SOIL CARBON DYNAMICS IN LAWNS CONVERTED FROM APPALACHIAN MIXED OAK STANDS

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ABSTRACT

Conversion of native forests to turfgrass-dominated residential landscapes under a wide range of management practices results in dramatic changes to vegetation and soils, which may affect soil carbon storage. To better understand the effects of landscape conversion and management on soil carbon, we conducted a study on residential properties in the Valley and Ridge physiographic province of southwest Virginia to compare soil carbon storage and dynamics between turfgrass landscapes and the surrounding mixed oak forests from which they were developed.

Sixty-four residential properties ranging from 5 to 52 years since site development were investigated. Soil samples were collected from lawns and adjacent forest stands to a depth of 30 cm and analyzed for carbon and nitrogen content. Additional measurements taken were soil bulk density, temperature, moisture, and total soil CO_2 efflux rate. Homeowners participating in the study completed a survey on their lawn management practices so that the effects of specific practices (e.g. fertilization) and intensity levels on carbon dynamics could be analyzed. Also included in the survey were 11 questions regarding the homeowners' commitment to the environment. Homeowners were assigned an environmental commitment score based on their responses which was compared with lawn management practices in order to identify any connection between environmental attitude and lawn management practices.

Total soil carbon content to 30 cm depth of lawn (6.5 kg C/m^2) and forest (7.1 kg C/m^2) marginally differed (P=0.08); however, lawn soil contained significantly greater C than forest soil at the 20-30 cm depth (0.010 vs. 0.007 g C/cm^3, P=.0137). There was a weak negative relationship between carbon in the lawn and time since development at the 20-30 cm depth (P=0.08), but no significant relationship between time and C content at shallower depths. We found a positive relationship between time since development and percent C of lawn at the 0-5 cm depth (P=0.04), whereas there was a negative relationship with percent C and time at the 20-30 cm depth (P=0.03). Based on the homeowner survey, we found a positive correlation between lawn fertilization frequency and both lawn nitrogen content (P=.07) and lawn carbon content (P=.0005) in the top 0-5 cm of soil. Nitrogen content was greater in lawn than forest soil at the 0-5 cm depth (0.0025 vs. 0.0018 g/cm^3, P<.0001) and the 5-10 cm depth (0.0013 vs. 0.0009 g/cm^3, P <.0001). There was a positive relationship (P=0.059) between overall environmental commitment score and level of management intensity. Higher environmental commitment (EC) score corresponded with a higher level of management intensity (fertilizer and pesticide use).

Our results indicate that converting unmanaged Appalachian hardwood forest into managed, turf-grass dominated residential homesites results in similar soil organic concentration and depth distribution as the previous forest within a short period of time following development. Although total soil carbon does not differ between lawn and forest, lawn may develop greater density at 20-30cm depth over time. Fertilization enhances carbon and nitrogen content in the upper 0-5cm in lawns. Homeowner's who feel that they are more strongly committed to the environment are more likely to apply higher levels of fertilizer to their lawn.

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CHAPTER 1 – INTRODUCTION

1.1. Research Background

Urban development of forested land results in substantial, long-term changes in vegetation composition, soil properties, impervious surface area, and management intensity (Pouyat et al. 2006, Scharenbrock et al. 2005). As a result, urbanization significantly alters biogeochemical cycling and other ecosystem processes including hydrology and biological community structure (Lorenz & Lal 2009). Specific interest has arisen in the effects of urban transformation on carbon cycling due to the rapid rate of urbanization in the United States and around the globe (Brown et al. 2005), the potential for urban soils to sequester carbon and reduce atmospheric concentrations of CO_2 (Lal 2004), and the importance of soil organic matter for urban vegetation productivity (Beyer et al. 1995). Soil organic matter is on average 58% organic carbon, and consists of (1) the tissues from dead plants and animals, (2) the products formed as these decompose and (3) the soil microbial biomass. The North American carbon cycle is highly influenced both directly and indirectly by urban development patterns, and future efforts to reduce carbon emissions require accurate models of carbon storage and flux in these settings (Pataki et al. 2006).

While the effects on soil organic carbon (SOC) dynamics from transforming natural ecosystems (forests, grasslands, wetlands) to agricultural systems has been widely studied, little is known about the long-term effects of conversion to urban land uses. Yet retention and enhancement of SOC in urban soils has the potential to provide numerous benefits to urban inhabitants, including increased productivity of vegetation, enhanced soil pollution remediation, and reduced air pollution (Lal 2004). Therefore, understanding the effects of land urbanization and post-development management practices on carbon dynamics is critical to conservation of the SOC resource.

Conversion of non-urban lands to urban uses is occurring from local toglobal scales, thereby compounding the impact of urbanization on carbon cycling and other ecosystem processes. The amount of urban land area in the coterminous United States is estimated to be 60 million acres (2.6%) (US Census 2002) and is projected to increase from 2.5% in 1990 to 8.1% by 2050 (Nowak 2006). In the next fifty years, up to 23 million acres of forest may be converted to urban uses in the southern United States (Weir & Greis 2011). At present, 80% of Americans live in medium to high density urban and suburban areas, and this percentage is projected to increase (Carrerio 2008). Beyond major metropolitan areas, exurban development is an increasingly important land development pattern characterized as being distant from metropolitan urban centers, driven by natural amenities, and dominated by large residential parcels greater than one acre. Highly dispersed, low-density development now occupies 94 million acres in the U.S. (US Census 2002), which is 15 times more land area than higher density uses and has large impacts on fragmentation of natural systems and alteration of ecosystem processes (Brown et al. 2005). For example, dispersed development affects wildlife habitat corridors, soils, vegetation structure, and hydrology. Residential developments in rural areas often convert forests directly to intensively managed ornamental landscapes, potentially having a significant effect on regional SOC. Forest soils and biomass are known to be an important carbon sequestering system (Curtis et al. 2002), and therefore, the effects of converting forest to residential landscapes on SOC and total carbon storage need to be quantified.

SOC is a function of soil organic matter additions due to net primary production (NPP) and losses due to heterotrophic respiration (Hr). Because both NPP and Hr depend on moisture, temperature, and organism activity; native SOC concentration is geographically variable due to differences in climate and ecosystem. Conversion of a native ecosystem to an urban development may cause an initial decline in C stocks (Pouyat et al. 2007), but post-conversion management may facilitate recovery and eventual enhancement of SOC mass beyond that of the native system (Pouyat et al. 2006; Pouyat et al. 2007; Pickett et al. 2008). Quantifying SOC response to urbanization must account for (1) SOC characteristics of the background ecosystem, (2) modifications to SOC that occurred during development, and (3) post-development cover type and management intensity (Pouyat et al. 2009).

Of the numerous cover types found in urban areas, turfgrass is one of the more prominent features due to its abundance and management intensity. It is estimated that there are 163,800 km^2 (± 35,850 km^2) of managed turfgrass lawns in the continental United States (Milesi et al. 2005; Brown et al. 2005), and private residential lawns account for 80% of this managed lawn area (Borman et al. 2001). Turfgrass management inputs (e.g. irrigation, fertilization, mowing, pesticides) aimed at improving turf appearance and health consequentially increase net primary productivity, resulting in a high rate of SOC input, including root turnover and leaf clippings addition (Qian & Follett, 2002). Although residential lawns receive inputs similar to agricultural systems, they are disturbed less frequently, thereby minimizing losses of SOC (Kaye et al. 2006). Turfgrass is a carbon sequestering system (Qian & Follett 2002); yet emissions associated with management (mowing, fertilizer use) may more than offset sequestration value when these losses are included in the carbon budget for turf systems (Jo & McPherson, 1995).

Studies of turfgrass in golf courses and residential areas in the U.S. have estimated mean carbon densities of 10-15 kg m^{-2} (1-m depth) in turfgrass (Qian & Follett 2002, Pouyat et al. 2006, 2009). Carbon is sequestered in lawns at rates of up to 1 t ha^{-1} $year^{-1}$ under high intensity management and will accumulate for 30-50 years until a steady state between gains and losses has occurred (Qian & Follett 2002, Bandaranayke et al. 2002). Due to intensive management to improve lawn growth and appearance, SOC concentrations found in urban residential areas across the United States exhibit lower relative variability than unmanaged natural ecosystems, however the variability found within the turf cover type is explained by differences in management intensity (Pouyat et al. 2006). Pouyat et al. (2009) found that urban residential soils in Baltimore, MD and the arid region of Denver, CO have similar SOC densities, while SOC density of the native forest in Baltimore had 60% higher SOC in the 0-20cm depth than in the short grass steppe soil found in Denver. Previous studies of urban SOC have established the basic factors affecting carbon storage and flux in turfgrass ecosystems (Bandaranayke 2003; Milesi 2005, Qian & Follett 2002) as well as quantified SOC densities found in residential urban areas (Pouyat et al. 2002, 2003, 2006, 2009; Pataki et al. 2006). However, there has been no study that has investigated the relationship between homeowner management practices and SOC content and accumulation rates in residential lawns.

Given that the rate at which urban ecosystems store or emit C following conversion depends largely on human choice and the effects of individual practices implemented at a parcel scale (Pickett et al. 2005; Kaye et al. 2006; Pataki et al. 2006), linking SOC dynamics to management intensity and specific management practices is key to understanding the variability of SOC within the turfgrass cover type. Further, identification of social and psychological drivers affecting a homeowner’s lawn care practices could explain where higher or lower intensity management is occurring within urban areas based on demographic patterns if coupled effectively with psychosocial measures. Knowing the soil carbon characteristics of the transformed ecosystem, in addition to the effect of turf grass management, is critical to comparing factors affecting SOC between native forest ecosystems and transformed urban landscapes.

1.2. Research Objectives

The specific objectives of this study were to:

(1) Measure the content and respiration of soil carbon in exurban, residential turfgrass lawns as contrasted with adjacent hardwood forest land from which they originate.

(2) Investigate the temporal pattern of SOC dynamics following conversion of hardwood forest land to residential turfgrass.

(3) Analyze the effects of typical lawn management practices (e.g. fertilizing, mowing, fate of clippings) and relative intensities (e.g. low, medium, or high input) implemented by homeowners on carbon content and respiration in turfgrass ecosystems.

(4) Measure homeowner environmental attitudes and investigate their relationships with lawn management practices and intensities.

CHAPTER 2 – LITERATURE REVIEW

2.1. Land Conversion Effects on Carbon Storage and Flux

Transformation of natural ecosystems to urban uses has significant effects on soil carbon storage and flux due to alterations in soil and ecosystem structure during site development and management practices implemented post-development (Pouyat et al. 2003). The first consideration for quantifying changes in SOC resulting from urbanization and changes in management is the SOC characteristics of the background ecosystem that was developed into urban use (Figure 2.1).

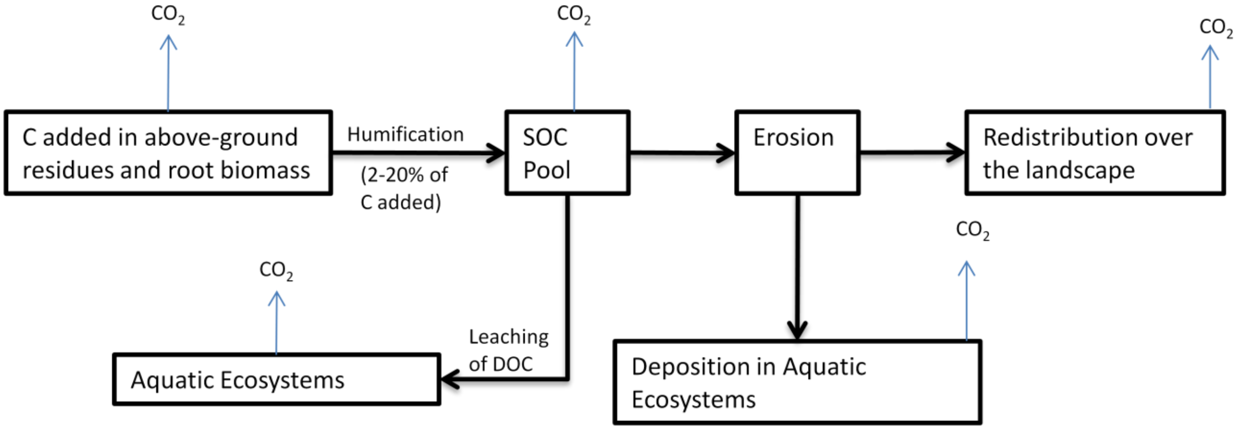


Figure 2.1. Pathways of carbon flux in terrestrial ecosystems (Redrawn from Lal 2004). Natural characteristics of the specific ecosystem (vegetation, climate, topography, other soil properties, time since disturbance) determine the rate and depth distributions of carbon additions and losses, used under fair use guidelines, 2012.

At a global scale, moisture and temperature are the two strongest factors driving gains (due to NPP) and losses (due to Hr) of SOC (Pouyat et al. 2003). As a result, SOC varies geographically and by ecosystem due to differences in rainfall and vegetation composition (Jobaggy & Jackson, 2000). For example, Birdsey (1992) estimated that forests in the southeastern United States have a mean SOC density (1-m depth) of 7.74 kg m^{-2}, in comparison to a SOC density of 3.81 kg m^{-2} in a Rocky Mountain prairie. SOC density for mixed oak forests in the southeastern United States have been reported at 8.3 kg m^{-2} (Turner et al. 1995).

At the regional scale, edaphic and microclimate variables become significant determinants of SOC density. Homann et al. (2005) compiled SOC data for 499 pedons in the forested, mountainous region of western Oregon and found that site characteristics explained up to 50% of the SOC variability amongst sites. SOC decreased with slope and increased with annual temperature, annual precipitation, actual evapotranspiration, clay content, and available water-holding capacity. Other factors that may not have been accounted for, but that affect SOC comparisons, include differences in methods and accuracy of measuring C concentrations, bulk density and rock volume; natural within-site variability; and site-characteristic measurements (Homann et al. 2005).

Although a great deal of recent interest has been directed at understanding the effects of urbanization on soil carbon, the effects of other types of land use conversion of carbon stocks has been studied for the past twenty years. The effect of land use conversion on soil organic carbon has been widely studied for conversions from forest to agricultural land, and agricultural land abandoned to return to forest. In general, converting forested land to agricultural (crop) land results in depletion of soil organic carbon due to continued disturbance due to tillage (Lal 2002). Converting forested land to pasture results in initial losses due to disturbance, and soil organic carbon under pasture land could potentially recover to levels similar to that of the previous forest, depending on management (Bolstad & Vose 2005). Abandoning agricultural land (pasture or cropland) to return to forest results in slow recovery of soil organic carbon, eventually returning to a level similar to pre-disturbance.

In addition to understanding background SOC of the natural system, the manner of land conversion and fate of native soil horizons must be considered when investigating SOC content of urbanized landscapes. Accurately measuring the effect of land use change on SOC content becomes complicated by the effect that land use transformations have on soil aggregates. Aggregation is higher in less disturbed forested sites, and organic materials within soil aggregates have lower decomposition rates than those located outside of aggregates (Six et al. 2000). Therefore, the impact of initial site disturbance on soil aggregation may result not only in rapid initial losses of SOC, but also alter decomposition rates in the long-term (Six et al. 2002).

