p=0.49$, $p=0.67$). There was also no relationship between TOC concentration and soil texture composition at either depth.

Total organic carbon content was significantly greater under trees than lawns at 0-10 cm ($p=0.06$), but not at 10-20 cm ($p=0.56$) depth. Maintenance level had no significant effect on TOC content at 0-10 cm ($p=0.77$) or 10-20 cm ($p=0.85$) depth. There was also no significant interaction between cover type or maintenance level ($p=0.19$, $p=0.22$) at either depth. However, there was a negative relationship between bulk density and TOC content from 0-10 cm ($p<0.1$) but not at 10-20 cm ($p=0.88$) depth (Fig. 10). There was no relationship between TOC content and home age at either depth ($p=0.60$, $p=0.24$). Total organic carbon content was positively related to percent sand ($p<0.1$) at 0-10 cm depth. Total organic carbon concentration and content shared a positive linear relationship ($p<0.1$) with distance from primary roads at both depths but lacked any relationship with distances to secondary highways (Fig. 11).

**Total Nitrogen**

Total N concentration was greater under trees than lawns at 0-10 cm ($p=0.10$) but not at 10-20 cm depth ($p=0.57$). Maintenance level had no significant effect of N concentration at 0-10 cm ($p=0.98$) or 10-20 cm ($p=0.74$) depth. There was also no significant interaction between cover type or maintenance level at either depth ($p=0.56$, $p=0.30$). However, total N concentration was negatively related ($p<0.1$) to bulk density at 0-10 cm depth. Total N also
shared a positive relationship with distance from primary highways (p<0.1) at both depths but none with distance to secondary highways (Fig. 12).

No significant differences in TN content were detected between cover type (p=0.20, p=0.96) or maintenance level (p=0.99, p=0.52) at 0-10 or 10-20 cm depth. There was also no significant interaction between cover type and maintenance level at either depth (p=0.22, p=0.24). No relationship was seen between N content and bulk density at either depth (p=0.52, p=0.72). However, N content did increase with percent sand at 0-10 cm (p<0.1) and distance to primary highways at 10-20 cm (p<0.1) depth (Fig. 13). Neither N concentration nor N content were related to home age at either depth. However, TN and TOC concentration and content were strongly positively related at both 0-10 cm (R²=0.940, R²=0.732) and 10-20 cm (R²= 0.792, R²=0.729) depth (Fig. 14).

*Carbon Nitrogen Ratio*

Soil C:N ratios were not significantly affected by cover type at 0-10 cm (p=0.65) or at 10-20 cm (p=0.54). Maintenance level had no significant effect on C:N at 0-10 cm (p=0.28) or 10-20 cm (p=0.55) depth. However, C:N did increase marginally with maintenance level from low (12.0±0.45) to moderate (12.3±0.41) to high (13.9±1.2) at 0-10 cm. There was no significant correlation between home age and soil C:N at 0-10 cm (p=0.52) or 10-20 cm (p=0.08) depth. Soil C:N ratio exhibited a negative relationship (p<0.1) with bulk density at 10-20 cm depth and had no relationship with distance to primary or secondary highways at either depth (Fig. 15).
Table 3: Mean (standard error) of total organic carbon and nitrogen concentrations and content, C:N ratio, and bulk density in the <63 µm fraction of soil samples collected in Denton, Texas.

