EVALUATION OF HOME LAWN MANAGEMENT BEHAVIORS AND SUSTAINABLE FERTILITY PRACTICES IN VARIOUS TURFGRASS SYSTEMS.

by

REBECCA ANNE GRUBBS

(Under the Direction of Gerald M. Henry)

ABSTRACT

High-input management regimes used to maintain aesthetic quality and playability of turfgrass are increasingly viewed as non-sustainable and detrimental to the environment. The objective of this work was to evaluate sustainable management practices for large- and small-scale turfgrass systems and to develop a greater understanding of what drives turfgrass management behaviors. Three separate projects were completed: (1) an evaluation of a mobile soil apparent electrical conductivity (EC_a) sensor to predict spatial variability of soil properties on golf course fairways, (2) an evaluation of the effect of mowing frequency on turfgrass clipping composition and nitrogen (N) transformations, and (3) a qualitative assessment of homeowner decision-making with respect to the lawn. Spatial mapping and data analysis for six golf course fairways revealed variable relationships between EC_a and five soil properties [clay content, cation exchange capacity (CEC), soil pH, and organic matter (OM)]. Further research is warranted to examine the dominant properties driving EC_a to ensure the accuracy of a mobile EC_a device in mapping soil spatial variability in turfgrass systems. Clippings from four different mowing frequencies were analyzed for tissue content and incubated on soil for 90 days to evaluate N mineralization and ammonia (NH_3) volatilization losses. Mowing frequency did not appear to impact tissue composition, however mulched clippings could recycle a significant portion of plant-available N to the soil. More frequent mowing may reduce overall NH_3 losses. Fourteen households participated in a qualitative study consisting of two interviews and twenty weekly surveys to collect information on lawn management and decision-making over a growing season. Findings revealed homeowner decision-making in regards to the lawn is a complex process involving personal and social identities, as well as affective attachments. When designing outreach and education tools to shift homeowner behavior on the lawn, researchers should consider a multi-faceted approach that addresses deeper internal drivers. Overall conclusions for this study point to the importance of adopting a diverse, interdisciplinary approach to environmental turfgrass management in order to affect the greatest change and improve overall sustainability of turfgrass systems.

INDEX WORDS: Interdisciplinary; Mixed-methods; Nitrogen; Precision Turfgrass Management; Qualitative Methods; Soil Fertility; Sustainability; Turfgrass

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CHAPTER 1

INTRODUCTION

As of 2005, turfgrass accounted for an estimated 20 million hectares, or approximately 1.9% of total surface area in the United States (U.S.), making it the single largest irrigated crop (Milesi et al., 2005). Beard and Kenna (2008) predicted that an area of managed turfgrass that size had an estimated value of roughly $40 billion (Bn) annually. However, in 2002, the Turfgrass and Lawn Care industry as a whole generated an estimated revenue of $57.9 Bn (Haydu et al., 2006). This was divided across several industry subsectors including sod production ($1.7 Bn), lawn equipment manufacturing ($7.5 Bn), lawn care services ($18.5 Bn), lawn care retailing ($8.5 Bn), and golf courses ($21.8 Bn). In total for 2002, the Turfgrass and Lawn Care industry provided roughly 823,000 jobs. These numbers have likely increased in recent years due to rapid national urbanization and the establishment of new concentrated residential areas with turfgrass lawns and recreational facilities (Carey et al., 2012).

In addition to an attractive aesthetic, turfgrass provides a relatively safe, uniform surface for a number of outdoor sports and activities (Beard and Green, 1994). Golf courses, accounting for the largest percentage of annual revenue in the turfgrass industry, cover an estimated 19,200-25,000 km^2 worldwide (Bartlett and James, 2011). According to the Millennium Ecosystem Assessment (2005), golf courses provide certain ecosystem services including sequestration and cycling of essential nutrients, improved water infiltration and attenuation, and support of above- and below-ground biodiversity. Turfgrass soils have been found to sequester between 0.9 to 5.4 Mg carbon (C) ha^{-1} yr^{-1} depending on the age, ecoregion, and management practices of the turfgrass (Selhorst and Lal, 2013). When applied to the nearly 20 million ha of turfgrass estimated by Milesi et al. (2005), between 18 and 108 Tg C may be sequestered by turfgrass systems in the U.S. each year. Many of these benefits can be extended beyond golf courses to turfgrass in general, along with phytoremediation of contaminated soils, temperature moderation, and soil erosion control (Beard and Green, 1994, Stier et al., 2013). In a study evaluating the use of EDTA (Ethylenediaminetetraacetic acid)-assisted perennial ryegrass (*Lolium perenne* L.) as a permeable barrier to prevent heavy metal leaching, Zhao et al. (2011) found that the leaching of copper (Cu), Zinc (Zn), and lead (Pb) was reduced by approximately three times.

In order to maintain aesthetic quality and playability, turfgrass systems tend to be intensively managed through a range of practices that include irrigation, mowing, fertilization, and pest-management. These management regimes can be controversial, as they consume large amounts of water (Kjelgren et al., 2000), pollute urban air and groundwater (Barton and Colmer, 2006), and contribute to urban carbon emissions through regular mowing (Allaire et al., 2008). Selhorst and Lal (2013) estimated that over time, hidden carbon costs from mowing and fertilization may not only equal the amount of C sequestered, but exceed it, negating certain environmental benefits. In one study conducted in Australia, small utility engines, such as those used by contemporary lawn mowers, were found to contribute 5.2 and 11.6% of total carbon-monoxide (CO) and non-methane hydrocarbons, respectively (Priest et al., 2000).

In recent years, there has been increasing concern around the use of turfgrass pesticides both on home lawns and public recreation sites. Defined by the EPA as "any substance intended for preventing, destroying, repelling, or mitigating any pest," pesticides target unwanted weeds, rodents, insects, nematodes, fungi, and bacteria (EPA, 2014a). Despite insistence by the industry that pesticides are generally safer and more effective than ever, the past decade has given rise to a new flush of concern over potential exposure to harmful substances (Gilden et al., 2012, Alarcon et al., 2005, Owens, 2009). In the case of athletic fields, parents are increasingly fearful of child exposure through direct contact with treated grass (Peeples, 2012, Owens, 2009). These fears have spurred heated debates and demands for policy changes that would better regulate or completely ban pesticide use altogether on fields used by children and adolescents (Owens, 2009). Many common pesticide chemistries have been associated with public health risks including complications during pregnancy (Greenlee et al., 2004) and childhood cancer (Zahm and Ward, 1998). Children are considered more susceptible to pesticide poisoning due to their size and active development (Alarcon et al., 2005, Gilden et al., 2012). In many cases, pesticide poisoning presents as an acute, ambiguous illness (upper respiratory illness, gastrointestinal distress, conjunctivitis, etc.) (Alarcon et al., 2005, Gilden et al., 2012). This can make it difficult to properly discern and report poisoning incidents. Still, there are moderate and high severity cases in which illness may be considered life-threatening with mandatory hospitalization or more permanent effects.

Understanding system nutrient balances is critical to maintaining health and resilience of turfgrass while simultaneously preventing subsequent water and air pollution through leaching, runoff, and volatilization of harmful trace gases (Carey et al., 2012, Qian et al., 2003, Milesi et al., 2005). Poor understanding of complex nutrient budgets in turfgrass could easily lead to fertilizer mismanagement (Bartlett and James, 2011). There is currently no federal legislation targeting urban fertilizer use; however, many state and local government entities are implementing new laws to address growing concerns about urban contributions to fertilizer pollution (Carey et al., 2012, Milesi et al., 2005).

Requirements for applied N fertilizers are highly variable and are typically dictated by both environmental needs and land usage, where athletic fields and golf courses often demand greater inputs. Urbanization can result in the removal of top soil and disruption of the soil profile in a way that interferes with or limits nutrient cycling (Cheng and Grewal, 2009). Consequently, urban soils tend to provide insufficient plant-available nitrogen (N) and phosphorous (P) to support plant growth, and supplemental fertility from synthetic fertilizers is often required to maintain aesthetic quality and playability (Carey et al., 2012).

In urban ecosystems, N inputs have been found to exceed demands by as much as 51% (Fissore et al., 2012). Mismanagement of applied N has several environmental consequences including contamination of urban air and ground water through nitrate (NO_3^-) leaching, and emission of greenhouse and ozone depleting gasses including N_2O, NO_x, and NH_3 (Barton and Colmer, 2006, Carrow et al., 2001, Qian et al., 2003). Nitrate contamination in groundwater has been associated with methemoglobinemia in infants (Vigil et al., 1965, Fan and Steinberg, 1996) and subclinical hypothyroidism in women (Aschebrook-Kilfoy et al., 2012). Additionally, atmospheric deposition of gaseous emissions such as NH_3 can result in soil acidification and plant toxicity (Pearson and Stewart, 1993), as well as eutrophication of surface water (Boyd, 2015).

Losses of applied P from turfgrass systems vary significantly based on application timing, rate, and source (Soldat and Petrovic, 2008). As much as 18% of P fertilizer applied to turfgrass is subject to loss through various pathways. Displacement of P through surface runoff, soil erosion, and atmospheric deposition is believed to be the most common cause of freshwater eutrophication (Sims et al., 1998, Correll, 1998).

Methods to combat environmental concerns have largely been rooted in conventional biophysical research and a rationalist approach to outreach. Research is conducted and presented in the form of informational publications and presentations with the hope of shifting environmental attitudes and behaviors in the public. Likewise, research is often partitioned into individual disciplines, with minimal interdisciplinary considerations.

Interdisciplinary approaches to teaching and research facilitate opportunities to “critique the insights of different disciplines and to seek common ground when these insights disagree” (Szostak, 2007). Additionally, interdisciplinary programs have been associated with improved communication skills and the expansion of student/researcher understanding and achievement between disciplines (Jones, 2010). Effective communication of scientific findings is critical to implementing change in behavior. In the case of turfgrass, scientists and educators must be able to communicate to professional turfgrass managers as well as average homeowners regarding lawn care. An interdisciplinary approach that incorporates qualitative research methods creates new opportunities to investigate the way homeowners interact with and make decisions about their lawn phenomenologically (Maxwell, 2013). Disadvantages to an interdisciplinary research program include a ‘fringe’ understanding of individual disciplines and specializations, as well as some career risk for academics who may not be taken as seriously by colleagues. In contrast to this, Duerr (2008) suggested that an interdisciplinary background better prepared students for real-world problem-solving.

The objective of this research was to take an interdisciplinary approach to exploring new ways to improve resource-use efficiency in turfgrass systems and discern potential pathways for disseminating research findings to the public. This was achieved through three unique projects that approach environmental turfgrass research from different angles: (1) applications for new technology in the implementation of site-specific management on golf courses, (2) conventional biophysical research evaluating small scale management changes to improve nitrogen-use efficiency in turfgrass systems, and (3) a qualitative assessment of homeowner decision-making in lawn care management. These three projects allowed for the evaluation of management practices in both large- and small-scale turfgrass production, as well as an opportunity to evaluate decision-making and paths to shifting behavior in homeowners managing turfgrass lawns.