Typical site preparation involved in building a residential neighborhood in a wooded setting involves (1) clearing of the vegetation, (2) grading and compacting soil for homesites and roads, (3) building of housing and infrastructure including the septic drain field, and (4) replanting with vegetation. Site development represents a dramatic disturbance to soil; the native soil profile may be severely compacted, horizons may be mixed, and fill material (e.g. subsoil from the site, subsoil from offsite, construction debris) may be added. The disturbance of topsoil, litter layer, stems, and roots that occur when a forested site is cleared for development may result in losses of SOC due to erosion and oxidative release as carbon dioxide (Lal 2003).

Another important consideration is the time since disturbance of the compared sites because carbon accumulation and steady state varies not only by system, but by stage of system development post-disturbance (Harmon 2001). To avoid overlooking temporal differences in SOC accumulation due to site history of two compared systems, a method for assessing spatial, temporal, and process levels must be identified (Harmon 2001). The steady state SOC concentration of the lawns may be applied over larger timescales in order to accurately compare to the longer time that it may take for the native forest to reach a steady state where SOC levels remain relatively constant over time. Turf grass systems accumulate SOC for 30-50 years or more (Qian & Follett 2002) and may reach steady-state concentrations of up to 15 kg m^{-2} to 1-m depth (Pouyat 2009), while forest ecosystems may accumulate carbon for a much longer period (100-500 years) and eventually reach a similar steady-state density (Pouyat et al. 2006). Therefore, the relative stand age and use history of the forest area and the time since development of the lawn area must be measured, and SOC densities must be considered a snapshot of the current state of the aggrading systems.

Once site development and construction disturbance cease, SOC begins recovering as the site is revegetated, although significant efflux of CO_2 may occur simultaneously as residual root and litter biomass decompose (Post & Kwon 2000). If a forested site is cleared and left to natural recovery, vegetation dynamics on the site follow a successional pathway based on mostly natural factors (e.g. available seed stocks, soil type and condition, aspect, clearing size) (Post & Kwon 2000). However, the unique aspect of urban residential land – particularly lawn – is the high level of management that it receives, which results in anthropogenic drivers being more important than natural factors in determining landscape characteristics (Pouyat et al. 2009). Vegetation composition and other landscape characteristics (impervious surfaces, management intensity) of the transformed urban ecosystem are guided largely by landowner choices, which can be highly variable. Therefore, the potential difference in carbon sequestration between turfgrass-dominated landscapes and mid-succession forests lie in: (1) the rate of SOC accumulation, (2) the amount of time that it takes to reach steady-state C content following disturbance, (3) the maintained steady-state SOC concentration, and (4) the time that the system is maintained before disturbance occurs (Harmon 2001) (Figure 2.2).

FOREST →	**SITE DEVELOPMENT**	**→ LAWN**
Inputs	Inputs	Inputs
• Aboveground residues: Leaves, coarse woody debris (C/N 40-80:1) • Belowground residues: Coarse and fine roots, exudates • Microbial biomass	• Residues buried during grading • Foreign soil (topsoil, fill dirt, soil amendment)	• Aboveground residues: Grass clippings, mowed leaves(C/N 9-25:1) • Belowground residues: Fine roots only • Microbial biomass
Losses	Losses	Losses
• Microbial respiration • Leaching (DOC)	• Removal of trees • Microbial respiration increase • Erosion • Leaching increase	• Microbial respiration • Leaching (DOC)
	Changes to Soil Properties	Changes to Soil Properties
	• Aggregation • Compaction • Mixing • Removal of upper horizons	• Aeration • Liming (inorganic C) • Fertilization • Pesticides • Soil decomposer community

Figure 2.2. Inputs and losses of soil carbon and changes to soil properties before, during, and after lawn establishment on a previously forested site.

2.2. Management Impacts on Carbon Storage and Flux in Turf Grass Lawns

Despite the varied effects of initial site disturbance, measurements of urban soils from diverse climate and ecosystem conditions have shown relatively consistent SOC densities across urban residential areas at the continental scale. The urban convergence hypothesis proposed by Pouyat et al. 2003 predicts that “urban land-use change drives ecosystem structure and function over time toward a range of similar endpoints regardless of ecosystem life zone starting points.” For example, SOC density of urban residential soils in Denver, CO was similar to urban residential soils in Baltimore, MD at depths of 0-1 m, although the native forest soil of Baltimore had almost two-fold higher SOC than the native short grass steppe soils of Denver (Pouyat 2009). Similarity in urban SOC is attributed to the dominance of human drivers (e.g. soil alterations, cover type selection, landscape choices) over natural drivers (climate, organisms, soil type) of carbon storage and flux in urban landscapes (Pouyat et al. 2006). Despite inter-regional similarities in urban SOC, variability within regions may be high (Milesi et al. 2005, Pouyat et al. 2009), and more data is needed to understand the effects of variable management practices on carbon accumulation (Qian et al. 2003).

Maintained turf grass lawns have a high potential rate of NPP due to management practices such as fertilization, irrigation, mowing, and liming (Pouyat et al. 2003). Management inputs serve to ameliorate factors that limit plant growth, which vary based on site conditions. Since carbon inputs in turf grass systems arise mostly from the addition of grass clippings and fine root contributions, any activity that increases their production may result in enhanced carbon sequestration. Management actions also impact microbial community biomass, structure, and activity, and therefore may affect SOC losses due to heterotrophic respiration. Since the optimal pH range for turf grass growth is 6.0 to 7.0, liming is an important management factor that increases lawnscape NPP in the acidic forest soils of the Appalachian region. (Carrow, Waddington, & Rieke 2001). Liming may also significantly alter the microbial community, especially when the pH is raised considerably on previously acid sites. Total soil actinomycete and bacteria populations remain relatively constant over a wide pH range, but steadily decline at pH <5.5, while fungal populations are favored at such a low pH level (Carrow, Waddington, & Rieke 2001). Therefore, liming may boost microbial activity of the most acidic sites and potentially enhance fungal and bacterial diversity. Nitrogen is typically the most limiting nutrient to lawn growth and therefore is often applied in order to improve the vigor and color of turf grass. If pH is within the optimal range, N fertilization is the most important factor that enhances NPP and potential carbon contributions (Carrow, Waddington, & Rieke 2001). Therefore, the frequency and rate of fertilizer application is an important indicator of management intensity.

Deposition of mowed grass clippings occurs regularly throughout the growing season, especially during times of increased grass growth (for cool season grasses, spring and fall). Fresh grass clippings are a high quality litter having a C:N ratio of 9:1-25:1 (Cornell University 1996), and their addition by mowing results in rapid microbial activity (losses as CO_2) for 1-7 days as well as retention of some organic carbon (Shi et al. 2006). Therefore, depositing clippings can increase C accumulation by 11-59% (Qian et al., 2003), whereas removing clippings will reduce the rate of SOC accumulation (Shi et al. 2006). In contrast to a turf system, above-ground additions in a forest ecosystem result from fallen woody debris and annual autumn leaf drop. Tree leaves have a much higher C:N ratio (40:1-80:1) (Cornell University 1996) than grass clippings and represent an infrequent, low-quality addition. Therefore, quantity, quality, and temporal occurrence of litter additions differ between managed lawns and the forest ecosystems that they replace, potentially affecting the soil carbon balance and the microbial community.

There are distinct differences in below-ground SOC inputs between forest and turfgrass ecosystems that arise from major differences between tree and grass roots. Jobaggy & Jackson (2000) determined that depth distribution of SOC is significantly different between temperate forest and temperate grass land ecosystems due to differences in root systems and above- and below- ground carbon allocation patterns. The tree roots that dominate the forest soil exploit lower horizons and can be found several meters deep, depending on tree species, growing conditions, and depth to a restrictive horizon. In addition to coarse roots found throughout the profile, trees produce fine roots, which are concentrated in the top 10 centimeters of A-horizon and extend into O-horizon litter material. In contrast, typical turfgrasses produce only fine roots, which densely colonize the soil profile to a uniform depth (Jobaggy & Jackson 2000). Although soils may be deep in natural temperate grasslands and allow for deep penetration of grass roots (2.6±0.2 m) (Canadell et al. 1996), grading and compaction that occur during land development result in a shallow A-horizon with compacted subsoil beneath, limiting the growth of lawn grass roots into it. Even on deeper soils, turfgrass roots are generally limited to the top 30-cm of soil (Beard 1989) due to the limited height the grass is allowed to reach, which results in shallower roots than are found in taller, unmanaged grasslands.

Pouyat et al. (2009) observed that residential turf lawns (>40 years old) in Baltimore, MD had similar carbon densities to urban forest remnants, but a significantly greater proportion of SOC was found in the top 20 cm of the forest soil than in the top 20 cm of the turf grass soil. Turfgrass systems function similarly to perennial grassland systems under ruminant grazing, but in the case of turf grass, the ruminant is the lawnmower. In grazed grasslands, efforts to increase soil organic carbon focus on allowing the grass to fully recover between grazing events in order for the grass to establish deeper roots. The result of properly timed grazing is more productive grass and higher NPP, increased SOC contribution, and deeper vertical distribution of SOC (Schuman et al. 2002). This phenomenon is the result of the evolved positive physiological response of grasses to moderate grazing, and applies similarly to turf grass systems. Therefore, less frequent mowing and setting the mowing deck higher allows for larger shoots and larger roots, resulting in a greater quantity of root additions that occurs less frequently, and also lends to deeper vertical distribution of SOC from roots (University of Minnesota 2006).

There are potential significant differences in total microbial biomass and the fungal to bacteria (F:B) ratio between deciduous forest and turf grass lawns, which could affect SOC accumulation rates over time. Because the decomposition pathways of the two organism groups differ, they respond differently to litter inputs, temperature, and moisture (Six et al. 2002). The most notable difference is that fungi have hyphae that allow them to move, colonize, and degrade surface litters with which soil bacteria may have no contact (Holland & Coleman 1987). Also, fungal cell structure is more resistant to decay, and has greater C assimilation efficiencies than bacteria; therefore fungi store more C relative to bacteria (Guggenberger et al. 1999). Because fungi are favored by cooler, moister conditions, and litter with higher lignin content, a higher F:B ratio is likely on a forested site than a managed turf lawn.

2.3 Social Factors Impacting Lawn Management

The maintained turfgrass lawn concept dates back to 16th Century England and has been a major component of American urban landscapes since before the turn of 19th the century (Jackson 1985). Chemical fertilizers and pesticides along with gas-powered lawn mowers introduced to the public after World War II revolutionized monoculture turf grass production. At the same time, extensive suburbanization drove the expansion of turf area, and the lawn quickly came to represent the classic American leisure landscape (Robbins & Birkenholtz 2003). It is estimated that there are now 163,800 km^2 (± 35,850 km^2) of managed turfgrass lawns in the United States (Milesi et al. 2005; Brown et al. 2005), and private residential lawns account for 80% of this managed lawn area (Borman et al. 2001).

The popularity of turf grass in America results from its functionality as an erosion controlling ground cover and recreational surface that can withstand traffic. When non-urban lands (agricultural, native landscapes) are developed for urban uses, disturbed soil is seeded with grass or planted with sod upon construction completion in order to create a finished look and to control erosion. The lawn has thus become an aesthetic necessity as a component of modern landscape design, ubiquitous throughout developed areas of all types (residential, commercial, industrial, public). A lush monoculture of planted grasses with no broadleaf species has come to represent the ideal lawn. Maintaining such a manicured grassland, however, requires large amounts of management intervention in the form of mowing, weeding, and fertilization in order to stop the natural process of vegetation succession (aggradation to forest in the eastern United States) from occuring. Expanding lawn area along with growing expectations of the ideal lawn has resulted in a continuously expanding turf industry which is now valued at over $40 billion per year (USDA 2007). When compared with unmanaged native ecosystems, the management of turfgrass is uniquely intensive generating both positive (carbon sequestration, erosion control, reduction of heat island effect) and negative (emissions due to mowing, fertilizer and pesticide runoff, habitat loss) environmental effects.

Although residential lawns receive inputs similar to agricultural systems, they are disturbed less frequently, thereby minimizing losses of soil organic carbon (SOC) (Kaye et al. 2006). Therefore, turfgrass is a carbon sequestering system, accumulating at rates up to 140 g C m^2 yr^{-1}, depending on level of fertilization (Qian & Follett 2002, Townsend-Small & Czimczik 2010). Greater levels of fertilization enhance turf growth, increasing subsequent contributions of clippings and root biomass, which results in an increased rate of accumulation, mostly in the top 0-6 cm of soil (Singh 2007). Fertilization level, frequency, analysis, and type (mineral or organic) are all factors affecting potential gains in sequestration due to fertilization. The other main factor determining grass growth is moisture availability, so irrigation or adequate rainfall is also an important determinant of sequestration.

The gain or loss in soil carbon storage which results from transforming native landscapes to urban areas is relative to the carbon characteristics (quantity, quality, depth distribution) of the native soil. Turf grass systems accumulate SOC for 30-50 years or more (Qian & Follett 2002) and may reach steady-state densities of up to 15 kg m^{-2} (Pouyat 2009), while forest ecosystems may accumulate carbon for a much longer period (100-500years) and eventually reach similar steady-state densities (Pouyat et al. 2006). Therefore, the relative stand age and use history of the forest area and the time since development of the lawn area must be measured, and SOC densities must be considered a snapshot of the current state of the aggrading systems.

Since the rate of carbon and nitrogen sequestration by turfgrass and rate of reciprocal management-related emissions is driven by the intensity of management applied, predicting a sequestration rate for turfgrass at a landscape scale relies on understanding the spatial distribution of management intensities (Pouyat 2009). Intensity of lawn management does not necessarily correspond to development density, and therefore, cannot be adequately explained using the urban-to-rural gradient model (Pouyat et al. 2003). For example, a homeowner in a high-density urban center may use similar management practices as a homeowner in a suburban or exurban area, possibly even using the same professional lawn care service. Fertilizer application is a primary component of lawn management, resulting in substantial inputs of nitrogen to urban soils. Cassman and Mosier (2000) arrayed turf management intensity into three groups according to the estimated amount of N-fertilizer applied annually: residential lawns maintained by homeowners (0.06 kg m^{-2}), residential lawns cared for by professional lawn care companies (0.25 kg m^{-2}), and athletic fields and golf courses (0.34 kg m^{-2}). Previous studies have confirmed that residential lawns receive high intensities of fertilizer application second only to athletic fields and golf courses (Pouyat 2009) and that development density (low, medium, high) (Pouyat 2008) does not explain differences in fertilization intensity within the residential use category. Lawn management practices and their effects on urban ecosystems need to be quantified, but this is particularly difficult due to individual practices implemented by each parcel owner.

Because the turfgrass lawn is entrenched in American landscape aesthetic preference, lawn quality has come to represent an important social value. In American neighborhoods, good lawns are associated with socially desirable resources such as wealth, education, property values, and the personal characteristics assumed to go with such resources (Weigert 1994). Zhou & Troy (2009) studied groups of private residential homes within a single watershed in Baltimore, MD and found that house value was positively correlated with lawn care expenditures and lawn greenness and that other lifestyle indicators (percent of population married, percent of population with children) were also important predictors of lawn care expenditures. In a survey of residential fertilizer use in the Balitmore region, Law et al. (2004) found that middle-level income households had the highest level of N fertilization. Potential linkages between socio-economic and psychological drivers of lawn management practices are in need of further exploration not only in terms of modeling carbon sequestration, but also for other environmental effects of lawn care, such as air and water pollution due to fertilizer and pesticide application (Milesi et al. 2005).