<table>
<thead>
<tr>
<th></th>
<th><strong>Low</strong></th>
<th><strong>Moderate</strong></th>
<th><strong>High</strong></th>
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<tbody>
<tr>
<td></td>
<td>Tree</td>
<td>Lawn</td>
<td>Tree</td>
</tr>
<tr>
<td></td>
<td>0-10 cm</td>
<td>10-20 cm</td>
<td>0-10 cm</td>
</tr>
<tr>
<td><strong>TOC (%)</strong></td>
<td></td>
<td></td>
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<tr>
<td>0-10 cm</td>
<td>5.12(0.99)</td>
<td>2.51(0.34)</td>
<td>5.12(1.46)</td>
</tr>
<tr>
<td>10-20 cm</td>
<td>3.43(1.19)</td>
<td>1.58(0.24)</td>
<td>3.91(0.54)</td>
</tr>
<tr>
<td><strong>TOC Content (kg/m²)</strong></td>
<td></td>
<td></td>
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<tr>
<td>0-10 cm</td>
<td>5.32(0.53)</td>
<td>3.63(0.40)</td>
<td>4.79(1.40)</td>
</tr>
<tr>
<td>10-20 cm</td>
<td>4.76(0.49)</td>
<td>2.73(0.37)</td>
<td>5.14(0.49)</td>
</tr>
<tr>
<td><strong>Total Nitrogen (%)</strong></td>
<td></td>
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<tr>
<td>0-10 cm</td>
<td>0.42(0.08)</td>
<td>0.22(0.04)</td>
<td>0.32(0.13)</td>
</tr>
<tr>
<td>10-20 cm</td>
<td>0.45(0.16)</td>
<td>0.30(0.04)</td>
<td>0.38(0.04)</td>
</tr>
<tr>
<td><strong>Nitrogen Content (kg/m²)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-10 cm</td>
<td>0.42(0.03)</td>
<td>0.30(0.04)</td>
<td>0.45(0.16)</td>
</tr>
<tr>
<td>10-20 cm</td>
<td>0.49(0.06)</td>
<td>0.19(0.02)</td>
<td>0.49(0.06)</td>
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<tr>
<td><strong>C:N</strong></td>
<td></td>
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<tr>
<td>0-10 cm</td>
<td>12.65(0.44)</td>
<td>12.35(0.59)</td>
<td>11.24(0.70)</td>
</tr>
<tr>
<td>10-20 cm</td>
<td>11.42(0.51)</td>
<td>14.21(0.64)</td>
<td>13.19(0.88)</td>
</tr>
<tr>
<td><strong>Bulk Density (g/cm³)</strong></td>
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<tr>
<td>0-10 cm</td>
<td>1.07(0.15)</td>
<td>1.38(0.11)</td>
<td>1.44(0.07)</td>
</tr>
<tr>
<td>10-20 cm</td>
<td>1.45(0.07)</td>
<td>1.44(0.06)</td>
<td>1.45(0.10)</td>
</tr>
</tbody>
</table>
Black Carbon

Black carbon concentrations were analyzed at three (1, 6, 10) of the 16 paired sites, one at 0-10 cm and two at 10-20 cm depth. The largest BC concentration and content under both lawns (0.52%, 0.80 kg BC/m²) and trees (0.32%, 0.53 kg BC/m²) were found at site 6 from 10-20 cm depth (Fig. 14). A simple scatterplot using the four points available at 10-20 cm depth showed a significant positive correlation ($p<0.05$) between SOC and BC concentration (Fig. 16).

Discussion

Higher Organic Carbon Underneath Trees than Lawns in Surface Soils

In our urban ecosystem, we found that total organic carbon concentration and content were both greater under trees (5.47%, 5.30 kg/m²) than lawns (3.58%, 4.84 kg/m²) at 0-10 cm depth. Similar results were found in Seoul Forest Park in South Korea, where SOC concentrations and content were higher under deciduous tree cover (2.0%, 7.27 kg/m²) compared to urban lawns (1.7%, 3.74 kg/m²) and bare land cover (0.4%, 1.58 kg/m²) at 0-15 cm depth (Bae & Ryu 2015). Greater SOC concentration and content were also found underneath trees (7.52%, ~4.5 kg/m² (0-7 cm), 13.5 kg/m² (0-21cm)) in managed domestic gardens compared to non-domestic urban grasslands (4.55%; ~3 kg/m² (0-7 cm), 8.6 kg/m² (0-21 cm)) in Leicester, UK (Edmondson et al. 2014a). Interestingly, although the locations of these studies differ in terms of climate, soil type, and vegetation from the sites sampled in Denton, carbon content within Denton’s urban soils are comparable to those in other mid to large cities around the world.