CHAPTER 2

LITERATURE REVIEW: NUTRIENT MANAGEMENT IN TURFGRASS SYSTEMS AND APPLICATIONS FOR PRECISION TURFGRASS MANAGEMENT

To maintain optimum aesthetic quality, turfgrass systems are managed with considerable inputs to support dense, green, vigorous growth (Fry and Huang, 2004). Common turfgrass management practices include irrigation, mowing, fertilization, cultivation, and the addition of plant growth regulators/biostimulants. Effective nutrient management in turfgrass systems must take a comprehensive approach, considering the effects of the environment, cultural practices, and recreational activities on nutrient cycling and nutrient availability in the soil (Carrow et al., 2001).

Plants require 17 essential elements in order to survive (Carrow et al., 2001). The three most abundant elements in plant tissue [carbon (C), hydrogen (H), and oxygen (O)] are provided by the natural environment, and are not considered mineral nutrients. Of the 14 mineral nutrients, six are classified as macronutrients, or nutrients with dry matter concentrations of at least 1000 mg kg^{-1} in plant material, and 8 are classified as micronutrients with dry matter concentrations of less than 1000 mg kg^{-1} (Havlin et al., 2005). There are three primary macronutrients [nitrogen (N), phosphorous (P), and potassium (K)] and three secondary macronutrients [calcium (Ca), magnesium (Mg), and sulfur (S)]. The eight essential micronutrients for plant growth include iron (Fe), manganese (Mn), Zinc (Zn), Copper (Cu), Molybdenum (Mo), Boron (B), Chlorine (Cl), and Nickel (Ni) (Havlin et al., 2005). A handful of other elements [silicon (Si), sodium

(Na), cobalt (Co) and selenium (Se)] remain poorly understood, and may be plant-essential or beneficial on a species-specific basis.

Nutrient imbalances in the soil can significantly inhibit plant growth and appearance, as most nutrients have important metabolic functions within the plant (Carrow et al., 2001). Insufficient or excess availability of essential nutrients may result in plant deficiency or toxicity. Plants are considered deficient when nutrient levels are low enough to induce more than a 10% reduction in growth (Carrow et al., 2001). Likewise, toxicity levels will also inhibit growth. Micronutrient toxicity is more common than macronutrient toxicity. In turfgrass systems, deficiencies of N, Fe, P, K, Mg, S, and Mn are more likely to occur, whereas deficiencies in Ca, Zn, Cu, Mo, B, Cl, and Ni are rare.

Nitrogen is commonly identified as the most limiting nutrient to plant growth, accounting for the greatest percentage of plant tissue (2 – 5%) (Carrow et al., 2001). Nitrogen is a critical constituent of amino acids in the plant that serve as fundamental building blocks for key compounds that support plant growth and metabolism. Deficiency of N is typically associated with sandy soils, low organic matter, and regular clipping removal (mowing), and presents as chlorosis or yellowing of the leaves. Nutrient availability and the potential for nutrient deficiencies in turfgrass systems is influenced by several key factors including climate, soil properties, and human activities/cultural practices.

The Impact of Climate on Turfgrass Nutrient Management

In this context, climate refers to the role of above-ground conditions on turfgrass soil fertility and nutrient management including atmospheric temperature, humidity, wind, atmospheric pollutants, light, and pests (Carrow et al., 2001). Many of these factors, particularly temperature and light, will significantly impact metabolic activity within the plant, which will ultimately determine nutrient requirements throughout the season. Above-ground pests, particularly weeds, can also significantly impact nutrient availability in the soil by competing with turfgrass for nutrients. In addition to this, atmospheric conditions may influence gaseous losses from turfgrass systems, as well as atmospheric deposition of nutrients that may be beneficial or toxic to plant growth (Havlin et al., 2005).

Fertility research in turfgrass has focused primarily on N cycling. Volatilization of ammonia (NH_3) is one pathway to N loss from turfgrass systems that is strongly influenced by ambient temperature, humidity, and wind (Carrow et al., 2001). Generally, NH_3 volatilization in turfgrass systems has been associated with the use of urea-based N fertilizers, but volatilization can also occur from other sources including freshly mulched grass clippings (Carrow et al., 2001).

De Ruijter et al. (2010) found that NH_3 volatilization from fresh plant material left on the soil surface was significantly greater than that which was incorporated into the soil. In pasture systems, losses of between 10% (Whitehead and Lockyer, 1989) and 15.9% (De Ruijter et al., 2010) of total N from surface-applied grass residues have been reported. In most cropping systems, NH_3 volatilization is primarily influenced by soil dynamics, as crop residues and N fertilizers come into direct contact with the soil, or are soil-incorporated. The enzyme urease is necessary for the hydrolysis of urea [$CO(NH_2)$] to occur (Carrow et al., 2001). Urease activity in the soil is relatively stable and does not fluctuate significantly with seasonal changes in atmospheric temperature or relative humidity. Turfgrass systems are unique since they are not cultivated and often develop a thatch layer, or a layer of intermingled living and dead tissue between the canopy and the soil surface (Beard, 1972). Urease activity in the thatch layer is less stable than that of the soil, and more significantly influenced by the above-ground climate (Torello and Wehner, 1983). Potential N losses from surface-applied urea fertilizers and clipping residues are therefore more likely to occur in turfgrass systems than most other cropping systems where soil contact and soil incorporation is possible.

Decomposition rates of grass clippings are greatly influenced by changing weather conditions, particularly in more temperate climates (Kauer et al., 2012). Indirectly, climate will affect net primary productivity (NPP), ultimately affecting clipping yields and tissue structure. Biomass production varies on an annual and monthly basis due to natural fluctuations in NPP (Zhang et al., 2013, Qian et al., 2003).

Clipping decomposition is significantly influenced by above-ground climate conditions (Kauer et al., 2012). Atmospheric temperature and relative humidity tends to fluctuate more readily than soil temperature and moisture. In a study evaluating the effect of weather conditions on the decomposition of grassland material, Kauer et al. (2012) found that microbial activity tends to be greater immediately following clipping deposition when tissue moisture was highest, followed by a subsequent decline in decomposition rate at about 40% remaining material. Previous research indicates a temperature range between 35 and 45 degrees in conjunction with approximately 50-60% moisture facilitates optimum decomposition rates for soil-incorporated residues (Dalias et al., 2001). Nevertheless, optimum temperature range is highly contingent on moisture availability and vice versa, as excess of one cannot compensate for absence of the other (Kauer et al., 2012). Temperature will either slow or accelerate decomposition depending on ratio of increased microbial activity relative to rate of tissue-drying.

Atmospheric deposition of particle nutrients may also be significantly influenced by climate, particularly relative humidity and precipitation. Atmospheric deposition of N can be both wet and dry, though dry deposition or N deposition in the absence of precipitation accounted for only 10% of total N deposition in some studies (WSDE, 2017). In one study, turfgrass lawns were found to retain higher atmospheric N than forests overtime, indicating that turfgrass may be an important net sink for N deposition in urban ecosystems (Raciti et al., 2008).

Other atmospheric constituents such as sulfur dioxide (SO_2) may also influence nutrient balances in turfgrass systems. Sulfur facilitates the synthesis of cystine, cysteine, and methionine which aid in the assembly of tertiary and quaternary protein structures through the formation of disulfide bonds (St. John et al., 2013). As a constituent of coenzyme A, sulfur supports fatty acid synthesis and oxidation, while also assisting in the formation and stabilization of chlorophyll (St. John et al., 2013, Havlin et al., 2005). Due to a higher S:C ratio than many dicotyledonous plants, turfgrass leaves are more capable of SO_2 absorption that bypasses traditional root uptake pathways (St. John et al., 2013, Li et al., 2014). This same mechanism is thought to make many grass plants more resistant to SO_2 under conditions of extreme industrial air pollution (Li et al., 2014, Ayazloo and Bell, 1981). Though S deficiency is less common, turfgrass managed with high N inputs may be subject to sulfur deficiency due to a poorly understood competition between sulfate and nitrate uptake mechanisms (St. John et al., 2013). This may be especially true for putting greens or other systems with predominantly sandy soils prone to leaching. Sulfate toxicity from root uptake is not common, as excess uptake can be degassed from the leaves; however, sulfur-induced acidification of the soil solution or irrigation water may prove inhibiting to growth and maintenance (St. John et al., 2013).

<u>The Impact of Soil Properties on Turfgrass Nutrient Management</u>

Nutrient availability in turfgrass systems is strongly influenced by soil chemical, physical, and biological properties including soil texture, soil structure, pore size/distribution, soil pH, cation exchange capacity (CEC), soil moisture, soil temperature, and microbial activity (Carrow et al., 2001). Soil properties are determined both by environmental factors, as well as human interaction by way of wear/traffic and cultural practices such as mowing, fertilization, and irrigation.

Soil texture classification, or the percentage of sand, silt, and clay particles, can significantly impact nutrient availability in the soil. Clay particles are colloidal in nature, and significantly contribute to soil CEC (Carrow et al., 2001). For example, exchangeable Mg persists in the soil as a function of mineral weathering, decomposed plant material, and release from 2:1 clay interlayers (St. John et al., 2013). Since Mg may be released directly from clay structures, the type of clay present is more important to availability than with some other nutrients. In general, higher clay content is correlated with increased nutrient availability; however, some bonds are so strong that abundant nutrients are not accessible by plants. Calcium deficiencies in turfgrass can be common in calcareous soils, like those found in the Southwestern United States or on some golf course putting greens (St. John et al., 2013, St John et al., 2003). Though Ca is abundant, it is unavailable for plant uptake due to tight bonds forged with carbonates, bicarbonates, and soil particles (St John et al., 2003).

Coarser texture soils with higher sand contents have a low CEC and are particularly susceptible to leaching. Heavy rainfall on sandier soils with low CEC can often result in nutrient deficiencies, particularly in the case of macronutrients (Carrow et al., 2001). Limited exchange sites and competition between cations may also lead to nutrient deficiencies of Mg, Ca, and K particularly in the presence of Na (St. John et al., 2013). Fertility practices must consider the role of soil texture and CEC in determining nutrient retention and availability.

Soil organic matter can also contribute significantly to CEC. Because they are not regularly cultivated, turfgrass systems will develop a well-defined organic matter layer adjacent to plant roots overtime (Krum et al., 2011). Because of this layered effect, organic matter in turfgrass systems may contribute more to soil dynamics and nutrient management than in cultivated cropping systems with a more homogeneous soil profile. Microbial activity in the soil, and particularly in soil organic matter, can significantly impact N mineralization and availability of inorganic N (NO_3^- and NH_4^+) (Carrow et al., 2001). Additionally, iron concentrations (Fe^{+2} and Fe^{+3}) are relatively low in soil solution, but become more available in the presence of organic chelates. Iron is critical to the biosynthesis of chlorophyll as it is an important structural component to thylakoid membranes in the cell (Carrow et al., 2001). Low concentrations of Fe in the soil solution make Fe-deficiency perhaps the second most common nutrient deficiency in turfgrass following N. Symptoms of iron deficiency include interveinal chlorosis with an overall mottled appearance that compromises aesthetic quality. Spatial distribution of organic matter can have an impact on the availability of individual nutrients throughout a given area, and is influenced simultaneously by multiple soil properties including temperature, moisture, texture, and structure (Parton et al., 1987).