Growing public environmental awareness has sparked interest in sustainable landscape management and resulted in movements to manage lawns in a more environmentally-friendly manner or to reduce the area of lawn altogether (University of Minnesota Sustainable Urban Landscape Information Series, 2006). For example, the “Food Not Lawns” movement – based on the book of the same name by H.C. Flores (2006) – has established in many communities across the nation and is based on putting lawn space to more environmentally and socially friendly uses. Therefore, environmental awareness of lawn owners may impact the practices and products used on their land. Other social factors affecting lawncare include regional and neighborhood norms as well as subdivision requirements, and most importantly, media advertising.

Commercial advertising and public education campaigns present both positive and negative perspectives of lawns to consumers. Due to concerns about the adverse effect of runoff from residential lawns on water quality, Minnesota recently enacted a law (Minnesota Statutes 18C.60. Effective date 2005 statewide) which restricts the use of fertilizers with phosphorus unless a phosphorus deficiency was identified. This type of legislation is being considered in other communities across the nation. A law approved on March 22, 2011 in Virginia (HB 1831) proposes changing application rates displayed on bags of fertilizer sold in the state (http://lis.virginia.gov/cgi-bin/legp604.exe?111+sum+HB1831). Efforts such as banning phosphorus or changing application rate labeling are aimed at educating and changing the behavior of residential lawn consumers. At the same time, advertisements for lawn care services and products reinforce individual and group perspectives of what a lawn should be, resulting in an ever-increasing ideal of perfect grass. Lawn industry advertisements exploit the social assumptions of a good lawn through marketing that seeks to produce an association of community, family, and environmental health with intensive turfgrass aesthetics (Robbins &

Sharp 2003). Therefore, the management actions of lawn consumers may be influenced by conflicting media from various sources.

In summary, the spatial distribution of lawn management intensities within residential land uses may be best explained by accounting for the many factors affecting the social phenomenon of lawn management: demographic distribution, location (e.g. subdivision with mowing requirements, rural home, cluster housing, urban area), media exposure, and environmental knowledge and attitude of the parcel owner. For this project, we explored the connection between a homeowner's commitment to the environment, their management practices and soil carbon sequestered in their lawns. Our specific goal was to (1) identify relationships between the homeowner's environmental commitment and their fertilization behavior, and (2) identify any effects of this behavior on soil carbon and nitrogen under their lawn.

CHAPTER 3 – COMPARISON OF SOIL CARBON DYNAMICS IN RESIDENTIAL LAWNS AND UNMANAGED FOREST

ABSTRACT

Conversion of native forests to turfgrass-dominated residential landscapes under a wide range of management practices results in dramatic changes to vegetation and soils, which may affect soil carbon storage. To better understand the effects of landscape conversion and management on soil carbon, we conducted a study on residential properties in the Valley and Ridge physiographic province of southwest Virginia to compare soil carbon storage and dynamics between turf grass landscapes and the surrounding hardwood forests from which they were developed.

Sixty-four residential properties ranging from 5 to 52 years since site development were investigated. Soil samples were collected from lawns and adjacent forest stands to a depth of 30 cm and analyzed for carbon and nitrogen content. Additional measurements were taken of soil bulk density, temperature, moisture, and total soil CO_2 efflux rate. Homeowners participating in the study completed a survey on their lawn management practices so that the effects of specific practices (e.g. fertilization) and intensity levels on carbon dynamics could be analyzed.

Total soil carbon content to 30 cm depth of lawn (6.5 kg C/m^2) and forest (7.1 kg C/m^2) marginally differed (P=0.08); however, lawn soil contained significantly greater C than forest soil at the 20-30 cm depth (0.010 vs. 0.007 g C/cm^3, P=0.0137). There was a weak negative relationship between carbon contained in the lawn and time since development at the 20-30cm depth (P=.08), but no significant relationship between time and C density at shallower depths. We found a positive relationship between time since development and percent C of lawn at the 0-

5 cm depth (P=0.04), whereas there was a negative relationship with percent C at the 20-30cm depth (P=0.03). There was no relationship between lawn soil CO_2 efflux rate (measured on a single date) and time since land development. Based on the homeowner survey, we found a positive correlation between lawn fertilization frequency and both lawn nitrogen density (P=0.07) and lawn carbon density (P=0.0005) in the top 0-5 cm of soil. Nitrogen density was greater in lawn than forest soil at the 0-5 cm depth (0.0025 vs. 0.0018 g/cm^3, P<.0001) and the 5-10 cm depth (0.0013 vs. 0.0009 g/cm^3, P <0.0001).

Forest soil CO_2 efflux was positively affected by aspect (P=0.042), soil temperature (P=0.0004), and soil moisture (P<0.0001), and negatively affected by bulk density (P=0.0027). In lawns, soil CO_2 efflux was positively affected by the CN ratio (P=0.0012), nitrogen density (P=0.0902) of the top 0-5 cm of soil, soil temperature (P=0.047), and soil moisture (P<0.0001). The overall regression explained 43% of the variation in lawn soil CO_2 efflux and 50% in the forest. Management intensity (combined effects of fertilizer and pesticide level) had no effect on lawn soil CO_2 efflux (P=0.4302), nor did fertilization frequency (P=0.3438). Slope and property age were likewise found not to be significant predictors of lawn efflux in the presence of other variables.

Our results indicate that converting unmanaged Appalachian hardwood forest into managed, turf-grass dominated residential homesites results in similar soil organic concentration and depth distribution as the previous forest within a short period of time following development. Although total soil carbon does not differ between lawn and forest, the lawn had a greater density at 20-30cm depth.

3.1. Introduction

Urban development of forested land results in dramatic, long-term changes in management intensity, vegetation composition, soil properties, and impervious surface area (Pouyat et al. 2006, Scharenbrock et al. 2005). As a result, urbanization significantly alters biogeochemical cycling and other ecosystem processes (Lorenz & Lal 2009). Specific interest has arisen concerning the effects of urban transformation on carbon cycling due to the rapid rate of urbanization (Brown et al. 2005), the importance of soil organic matter (SOM) for urban vegetation productivity (Beyer et al. 1995), and the potential for urban soils to sequester carbon and reduce atmospheric concentrations of CO_2 (Lal 2004). The North American carbon cycle is highly influenced both directly and indirectly by urban development patterns, and future efforts to reduce carbon emissions require an accurate model of the carbon storage and flux in these settings (Pataki et al. 2006).

While much is known about the effects on soil organic carbon (SOC) dynamics from transforming natural ecosystems (forests, grasslands, wetlands) to agricultural systems (Lal 1998) and reversion to unmanaged forest (Post & Kwon 2000), little is known about the long-term effects of conversion to urban land uses. Yet enhancement of SOC in urban soils has the potential to provide direct and indirect benefits to urban inhabitants, including increased productivity of vegetation, enhanced pollution remediation, and reduction of air pollutants (Lal 2004). Therefore, understanding the factors affecting carbon gains or losses caused by transforming natural ecosystems to urban landscapes and by post-development management practices is critical to conservation of the SOC resource.

Conversion of non-urban lands to urban uses is occurring on global and local scales, increasing the impact of urbanization on carbon cycling and other ecosystem processes. The amount of urban land area in the United States is currently greater than 3% (US Census 2002), and is projected to increase from 2.5% in 1990 to 8.1% by 2050 (Nowak 2006). In Virginia alone from 2001 to 2007 nearly 500,000 acres of forest land was diverted to non-forest and the majority of that (63%) was due to losses to urban development (Rose 2009). Weir & Greis (2011) project that up to 23 million acres of forest may be converted to urban uses in the next fifty years. At present, 80% of Americans live in medium to high density urban and suburban areas, and this percentage is projected to increase (Carrerio 2008). Beyond major metropolitan areas, exurban development, or "rural sprawl", is an increasingly important land development pattern characterized as being distant from metropolitan urban centers, driven by natural amenities, and dominated by large residential parcels greater than one acre. Highly dispersed, low-density development now occupies 94 million acres (US Census 2002), which is 15 times more land area than higher density uses (Brown et al. 2005), and has large impacts on fragmentation of natural systems and alteration of ecosystem processes (Brown et al. 2005). Residential developments in rural areas often convert forest directly to intensively-managed ornamental landscaping, potentially having a significant effect on regional SOC. Forest soils and biomass are known to be an important carbon sequestering system (Curtis et al. 2002), and therefore, the effects of converting forest to residential landscapes on SOC and total carbon storage needs to be quantified.

Conversion of a native ecosystem to an urban development may cause an initial decline in C stocks, but post-conversion management could result in recovery and eventually increase the SOC mass beyond that of the native system (Pouyat et al. 2006; Pouyat et al. 2007; Pickett et al. 2008). SOC is a function of additions of soil organic matter due to net primary production (NPP), and losses due to microbial respiration (Hr), and both NPP and Hr are dependent on moisture and temperature. Therefore, native SOC concentration is geographically variable due to differences in climate and ecosystem. Quantifying gains or losses due to urban transformation must account for (1) SOC characteristics of the background ecosystem, (2) modifications to SOC that occurred during development, and (3) post-development cover type and management intensity (Pouyat et al. 2009).

Of the numerous cover types found in urban areas (turfgrass, remnant forest, urban tree canopy, impervious surface, wetland), turfgrass is a prominent feature due to its abundance and management intensity. It is estimated that there are 163,800 km^2 (± 35,850 km^2) of managed turfgrass lawns in the United States (Milesi et al. 2005; Brown et al. 2005), and private residential lawns account for 80% of this managed lawn area (Borman et al. 2001). Turfgrass management inputs (e.g. irrigation, fertilization, mowing, pesticides) aimed at improving turf appearance and health consequentially increase net primary productivity, resulting in a high rate of root turnover and leaf clipping addition (Qian & Follett, 2002). Although residential lawns receive inputs similar to agricultural systems, they are disturbed less frequently, thereby minimizing losses of SOC (Kaye et al. 2006). Turfgrass is a carbon sequestering system (Qian & Follett 2002), although emissions associated with management (mowing, fertilizer use) may more than offset sequestration value when these losses are included in the carbon budget for turf systems (Jo & McPherson, 1995).

Various studies of turfgrass in golf courses and residential areas have estimated mean carbon densities of 10-15 kg m^{-2} (1-m depth) in turfgrass (Qian & Follett 2002, Pouyat et al. 2006, 2009). Carbon is sequestered at rates of up to 1 t ha^{-1} year^{-1} under high intensity management, and will accumulate for 30-50 years until a steady state between gains and losses has occurred (Qian & Follett 2002, Bandaranayke et al. 2002). Due to intensive management to improve lawn growth and appearance, SOC concentrations found in urban residential areas across the United States vary on a smaller magnitude than unmanaged natural ecosystems (Pouyat et al. 2006). Pouyat et al. 2009 found that urban residential soils in Baltimore, MD and the arid region of Denver, CO have similar SOC densities, while SOC density of the native forest in Baltimore had 60% higher SOC in the 0-20cm depth than in the short grass steppe soil found in Denver. Research findings from golf courses along with regional comparisons have established the background for the effects of converting native vegetation to turfgrass lawn vegetation, but do not adequately explain effects of management and intraregional variability (Milesi et al. 2005; Qian et al. 2003).

Previous studies of urban SOC have established the basic factors affecting carbon storage and flux in turfgrass ecosystems (Bandaranayke 2003; Milesi 2005; Qian & Follett 2002) as well as quantified SOC densities found in residential urban areas (Pouyat et al. 2002, 2003, 2006, 2009; Pataki et al. 2006). However, there has been no study that has investigated the relationship between homeowner management practices and SOC densities and SOC accumulation rates. Given that the rate at which urban ecosystems store or emit C following conversion depends largely on human choice and the effects of individual practices implemented at a parcel scale (Pickett et al. 2005; Kaye et al. 2006; Pataki et al. 2006), connecting SOC to management intensity and component management practices is key to understanding the variability of SOC within the turfgrass cover type.

Therefore, the goal of this study was to (i) compare the SOC to a depth of 30-cm (increment depths of 0-5 cm, 5-10 cm, 10-20 cm, 20-30 cm) in lawn and adjacent forest landscapes, (ii) estimate the soil CO_2 efflux in both lawns and adjacent forest, (iii) determine site factors which may relate to soil carbon accumulation and CO_2 efflux (e.g. bulk density, nitrogen density, slope, aspect, tree basal area), and (iv) survey the property owners regarding management practices applied and the age of their property in order to measure the effect of these management factors.

3.2. Materials and Methods

3.2.1. Site Selection

The scope of this study was exurban, residential, turfgrass-dominated landscapes established on previously mixed-oak forested lands in the valley and ridge physiographic province of southwest Virginia. The experimental unit was defined as a single-family residential parcel that possessed a substantial turfgrass lawn (>75m^2) and was situated adjacent to native forest from which it was developed. Potential study sites were identified by visually surveying tax parcel boundaries overlaid on aerial imagery of exurban residential areas in Montgomery and Roanoke County, VA. Average annual precipitation in the study area is 106 cm, with mean annual temperature of 11.9°C. Average frost-free period is 117 to 185 days. Being at higher elevations in the valley and ridge province, soils are of shale, siltstone, and sandstone residuum, often with significant coarse fragments and shallow depths to bedrock (as shallow as 20-cm) . Forest soils were of well-drained silt loam texture to 10-20 cm depth, with increase in clay content at lower depths. PH ranges from 4.8 -5.2, and organic matter from 2-3%. Most common soil series represented include Berks-Weikert and Tumbling Urban Land Complex. Forests consist mainly of oak (*Quercus alba* L., *Quercus prinus* L., *Quercus velutina* Lam., *Quercus coccinea* Muenchh.) with some hickory (*Carya glabra* Mill)., *Carya alb*a (L.) Nutt.), red maple (*Acer rubrum*), and tulip tree (*Liriodendron tulipifera*) forming the canopy, with dogwood (*Cornus florida* L.), sourwood (*Oxydendrum arboretum* (L.) DC.) and blackgum (*Nyssa sylvatica* Marsh.) often found in the mid-story, vaccinium species and mountain laurel

(*Kalmia latifolia* L.) understory, with infrequent downy rattlesnake plantain (*Goodyera pubescens* (Willd.) R. Br.) in an otherwise sparse herbaceous layer. Average stand age was ~100 years, with mean basal area of 10.7 m^2/ha (Table 3.1).

Homeowner contact information was obtained from tax parcel public records, and recruitment letters were sent to owners of parcels that appeared suitable for the study. The recruitment letter included a document outlining the purpose of the project and requesting participation, a response card, and a postage-paid return envelope. Of 325 letters sent, 147 residents responded that they were willing to participate, 26 indicated that they did not wish to participate, and the remaining 152 letters were not returned, a response rate of 53%. Parcels for which the current owner could not account for lawn care practices for a minimum of five years were immediately disqualified from the candidate pool. Once the list of candidate parcels was compiled, a field survey was conducted to determine the suitability of individual parcels for inclusion in the study.

Criteria for parcel selection included extent of lawn area, proximity to remnant forest, and degree of disturbance of the native land form. The confounding nature of variable site development effects was minimized by sampling sites or portion of the lawn where there appeared to have been minimal modification of the natural landform (Figure 3.1). Identification of such sites required finding areas where the contour of the land under the lawn matched the contour of the surrounding forest, indicating that only the forest O-horizon had been altered followed by grass seeding upon the residual O- or A-horizon. This determination was facilitated on many parcels by the presence of remnant forest trees whose trunk flair exposure served as a visual gauge to the extent of soil cutting and filling that had occurred during site development. Based on these criteria, 64 parcels out of 147 were selected for the study (Table 3.2).