The difference in TOC between trees and lawns could be due to a number of different
factors. Soils beneath tree canopies receive greater organic carbon input from leaf litterfall and, in some cases, from mulch and compost (Edmondson et al. 2014a, Bae & Ryu 2015, Pouyat et al. 2009, Livesley et al. 2015, Huyler et al. 2014). In contrast, higher compaction of lawn soils may result in decreased root growth and microbial activity, reducing belowground carbon inputs (Li et al. 2001). Differences in turfgrass species, also may have influenced the amount and distribution of belowground soil carbon. Zoysiagrass has lower root length and density than compared to Bermudagrass and St. Augustine, for example. This is further supported by Edmondson et al. (2014) which suggested that greater SOC could be explained by larger root length and density. The higher soil bulk density of lawn compared to tree soils and the negative correlation between soil bulk density and total organic carbon concentration—widely reported in research on urban soil carbon (Edmondson et al. 2011, 2014a; Livesley et al. 2015; Campbell et al. 2014; and Bae & Ryu 2015)—further suggest that either organic matter inputs to lawns are lower than to soils under trees, carbon losses from lawns are higher than from below trees (Bae & Ryu 2015), or both. Management practices, such as additions of mulch to tree soils and removal of grass clippings from lawns could explain why TOC differences were greatest in highly maintained areas.

We were surprised to find that total organic carbon content was positively correlated with percent sand at 0-10 cm depth. In contrast, other urban soil carbon studies (Selhorst & Lal 2012; Huyler et al. 2014; Kaye et al. 2005; Edmondson et al. 2014a) found no relationship between SOC and soil texture. Poeplau et al. (2016) did find that SOC concentration increased with percent clay in highly maintained lawns, but not within unmanaged lawns; therefore, percent clay was unsupported as a causality to SOC changes. Thus, it appears that clay content
may be a poor predictor of TOC concentration and content (Vaughan et al. 2019). Vaughan et al. (2019) showed that clay content alone could not explain the large variations seen in SOC among different soil orders and land covers in Puerto Rico. Instead, anthropogenic influences, rather than soil texture, may be more influential in driving TOC concentrations and content.

The home age of our sample sites ranged from 40 to >80 years old and had no significant effect on TOC concentration or content. Similarly, Raciti et al. (2011) and Campbell et al. (2014) found no relationship between SOC content and home age. This could be due to the fact that both of these studies, including our own, were conducted in areas where forest was likely the previous land cover. In contrast, studies that sampled from lawns developed from former agriculture land cover saw a positive correlation between SOC and home age (Huyler et al. 2014, Golubiewski 2006). Former forest soils tend to have higher initial C content after development compared to former agriculture soils and can quickly recover SOC within 20-25 years after development (Raciti et al. 2011, Golubiewski 2006). For example, in one study on formerly forested residential parks in Helsinki, Finland, TOC concentration and content did increase from young (7-15 years) to intermediate (40-60 years) soil underneath park lawns and trees but did not differ among sites greater than 40 years old (Setala et al. 2016). Thus, previous land use may explain why home age had no significant effect on TOC under trees or in lawns at our older (>40 years) study sites. However, it should be noted that, although not significant, the greatest difference in SOC concentration and content between trees and lawns was seen at the two oldest sites (>80 years) within this study. This may be attributed to slower but greater accumulation of SOC underneath trees with time after soil stabilization.
Total organic carbon concentration and content significantly increased with distance from primary highways. However, other studies such as Park et al. (2010) found significantly greater TC concentrations in roadside soils compared to interior lawns further away within urban centers. Luo et al. (2014) also noted a significant negative correlation with TOC and distance from urban centers, which is identified by its overall population and traffic density. This suggest that the variations we see in TOC may not be due to the linear distance to highways, but a function of urban or traffic activity.