Soil pH can significantly affect nutrient availability in the soil, because pH will cause precipitation of chemical compounds that render some nutrients unavailable. Under a pH of approximately 5.5, P fixation with Fe, aluminum (Al), and Mn may occur, while P fixation with

Ca occurs at a pH between 7.5 and 8.5 (Carrow et al., 2001). Acidic soils in general can lead to nutrient deficiencies for K, Ca, and Mg. In an effort to raise soil pH, turfgrass managers tend to rely on liming materials [$CaCO_3$ and $CaMg(CO_3)_2$] (Havlin et al., 2005). Since turfgrass systems are not conventionally tilled, liming may be less effective than in other systems where material can be easily and uniformly incorporated into the soil profile (Schlossberg et al., 2008). Lime treatment of acid soils is most efficacious prior to turfgrass establishment, but may not last as turfgrass ages and thatch accumulation begins to limit air and water movement through the soil profile. Soil pH may also influence microbial activity and pressure from soil-borne diseases that compromise overall plant health (Carrow et al., 2001).

The Impact of Human Activities and Cultural Practices on Turfgrass Nutrient Management

Common cultural practices in turfgrass management include irrigation, mowing, and cultivation. Each of these practices may significantly impact nutrient management of turfgrass systems by influencing demand via metabolic stress and affecting nutrient availability in the soil. Mowing is perhaps the most common turfgrass management practice. The intermittent removal of shoot growth can play a significant role in turfgrass nutrient cycling (Carrow et al., 2001). Nitrogen is a mobile nutrient, actively transported into fresh tissue to support new growth (Havlin et al., 2005). Fresh turfgrass clippings can contain between 25 and 60% of total applied N (Carrow et al., 2001). Recycled clippings (left on the canopy surface after mowing) can improve visual quality of turfgrass at half the rate of a typical nitrogen application (Heckman et al., 2000) and increase carbon sequestration by between 11 and 59% (Qian et al., 2003). However, recycled clippings can be unsightly and lead to greater potential for disease through increased moisture and microbial activity (Qian et al., 2003).

Irrigation practices influence nutrient management in three primary ways: 1) by moving water through the soil profile which may displace nutrients, particularly in sandy soils, 2) by changing soil chemistry through pH and the addition of water-based nutrients, and 3) by impacting soil moisture and microbial activity in the soil. It has already been established that heavy rainfall or irrigation of sandy soils can leach critical nutrients through the soil profile (Carrow et al., 2001). Water quality can play a critical role in nutrient cycling, particularly for turfgrass systems managed with reclaimed or secondary water resources. Under anaerobic conditions, high levels of sulfate may reduce to hydrogen sulfide (H_2S) causing a strip of root necrosis known as "black-layer" to develop (Carrow, 2012). Reclaimed water resources tend to have a greater sulfate concentration than conventional water resources. As more golf courses and athletic fields are irrigated with reclaimed water, zones with poor drainage may be particularly susceptible to black-layer (Carrow, 2012). Additionally, Mg deficiency as a function of precipitation and adsorption to clay particles is less common than with Ca, but one exception to this is with carbonates and bicarbonates found in reclaimed water (Carrow, 2012). Reclaimed water may also contain excess Na that can negatively affect soil structure and outcompete nutrient cations for plant uptake (Carrow, 2012). Irrigation water can occasionally be modified to influence soil pH. Leinauer and Devitt (2013) found that on some golf courses, the addition of acids to irrigation water will naturally release Ca from precipitate material by altering the pH in the soil solution.

Turfgrass sites are often exposed to vehicular and foot traffic that can significantly damage turfgrass tissues and result in soil compaction (Carrow and Petrovic, 1992). Compaction of soil particles can result in changes to the root zone, impacting soil water and air movement and negatively affecting plant growth. Soil compaction can be particularly problematic in fine-textured soils high in clay and silt content (Fry and Huang, 2004). Cultivation practices such as aerification and verticutting are implemented to reduce thatch layer build-up and expose compacted material to additional moisture and oxygen (Stier et al., 2013). Though previous studies have hypothesized a relationship between cultivation and increased infiltration of rainwater and N and P solutes, results did not demonstrate a significant reduction in surface runoff of soil nutrients (Rice and Horgan, 2013). Instead, cultivation practices may more significantly influence nutrient cycling by changing oxygen concentration in the soil and impacting microbial activity responsible for N transformations and the production of organic chelates that facilitate nutrient uptake by plants (Carrow et al., 2001, Stier et al., 2013). Some research has also indicated that antecedent mechanical cultivation may improve liming efficacy through increased amendment contact with soil as deep as 12 cm (Schlossberg et al., 2008).

Precision Agriculture and Precision Turfgrass Management

Precision Agriculture (PA) takes a systems-approach to crop management, incorporating technological advancements to quantify and manage spatial and temporal variability in various cropping systems (Zhang et al., 2002). In addressing spatial and temporal variability, farm managers are better able to improve resource-use efficiency (RUE) which offers a number of environmental and monetary benefits. The emergence of new technology including global positioning systems (GPS), geographic information systems (GIS), and remote sensing and mobile sensor devices has given momentum to PA, streamlining implementation for growers (Gibbons, 2000). This technology allows growers to delineate site-specific management units (SSMUs) to cater management practices to the needs of an individual management zone.

Because of this, site-specific management only becomes practical when three primary criteria are met: (1) that there is significant within-field variability of properties relevant to crop management, (2) that the variability can be properly measured, and (3) that modified management practices offer some environmental or economic benefits (Plant, 2001). In a comprehensive literature review, Pierpaoli et al. (2013) identified several driving forces behind the adoption of PA including farm size, farmer income/education, cost reduction/higher revenue, location, and familiarity with computers. They discerned that educated farmers that owned large farms and had goals of implementing more competitive and productive practices to increase revenue were the most likely to adopt PA.

Similarly, turfgrass managers seeking to implement precision management practices have begun doing so under the name Precision Turfgrass Management (PTM) (Carrow et al. 2010; Ganjegunte et al. 2013; Straw et al. 2016; Straw and Henry 2017). Carrow et al. (2010) identified several driving forces behind the adoption of PTM including improved input efficiency, pressure to be more environmentally conscious, and the desire to adopt a ‘green company image’. Studies in PTM have focused primarily on improving water-use efficiency (Blonquist et al., 2006), site-specific salt leaching (Ganjegunte et al., 2013), and the evaluation of sensor technology to quantify turfgrass and turfgrass soil properties for various applications (Bell et al., 2013, Straw et al., 2016, Straw and Henry, 2017, Miller and Thomas, 2003). Applications for PTM in nutrient management of turfgrass systems have only been explored theoretically. Methods for improving resource-use efficiency and reducing environmental inputs of synthetic fertilizers could make a positive contribution to the sustainability of turfgrass systems as a whole (Carrow et al., 2010).

For reasons outlined by Carrow et al. (2010), delineation of SSMUs in turfgrass systems has proven challenging. A handful of studies have begun delineating SSMUs in turfgrass based on volumetric water content (VWC) of soil (Krum et al., 2010) and soil compaction via penetration resistance (Flitcroft et al., 2010). Straw and Henry (2017) also evaluated the spatiotemporal change of soil moisture, soil compaction, and turfgrass vigor SSMU's on athletic fields, and found that short-term variations during a dry down can be significant with implications for PTM practices.

Conventional Soil and Tissue Sampling

In order to determine nutrient requirements, turfgrass managers may sample soil or plant tissue directly. Soil tests are primarily used prior to planting or establishment to provide a general index of nutrient availability before plants are established (Havlin et al., 2005). Havlin et al. (2005) identified three primary objectives for soil testing: 1) to provide an estimate of the nutrient availability of a given soil, 2) to predict the profitability of fertilizer/lime applications, and 3) to build a foundation for providing fertilizer/lime recommendations. Though soil testing for inorganic N is possible, it is not useful for predicting N requirements, as NO_3 and NH_4 levels fluctuate widely over short periods of time (Carrow et al., 2001). Instead, estimates for soil N requirements are generally based on approximate annual recommendations reflective of environmental conditions and management practices.

In general, conventional soil sampling procedures can be both costly and time-consuming, rendering them impractical for predicting spatial variability of soil properties (Allred et al., 2008). Wollenhaupt et al. (1994) evaluated methods for improving soil sampling efficiency for VRF applications in large-scale agronomic production. Two primary methods were evaluated: 1) grid-cell method and grid-point method. The grid-cell method involved delineation of a large square cell in which soil samples were collected and composited for each cell, whereas the grid-point method involved collecting soil samples and sampling grid intersections. Following soil sampling, multiple methods of interpolation were used to generate spatial maps of the managed area. Interpolation techniques produce a continuous surface of estimated values from observed point values using different mathematical algorithms to generate estimates (Fortin and Dale, 2005). In this study, the grid-cell method appeared to improve mapping accuracy by between 14 and 33% over the field average; however, grid-cell methods were still determined unacceptable at generating maps for VRF applications. It was determined overall that soil samples should be collected on an unaligned systematic grid and that sample spacing would depend on field variability and application.

Tissue testing is more often used in conjunction with visible symptoms of nutrient deficiency or toxicity such as discoloration of leaf tissue, tip burn, and overall decline in plant health. Two methods can be used to test plant tissue: 1) total analysis of elemental content of plant tissue, and 2) rapid test of soluble nutrients (Murphy, 1993). While tissue testing can be a useful diagnostic tool, it is not a feasible method for estimating the spatial variability of nutrient requirements across a given area of turfgrass.

Sensor Technology

New advancements in sensor technology provide a faster, more efficient alternative method for quantifying soil spatial heterogeneity to implement precision management. For applications in nutrient management, sensor technology can be used to estimate nutrient content in plant tissue directly, and to estimate spatial distribution of soil properties related to soil fertility and nutrient availability.

Remote Sensing of Tissue Nitrogen

Optical sensing methods based on reflectance spectral measurements have been thoroughly explored as one pathway for estimating chlorophyll content in leaf tissue, which has been strongly correlated to tissue N (Bell et al., 2004a). Influenced by red (visible) and near infrared (NIR) (invisible) reflectance, NDVI is computed as [NIR – Red)]/[NIR + Red] (Bremer et al., 2011). Trenholm et al. (1999) found relationships between multispectral radiometry including NDVI and visual turf quality, shoot density, and shoot tissue injury. Because NDVI is strongly correlated to chlorophyll content, it provides an opportunity to quantify stress in plant tissues that results in chlorosis or discoloration of leaf tissue, as well as areas of reduced canopy density. In this regard, NDVI has also been used as a basis for delineating SSMUs based on turfgrass vigor (Straw and Henry, 2017).