Table 3.1. Tree measurement data for forest and lawn areas grouped by subdivision. Each value is the mean of all sample plots for each landscape type within each subdivision.

Subdivision (n)	Basal Area (m^2/ha)	Tree Height (m)	Trees Per Hectare	Basal Area of Most Common Species (m^2/ha)
Brush Mountain				
Forest (5)	13	23	89	Quercus alba (10.1); Q. prinus (1.2); Q. coccinea (1.0)
Lawn (5)	2	20	36	Q. prinus (3.4); Q. alba= (0.9); N. sylvatica (0.1)
Cherokee Hills				
Forest (4)	13	24	111	Acer rubrum (3.2); Q. prinus (2.7); N. sylvatica (1.7)
Lawn (4)	9	18	40	Q. alba (14.1); Q. prinus (7.5); Carya alba (0.6)
DeerCroft				
Forest (5)	15	24	69	Q. prinus (8.8); Q. alba (2.7); C. alba (1.5)
Lawn (5)	9	22	55	Q. prinus (0.4); Q. alba (1.2); C. glabra (2.0)
Forest Hill				
Forest (2)	14	25	53	Q. alba (8.9); Q. rubra (2.2); Liriodendron tulipifera (2.6)
Lawn (6)	9	25	41	Q. alba (1.3); Q. rubra (0.2); L. tulipifera (0.9)
Glenvar Heights				
Forest (8)	4	25	75	A. rubrum (1.4); Q. alba (0.9); Q. coccinea (0.5)
Lawn (11)	3	25	51	Q. rubra (0.4); Q. alba (2.2); Q. prinus (0.2)
Laurel Ridge				
Forest (14)	13	21	113	Q. prinus (4.6); A.rubrum (2.3); Pinus rigida (2.0)
Lawn (14)	10	19	86	Q. prinus (3.5); Q. rubra (1); N. sylvatica (0.4)
Mossy Spring				
Forest (2)	8	27	81	Q. alba (2.5); C. alba (0.4); Q. rubra (0.2)
Lawn (3)	6	25	58	L. tulipifera (1.2); C. alba (0.4); Q. alba (0.8)
Oilwell Road				
Forest (8)	8	23	109	A. rubrum (1.9); Q. prinus (1.4); Q. alba (1.4)
Lawn (8)	5	20	75	Q. alba (1.2); A. rubrum (0.8); Q. rubra (0.2)
Preston Forest				
Forest (5)	10	23	101	Q. prinus (5.1); Q. coccinea (1.2); Q. alba (1.04)
Lawn (6)	7	19	30	Q. prinus (3.0); A. rubrum (1.8); Q. alba (1.8)
Entire Study Area				
Forest (57)	11	24	89	Q. alba (3.2); Q. prinus (2.4); A. rubrum (0.8)
Lawn (64)	7	21	52	Q. alba (1.6); Q. prinus (1.2); A. rubrum (0.2)

Figure 3.1. Typical lawn sampling site adjacent to forest, where the grade of the lawn matches that of the residual forest and root flares of trees indicate that no fill was added.

Table 3.2. Characteristics for 64 parcels included in the study.

	Min.	**Mean**	**Max.**
Parcel Size (Hectares)	0.728	1.7	3.76
Parcel Elevation (Meters)	366	640	838
Parcel Year Built	2005	1986	1958
Lawn Size (Square Meters)	100	200	800

3.2.2. Plot Selection

Placement of lawn and forest plots on each parcel required finding areas that were representative of the prevailing landscape and minimal influenced by attributes of the adjacent land use (e.g. forest tree roots growing into the lawn, yard waste stockpile areas in the forest). Major considerations when establishing the lawn measurement plot included the proximity to the house (where maximum levels of soil profile disturbance likely occurred), septic field, impervious surfaces, and forest edge (minimum of 4 meters from plot center). When positioning the forest plot, the forest area around the house was carefully observed in order to identify a representative forest area that was undisturbed. Areas where yard waste (e.g. leaves) had been raked into the adjacent forest edge and areas where the forest had been managed for aesthetics by clearing and thinning of the understory were avoided during plot placement. In most instances, the forest plot was situated at the same aspect, elevation, and slope position as the adjacent lawn plot.

3.2.3. Field Measurements

A total of 64 parcels were sampled between May and July 2010. Two measurement plots were established on each parcel: one in a representative region of turf grass and one in the adjacent forest remnant. At the plot center of each lawn and forest plot, four sequential soil cores (0-5 cm, 5-10cm, 10-20 cm, and 20-30 cm depth) measuring 5 cm in diameter were collected using a slide hammer sampler for measurement of soil bulk density (figure 3.2). Samples were placed into bags and stored for later processing in the lab. Next, a 3-cm diameter push-tube sampler was used to collect four soil subsamples 1 meter away from the plot center in the cardinal directions. Each subsample was sub-divided into four sequential depths (0-5 cm, 5-10 cm, 15-20cm, and 25-30 cm). The four subsamples for each depth interval were mixed on site and stored for later processing of C and N in the lab. Two measurements of soil CO_2 efflux, temperature, and moisture were taken within 1 meter of plot center using a thermocouple, TDR (Time Domain Reflectometry), and Li-COR 6200. A fixed area (1/50 hectare) plot was situated at each plot center and all trees greater than 5 cm in diameter were tallied by species and trunk diameter. In lawns, trees were categorized as residual forest trees or transplanted landscape trees.

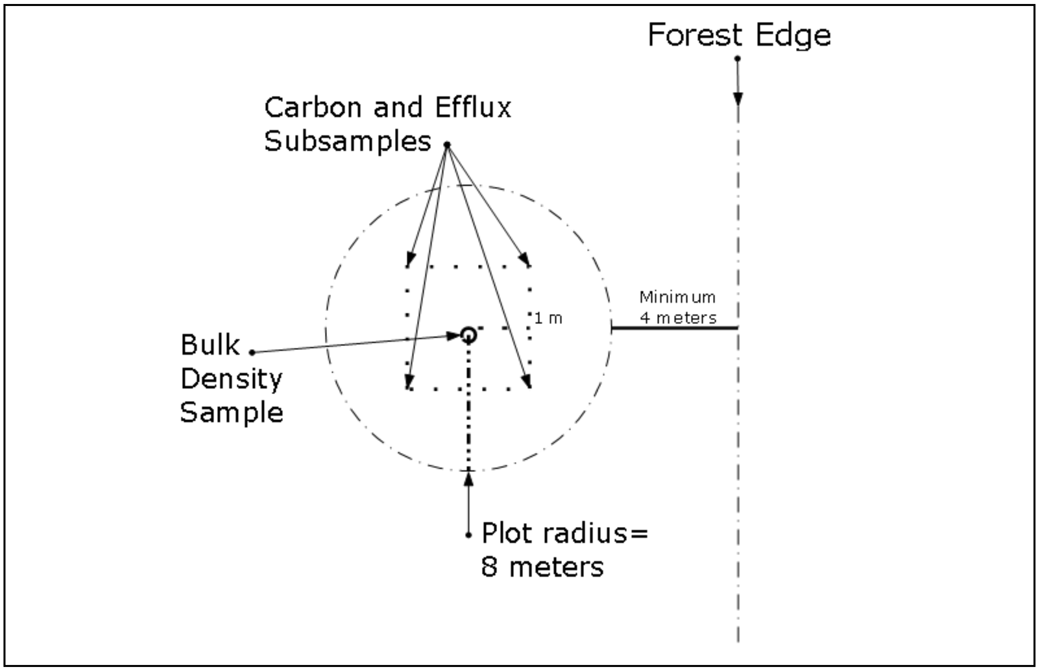


Figure 3.2. Sampling design used at each site to measure both forest and lawn variables. The plot was established 4 meters or more from the forest edge for the lawn measurements, and 4 meters or more from the lawn edge for the forest measurements listed in the text.

In addition to collecting soil samples, potentially influential site variables were measured at each plot for later use in statistical analyses (Appendix B: Data Collection Sheet):

- Distance and azimuth to the dripline of nearest tree(s) in the lawnscape
- Height of nearest trees
- Distance and azimuth to the house
- Slope aspect
- Slope grade
- Distance and azimuth to the septic field
- Turf grass density (low density with bare spots, medium density no bare spots, high density)

Two subsample measurements of soil CO_2 efflux were taken in the forest and lawn plots at each site. On seven parcels, a single forest remnant was sampled only once for several adjacent lawns. In these cases the forested areas were between several adjacent lawns and had similar aspects and slope. In the vicinity of the original lawn plot center, two efflux measurement sites (15-cm diameter circular area) were prepared by pruning of turf stubble down to the soil surface in order to minimize effects of respiring grass leaf surfaces. Once the surface was prepared, an efflux measurement was taken using the Li-COR 6200 (LiCor Inc., Lincoln, NE). Measurements were taken as described by Gough and Seiler (2004) to obtain total CO_2 efflux with the exception of the cuvette size. A Li-Cor model 6000-09S cuvette was used with a volume of 926.0 cm^3 covering 71.5 cm^2 of soil surface.

3.2.4. Laboratory Measurements

Bulk density samples were first oven dried (105°C) for 24 hours, then run through a 2-mm sieve to remove coarse woody and mineral fragments. Total mass of sieved soil coarse fragments was then recorded. The homogenized subsamples taken with the push tube sampler were air dried for 24 hours, passed through a 2-mm sieve, and hand-sorted to remove visible root fragments using tweezers. The 1 gram samples were then placed in a 105°C drying oven for at least 24 hours prior to being analyzed for carbon and nitrogen content using a CNS analyzer (Vario Max Model, Elementar Americas, Trenton, NJ). A portion of the homogenized subsample from the 0-10cm depth were sent to the Virginia Tech soil testing lab for standard analysis of pH, CEC, soluble salts, and extractable nutrients (P, K, Ca, Fe, B, and Al).

3.2.5. Survey of Lawn Management Practices

Each participant was surveyed to document lawn management practices. Participants had the choice of completing the survey on a website or on a paper form. The survey first asked a series of questions regarding the homeowner’s lawn care practices, including questions about fertilization, irrigation, and aeration frequency and intensity (Appendix A). The purpose of identifying lawn care practices that have been used over time is so that relationships can be established between those practices and SOC contained in the lawn where the specific regime has been utilized.

3.2.6. Data Analysis

All statistical analyses were performed using JMP 9 software system (SAS Institute, Cary, NC). For variables that were subsampled (e.g. soil C), the mean of the subsamples were used as the experimental unit. Simple linear and multiple linear regression techniques were used to analyze relationships between continuous independent and dependent variables. One-way analysis of variance (ANOVA) was used to test hypotheses of categorical independent variable effects on continuous dependent variables, including tests of covariates thought to influence experimental error. To meet model assumptions of normality and homogeneity of variance, dependent variables were transformed where needed prior to analysis. Transformations of independent variables were also tested in regression analyses to improve model fit and coefficient of determination.

Soil Carbon Content Analysis

Step-wise regression analysis, using mixed direction selection with p-value requirement of 0.25 was used to examine relationships between lawn soil carbon content and a range of independent, parcel-level variables including time since land conversion, lawn management intensity (e.g. fertilization, clipping management), and site characteristics (e.g. aspect, temperature, moisture). Paired t-tests were used to compare carbon, nitrogen, and bulk density between adjacent forest and lawn. SAS (SAS Institute Cary, NC)

Soil CO_2 Efflux Analysis

Step-wise regression analysis was used to determine the relationship between CO_2 efflux rates, environmental variables (management variables in the lawn), and soil variables.

Additionally, analyses of covariance were conducted to identify interactions between treatment effects and other variables.

3.3. Results

3.3.1. Carbon Storage in Lawns and Adjacent Forest

Percent carbon in forest soils was higher at the 0-5cm ($P<0.0001$) and 5-10cm ($P=0.0014$) depths, while lawn soil had greater percent carbon at the 20-30cm depth ($P=0.0125$) (Fig 3.3). There was a positive relationship between percent carbon in the lawn and time since development at the 0-5 cm depth ($P=0.04$) (Fig. 3.4). Total soil carbon content to 30 cm depth of lawn (6.5 kg C/m^2) and forest (7.1 kg C/m^2) marginally differed ($P=0.08$); however, lawn soil contained significantly greater C than forest soil at the 20-30 cm depth (0.010 vs. 0.007 g C/cm^3, $P=0.0137$), (Fig. 3.5).

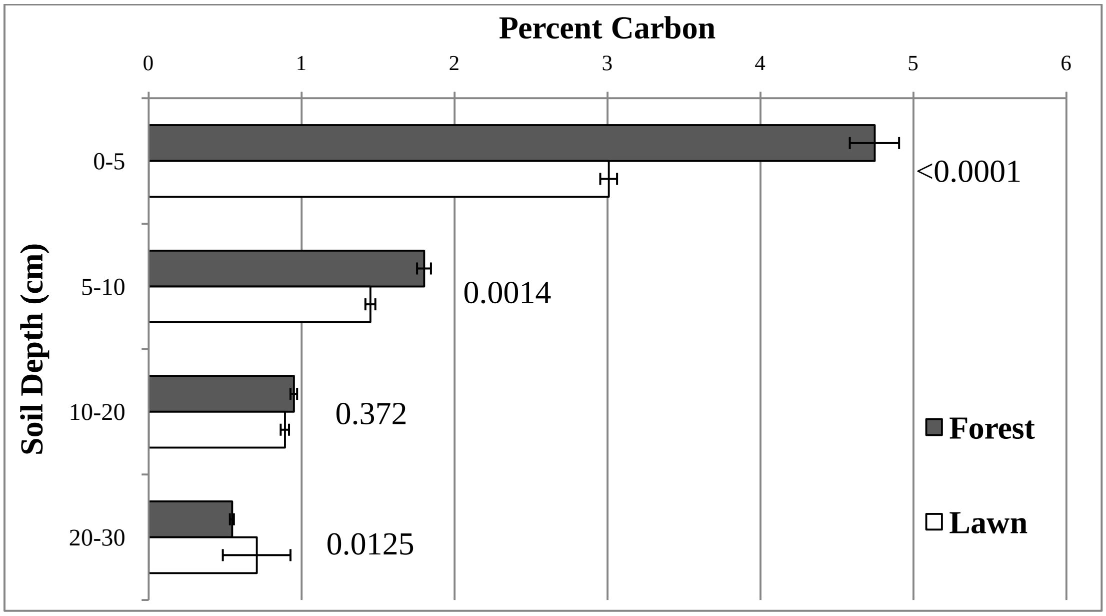


Figure 3.3. Percent soil carbon at four depths in mixed oak forests and adjacent areas converted to lawns in the valley and ridge physiographic province of southwest Virginia. P-values are indicated to the right of each comparison.