Higher Nitrogen Concentration Underneath Trees than Lawns in Surface Soils

Total nitrogen concentration was greater underneath trees (0.43%) than lawns (0.31%) at 0-10 cm depth. However, due to higher soil bulk density underneath lawns, nitrogen content did not differ between trees (0.42 kg/m²) and lawns (0.42 kg/m²). Livesley et al. (2015) also measured higher N concentrations underneath trees (0.30%) than in fairway shortgrass (0.20%) in golf courses. Unlike our study and Livesley et al. (2015), Raciti et al. (2011) found greater N concentration and content under residential yards (0.20%, 0.16 kg/m²) compared to forest cover (0.16%, 0.12kg/m²) at 0-10 cm depth. Larger N concentration underneath trees than lawns contradicts the assumption that residential lawns would receive greater N inputs such as fertilization while trees and woody biomass would take up more N, resulting in lower N concentration underneath trees (Berthrong et al. 2009).

The strong positive correlation between TOC and TN concentrations at 0-10 cm depth is well documented (Huyler et al. 2014, Raciti et al. 2011, Golubiewski 2006, Campbell et al. 2014, Selhorst & Lal 2012) and indicates that most soil nitrogen is contained in organic matter. Thus, differences in decomposition rate between cover types could affect soil N concentrations. In
this study, however, the carbon to nitrogen ratio did not differ between trees (12.9) and lawns (13.0) at either depth. This is consistent with other studies which also found no significant effect of tree canopy cover on soil C:N ratio within urban and residential soils (Edmondson et al. 2014b, Raciti et al. 2011, Setala et al. 2016). Soil C:N is an indicator of leaf litter quality, with lower C:N ratios associated with faster decomposition rates (Kaye et al. 2005, Chapin et al. 2011, Schmidt et al. 2011). Therefore, the lack of difference in C:N underneath trees and lawns within our study suggest that leaf litter quality is not the primary factor affecting TOC and TN concentration within surface soils (Midgley et al. 2015).

Greater N underneath trees may be due to greater N inputs from atmospheric deposition. It is well established that atmospheric N inputs to soils beneath trees are often considerably greater than to areas without tree canopy cover due to dry N deposition (Decina et al. 2019, 2020; Ponette-Gonzalez et al. 2017). The negative linear relationship seen between primary highways, a potential atmospheric N pollutant source, and TN concentration may be supporting evidence that, rather than linear distance, overall street and traffic density may be a greater contributing factor to soil N distribution (Oanh et al. 2016). On the other hand, lower N concentration in lawns can be attributed to the loss of N through several avenues. Nitrogen could be exported from lawns as runoff in areas with higher bulk density (Law et al. 2004) or through the removal of nitrogen rich grass clippings (Kaye et al. 2005).
CHAPTER 3
CONTRIBUTIONS TO THE FIELD

Soil C, N, and BC were examined from underneath post oak trees and open urban lawns throughout Denton, TX to analyze the effects of canopy cover and maintenance levels on soil carbon accumulation. Results from this study found that soil underneath post oak canopy had greater ability in sequestering TOC and N.

Research within urban ecosystem services, particularly carbon storage, has become more prevalent over the years, especially in the face of growing development and urban migration. The fields of environmental quality, forest ecology and urban soil quality have all contributed research studying the impact of urban greenspaces on urban soil nutrient and pollutant regulative services (Livesley et al. 2015, Edmondson et al. 2015 & 2018, Setala et al. 2016, Campbell et al. 2014, Pouyat et al 2006, Hamilton & Hartnett 2013). This thesis focuses specifically on the effect of urban post oak trees and lawn management in the spatial distribution of SOC across the urban landscape, furthering our understanding the influence of anthropogenic factors on the urban C cycle.