Optical sensing and NDVI have been correlated to N fertility in creeping bentgrass (*Agrostis palustris*) (Bell et al., 2002) and bermudagrass (Bell et al., 2004b). Similarly, Agati et al. (2013) compared fluorescence-based indices with proximal sensing of N content in *Paspalum vaginatum* and *Zoysia matrella* turfgrasses. A fluorimetric sensor and LICOR device were used to collect spectral reflectance data from turfgrass plots treated with different amounts of N fertilizer. Multiple indices were employed to estimate the level of N fertilization, and then compared across species. Though no standard index could be identified as a proxy of leaf N across species, optical sensing methods demonstrated strong potential for sensing tissue N and determining N requirements in turfgrass management.

Spectral reflectance data can be collected by handheld (Straw et al., 2016), field (Agati et al., 2013), and aerial (Caturegli et al., 2016) sensors. Caturegli et al. (2016) compared spectral reflectance data from a handheld NDVI sensor with data collected from an unmanned aerial vehicle (UAV) and found strong correlations in the data, suggesting that handheld sensors offer a more practical alternative for measuring NDVI in small areas, whereas a UAV may be more appropriate for large-scale turfgrass evaluations.

In a collaborative project across 448 soil research sites, near-infrared spectroscopy (NIRS) has also been strongly correlated ($r^2 > 0.8$) to select soil properties including total C, total N, moisture, CEC, sand, silt, and Mehlich III extractable Ca (Chang et al., 2001). Additional soil properties including concentration of extractable metals and exchangeable cations, as well as clay, mineralizable N, and soil pH could also be estimated by NIRS with less accuracy ($r^2 = 0.8 – 0.5$). It is unclear whether similar correlations could be made in turfgrass systems with uniform vegetation over the soil surface.

Mapping of Soil Properties Related to Soil Fertility

Measurement of soil spatial heterogeneity of soil properties in turfgrass systems can be difficult due to the need for minimally-invasive technology (Krum et al., 2011, Carrow et al., 2010). Several studies have evaluated the use of subsurface soil moisture sensors to improve irrigation and water-use efficiency in turfgrass systems (Cardenas-Lailhacar et al., 2005, Cardenas-Lailhacar et al., 2008, Blonquist et al., 2006). Blonquist et al. (2006) used submerged time domain transmission (TDT) soil moisture sensors to implement precision irrigation. Rather than delineating SSMU's the TDT system was programmed to only irrigate when the estimated water content dropped below a pre-determined threshold. In doing this, the system theoretically only received water when necessary rather than on a set schedule. This study revealed that when compared to a conventional fixed irrigation system, the TDT system used approximately 53% less water, offering a monthly savings of between \$5.00 and \$100.00 month^{-1} 1000 m^{-2} irrigated turfgrass plot.

Handheld devices including NDVI sensors, VWC probes, and devices used to measure soil compaction and surface hardness provide turfgrass managers with cost-effective ways to quantify plant and soil properties on a smaller scale (Straw et al., 2016). However, to improve data collection efficiency over large areas, turfgrass researchers have begun developing and evaluating mobile sensor devices that can collect large volumes of data in small amounts of time (Flitcroft et al., 2010, Krum et al., 2010, Straw and Henry, 2017). The Toro Precision Sense 6000 (PS6000) was engineered to simultaneously measure VWC, soil compaction, soil salinity, and plant performance (NDVI), and has been evaluated for its efficacy in implementing site-specific management on golf courses (Flitcroft et al., 2010, Krum et al., 2010) and athletic fields (Straw et al., 2016, Straw and Henry, 2017). Data collected from the PS6000 was used to generate spatial maps of soil properties using kriging, a geostatistical interpolation technique so that SSMUs could be delineated (Straw and Henry, 2017).

In PA, mobile devices that measure soil apparent electrical conductivity (ECa) have been used to predict soil properties including soil texture (Cho et al. 2016; Pedrera-Parrilla et al. 2016a; Stadler et al. 2015), organic carbon (Gholizadeh et al. 2011), soil moisture (Pedrera-Parrilla et al. 2016b), and saturated hydraulic conductivity (Rezaei et al. 2016). Research employing EC_a sensors in turfgrass systems have primarily focused on the measurement of soil salinity for the purpose of implementing site-specific salt leaching (Carrow et al. 2010;

Ganjegunte et al. 2013; Krum et al. 2011). In non-saline soils, EC_a appears to be strongly driven by soil texture, or clay content, as EC_a measures conductance through solid soil particles and conductance by way of exchangeable cations in the solid-liquid interface of clay minerals. Mobile EC_a devices are able to collect large volumes of data in a short amount of time, but have not been used heavily in turfgrass due to the fact that many are invasive, penetrating the soil surface (Krum et al. 2011).

Krum et al. (2011) compared a minimally-invasive mobile salinity sensor device with saturated paste extract electrical conductivity, and found relationships with r^2 values ranging from 0.59 to 0.87. It was also suggested that the layered profile of turfgrass systems, particularly the stratification of a subsurface organic matter layer, may have affected soil salinity readings by impacting water holding capacity and soluble salt retention differently from more homogenous cropping soils. No research has evaluated the use of EC_a data for predicting soil properties in non-saline soils with potential applications for PTM and VRF.

Conclusion

Nutrient management of turfgrass systems is complex and requires a comprehensive understanding of above- and below-ground environmental properties, as well as the role of human activity and cultural practices. The emergence of Precision Turfgrass Management presents new opportunities to improve resource-use efficiency through site-specific management of turfgrass systems; however, limited research has evaluated practical applications for PTM in nutrient management. Future research should continue to explore applications for sensor technology in implementing variable rate fertility and PTM geared toward nutrient management, as conventional soil and tissue sampling methods are not practical for assessing large-scale spatial variability. In particular, researchers should continue to evaluate mobile and aerial sensor devices capable of measuring large volumes of data over short periods of time.

CHAPTER 3

PREDICTING SPATIAL STRUCTURE OF SOIL PHYSICAL AND CHEMICAL PROPERTIES OF GOLF COURSE FAIRWAYS USING AN APPARENT ELECTRICAL CONDUCTIVITY SENSOR[1]

[1] Grubbs, R.A., C.M. Straw, W.J. Bowling, D.E. Radcliffe, Z. Taylor, and G.M. Henry. Submitted to *Precision Agriculture*, 09/08/17

Abstract

Soil apparent electrical conductivity (EC_a) has been used to map spatial variability of soil properties in multiple cropping systems and may have applications in precision turfgrass management. The objective of this research was to determine whether EC_a data could predict the spatial structure of soil properties relevant to nutrient management in turfgrass. Research was conducted at the University of Georgia (UGA) golf course in Athens, GA and the Georgia Club (GC) golf course in Statham, GA during the summer of 2016. A mobile Veris Q1000 device was used to collect georeferenced EC_a data from six golf course fairways (three per course). Soil samples were collected from each fairway using a georeferenced 7 m x 7 m grid to compare EC_a data with clay content, soil pH, cation exchange capacity (CEC), and organic matter (OM). The positive relationship between EC_a and soil pH was consistent across all six fairways. Positive relationships between EC_a and clay content, and EC_a and OM, were also observed on fairways at UGA, though not at GC. Relationships between EC_a and CEC did not provide clear trends across both courses. However, significant positive relationships were observed between CEC and OM on all fairways. Spatial maps were used as a visual demonstration of these relationships. In conclusion, EC_a data may be able to accurately predict soil pH, clay content, and OM in turfgrass systems; however, further research is warranted to examine the dominant properties driving EC_a to ensure the accuracy of the mobile Veris Q1000 device.

Introduction

As of 2010, the number of golf courses worldwide was estimated to be upwards of approximately 32,000, covering between 19,200 and 25,600 km^2 of land (Bartlett and James 2011). Though comparatively smaller than many other cropping systems, golf courses tend to be concentrated around urban ecosystems and can have a significant impact on urban air and water quality. Traditional golf course management relies heavily on supplemental fertility to support healthy vegetative growth, since biogeochemical cycling in urban soils is often disrupted by anthropogenic activity that limits nutrient availability (Cheng and Grewal 2009; Milesi et al. 2005; van Delden et al. 2016). Poor understanding of turfgrass nutrient requirements can lead to fertilizer mismanagement and subsequent water and air pollution through leaching, runoff, and volatilization of harmful trace gases (Bartlett and James 2011; Milesi et al. 2005; Qian et al. 2003). On the other hand, nutrient deficiencies resulting from low fertility could lead to stunted vegetative growth, tissue chlorosis, as well as eventual necrosis and potential plant death (Carrow et al. 2001; Havlin et al. 2005). Even small nutrient imbalances can have large consequences for turfgrass managers, since they may compromise aesthetic quality, stress tolerance, and overall playability.

The implementation of Precision Agriculture (PA) may optimize nutrient management (Corwin and Lesch 2003; Rhoades et al. 1999). In PA, site-specific management units (SSMUs) are delineated in accordance with the spatial distribution of soil properties that ultimately affect management needs. These same principles are now being applied to turfgrass systems under the name Precision Turfgrass Management (PTM) (Carrow et al. 2010; Ganjegunte et al. 2013; Straw et al. 2016; Straw and Henry 2017). Similar to PA, PTM affords turfgrass managers the opportunity to improve input efficiency, thereby fostering environmental stewardship on large-scale turfgrass production (Carrow et al. 2010). One of the greatest challenges to implementing PA and PTM is that soil sampling procedures are both costly and time-consuming, rendering them impractical when mapping soil spatial heterogeneity (Allred et al. 2008). As such, alternative methods of data collection are employed to provide faster, more efficient methods for predicting spatial distribution of soil properties. The continuous surface of vegetation indicative of turfgrass systems presents a unique challenge to precision management, which limits data collection methods to those that are relatively non-invasive.

In recent years, quantification of apparent electrical conductivity (EC_a) has been used as a minimally-invasive method for predicting spatial patterns of soil properties important to crop management. The EC_a measures conductance through solid soil particles and via exchangeable cations in the solid-liquid interface of clay minerals in addition to the soil solution (Corwin and Lesch 2003; Rhoades et al. 1999). It is well-established in the literature that EC_a is effective at producing accurate, large-volume measurements that have practical applications for PA (Cho et al. 2016; Corwin and Lesch 2003; Huang et al. 2016; Pedrera-Parrilla et al. 2016b; Stadler et al. 2015). The applications of EC_a in PTM have centered primarily on salinity management and site-specific leaching (Carrow et al. 2010; Ganjegunte et al. 2013; Krum et al. 2011). However, in non-saline soils, EC_a has been correlated to a number of soil properties pertinent to nutrient management including soil texture (Cho et al. 2016; Pedrera-Parrilla et al. 2016a; Stadler et al. 2015), organic carbon (Gholizadeh et al. 2011), soil moisture (Pedrera-Parrilla et al. 2016b), and saturated hydraulic conductivity (Rezaei et al. 2016).