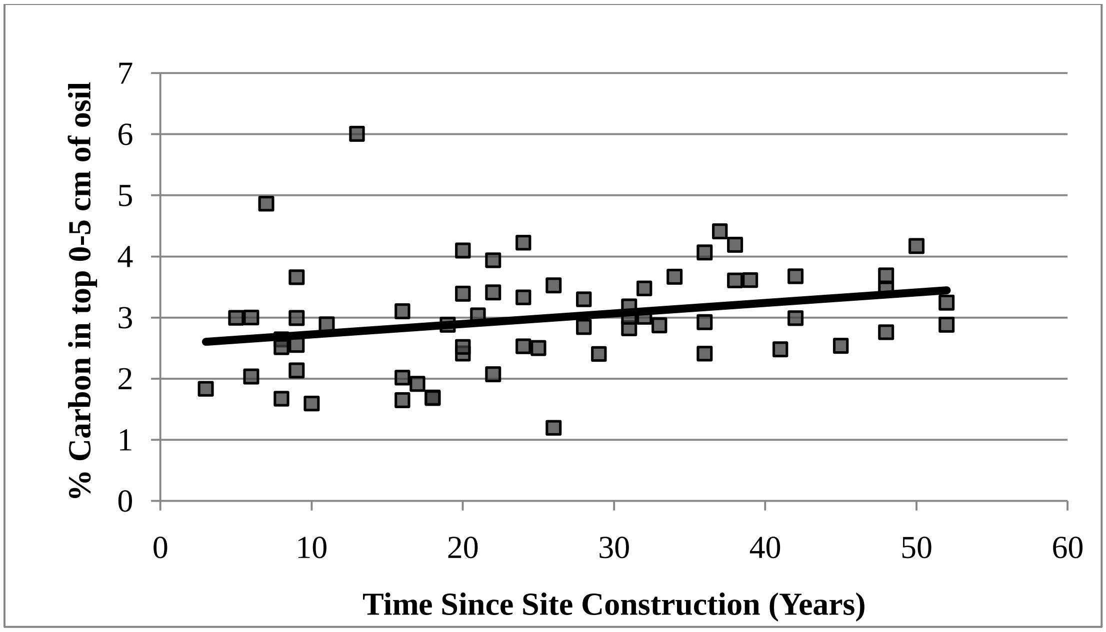


Figure 3.4. Relationship between percent carbon in the upper 0-5 cm of lawn soil compared with time since site construction (P=.04). Relationships at deeper depths were not significant.

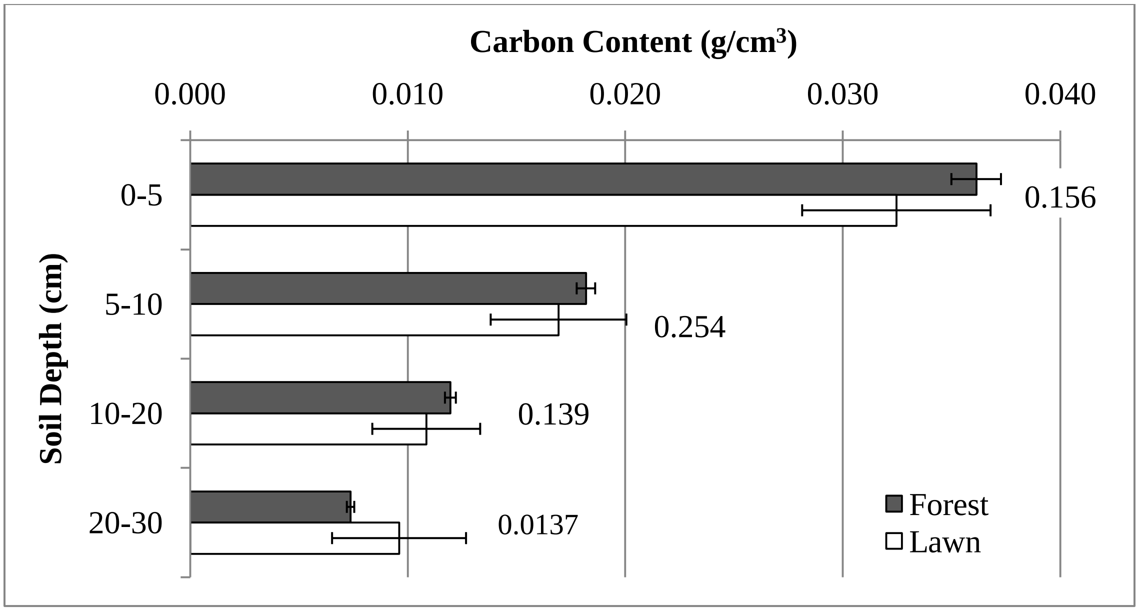


Figure 3.5. Carbon content at four depths in mixed oak forests and adjacent areas converted to lawns in the valley and ridge physiographic province of southwest Virginia. P-values are indicated to the right of each comparison.

In lawns, there was a significant positive relationship between fertilization frequency and carbon content at the 0-5cm depth (P=0.0005) (Figure 3.6).

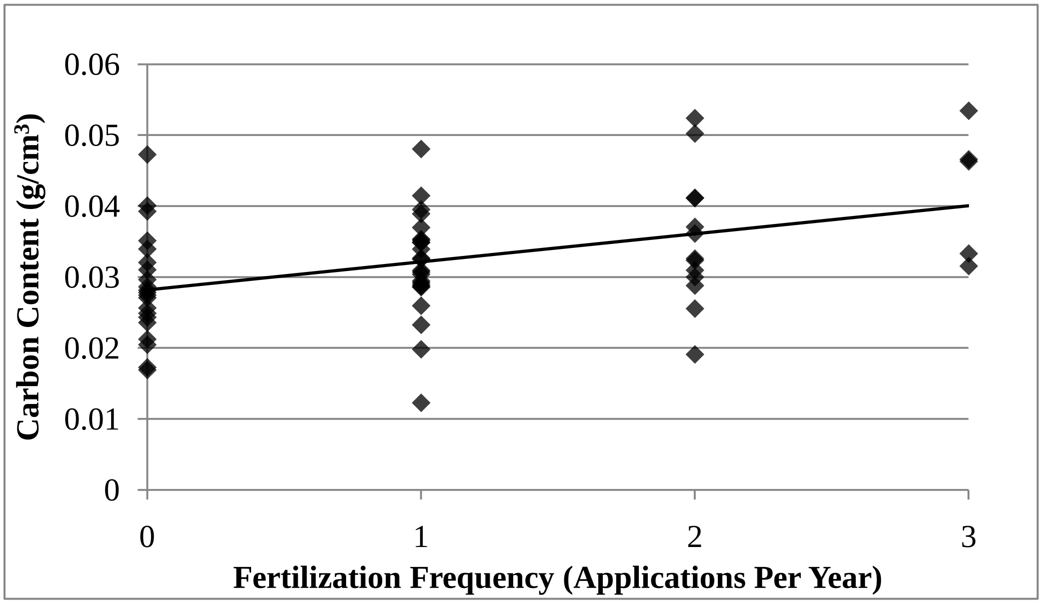


Figure 3.6. Relationship between fertilization frequency (applications per year) reported by homeowners and carbon content (g/cm^3) in the top 0-5 cm of soil (P=0.0005).

Management intensity (an index based on frequency of lawn fertilizer and pesticide application reported by homeowners) was not found to be a significant predictor of carbon content (P=0.35), nor were slope, aspect, parcel age, or soil pH significant covariates. The relationship between carbon content in lawn soil and parcel age was weak across all depth intervals. There was a marginal positive relationship at the 0-5cm depth (P=0.12) and a marginal negative relationship at the 20 -30cm (P=0.08).

3.3.2 Nitrogen Storage in Lawns and Adjacent Forest

Percent nitrogen did not differ between forest and lawn soil except at the 20-30cm depth, where lawn contained higher percent nitrogen (P=.021, Fig. 3.7). Lawn soil had significantly greater nitrogen content than forest soil at depths 0-5cm (P<0.001), 5-10cm (P<0.001), and 20-30cm (P=0.046), (Figure 3.8).

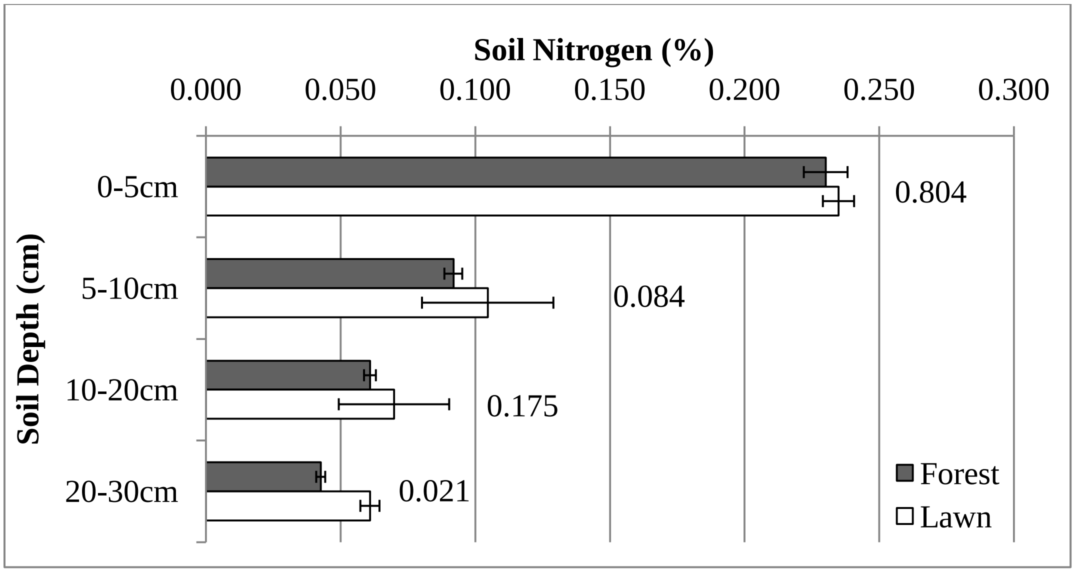


Figure 3.7. Percent soil nitrogen at four depths in mixed oak forests and adjacent areas converted to lawns in the valley and ridge physiographic province of southwest Virginia. P-value is indicated to the right of each comparison.

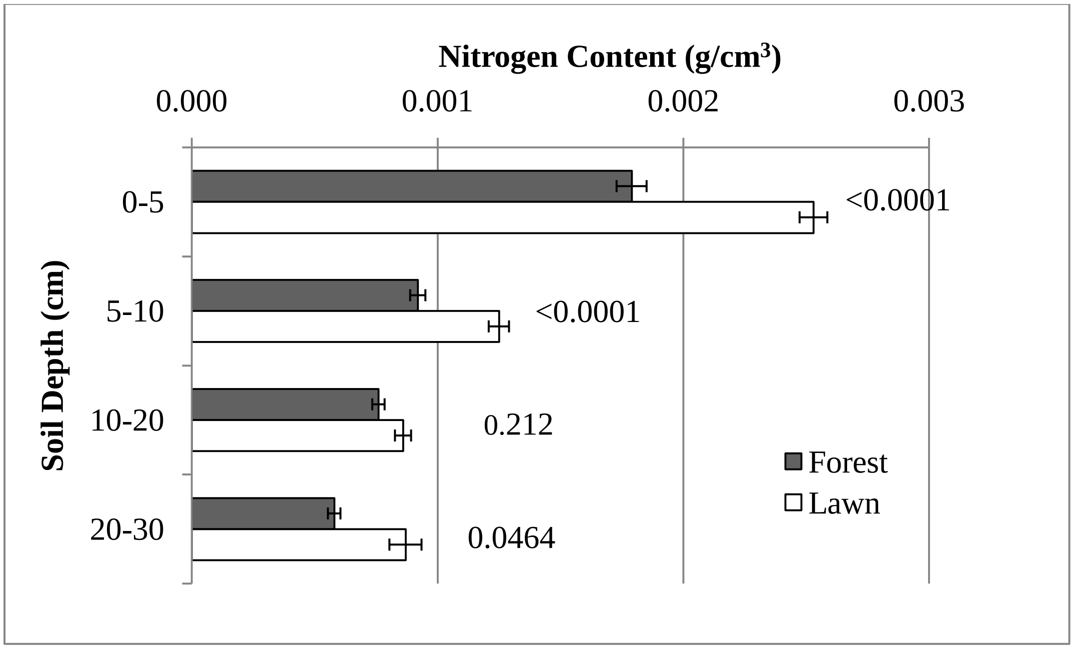


Figure 3.8. Nitrogen content at four depths in mixed oak forests and adjacent areas converted to lawns in the valley and ridge physiographic province of southwest Virginia. P-value is indicated to the right of each comparison.

The relationship between nitrogen content in lawn soil and parcel age was weak across all depth intervals, except the 0-5 cm depth. There was a significant positive relationship between property age and nitrogen content at the 0-5 cm depth (P=0.015) (Figure 3.9), and a marginal negative relationship at 20-30cm depth (P=0.08). There was also a marginal positive relationship between fertilization frequency and nitrogen content (P=0.0734) at 0-5cm depth (Figure 3.10).

Figure 3.9. Relationship between property age (years since property development) and nitrogen content (g/cm^3) in the top 0-5 cm of lawn soil (P=0.015).

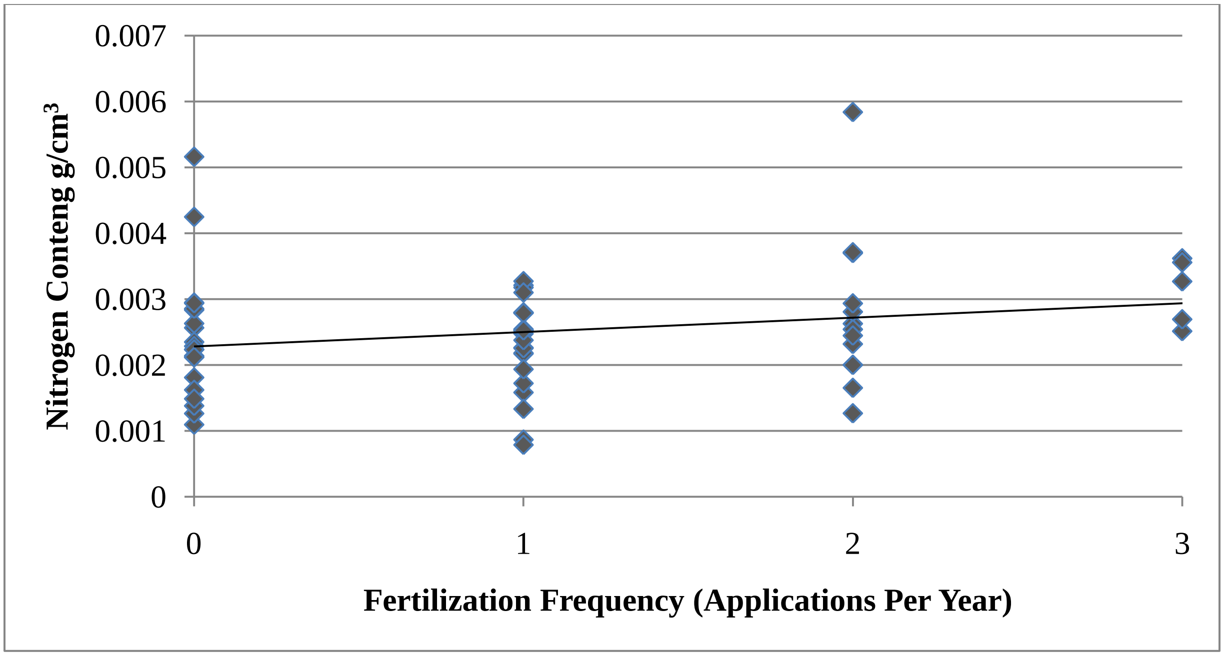


Figure 3.10. Relationship between fertilization frequency (applications per year) reported by homeowners and nitrogen content (g/cm3) in the top 0-5 cm of lawn soil (P=0.0734).