Urban Lawn and Post Oak Canopy in Ecosystem Services

Results from this study supports a growing body of literature which suggest urban soils, especially underneath tree canopy cover, can sequester greater levels of C and N than previously assumed. Urban trees provide key ecosystem services which include the capture and storage of organic C, N and atmospheric pollutants. However, the successfully accumulation of these C and pollutants supports several other ecosystem services. Greater levels of SOC promote overall soil functionality and encourages root and vegetative growth. In turn, it also
enhances the ecosystems ability in mitigating floods, urban heat, and pollutant runoff. Therefore, results from this study supports the presence of post oak canopy cover as a driver for greater SOC accumulation throughout the urban ecosystem within Denton, Texas.

Urban Management in the Promotion of Soil Sequestration

Urban management practices are highly influential in determining the health and chemical balance of soil, especially when considering the direct effect of maintenance practices such as irrigation and fertilization which encourage soil fertility and growth. However, a consequence of greater soil maintenance practices could lead to rising potential of C and N loss through leaching or runoff and less soil stability over time (Pouyat et al. 2007). Results from this study found greater C and N concentration underneath trees than lawns within highly managed sites, suggesting intensive management on may lead to greater nutrient and pollutant loss in soils.

This knowledge may be beneficial to residential property owners and urban management planners in adapting maintenance practices to combat C and N loss from lawns, potentially through reducing overall soil disturbance and compaction, and less removal of litter clippings. In addition, greater N and C accumulation can also be promoted through the growth of post oak trees and overall canopy cover.

Conclusion

Total organic carbon and nitrogen was significantly greater underneath trees than lawns throughout the City of Denton, suggesting sites with post oak canopy cover may have the potential of facilitating greater soil C and N sequestration throughout urban ecosystems. Soil
bulk density was also greatest underneath lawns than trees indicating greater levels of compaction and reduction of organic matter inputs and increasing levels of C and N loss. Home age had no significant effect on C or N levels in sites greater than 40 years old due to soil stabilization; however, the oldest sites greater than 80 years old pointed to a gradual accumulation of nutrients over time. The lack of difference in C:N ratio between cover types may be evidence of greater N inputs to trees such as fertilization and atmospheric N deposition. Increase in TOC and N underneath post oak canopy cover encourages soil stabilization along with nutrient and pollutant capture. Therefore, management conditions should focus on reducing soil bulk density in lawns and encourage litter decomposition underneath post oak trees through N inputs. Future studies should work in identifying specific management practices and frequencies which promote greater C and N sequestration underneath post oaks throughout urban areas.
Figure 5: The effect of cover type and maintenance level of soil moisture concentration and its correlation between home age, bulk density, and soil texture.
Figure 6: The effect of cover type and maintenance on soil moisture concentration and its correlation with home age.
Figure 7: The effect of cover type and maintenance level on bulk density
Figure 8: The effect of cover type and maintenance level on total carbon concentration, its distribution between each paired site, and correlation with bulk density.
Figure 9: The effect of cover type, maintenance level, and bulk density on total organic carbon concentration, its distribution between each paired site, and correlation with bulk density.
Figure 10: The effect of cover type and maintenance level on total carbon content, its distribution between each paired site, and correlation with bulk density and soil texture.
Figure 11: The effect of cover type, maintenance level, and bulk density on total organic carbon content, its distribution between each paired site, and correlation to bulk density and soil texture.
Figure 12: The effect of cover type, maintenance level, and bulk density on total nitrogen concentration, its distribution between each paired site, and correlation with bulk density.
Figure 13: The effect of cover type and maintenance level on total nitrogen content, its distribution between each paired site, and correlation with soil texture.
Figure 14: Correlation between total organic carbon and total nitrogen concentration and content.
Figure 15: The effect of cover type and maintenance level on C:N ratio, distribution between each paired site, and correlation with bulk density.

Figure 16: Distribution of black carbon concentration at pair sites 1, 6, and 10.
REFERENCES