In many cropping systems, EC_a is predominantly driven by soil texture (Cho et al. 2016; Pedrera-Parrilla et al. 2016b; Stadler et al. 2015). Clay content in particular is often positively correlated with EC_a. Spatial variability in soil texture can greatly affect nutrient fate following fertilizer applications. Soils with a higher clay fraction will possess greater cation exchange capacity (CEC) due to clay particle structure (Brady and Weil 2008; Havlin et al. 2005). Greater CEC leads to nutrient adsorption to clay particles, which is further influenced by additional soil properties including soil organic matter and pH. However, in some cases the relationship between EC_a and soil texture is not consistent across locations, depth, or time (Cho et al. 2016; Stadler et al. 2015). This inconsistency has been attributed to influence from other soil properties including soil moisture and organic matter (OM), which can impact EC_a (Stadler et al. 2015). Therefore, it is important to explore the potential dependence of EC_a on other soil factors. Many studies examining the use of EC_a as a predictor for soil texture have focused on large agronomic cropping systems (Stadler et al. 2015) or orchard production (Fulton et al. 2011; Pedrera-Parrilla et al. 2016b). There is currently little to no research exploring the relationship between EC_a and soil texture in turfgrass systems.

The two primary geophysical survey methods employed to measure EC_a are electromagnetic induction (EMI) and electrical resistivity (ER) (Allred et al. 2008). This paper will focus on a newly developed mobile ER device specifically designed for turfgrass environments. Veris devices (Veris Technologies, Salina, KS) consist of cart-mounted coulters (discs) that function as four equally-spaced electrodes (referred to as a 4-Wenner array). Previously, these mobile units were not used in turfgrass systems to avoid potential surface damage (Krum et al. 2011). However, several units have been modified to penetrate the soil at a shallower depth of approximately 20 mm and collect measurements for the uppermost 0.3 to 0.4 m of the soil profile where most turfgrass roots are concentrated. The objective of this research was to determine whether the modified Veris device and EC_a data could be used to accurately predict the spatial structure of soil properties relevant to nutrient management in turfgrass systems (clay content, pH, CEC, and OM).

Materials and Methods

Site descriptions

Research was conducted at the University of Georgia (UGA) golf course in Athens, GA and the Georgia Club (GC) golf course in Statham, GA during the summer of 2016. Six fairways were selected (three per course). Individual fairways ranged from approximately 4000 m^2 to 8000 m^2 in area and were chosen to reflect changes in topography that may impact the spatial distribution of soil physical and chemical properties relevant to soil fertility. Fairways at UGA (F1, F2, and F3) and GC (F4, F5, and F6) were comprised of 'Tifway 419' hybrid bermudagrass [*Cynodon dactylon* L. (Pers.) x *C. transvaalensis* Burtt-Davy] established on native soil.

The UGA golf course was originally developed in 1968 and was extensively renovated in 2006; however, many of the fairways still reflect the original design. Soils for UGA fairways are classified as Pacolet sandy clay loams (severely eroded) with small sections of Cecil sandy loam (moderately eroded). Fairways were irrigated with an automated irrigation system as a supplement to rainfall. Fertility was applied in the spring as a combination of slow-release urea formaldehyde and conventional urea fertilizers at a rate of 48 to 96 kg N ha^{-1}. Micronutrients (Fe and Mg) were applied as needed.

The GC golf course has 27 holes and was built in two stages. Two fairways (F5 and F6) were constructed and established in 1999-2000, while F4 was established in 2005. Predominant soil classifications at GC were unique to each fairway, and included Pacolet sandy clay loam with moderate to severe erosion (F4), Cartecay and Chewacla soils (F5), and Madison sandy clay loam with moderate erosion (F6). Fairways were irrigated with an automated irrigation system as a supplement to rainfall. Fertility was applied as a slow-release urea-formaldehyde fertilizer (37-0-0) at a rate of 86 kg N ha^{-1}. A plant growth regulator (trinexapac-ethyl) with a liquid iron (Fe) fertilizer was applied intermittently throughout each growing season.

EC_a surveys

A 4-disc Veris Q1000 Soil EC Mapping System (Veris Technologies, Salina, KS) was used to collect EC_a data (mS m^{-1}) for each fairway. Veris devices measure resistivity (ρ, ω m^{-1}) using an electrode configuration referred to as the Wenner array given by the equation (Burger 1992):

$$\rho = \frac{2\pi r \Delta V}{i} = 2\pi a R \tag{1}$$

Where *V* is the voltage, *α* is the interelectrode spacing, *i* is the electrical current (A), and *R* is the measured resistance defined as one ohm (*ω*) of resistance that allows a current of one ampere to flow when a single volt of electromotive force is applied. Since EC_a is simply the inverse of *ρ*, the equation for EC_a in relation to resistivity can be written as:

$$EC_a = \frac{1}{2\pi a R} \tag{2}$$

The device was towed behind a utility vehicle which traversed each fairway at a speed of approximately 16 to 25 km h^{-1} and collected measurements at a rate of 1 Hz. The number of data points varied according to fairway size and shape, but ranged from 253 to 570 for a total of 2,493 points across all fairways. Device discs penetrated the ground at a depth of approximately 20 mm and collected EC_a measurements from the uppermost 0.3 to 0.4 m of the soil profile. A Trimble EZ Guide 250 (Trimble, Sunnyvale, CA) global positioning system (GPS) with an upgraded antenna for differential GPS was used in conjunction with the mobile device to simultaneously log EC_a and geographical coordinates. Resulting shapefiles were subsequently imported into ArcGIS (Esri, Redlands, CA) for geospatial analysis.

Soil sampling and analysis

Corresponding soil sampling grids for each fairway were generated in Geospatial Modeling Environment (Spatial Ecology LLC, St. Lucia, QLD, AUS) using a specified grid spacing of 7 m x 7 m. The total number of points per fairway varied according to fairway size, but ranged from 80 to 128 points per fairway for a total of 643 samples across all fairways. Each sampling grid was subsequently imported into a Trimble GPS Geoexplorer 6000 using ArcPad 10 mapping software (Esri, Redlands, CA). Composite samples of 10 to 15 soil cores (≈ 20 mm in diameter pulled to a 0.1-m depth) were collected within a 0.3-m radius of each georeferenced point. Intact cores were collected in 0.95-L plastic bags and were immediately frozen to preserve core integrity. Individual soil samples were air-dried for 48 hours, sieved through a 2-mm mesh, and shipped to Waypoint Analytical Labs in Memphis, TN for soil analysis.

Soil samples were analyzed for CEC, pH, and OM. Particle-size analysis (% sand, silt and clay) was completed using the hydrometer method to determine soil texture (Bouyoucos 1936; Day 1965). Soil pH was determined using methods outlined by Eckert and Sims (2009). However, deionized water was used in lieu of $CaCl_2$ solution. Determination of OM was completed through loss of ignition (Schulte and Hoskins 2009), with the soil heated at 400 °C instead of 360 °C. Macronutrients (K, Ca, and Mg) were extracted using the Mehlich 3 extraction procedure (Mehlich 1984). Cation exchange capacity (meq $100g^{-1}$) was subsequently calculated from the sum of Ca, Mg, and K obtained (ppm) using the following equation from Ross and Ketterings (1995):

$$CEC_{sum}\ \left(\frac{meq}{100\ g\ or\ cmol_c\ kg^{-1}}\right) = \left(\frac{ppm\ Ca}{200}\right) + \left(\frac{ppm\ Mg}{120}\right) + \left(\frac{ppm\ K}{390}\right) \tag{3}$$

EC_a semivariogram analysis and kriging

ArcMap 10.3.1 mapping software (Esri, Redlands, CA), RStudio version 3.2.1 (RStudio, Inc., Boston, MA), and SAS 9.4 (SAS Institute Inc., Cary, NC) were used to develop, display, analyze, and interpret the data. All analyses conducted in ArcMap utilized the projected coordinate system NAD 1983 State Plane Georgia East FIPS 1001. Descriptive statistics [mean, min, max, standard deviation, and coefficient of variability (CV)] were produced for all sampled fairways to evaluate central tendency and variability of the data for individual soil properties.

Spatial maps were created for both apparent electrical conductivity point data and corresponding soil sampling grids. These maps were used to visualize and compare spatial variability of clay content (%), EC_a (mS m^{-1}), soil OM (%), and CEC (meq $100g^{-1}$). Soil sample and EC_a data collected by the Veris Q1000 were interpolated using ordinary point kriging (Schabenberger and Pierce 2001). Kriging is a geostatistical technique that determines the best combination of weights for interpolation using the spatial parameters (range, nugget, and sill) of an experimental semivariogram (Fortin and Dale 2005). Semivariograms were plotted using the

VARIOGRAM Procedure in SAS 9.4 to depict the spatial autocorrelation of measured points for each parameter (clay content, OM, CEC, pH, and ECa) on each fairway. Models with Gaussian, spherical, or exponential structures were selected for all fairways and parameters according to lowest Akaike information criterion (AIC). Semivariogram parameters are presented in Tables 1 and 2. Lag sizes were determined either by sample grid spacing when uniform (clay content, pH, CEC, and OM) or by calculating the average 'Nearest Neighbor' in ArcMap for more irregular sampling schemes (EC_a data).

Estimated EC_a values were extracted to each sampling grid point to evaluate the relationship between EC_a and soil physical and chemical properties (clay content, pH, CEC, and OM). The 'modified.ttest' function in the SpatialPack package of RStudio version 3.2.1 was used to calculate a corrected Pearson's *r* correlation coefficient that accounted for spatial autocorrelation between soil properties (Osorio et al. 2012). In cases where data distributions were not normal, modified t-tests were conducted on ranked data sets to adjust for skewness.

Simple linear regression models were determined for UGA and GC to predict clay content and pH based on EC_a using the generalized least squares ('gls') function in the 'nlme' package of RStudio (Pinheiro et al. 2015). Models were only generated for those relationships which had significant correlation coefficients. Other relationships were not modeled because EC_a-CEC and EC_a-OM correlation coefficients were either weak or nonsignificant; however, regression models were determined to predict CEC from OM to demonstrate the importance of OM in determining nutrient availability in turfgrass systems. To account for spatial association among observations, multiple spatial correlation structures (Gaussian, spherical, exponential, and linear) were incorporated into the residual patterns. The correlation of residuals is determined by the distance between all pairs of data points. Models with Gaussian or exponential correlation structures were selected for all fairways and parameters according to lowest AIC.

Results and Discussion

Descriptive statistics and kriged maps

Descriptive statistics for soil and sensor data are summarized in Tables 3 and 4. Average soil EC_a was slightly higher at GC ($\bar{x}$ = 6.6 mS m^{-1}) compared to UGA ($\bar{x}$ = 4.8 mS m^{-1}). The UGA location exhibited more spatial variability in EC_a with a range of 15.4 mS m^{-1} and a CV of 37.7% compared to a range of 14.2 mS m^{-1} and a CV of 32.5% at GC. Mean clay contents for UGA and GC were 15% and 9%, respectively. Ranges in clay content at each course were comparable (26% at UGA and 24% at GC). However, clay content at GC had a higher coefficient of variation (49.0%) than UGA (31.1%) indicating a greater degree of spatial variability in clay content for sampled GC fairways.