3.3.3. Other soil and turf variables

Fertilization frequency reported by homeowners showed a strong positive correlation with turfgrass density (P=0.0003). Forest soil had a significantly higher CN ratio than lawn soil at all depth intervals except 20-30 cm. Lawn soil had significantly higher bulk density at 0-5 cm and 5-10cm depths, but did not differ at deeper depths (Table 3.3) There was a positive relationship between forest carbon density and nitrogen content at 0-5cm depth (P=0.05), a positive relationship between carbon density and CN ratio (P<0.0001) and nitrogen content (P=0.05) at 5-10 cm depth, a positive relationship between carbon content and CN ratio at 10-20cm depth (P<0.0001), and a positive relationship between carbon content and CN ratio (P<0.0001), nitrogen density (P=0.03), bulk density (P=0.005), and pH (P=0.04) at the 20-30 cm depth.

Table 3.3. Comparisons of Carbon-Nitrogen ratio and Bulk Density measured at four soil depths in mixed oak forests and adjacent areas converted to lawns in the valley and ridge physiographic province of Virginia.

	Carbon/Nitrogen Ratio				**Bulk Density (g/cm^3**			
Depth (cm)	**N**	**Forest**	**Lawn**	**p value**	**N**	**Forest**	**Lawn**	**p value**
0-5	62	21.8	13.6	<0.0001	64	0.81	1.10	<0.0001
5-10	62	22.4	14.9	<0.0001	63	1.02	1.18	<0.0001
10-20	61	18.4	14.5	0.0002	59	1.26	1.26	0.97
20-30	55	14.3	13.5	0.3845	44	1.37	1.40	0.65

3.3.4 Effect of Site Variables on CO2 Efflux

Step-wise regression analysis of multiple soil and landscape variables derived a model explaining 51% of observed variation in forest soil CO_2 efflux. Forest soil CO_2 efflux was positively affected by aspect (P=0.042), soil temperature (P=0.0004), and soil moisture (P<0.0001), and negatively affected by bulk density (P=0.0027) (Table 3.4). Aspect azimuth measured in degrees was transformed using Beers Transformation (Beers et al. 1966), where degrees are assigned to a number ranging from 0.00-2.00, where 0 is southwest (the hottest, driest aspect) and 2 is northeast (the coolest, most moist aspect). Therefore, forest soil CO_2 efflux was higher at azimuths closer to northeast. In lawns, soil CO_2 efflux was positively affected by the CN ratio (P=0.0012), nitrogen content (P=0.0902) of the top 0-5 cm of soil, soil temperature (P=0.047), and soil moisture (P=<0.0001). The overall regression explained 43% of the variation in lawn soil CO_2 efflux (Table 3.5). Management intensity (combined effects of fertilizer and pesticide level) had no effect on lawn soil CO_2 efflux (P=0.4302), nor did fertilization frequency (P=0.3438). Slope, age, and aspect were likewise found not to be significant predictors of lawn efflux in the presence of other variables. Figure 3.11 shows predicted soil CO_2 efflux for forest (panel A) and lawn (panel B) plotted with the actual data.

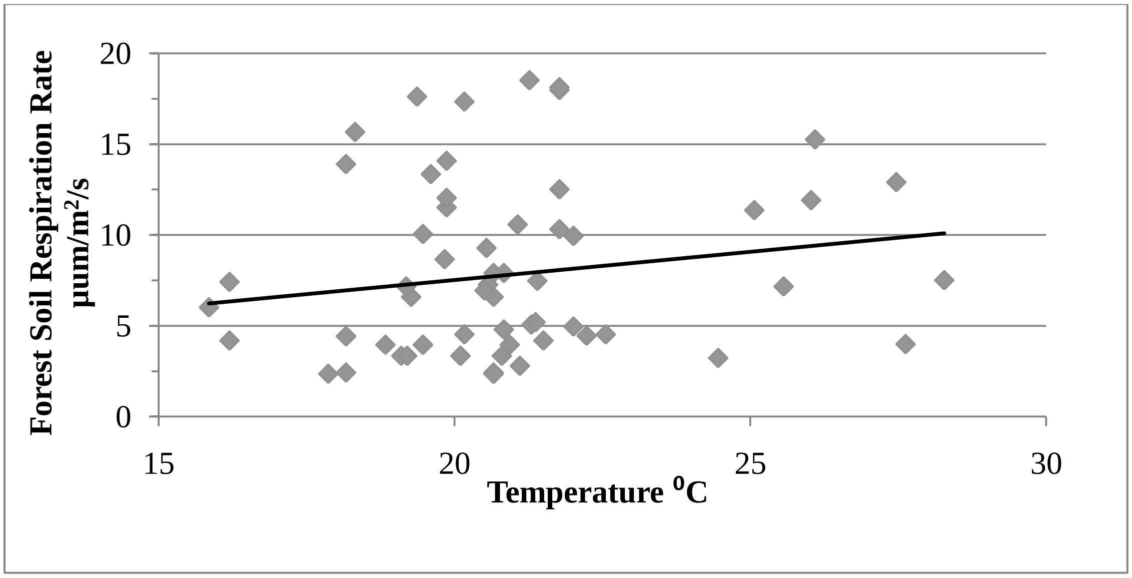
The effect of temperature on respiration was relatively the same in the lawn and forest soil, with lawn temperatures slightly higher probably due to the effect of less shading from trees.

Table 3.4. Regression parameter estimates, standard errors and test of significance for forest soil CO_2 efflux model.

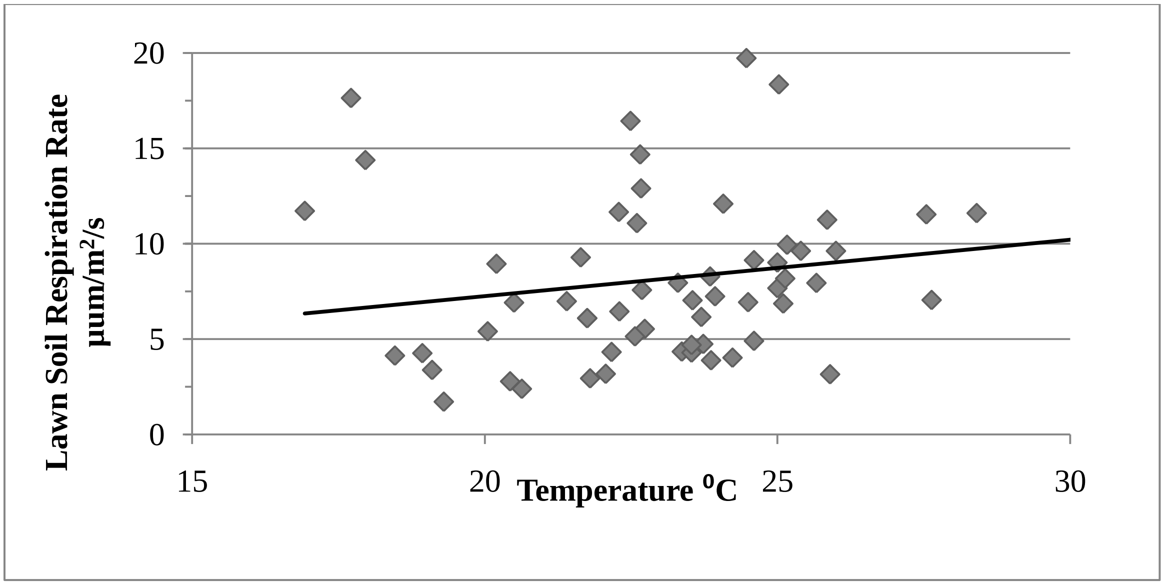
Forest Soil CO_2 efflux (μmol/m²/s)				
Term	N	Parameter Estimate	Std Error	Prob>|t|
Intercept	64	0.205	0.522	0.6954
Soil Moisture	64	0.044	0.010	<0.0001
Soil Temperature	64	0.082	0.022	0.0004
Bulk Density (0-5cm)	64	-0.897	0.286143	0.0027
Aspect	64	0.177	0.085141	0.0422
Model	R^2=0.51			

Table 3.5. Regression parameter estimates, standard errors and test of significance for lawn soil CO_2 efflux model.

Lawn Soil CO_2 efflux (μmol/m²/s)					
Term	N	Parameter Estimate	Std Error	t Ratio	Prob>|t|
Intercept	62	2.220	0.37	6.06	<0.0001
N Density (0-5 cm)	62	130.027	75.42	1.72	.0902
CN Ratio ^{2} (0-5 cm)	62	0.002	0.000607	3.41	0.0012
Aspect (Square root)	62	-0.042	0.0.019	-2.19	0.0329
Soil Temperature (Exp)	62	2.621e-13	1.3e-13	2.04	0.0465
Soil Moisture (Recip.)	62	-5.778	1.28	-4.30	<0.0001
Model	R^2=0.43				



PANEL A: Forest Soil Respiration



PANEL B: Lawn Soil Respiration

Figure 3.11 Predicted forest soil CO_2 efflux (panel A) and lawn (panel B) using models from table 3.4 and table 3.5 plotted with actual data as affected by soil temperature. All other variables in the models were held at the averages for the study and temperature was allowed to vary across the range of observed values. Forest regression equation y=0.0445(Soil Moisture) + -0.8968(Bulk Density 0-5 cm) + 0.1768(Aspect) + 0.082(Soil Temp.). Lawn regression equation y=130.027(N Density 0-5cm) + 0.002(CN Ratio^2 0-5cm) + -.042(√Aspect)+2.621e-13(Soil Temp. Exp.)+-5.778(1/Soil moisture).

3.4 Discussion

Total soil carbon content to 30 cm depth of lawn (6.5 kg C/m^2) and forest (7.1 kg C/m^2) marginally differed (P=0.08); however, lawn soil contained significantly greater C than forest soil at the 20-30 cm depth (0.010 vs. 0.007 g C/cm^3, P=0.0137). These results support previous comparisons by Pouyat et al. (2006, 2009), and Raciti et al. (2011) that found comparable levels of soil organic carbon in lawns and nearby forests in the northeastern and mid-Atlantic U.S. The difference in depth distribution between forest and lawn is supported by Pouyat et al. (2009), where nearby forest soil was found to have a greater proportion of carbon in the top 20cm than residential lawns, lawn carbon being more evenly and distributed across deeper depths. This deeper distribution of carbon in turf systems is attributed to the deeper soil depths attained by fine root mass in managed turf grass as well as natural grassland systems than by fine tree roots in a forest setting (Jobaggy & Jackson 2000). During sample collection, grass roots were observed to depths of up to 30-cm, while fine tree roots were concentrated in the top 10-cm (Oa and upper A horizons).

Given that there was a relationship between percent carbon and time since development in lawn soils at the 0-5 cm depth (P=.04), but no significant trend between carbon content and time, bulk density may have affected comparisons of carbon content and time at this depth and the 5-10cm depth. Higher bulk density measurements may have interacted with carbon content calculations. Raciti et al. 2011 also observed lack of significant carbon accrual trend with property age in parcels transformed from forest. Compaction in the upper 0-10 cm of lawn, which likely resulted from site development, also impacted comparisons of forest and lawn carbon content. Lawns had significantly lower carbon percentages than forests at 0 – 10 cm but due to their significantly increased bulk density carbon content did not differ from forests. At similar temperatures and moistures, soil CO_2 efflux rates differed little between forests and lawns. Despite management intensity and fertilization frequency having significant effects on lawn characteristics (e.g. turfgrass density, carbon content) they did not significantly influence total soil CO2 efflux. Studies of forests (Gough & Seiler 2004) and grasslands (Johnson et al. 2005) have consistently found fertilization to have a negative effect on heterotrophic respiration. Perhaps autotrophic rates increased with increased turf rooting while heterotrophic rates decreased due to fertilization. However we did not separate hetrotrophic from autotrophic respiration in this study. There was no relationship between lawn soil CO_2 efflux rate (measured on a single date) and time since land development. Efflux rates varied widely based on current moisture, temperature, carbon, and CN ratio characteristics. These conditions vary day-to-day based on natural (rainfall, temperature) and human (time when mowing, fertilization, pesticide application occurs) factors. Therefore, using measurements from different days may have affected the comparison of respiration rates when environmental conditions were the same.

Based on the homeowner survey, we found a positive correlation between lawn fertilization frequency and both lawn nitrogen content (P=0.07) and lawn carbon content (P=0.0005) in the top 0-5 cm of soil. Singh 2000 observed the same phenomenon in a controlled lawn study where higher levels of fertilization resulted in a faster rate of soil organic carbon accrual in the top 0-6 cm. Fertilization enhances vegetation productivity and therefore, below ground C additions. Therefore, fertilization increases root respiration, and also impacts microbial respiration and biomass. The effect of fertilizer on soil respiration is well documented, and the timing of the last fertilizer application on lawns sampled likely impacted respiration rates. Gough & Seiler (2004) observed increased root respiration for 49 days following a fertilizer treatment in potted loblolly pine seedlings, while microbial respiration was depressed for that same time period. Bowden et al. (2004) observed the same phenomenon in a deciduous forest, with microbial respiration rates reduced by 41% during the growing season in fertilized plots. Therefore, our measurement of total soil respiration was likely confounded by the interaction of root and microbe respiration. Although total soil CO_2 efflux was not impacted by lawn management, it is possible that heterotrophic rates were decreased, leading to greater C accumulation over time. Another factor impacting nitrogen and carbon content, as well as respiration, in turf grass is the addition or removal of cut grass clippings, although a relationship was not identified in our study. Shi et al. 2006 observed elevated microbial respiration and N mineralization for 7 days following clipping addition before returning to background rates. Nitrogen content was greater in lawn than forest soil at the 0-5 cm depth (0.0025 vs. 0.0018 g/cm^3, $P<0.0001$), the 5-10 cm depth (0.0013 vs. 0.0009 g/cm^3, $P <0.0001$, and the 20-30cm (0.0009 vs. 0.0006 g/cm^3, $P=.046$). The higher nitrogen is probably the result of both fertilization and the N contained in dead fine roots.

We found little difference in soil carbon storage between unmanaged forest and residential turfgrass in the Valley & Ridge physiographic province of southwestern Virginia. Therefore, the soil component of the carbon sequestration value of residential turf grass developed on forest land is the same as the surrounding forest, and accounting for regional soil carbon stocks could consider these two types of land use equal. However, soil is only one reservoir in terrestrial ecosystems, with carbon also contained in above and below-ground biomass (plant and animal). Forest ecosystems of the United States contain approximately 52 billion metric tons of carbon, 59% in soils (to a depth of 1 m), 31% in trees, 9% in litter above soil surfaces, and 1% in understory vegetation (Birdsey, 1990). Jo & McPherson (1995) found that storage, turf grass stubble and roots accounted for 0.5-0.7% of carbon, trees and shrubs accounted for 10.6-20.8%, and soil storage accounted for 78.7-88.7% of total carbon stored in an urban residential area. Besides measuring the carbon uptake and loss associated with vegetation and soils, accounting for the carbon sequestration of a given land use includes measurement of carbon losses associated with management. Unmanaged forest land requires no management input while residential lawns are constantly maintained during the growing season. Management activities, including mowing and application of fertilizer and pesticides, result in direct and indirect emissions of CO_2. Jo & McPherson (1995) quantified carbon gains and losses associated with turf grass, and found that lawns return annually to the atmosphere 1-5 times the carbon sequestered due to mowing.