Soil pH was acidic for both locations, but more so at UGA ($\bar{x}$ = 5.5) than at GC ($\bar{x}$ = 6.3). Optimum pH range for most turfgrasses is between 6 and 7; however, bermudagrass typically tolerates a much wider range (Carrow et al. 2001). Neither location exhibited a high degree of variability with a CV of 3.8% at UGA and 4.1% at GC. Organic matter content was greater at GC (x = 8.1%) compared to UGA ($\bar{x}$ = 5.7%). Coefficients of variation for OM at UGA and GC were 20.1% and 24%, respectively. Finally, mean CEC was calculated at 5.7 meq 100 g^{-1} at UGA (CV = 19.2%) and 8.3 meq 100 g^{-1} at GC (CV = 14.3%).

Semivariogram parameters for EC_a, clay content, OM, CEC, and soil pH for all 6 individual fairways can be found in Tables 1 and 2. A total of 30 maps were generated to visualize spatial distribution of soil physical and chemical properties; however, only select maps will be presented in order to demonstrate specific points for discussion.

Correlations between EC_a and soil properties

Correlation coefficients are summarized in Tables 5 and 6. Relationships between soil properties were site-specific and varied across and within individual golf courses. At UGA, EC_a positively correlated with all other soil properties (clay content, pH, CEC, and OM) on all fairways. However, the strength and significance of these correlations was different for individual fairways. Relationships between EC_a and soil physical and chemical properties at GC were generally weak and less consistent, with few discernible trends and patterns.

Soil EC_a and clay content

In general, EC_a-clay content correlation coefficients were positive at UGA and negative at GC; however, these relationships were only significant on three fairways (F3, F5, and F6). Only one fairway (F3) at UGA was found to have a significant relationship between EC_a and clay content (r = 0.40). Maps to compare EC_a and clay content for F3 are displayed in Fig. 1. Areas with high and low EC_a generally corresponded with areas of high and low clay content, respectively. A strong positive correlation was also observed on F1 (r = 0.70). Though this correlation coefficient was not significant, visual comparison of EC_a and clay content maps for F1 (not shown) indicated a clear relationship. The strength and positive nature of these relationships is similar to that seen by previous researchers who also found positive EC_a-clay correlation coefficients (Pedrera-Parrilla et al. 2016b; Stadler et al. 2015). However, even when positive EC_a-clay content relationships are established, these relationships are not necessarily consistent across multiple locations within the same study (Stadler et al. 2015). A weak, non-significant positive correlation was observed on F2 (r = 0.14). A visual comparison of the EC_a

and clay maps for F2 (not shown) disclosed no clear relationship. Parameters for linear models using EC_a to predict clay content are summarized in Table 2.7. Models for F1 and F3 were significant at the $P < 0.001$ level, while F2 was significant at the $P < 0.05$ level. This is consistent with the strength of correlation coefficients.

In contrast to UGA, relationships between EC_a and clay content at GC were generally weak and negative. Fairways 5 and 6 were similar to one another ($r = -0.25$ and $r = -0.22$, respectively), while Fairway 4 showed no relationship between EC_a and clay content ($r = 0.04$). Results indicate that EC_a collected with a Veris device may not be appropriate for predicting spatial structure of clay content at GC. The lack of relationship may be attributed to lower mean clay content. Mean clay content at UGA was greater than at GC (15% and 9%, respectively). Previous research with Veris devices reported poor correlation with coarser textured soils compared to noninvasive EMI devices (Corwin and Lesch 2003, 2005). Weak or inconsistent relationships between clay content and other soil properties including pH, CEC, and OM (Table 2.6) further supports the hypothesis that clay content is not a dominant property influencing soil physical and chemical processes at GC.

Soil EC_a and pH

Relationships between EC_a and soil pH were more consistent across locations. Though the strength of the relationship varied, positive relationships were identified across all fairways. Correlations between EC_a and soil pH at UGA ranged from 0.30 (F1) to 0.47 (F2). Trends were similar at GC, but correlation coefficients were generally weaker and ranged from 0.16 (F5) to 0.33 (F4). All correlations were significant with the exception of F1 at UGA.

Parameters for linear regression models using EC_a to predict soil pH are outlined in Table 2.8. Models for Fairways 2 and 3 were significant at the $P < 0.001$ level, while the model for Fairway 6 was significant at the $P < 0.05$ level. No other model was determined to be significant. Maps generated in order to visualize the spatial variability of EC_a and soil pH for F2 are displayed in Fig. 2. Visual comparison of the two maps point to a clear positive relationship with the highest EC_a and soil pH values concentrated on the eastern portion of the fairway and the lowest values concentrated down the center of the fairway. More moderate values for EC_a and soil pH also appear to be directly correlated to one another.

Minimal research has explored the relationship between EC_a and soil pH. Gholizadeh et al. (2011) observed a significant positive EC_a-soil pH correlation ($r = 0.35$) with shallow EC_a data collected using a Veris device in Malaysian paddy fields with a similar mean pH (5.3). Soil pH influences a number of soil processes and properties that are important for turfgrass management including CEC, soil microbial transformations, lime requirements, and nutrient availability (Carrow et al. 2001). The ability to predict spatial structure and identify spatial trends in soil pH may improve precision turf management practices, particularly for applications of soil amendments such as lime. Future research should evaluate the role of soil moisture for the prediction of soil pH from EC_a sensor devices. Additionally, it is unclear whether these relationships would extend to other pH ranges, since research has only evaluated acidic soils in the 5.5 to 6.5 range.

Soil EC_a, cation exchange capacity, and organic matter

At UGA, only F3 exhibited a weak significant correlation between EC_a and CEC ($r = 0.21$). Visual comparisons of EC_a and CEC maps for F3 did not support the existence of a strong spatial relationship. Correlation coefficients between EC_a and CEC on F1, F2, F4, F5, and F6 were highly variable, and tended to be more positive at UGA and more negative at GC (Tables 5 and 6). These correlations were generally weak with the exception of F1 (r = 0.39), which was not significant. Visual comparison of EC_a and CEC maps (not shown) for F1 did not show a strong spatial relationship. The absence of discernible trends across fairways indicates that Veris collected EC_a data is not a strong predictor for CEC at either GC or UGA. Although EC_a has been correlated to CEC in previous studies (McBride et al. 1990; Triantafilis et al. 2002), these relationships were attributed to greater variability in soil mineralogy and salinity. Additionally, researchers predominantly used EMI devices, which are noninvasive and less affected by soil moisture and coarse textures (Corwin and Lesch 2003). It is possible that EC_a-CEC correlations could be strengthened with the use of an alternative device, particularly on golf course fairways with lower clay content. Alternative methods for determining CEC may also change EC_a-CEC correlations. Mehlich III and similar extraction methods may overestimate CEC by dissolving precipitate materials in the soil when compared with methods that use different exchange solutions (Dohrmann and Kaufhold 2009). Traditionally, this is not an issue for southeastern soils since they are not calcareous; however, recent lime applications could impact CEC values.

The only fairway that exhibited a significant relationship between EC_a and OM was F3 at UGA (r = 0.21). Visual comparison of maps (not shown) confirmed a weak relationship. Based on these visual comparisons and a weak correlation value ($\leq$ 0.36), OM does not appear to be the dominant factor affecting EC_a values for this fairway. Though not significant, F1 had a moderately positive EC_a-OM correlation (r = 0.47). Visual comparison of spatial maps (Fig. 3) confirms a moderately positive relationship between these two parameters. All remaining fairways (F2, F4, F5, and F6) showed no significant EC_a-OM relationship, and no discernible trends could be established either within or across golf courses. The EC_a-OM relationship varied significantly across previous research (Gholizadeh et al. 2011; Jaynes 1996; Moral et al. 2010). Soil apparent electrical conductivity has been positively correlated to organic carbon in Malaysian paddy fields (Gholizadeh et al. 2011), but exhibited no correlation to OM in Spanish rapeseed fields (Moral et al. 2010).

Cation exchange capacity was more strongly correlated with OM than any other soil physical or chemical property. The CEC-OM relationship was significantly positive on all fairways with correlation coefficients ranging from $r = 0.24$ (F2) to $r = 0.63$ (F1). Parameters for linear regression models used to predict CEC from OM are outlined in Table 2.9. All models were determined to be significant at the $P < 0.001$ level with the exception of F2 ($P = 0.164$). This was consistent with correlation coefficients across fairways, since F2 was the only fairway that did not exhibit a strong or significant correlation between CEC and OM. Maps for CEC and OM from F5 are displayed in Fig. 4 to demonstrate the visible relationship between the two soil properties. Areas with higher CEC on the eastern section of the fairway correspond to areas with higher OM, and areas with lower CEC correspond to areas with lower OM on the western portion of the fairway.

The relationship between CEC and OM has not been extensively explored in turfgrass systems. Previous researchers have indicated that the role of OM may be unique in turfgrass due to the layered nature of the soil profile, indicative of a continuous perennial surface (Krum et al. 2011). Organic matter influence on root zone CEC may be greater for turfgrass than other cropping systems, because the OM layer is more pronounced and not subjected to cultivation practices that create a more homogeneous soil profile. This is important for nutrient management, since OM content may provide a more definitive indication of nutrient availability in the root zone than soil texture. However, it does not appear that EC_a data collected from a Veris device provides an accurate representation of CEC or OM spatial variability on golf course fairways. Alternative methods for mapping these properties need to be explored.

Other factors for consideration

Surface topography can influence the spatial variability of EC_a (Corwin and Lesch 2005; Fritz et al. 1999). Maps for F1 revealed strong visual trends between soil physical and chemical properties. Interestingly, despite visual evidence of soil spatial relationships between properties, correlation coefficients between EC_a and other soil properties (clay content, pH, CEC, and OM) were not significant (Table 2.5). Topographical data were not collected, but F1 generally slopes upward from west to east (toward the putting green). For all soil properties, greater values are concentrated on the western section of the fairway, while lower values are concentrated on the eastern portion. This may be an indication of soil moisture and clay colloid accumulation as a function of topographical changes, since smaller particles (clay and OM) are more likely to run off following rainfall and irrigation events (Corwin and Lesch 2005). Topography has also been found to impact soil aggregation, soil organic carbon, and total nitrogen in some systems (Auoubi et al. 2012). The UGA course is much older than GC, and may be more influenced by topographical changes as a consequence of age. Additional research exploring the role of topography could be important to understand the spatial variability of soil properties, particularly on golf course fairways that were designed with significant changes in elevation. The resulting accumulation at the base of this fairway could lead to an increase in clay content and OM, as well as CEC, pH, and EC_a since these properties are positively correlated with one another.

Soil moisture may impact results, because measurements of ER require close contact between the soil and device electrodes (Corwin and Lesch 2005). Several studies have suggested mapping at field capacity to establish stronger correlations between EC_a and soil physical properties such as clay content (Brevik et al. 2006; Islam et al. 2012; Pedrera-Parrilla et al. 2016b). Although Pedrera-Parrilla et al. (2016b) established stronger correlations when EC_a measurements were collected under wet soil conditions, they suggested that dry soil does not inhibit the efficacy of EC_a surveys to predict soil texture. However, accounting for soil moisture in future research may provide a clearer understanding of these relationships and increase the accuracy of Veris collected EC_a data of fairways on golf courses with lower clay content.