CHAPTER 4 – EFFECT OF HOMEOWNER ENVIRONMENTAL ATTITUDES ON LAWN MANAGEMENT PRACTICES AND SOIL CARBON AND NITROGEN

ABSTRACT

Conversion of native forests to turfgrass-dominated residential landscapes under a wide range of management practices results in dramatic changes to vegetation and soils, which may affect soil carbon storage. The specific practices (mowing, fertilizer, and pesticide application) implemented by homeowners potentially affect the rate of carbon sequestration and potentially cause other environmental effects (air and water pollution due to mowing and chemical application). To better understand the effects of lawn management on soil carbon and the potential drivers of practices implemented by homeowners, we conducted a study on residential properties in the Valley and Ridge physiographic province of southwest Virginia to measure soil carbon and nitrogen storage, as well as homeowner lawn management practices and environmental attitudes.

Sixty-four residential properties ranging from 5 to 52 years since site development were investigated. Soil samples were collected from lawns and adjacent forest stands to a depth of 30 cm and analyzed for carbon and nitrogen content. Homeowners participating in the study completed a survey on their lawn management practices so that the effects of specific practices (e.g. fertilization) and intensity levels on carbon dynamics could be analyzed. In addition to lawn care questions, the survey contained 11 questions about the homeowner's environmental attitudes.

There was a positive relationship (P=0.059) between overall environmental commitment score and level of management intensity. Higher environmental commitment (EC) score corresponded with a higher level of management intensity (fertilizer and pesticide use). EC scores were 5.63. 6.02 and 6.12 at the lowest, medium and highest management intensity cluster respectively (P=.077).

Although homeowners who perceive themselves as being more committed to the environment utilize more intensive management practices, there was no relationship between environmental commitment score and soil carbon metrics.

4.1 Introduction

The maintained turfgrass lawn concept dates back to 16th Century England and has been a major component of American urban landscapes since before the turn of 19th the century (Jackson 1985). Chemical fertilizers and pesticides along with gas-powered lawn mowers introduced to the public after World War II revolutionized monoculture turf grass production. At the same time, extensive suburbanization drove the expansion of turf area, and the lawn quickly came to represent the classic American leisure landscape (Robbins & Birkenholtz 2003). It is estimated that there are now 163,800 km^2 (± 35,850 km^2) of managed turfgrass lawns in the United States (Milesi et al. 2005; Brown et al. 2005), and private residential lawns account for 80% of this managed lawn area (Borman et al. 2001).

The popularity of turf grass in America results from its functionality as an erosion controlling ground cover and recreational surface that can withstand traffic. When non-urban lands (agricultural, native landscapes) are developed for urban uses, disturbed soil is seeded with grass or planted with sod upon construction completion in order to create a finished look and to control erosion. The lawn has thus become an aesthetic necessity as a component of modern landscape design, ubiquitous throughout developed areas of all types (residential, commercial, industrial, public). A lush monoculture of planted grasses with no broadleaf species has come to represent the ideal lawn. Maintaining such a manicured grassland, however, requires large amounts of management intervention in the form of mowing, weeding, and fertilization in order to stop the natural process of vegetation succession (aggradation to forest in the eastern United States) from occuring. Expanding lawn area along with growing expectations of the ideal lawn has resulted in a continuously expanding turf industry which is now valued at over $40 billion per year (USDA 2007). When compared with unmanaged native ecosystems, the management of turfgrass is uniquely intensive generating both positive (carbon sequestration, erosion control, reduction of heat island effect) and negative (emissions due to mowing, fertilizer and pesticide runoff, habitat loss) environmental effects.

Because the turfgrass lawn is entrenched in American landscape aesthetic preference, lawn quality has come to represent an important social value. In American neighborhoods, good lawns are associated with socially desirable resources such as wealth, education, property values, and the personal characteristics assumed to go with such resources (Weigert 1994). Zhou & Troy (2009) studied groups of private residential homes within a single watershed in Baltimore, MD and found that house value was positively correlated with lawn care expenditures and lawn greenness and that other lifestyle indicators (percent of population married, percent of population with children) were also important predictors of lawn care expenditures. In a survey of residential fertilizer use in the Balitmore region, Law et al. (2004) found that middle-level income households had the highest level of N fertilization. Potential linkages between socio-economic and psychological drivers of lawn management practices are in need of further exploration not only in terms of modeling carbon sequestration, but also for other environmental effects of lawn care, such as air and water pollution due to fertilizer and pesticide application (Milesi et al. 2005).

Growing public environmental awareness has sparked interest in sustainable landscape management and resulted in movements to manage lawns in a more environmentally-friendly manner or to reduce the area of lawn altogether (University of Minnesota Sustainable Urban Landscape Information Series, 2006). For example, the “Food Not Lawns” movement – based on the book of the same name by H.C. Flores (2006) – has established in many communities across the nation and is based on putting lawn space to more environmentally and socially friendly uses. Therefore, environmental awareness of lawn owners may impact the practices and products used on their land. Other social factors affecting lawncare include regional and neighborhood norms as well as subdivision requirements, and most importantly, media advertising.

Commercial advertising and public education campaigns present both positive and negative perspectives of lawns to consumers. Due to concerns about the adverse effect of runoff from residential lawns on water quality, Minnesota recently enacted a law (Minnesota Statutes 18C.60. Effective date 2005 statewide) which restricts the use of fertilizers with phosphorus unless a phosphorus deficiency was identified. This type of legislation is being considered in other communities across the nation. A law approved on March 22, 2011 in Virginia (HB 1831) proposes changing application rates displayed on bags of fertilizer sold in the state (http://lis.virginia.gov/cgi-bin/legp604.exe?111+sum+HB1831). Efforts such as banning phosphorus or changing application rate labeling are aimed at educating and changing the behavior of residential lawn consumers. At the same time, advertisements for lawn care services and products reinforce individual and group perspectives of what a lawn should be, resulting in an ever-increasing ideal of perfect grass. Lawn industry advertisements exploit the social assumptions of a good lawn through marketing that seeks to produce an association of community, family, and environmental health with intensive turfgrass aesthetics (Robbins & Sharp 2003). Therefore, the management actions of lawn consumers may be influenced by conflicting media from various sources.

In summary, the spatial distribution of lawn management intensities within residential land uses may be best explained by accounting for the many factors affecting the social phenomenon of lawn management: demographic distribution, location (e.g. subdivision with mowing requirements, rural home, cluster housing, urban area), media exposure, and environmental attitude of the parcel owner. For this project, we explored the connection between a homeowner's commitment to the environment, their management practices and soil carbon sequestered in their lawns. Our specific goals were to (i) identify relationships between the lawn management practices utilized by the homeowner and their environmental commitment, and (ii) identify any connection between a homeowner's environmental commitment and soil carbon and nitrogen sequestered under their lawn.

4.2. Materials and Methods

4.2.1. Site Selection

The scope of this study was exurban, residential, turfgrass-dominated landscapes established on previously mixed-oak forested lands in the valley and ridge physiographic province of southwest Virginia. The experimental unit was defined as a single-family residential parcel that possessed a substantial turfgrass lawn and was situated adjacent to native forest from which it was developed. Potential study sites were identified by visually surveying tax parcel boundaries overlaid on aerial imagery of exurban residential areas in Montgomery and Roanoke County, VA. Average annual precipitation in the study area is 106 cm, with mean annual temperature of 11.9°C. Average frost-free period is 117 to 185 days. Being at higher elevations in the valley and ridge province, soils are of shale, siltstone, and sandstone parent material, often with significant coarse fragments and shallow depths to bedrock (as shallow as 20-cm). Forest soils were of well-drained loam texture to 10-20 cm depth, with increase in clay content at lower depths.   Forests consist of oak (*Quercus alba* L., *Quercus prinus* L., *Quercus velutina* Lam., *Quercus coccinea* Muenchh.) and hickory (*Carya glabra* Mill)., *Carya alb*a (L.) Nutt.) forming the canopy, with dogwood (*Cornus florida* L.), sourwood (*Oxydendrum arboretum* (L.) DC.) and blackgum (*Nyssa sylvatica* Marsh.) often found in the mid-story, vaccinium species and mountain laurel (*Kalmia latifolia* L.) understory, with infrequent downy rattlesnake plantain (*Goodyera pubescens* (Willd.) R. Br.) in an otherwise sparse herbaceous layer. Average stand age was ~100 years, with mean basal area of 10.7 m^2/ha (Table 3.1).

4.2.2 Homeowner Survey

Each participant was surveyed to document lawn management practices. Participants had the choice of completing the survey on a website or on a paper form. The survey first asked a series of questions regarding the homeowner's lawn care practices, including questions about fertilization, irrigation, and aeration frequency and intensity (Appendix A). The purpose of identifying lawn care practices that have been used over time is so that relationships can be established between those practices and SOC contained in the lawn where the specific regime has been utilized. In addition to lawn care questions, the survey contained 11 questions about the homeowner's environmental attitudes utilizing the commitment to the environment scale devised by Davis et al (2009).

Demographic information was also collected, although not all participants chose to answer all demographic questions. These questions included: Marital status, number of people in the household, annual income, and highest level of education completed.

4.2.2 Data Analysis

Management Practices

Two-Step cluster analysis was conducted using SPSS (IBM Corporation) with combinations of management practices (e.g. fertilization, pesticide use, aeration) in order to identify groups of parcel owners with similar responses to management questions. High quality clustering schemes are indicated by the level of cohesion and separation, as well as the balance of the resulting clusters. The highest quality clustering group contained only the variables pesticide and fertilizer with level of separation and cohesion >0.5 (Table 4.1).

Table 4.1. Clustering matrix of pesticide and fertilizer use (frequency per year).

	N	**Fertilizer**	**Pesticide**
Management Cluster 1 (Low)	23	0	0
Management Cluster 2 (Medium)	21	0, 1	0, 1
Management Cluster 3 (High)	20	1, 2, 3	1, 2, 3

Environmental Commitment

ANOVA was utilized to identify relationships between the identified management clusters and environmental commitment responses. Analysis was conducted on each of the 11 questions, as well as the overall score (mean of all responses). ANOVA was also used to identify relationships between environmental score and demographic information.

4.3. Results

The average household size was 2.5 people, the median income range was $76,000 to $100,000 and the median education level was post graduate. The majority of participants were married without children currently living in their household (Figure 4.1).

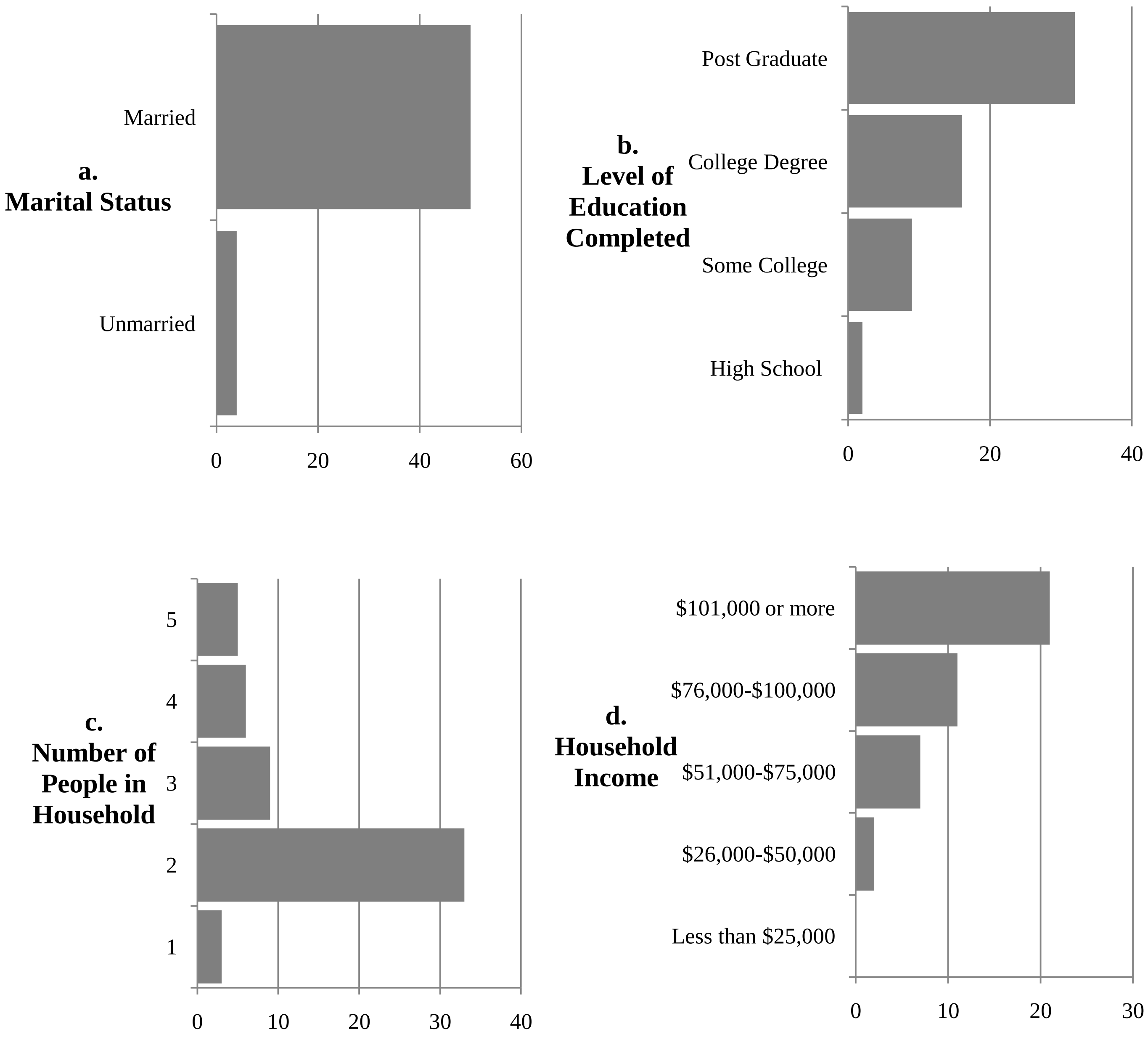


Figure 4.1. Distributions of demographic information reported by participants. Maximum number of responses (n) is 64, although not all responses sum to maximum n due to incomplete response.

4.3.1 Management Intensity & Environmental Commitment

There was a positive relationship (P=0.024) between overall environmental commitment score and level of management intensity. Higher environmental commitment (EC) score corresponded with a higher level of management intensity (fertilizer and pesticide use). The lowest management intensity cluster (I), had a mean EC score of 5.75, the medium management intensity cluster (II) had a mean EC score of 5.9, and the high management intensity cluster (III) had a mean EC score of 6.24 (Figure 4.2).