Soil depth may also play a role in EC_a applications for turfgrass systems. Although spatial structure remains intact, previous research in other cropping systems observed shifts in correlations between EC_a and other soil properties (including clay content) with increasing depth. Cho et al. (2016) noted a decline in fit between EC_a and clay content with increasing depth, while Stadler et al. (2015) observed an improvement in fit with increasing depth. Mapping soil properties of the uppermost soil profile is most relevant for fertility management in turfgrass systems, because most rooting occurs there. Current devices may collect data at depths that exceed this region and therefore do not provide the best representation of relevant soil spatial variability.

Conclusion

A modified Veris device was utilized to collect EC_a data across six fairways at two golf courses in North Georgia (UGA and GC) to determine whether EC_a could be used to predict the spatial variability of soil physical and chemical properties that are difficult to measure. Golf course fairways exhibited spatial variability of clay content, soil pH, CEC, and OM, all of which have an impact on fertility management in turfgrass. Relationships between EC_a and soil properties were established through a combination of traditional statistical methods and visual comparison of spatial maps. In general, the relationships between measured parameters varied significantly both across and within locations. Moderate to strong positive relationships were established between EC_a and clay content on two fairways at UGA (F1 and F3), but relationships on all remaining fairways were weak and varied between positive (F2 and F4) and negative (F5 and F6). Relationships between EC_a and OM were consistently weak across fairways with the exception of F1; however, moderate to strong positive relationships were observed between CEC and OM for five out of six fairways. Therefore, CEC in turfgrass root zones may be strongly influenced by OM, which could be important to turfgrass managers when delineating zones for site specific management. Consistent positive correlations between EC_a and soil pH observed for all fairways indicates that the Veris device is effective at predicting pH trends on golf course fairways at these locations. Accuracy of Veris collected EC_a data in predicting spatial structure of soil physical and chemical properties is location-specific. Future research should evaluate the role of soil moisture to strengthen the relationships between ER devices and soil properties in turfgrass systems.

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Table 2.1. Semivariogram parameters of EC_a[a] (mS m^{-1}), clay content (%), soil pH, CEC (meq $100g^{-1}$), and OM (%) at the University of Georgia golf course in Athens, GA in 2016.

	Sample Size	Nugget	Sill	Range	Lag Size[b]	Number of Bins[c]	Model[d]	RMSE
				F1				
EC_a	253	0.8	1.5	40.2	4.1	24	Exponential	1.0
Clay	93	1.2	29.0	98.0	7.0	14	Exponential	3.0
pH	93	0.0	0.0	98.0	7.0	14	Exponential	0.2
CEC	93	0.0	0.7	32.9	7.0	14	Exponential	0.6
OM	93	0.5	0.9	98.0	7.0	14	Exponential	0.9
				F2				
EC_a	293	2.9	1.0	98.0	3.5	28	Exponential	1.4
Clay	87	8.8	16.3	44.3	7.0	14	Spherical	3.2
pH	87	0.0	0.1	98.0	7.0	14	Exponential	0.2
CEC	87	0.5	1.1	28.7	7.0	14	Spherical	0.9
OM	87	0.6	1.1	49.6	7.0	14	Exponential	0.9
				F3				
EC_a	427	0.7	2.2	26.6	3.7	41	Spherical	1.1
Clay	147	9.6	20.4	98.0	7.0	22	Exponential	3.7
pH	147	0.0	0.0	154.0	7.0	22	Exponential	0.2
CEC	147	49.9	50.7	49.9	7.0	22	Exponential	0.7
OM	147	0.4	1.3	80.4	7.0	22	Exponential	0.9

[a]Abbreviations: EC_a (apparent electrical conductivity); OM, organic matter; CEC, cation exchange capacity; RMSE, root-mean-square error.

[b]The lag size is the respective sample grid spacing. If the grid was not symmetrical then the average 'Nearest Neighbor' was used (EC_a data).

[c]The number of bins was calculated from half the maximum distance in the data set divided by the respective sampling grid spacing.

[d]Models were selected from spherical, exponential, and Gaussian spatial correlation structures according to lowest Akike information criterion.

Table 2.2. Semivariogram parameters of EC_a[a] ($mS\ m^{-1}$), clay content (%), soil pH, CEC (meq $100g^{-1}$), and OM (%) at the Georgia Club golf course in Statham, GA in 2016.

	Sample Size	Nugget	Sill	Range	Lag Size[b]	Number of Bins[c]	Model[d]	RMSE
				F4				
EC_a	469	0.3	5.9	32.7	1.9	35	Exponential	1.3
Clay	80	3.7	6.2	16.0	7.0	9	Spherical	2.5
pH	80	0.0	0.1	63.0	7.0	9	Exponential	0.2
CEC	80	0.6	0.9	13.5	7.0	9	Exponential	1.0
OM	80	2.3	2.7	47.7	7.0	9	Spherical	1.6
				F5				
EC_a	570	1.2	1.1	54.9	2.8	44	Exponential	1.1
Clay	128	0.0	0.0	13.5	7.0	18	Gaussian	0.1
pH	128	0.0	0.0	13.5	7.0	18	Spherical	0.2
CEC	128	0.6	1.5	126.0	7.0	18	Exponential	0.9
OM	128	3.0	5.6	82.1	7.0	18	Spherical	1.9
				F6				
EC_a	481	0.3	4.3	14.7	2.6	43	Exponential	1.5
Clay	108	6.7	32.9	112.0	7.0	16	Exponential	3.6
pH	108	0.0	0.0	19.2	7.0	16	Spherical	0.2
CEC	108	0.5	1.5	22.3	7.0	16	Spherical	1.1
OM	108	1.5	2.5	112.0	7.0	16	Exponential	1.4

[a]Abbreviations: EC_a, apparent electrical conductivity; OM, organic matter; CEC, cation exchange capacity; RMSE, root-mean-square error.

[b]The lag size is the respective sample grid spacing. If the grid was not symmetrical then the average 'Nearest Neighbor' was used (EC_a data).

[c]The number of bins was calculated from half the maximum distance in the data set divided by the respective sampling grid spacing.

[d]Models were selected from spherical, exponential and Gaussian spatial correlation structures according to lowest Akike information criterion.

Table 2.3. Descriptive statistics for ECa[a] (mS m^{-1}), clay content (%), soil pH, CEC (meq $100g^{-1}$), and OM (%) at the University of Georgia golf course in Athens, GA in 2016.

	Fairway	Sample Size	Min	Max	Range	Mean	Standard Deviation	CV (%)
			mS m^{-1}					
	1	253	1.4	8.8	7.4	4.1	1.4	34.4
EC_a	2	293	1.3	16.7	15.4	4.4	1.9	43.6
	3	427	1.6	10.5	8.9	5.5	1.7	31.0
	Course[b]	**973**	**1.3**	**16.7**	**15.4**	**4.8**	**1.8**	**37.7**
			%					
	1	93	2	26	24	14	5.5	39.0
Clay	2	87	4	28	24	14	4.0	28.8
	3	147	6	27	21	16	4.2	25.5
	Course	**327**	**2**	**28**	**26**	**15**	**4.7**	**31.1**
	1	93	5.0	6.0	1.0	5.4	0.2	3.1
pH	2	87	5.1	6.4	1.3	5.5	0.2	4.4
	3	147	5.0	6.2	1.2	5.55	0.2	3.6
	Course	**327**	**5.0**	**6.4**	**1.4**	**5.5**	**0.2**	**3.8**
			meq $100g^{-1}$					
	1	93	3.4	7.2	3.8	4.8	0.9	18.1
CEC	2	87	3.5	9.6	6.1	6.1	1.0	17.2
	3	147	3.4	8.8	5.4	6.0	0.9	15.1
	Course	**327**	**3.4**	**9.6**	**6.2**	**5.7**	**1.1**	**19.2**

					%			
	1	93	3.8	8.2	4.4	5.1	0.9	18.3
OM	2	87	4.1	9.3	5.2	6.0	1.0	16.7
	3	147	3.1	10.3	7.2	5.9	1.2	20.7
	Course	**327**	**3.1**	**10.3**	**7.2**	**5.7**	**1.1**	**20.1**

[a]Abbreviations: EC_a, apparent electrical conductivity; OM, organic matter; CEC, cation exchange capacity; CV, coefficient of variation.

[b]Descriptive statistics for all three fairways measured at the UGA course.

Table 2.4. Descriptive statistics for EC_a[a] (mS m^{-1}), clay content (%), soil pH, CEC (meq $100g^{-1}$), and OM (%) at the Georgia Club golf course in Statham, GA in 2016.

	Fairway	Sample Size	Min	Max	Range	Mean	Standard Deviation	CV (%)
			mS m^{-1}					
EC_a	4	469	1.6	15.5	13.9	6.7	2.3	34.3
	5	570	1.3	12.7	11.4	5.6	2.1	37.0
	6	481	2.6	14.7	12.1	7.7	2.1	27.2
	Course[b]	**1520**	**1.3**	**15.5**	**14.2**	**6.6**	**2.1**	**32.5**
			%					
Clay	4	80	2	15	13	7	2.5	34.8
	5	128	4	14	10	8	2.2	29.8
	6	108	4	26	22	12	5.7	47.7
	Course	**316**	**2**	**26**	**24**	**9**	**4.4**	**49.0**
pH	4	80	6.2	7.2	1	6.6	0.2	3.1
	5	128	5.6	6.9	1.3	6.2	0.2	3.6
	6	108	5.7	6.9	1.2	6.3	1.2	3.0
	Course	**316**	**5.6**	**7.2**	**1.6**	**6.3**	**0.3**	**4.1**
			meq $100g^{-1}$					
CEC	4	80	5.3	10.6	5.3	7.8	1.0	12.3
	5	128	5.6	12.1	6.5	8.6	1.2	14.2
	6	108	5.8	13.1	7.3	8.4	1.4	14.3
	Course	**316**	**5.3**	**13.1**	**7.8**	**8.3**	**1.2**	**14.3**

				——————— % ———————				
	4	80	3.7	12.8	9.1	7.5	1.6	21.1
OM	5	128	4.6	18.3	13.7	8.8	2.3	26.0
	6	108	4.9	12.4	7.5	7.7	1.4	18.7
	Course	**316**	**3.7**	**18.3**	**14.6**	**8.1**	**1.9**	**24.0**

[a]Abbreviations: EC_a, apparent electrical conductivity; OM, organic matter; CEC, cation exchange capacity; CV, coefficient of variation.

[b]Descriptive statistics for all three fairways measured at the UGA course.

Table 2.5. Correlation coefficients between EC_a[a] (mS m^{-1}), clay content (%), soil pH, CEC (meq $100g^{-1}$), and OM (%) for fairways F1, F2, and F3 at the University of Georgia golf course in Athens, GA in 2016.