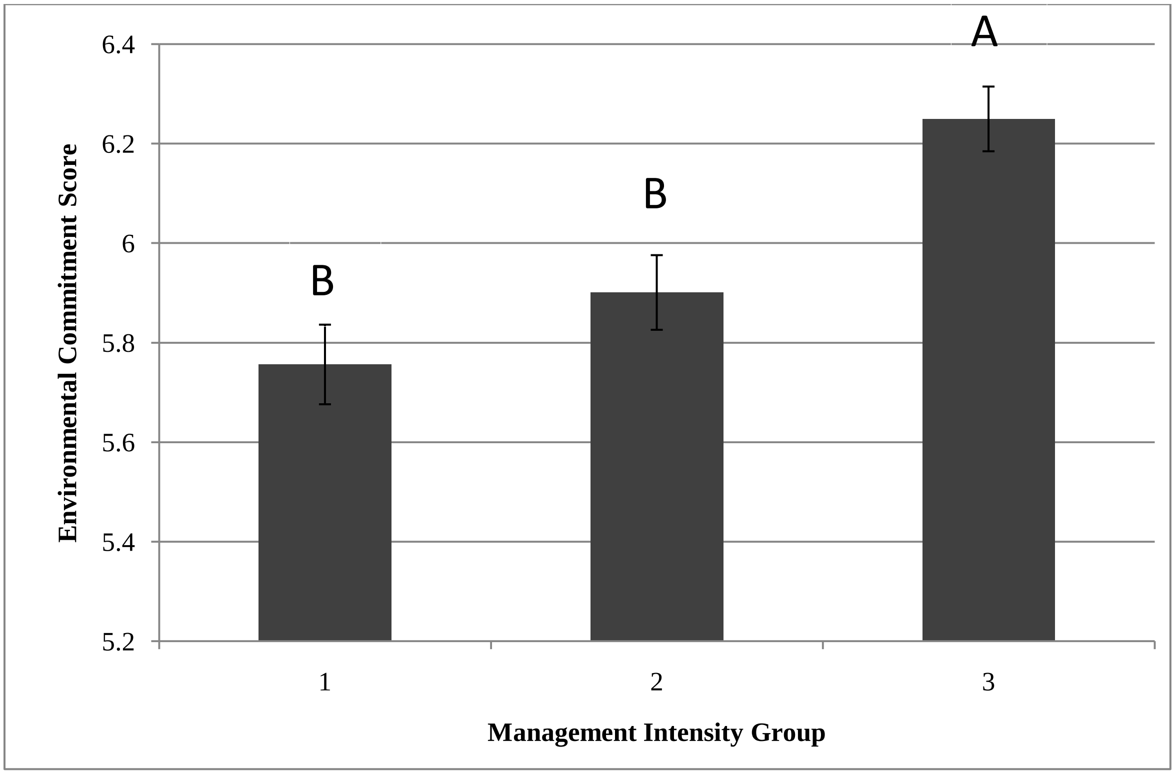


Figure 4.2 Relationship between environmental score and management intensity (P=0.024).

There was a significant positive relationship between fertilization frequency reported by homeowners and observed turf grass density (P=0.0003). There was a marginal positive relationship between environmental score and % C in the top 5 cm of soil (P=0.09), although there was no direct relationship between environmental commitment score and lawn carbon density (P=0.30). There was no relationship between demographic factors (household income and level of education) and environmental commitment score, nor was there a significant relationship between demographic factors and soil variables (Carbon, Nitrogen, Bulk Density).

4.4 Discussion

A higher overall environmental commitment (EC) score was related to a higher level of fertilizer and pesticide application by the homeowner (P=.059). This relationship between homeowners' assessment of their own environmental commitment and the level of fertilizer and pesticide they apply to their lawn indicates that there is not a negative perception of high intensity lawn management amongst this group of participants. This could also illustrate that homeowners who feel more strongly about the environment are more interested in gardening, including lawn management, and invest more time and money in lawn care. Zhou et al. 2009 found that 75% of variance in total lawn-care expenditure was explained jointly by income, percent college graduates, median house value, and percent of owner-occupied house. Residences with higher lawn care expenditure also had greener grass, and possibly greater soil carbon than those receiving lower management. Although higher environmental score was related to higher levels of fertilizer application, which causes an increase in SOC accumulation in the upper 5 cm under turf grass, there was no direct relationship between environmental commitment score and lawn carbon content (P=0.30). We found no significant relationship between demographic factors (income, education, number in household, marital status) and soil variables (Carbon, Nitrogen, Bulk Density). However, our data is representative mainly of exurban subdivisions with residents of high levels of education and income. Our results indicate that there is a connection between homeowner's environmental attitude and lawn management practices, which is in need of further investigation due to the impacts of intensive lawn care on air and water quality and resource consumption.

CHAPTER 5- CONCLUSIONS

5.1 Summary of Findings

Total soil carbon density to 30 cm depth of lawn (6.5 kg C/m^2) and forest (7.1 kg C/m^2) marginally differed ($P=0.08$). There was a positive relationship between time since development and percent C in the lawns at the 0-5 cm depth ($P=0.04$), whereas there was a negative relationship between time since development and both percent C and carbon content at the 20-30 cm depth. This depression in carbon content at the deeper depths may result from the development of the soil decomposer community over time under the undisturbed turf resulting in enhanced decomposition of grass roots at that depth. Also, eluviation of organic matter and dissolved carbon may develop over time and distribute carbon beneath 30 cm depth. Although carbon content at the 20-30cm depth was slightly less in older lawns than in younger, it remains significantly higher than that of the surrounding forest. Despite this difference, overall, there was no difference between carbon storage to 30-cm depth between lawn and forest. Therefore, converting forested land into managed, turfgrass-dominated residential homesites has little effect on regional soil carbon storage.

Based on the homeowner survey, we found a positive correlation between lawn fertilization frequency and both lawn nitrogen density ($P=0.07$) and lawn carbon density ($P=0.0005$) in the top 0-5 cm of soil. Besides directly adding nitrogen to the soil, fertilization improves turfgrass productivity, which increases contribution of above (clippings) and below (roots)-ground carbon and nitrogen.

There was a positive relationship ($P=0.059$) between overall environmental commitment score and level of management intensity (Figure 4.1). This relationship between a participant's assessment of their personal environmental stewardship and the use of chemical fertilizers and pesticides indicates that there is not a perception that intensive lawn care could be harmful to the environment.

5.2 Implications

Interest in quantifying soil carbon sequestration under different types of land use and management has arisen in recent years, as knowledge of the important role soil plays in storing atmospheric CO_2 has grown. Another reason for studying carbon in various ecosystems under various types of management is the importance of soil organic matter, consisting of 50-58% carbon, to cycling of other nutrients and vegetation productivity. Urbanization is an important land use trend which drastically and permanently alters natural ecosystems, with potential to affect cycling of carbon and other elements in these systems. Our findings show that although turf grass is morphologically and functionally different from forest vegetation, soil carbon sequestration is comparable between the two within our geographic and ecosystem context. The geographic and ecosystem context is important to this comparison, and ours is the mid-atlantic Appalachian Hardwood (Mixed Oak) forest. Carbon contained in soil is only one component of accounting for carbon in a given ecosystem, and the carbon contained in below and above ground biomass is an important aspect in comparison of forest and lawn. While large amounts of carbon are stored in the living and dead forest biomass, very little is stored in turf grass. Therefore, converting forest to residential turf grass has little effect on regional *soil* carbon sequestration, but has a large impact on the total sequestration value of the land. Additionally, unmanaged forest produces dramatically less management-related emissions than intensively managed turf grass. Emissions associated with lawnmowers, fertilizer and pesticide production and use, and other lawn care activities far offset the soil carbon sequestration value of turf grass.

Jo & McPherson (1995) included emissions due to mowing in their carbon budget for turf grass on two residential plots in northwest Chicago and estimated net carbon uptake by grass to be -.04 kg/m^2, emitting 1.5 times the amount of carbon it sequestered. We found little difference in carbon sequestration between high levels of management and low levels, indicating that improving the sequestration value of turf grass will rely on ways to minimize inputs.

5.3 Study Limitations

Subdivisions and individual properties included in this study were selected based on being located in relatively close proximity to the Virginia Tech campus in Blacksburg, VA, and also being in a forested setting. These subdivisions are all of upper-level income homes, and many of the residents are associated with Virginia Tech. This resulted in our data representing an unusually high population of homeowners of high income and education levels as shown in Table 4.1. Affiliation with the University likely increased the likelihood that a homeowner would be willing to participate in a University-sponsored project.

We visited each site prior to inclusion in the study in order to ensure there was an area where the forest and lawn could be sampled, and also to identify an area where the grade of the lawn matched that of the forest, and was not a septic field. This was our best effort to minimize dramatic alterations that may have occurred to soil during site development, such as removal of surface horizons and addition of foreign soil and amendments. However, treatment of soil prior to planting with grass seed likely varied widely, potentially affecting soil carbon measurements.

5.4 Direction for Future Research

This research contributes to the growing volume of data on carbon sequestration in managed turf grass and the effects of transforming natural systems into urban areas on soil carbon. Our data is representative of a small region, and is consistent with data from other areas of the United States and larger scale studies. Since higher rates of management only slightly increase the sequestration rate of turf grass while emitting CO_2 and other pollutants, future research on carbon in lawns should focus on developing methods which enhance carbon sequestration in turf grass by *reducing maintenance*. The concepts of low carbon turf management and gardening already exist but are not widely practiced. Research into the social and psychological aspects of lawn care is in need of further research in order to understand the choices of different groups and demographics of lawn managers. We explored the carbon storage and potential social drivers of lawn practices within a small geographic region and within a limited range of subdivision and homeowner socioeconomic characteristics. Future studies focusing on small areas and socioeconomic groups may be compared with our study to understand differences within the region. Information about lawn manager behavior can be paired with research into low-carbon, low pollution turf management techniques to promote practices which improve the carbon sequestration and ecological value of urban land under turf grass management.

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APPENDIX A: SURVEY OF LAWN CARE PRACTICES

Survey of Lawn Care Practices

Please answer all questions to the best of your knowledge. Responses are strictly confidential and will not be associated with you publicly.

SECTION 1: PROPERTY INFORMATION

1. Property Address____

2. What year was construction of your home completed? ________________________________

3. For how many consecutive years can you account for landscape management practices on this property? ______________

4. Provide an estimate of the area of your property with maintained turf grass. (Circle one)

- Less than 0.25 acre
- 0.26-0.5 acre
- 0.51-0.75 acre
- 0.76-1.0 acre
- Greater than 1 acre

SECTION 2: LAWN MANAGEMENT PRACTICES

1. How frequently, per month, is your lawn mowed during the growing season? (Circle one)

- None
- Once
- Twice
- Three times
- Weekly or more

2. How many hours per week are spent maintaining your lawn during the growing season?

- 0 hours
- 1-2 hours
- 3-4 hours
- 5 or more hours

3. Are lawn clippings bagged and removed from the lawn, or left on the lawn?

- Bag clippings and remove
- Leave clippings on the lawn
- Other (explain)_______________________

4. Are fallen leaves raked and removed, or mulched by mowing into the grass?

- Rake leaves
- Mow leaves
- Other (explain)______________________

5. Do you apply fertilizer to your lawn?

- Never
- Once per year
- Spring and fall
- Three or more times per year

6. To the best of your knowledge, please explain the type and quantity of fertilizer applied. (For example: Scotts Turf Builder applied at rate recommended on bag in spring and fall)

____

____

7. Do you apply organic soil amendments to your lawn? (Examples: Peat moss, compost, leaf mold, manure)

- ○ Never
- ○ Once per year
- ○ Spring and fall
- ○ Three or more times per year
- ○ If less than once per year, how many times since you have been maintaining the lawn?

  ____

8. Do you apply pesticides to your lawn? (Examples: weed control, disease control, or grub control)

- ○ Never
- ○ Once per year
- ○ Spring and fall
- ○ Three or more times per year
- ○ If less than once per year, how many times since you have been maintaining the lawn?

  ____

9. Do you irrigate your lawn during the growing season?

- ○ Never
- ○ Once per day
- ○ Once per week
- ○ Only during drought

10. Do you aerate your lawn during the growing season?

- ○ Never
- ○ Once per year
- ○ Spring and fall
- ○ Three or more times per year
- ○ If less than once per year, how many times since you have been maintaining the lawn?

  ____

11. Are there any other facts that could be of interest regarding your lawn?

SECTION 3: ENVIRONMENTAL ATTITUDES (Circle the choice that best describes you)

1. **I am interested in strengthening my connection to the environment in the future.**
    - Strongly disagree
    - Disagree
    - Mildly disagree
    - Neutral
    - Mildly agree
    - Agree
    - Strongly agree
2. **I feel strongly linked to the environment.**
    - Strongly disagree
    - Disagree
    - Mildly disagree
    - Neutral
    - Mildly agree
    - Agree
    - Strongly agree

3. **When I make plans for myself, I take into account how my decisions may affect the environment.**
    - Strongly disagree
    - Disagree
    - Mildly disagree
    - Neutral
    - Mildly agree
    - Agree
    - Strongly agree
4. **It seems to me that humans and the environment are interdependent.**
    - Strongly disagree
    - Disagree
    - Mildly disagree
    - Neutral
    - Mildly agree
    - Agree
    - Strongly agree
5. **It makes me feel good when something happens that benefits the environment.**
    - Strongly disagree
    - Disagree
    - Mildly disagree
    - Neutral
    - Mildly agree
    - Agree
    - Strongly agree

6. **Feeling a connection to the environment is important to me.**
    - Strongly disagree
    - Disagree
    - Mildly disagree
    - Neutral
    - Mildly agree
    - Agree
    - Strongly agree
7. **I expect that I will always feel a strong connection to the environment.**
    - Strongly disagree
    - Disagree
    - Mildly disagree
    - Neutral
    - Mildly agree
    - Agree
    - Strongly agree
8. **I believe that the well-being of the natural environment can affect my own well-being.**
    - Strongly disagree
    - Disagree
    - Mildly disagree
    - Neutral
    - Mildly agree
    - Agree
    - Strongly agree
9. **It is unlikely that I'll feel a connection to the environment in the future.**
    - Strongly disagree
    - Disagree
    - Mildly disagree
    - Neutral
    - Mildly agree
    - Agree
    - Strongly agree
10. **I feel very attached to the natural environment.**
    - Strongly disagree
    - Disagree
    - Mildly disagree
    - Neutral
    - Mildly agree
    - Agree
    - Strongly agree

11. I feel committed to keeping the best interests of the environment in mind.

- Strongly disagree
- Disagree
- Mildly disagree
- Neutral
- Mildly agree
- Agree
- Strongly agree

SECTION 4: DEMOGRAPHIC INFORMATION

1. What is your marital status?

- Single
- Married

2. How many people live in this household?

_______ people

3. What level of education did you complete?

- Elementary School
- High School
- Some College
- College Graduate
- Post-Graduate

4. What is your annual household income? (note: this information is strictly confidential)

- Less than $25,000
- $25,000 - $50,000
- $51,000 - $75,000
- $76,000 - $100,000
- $101,000 or more

APPENDIX B: DATA COLLECTION SHEET

Data Collection Sheet

Site address:____
Homeowner name(s): ___________________________________
Date/time of visit: _______________________________________

Forest Plot Measurements:

1. Collect bulk density samples, 3 depths (0-5cm, 5-10cm, 15-20cm, 25-30cm)
2. 4 push tube samples, 1m away
3. Forest Soil Respiration Zero, empty chamber______________ Zero, ambient__________

Trial	Rate	Temp.	Moisture
1			
2			
3			

4. 1/50th acre plot, r=16.7 feet from plot center

Species	Dbh	Height

5. Understory Description**:**

Lawn Plot Measurements

1. Lawn Soil Respiration (15 minutes after initial trimming)

Trial	Rate	Temp.	Moisture
1			
2			
3			

2. Plot site description

3. Distance and azimuth to portion of house closest to plot

4. Distance and location of plot relative to septic field:

5. Slope aspect

6. Slope grade

7. Turfgrass species composition description (Take photo)

8. Turf grass density description

9. 1/50th acre fixed area plot tree data

Distance	**Dripline √=yes**	**Species**	**Dbh**	**Height**	**Planted √=yes**	**Notes**

10. Site sketch/notes