	EC_a	Clay	pH	CEC	OM
			F1		
EC_a	1				
Clay	0.70	1			
pH	0.30	0.25	1		
CEC	0.39	0.49	0.02	1	
OM	0.47	0.46*	0.05	0.63*	1
			F2		
EC_a	1				
Clay	0.14	1			
pH	0.47*	0.01	1		
CEC	0.17	0.17	-0.07	1	
OM	0.14	0.12	-0.19	0.24*	1
			F3		
EC_a	1				
Clay	0.4*	1			
pH	0.36*	0.25	1		
CEC	0.21*	0.26*	-0.03	1	
OM	0.21*	0.13*	-0.13	0.54*	1

Significant correlations (*$P < 0.05$).

[a]Abbreviations: EC_a, apparent electrical conductivity; CEC, cation exchange capacity; OM, organic matter.

Table 2.6. Correlation coefficients between EC_a[a] (mS m^{-1}), clay content (%), pH, CEC (meq $100g^{-1}$), and OM (%) for fairways F4, F5, and F6 at the Georgia Club golf course in Statham, GA in 2016.

	EC_a	**Clay**	**pH**	**CEC**	**OM**
			F4		
EC_a	1				
Clay	0.04	1			
pH	0.33*	0.26*	1		
CEC	-0.12	-0.23*	0.07	1	
OM	-0.10	-0.48*	-0.34*	0.35*	1
			F5		
EC_a	1				
Clay	-0.25*	1			
pH	0.16*	-0.02	1		
CEC	-0.07	0.23	0.02	1	
OM	-0.07	0.27	-0.31	0.57*	1
			F6		
EC_a	1				
Clay	-0.22*	1			
pH	0.27*	0.22	1		
CEC	0.10	0.03	0.25*	1	
OM	0.11	-0.25	-0.20	0.44*	1

Significant correlations (*$p < 0.05$).

[a]Abbreviations: EC_a, apparent electrical conductivity; CEC, cation exchange capacity; OM, organic matter.

Table 2.7. Simple linear regression models for the University of Georgia golf course in Athens, GA and the Georgia Club golf course in Statham, GA to predict clay content based on EC_a[a] (mS m^{-1}) using the generalized least squares method.

University of Georgia							
Fairway	**Model**[b]	**Coefficient**	**Estimate**	**Std. Error**	***t***	**p-value**	**95% CI**
1	Exponential	Intercept	3.38	4.12	0.82	0.415	-4.7 – 11.45
		EC_a	2.68	0.79	3.40	0.001**	1.14 – 4.22
2	Gaussian	Intercept	9.31	7.44	1.25	0.214	-5.27 – 23.88
		EC_a	0.90	0.38	2.34	0.021*	0.15 -1.64
3	Gaussian	Intercept	9.49	1.78	5.35	<0.001***	6.01 – 12.97
		EC_a	1.26	0.31	4.01	<0.001***	0.64 -1.88
Georgia Club							
Fairway	**Model**[b]	**Coefficient**	**Estimate**	**Std. Error**	***t***	**p-value**	**95% CI**
4	Gaussian	Intercept	6.80	1.16	5.86	<0.001***	4.52 – 9.07
		EC_a	0.06	0.16	0.39	0.696	-0.25 – 0.37
5	Exponential	Intercept	9.18	2.09	4.40	<0.001***	5.06 -13.27
		EC_a	-0.30	0.36	-0.84	0.403	-1.01 – 0.4
6	Gaussian	Intercept	20.94	10.32	2.03	0.045*	0.70 – 41.17
		EC_a	-0.22	0.25	-0.89	0.374	- 0.71 – 0.27

*,**,*** significant at the 0.05, 0.01, 0.001 probability level, respectively.

[a]Abbreviations: EC_a, apparent electrical conductivity; CI, confidence interval.

[b]Models with Gaussian and exponential spatial correlation structures were selected according to lowest Akaike information criterion.

Table 2.8. Simple linear regression models for the University of Georgia golf course in Athens, GA and the Georgia Club golf course in Statham, GA to predict soil pH based on EC_a[a] (mS m^{-1}) using the generalized least squares method.

Fairway	Model[b]	Coefficient	Estimate	Std. Error	*t*	p-value	95% CI
		University of Georgia					
1	Gaussian	Intercept	5.36	0.14	38.95	<0.001***	5.09 – 5.63
		EC_a	0.02	0.03	0.47	0.637	-0.05 – 0.08
2	Gaussian	Intercept	4.97	0.13	38.35	<0.001***	4.71 – 5.23
		EC_a	0.12	0.03	4.35	<0.001***	0.07 – 0.18
3	Exponential	Intercept	5.51	0.29	19.26	<0.001***	4.95 – 6.07
		EC_a	0.06	0.01	5.46	<0.001***	0.04 – 0.09
		Georgia Club					
Fairway	Model[b]	Coefficient	Estimate	Std. Error	*t*	p-value	
4	Gaussian	Intercept	6.44	0.09	70.25	<0.001***	6.26 – 6.62
		EC_a	0.02	0.01	1.45	0.154	-0.01 – 0.04
5	Exponential	Intercept	5.90	0.17	34.08	<0.001***	5.56 – 6.24
		EC_a	0.05	0.03	1.59	0.115	-0.01 – 0.05
6	Gaussian	Intercept	6.09	0.09	68.76	<0.001***	5.92 – 6.24
		EC_a	0.03	0.01	2.55	0.012*	0.01 – 0.05

*,**,*** significant at the 0.05, 0.01, 0.001 probability level, respectively.

[a]Abbreviations: EC_a, apparent electrical conductivity; CI, confidence interval.

[b]Models with Gaussian and exponential spatial correlation structures were selected according to lowest Akaike information criterion.

Table 2.9. Simple linear regression models for the University of Georgia golf course in Athens, GA and the Georgia Club golf course in Statham, GA to predict CEC[a] (meq $100g^{-1}$) based on EC_a (mS m^{-1}) using the generalized least squares method.

University of Georgia							
Fairway	**Model[b]**	**Coefficient**	**Estimate**	**Std. Error**	***t***	**p-value**	**95% CI**
1	Gaussian	Intercept	3.10	0.39	7.93	<0.001***	2.33 - 3.86
		OM	0.37	0.07	5.40	<0.001***	0.23 - 0.50
2	Gaussian	Intercept	5.23	0.74	7.06	<0.001***	3.78 - 6.68
		OM	0.15	0.11	1.40	0.164	0.06 - 0.37
3	Exponential	Intercept	3.08	0.38	8.01	<0.001***	2.33 - 3.83
		OM	0.48	0.06	8.43	<0.001***	0.37 - 0.59
Georgia Club							
Fairway	**Model[b]**	**Coefficient**	**Estimate**	**Std. Error**	***t***	**p-value**	**95% CI**
4	Gaussian	Intercept	6.00	0.44	13.51	<0.001***	5.13 - 6.87
		OM	0.25	0.06	4.36	<0.001***	0.14 - 0.36
5	Exponential	Intercept	6.10	0.47	12.85	<0.001***	5.17 - 7.02
		OM	0.23	0.06	3.84	<0.001***	0.12 - 0.35
6	Exponential	Intercept	5.47	0.59	9.28	<0.001***	4.32 - 6.63
		OM	0.37	0.07	5.41	<0.001***	0.24 - 0.51

*,**,*** significant at the 0.05, 0.01, 0.001 probability level, respectively.

[a]Abbreviations: CEC, cation exchange capacity; EC_a, apparent electrical conductivity; CI, confidence interval.

[b]Models with Gaussian and exponential spatial correlation structures were selected according to lowest Akaike information criterion.

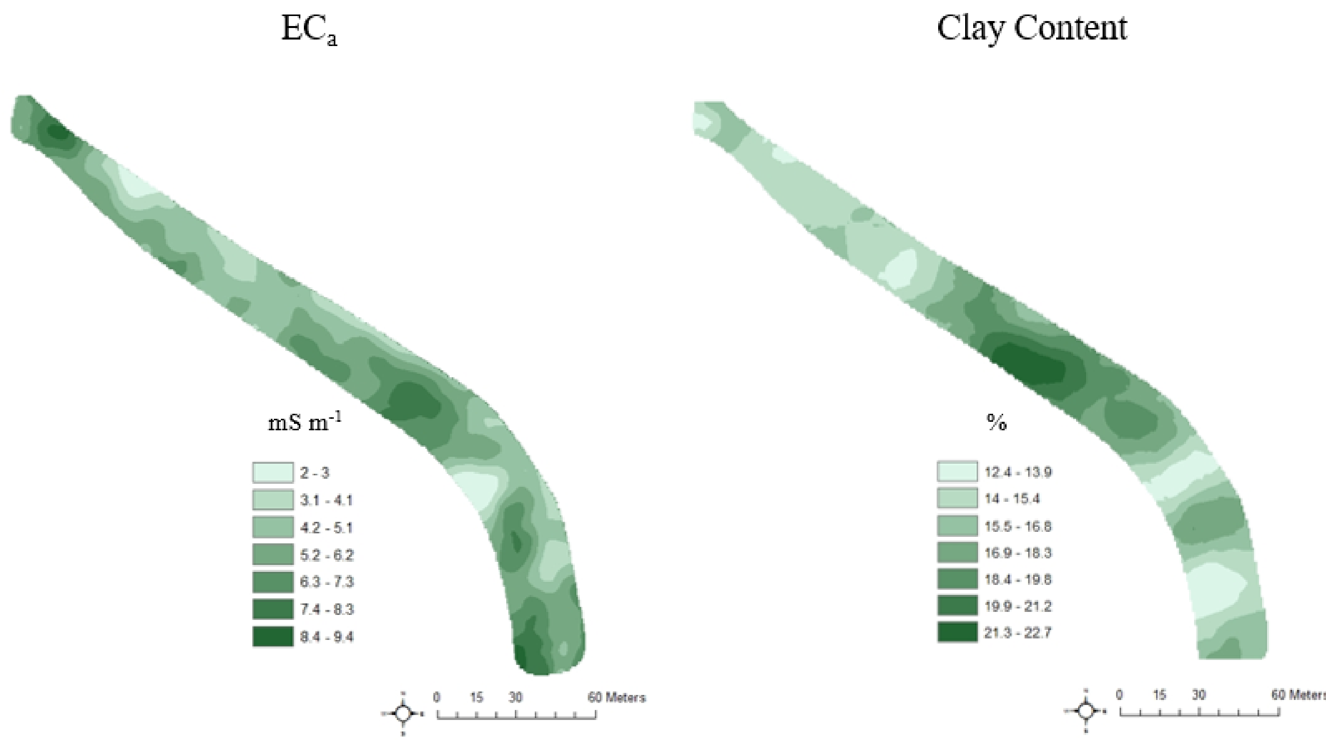

Figure 2.1. Kriged maps of apparent electrical conductivity (EC_a) and clay content for Fairway 3 (F3) at the University of Georgia golf course in Athens, GA in 2016 (equal interval legend classifications).

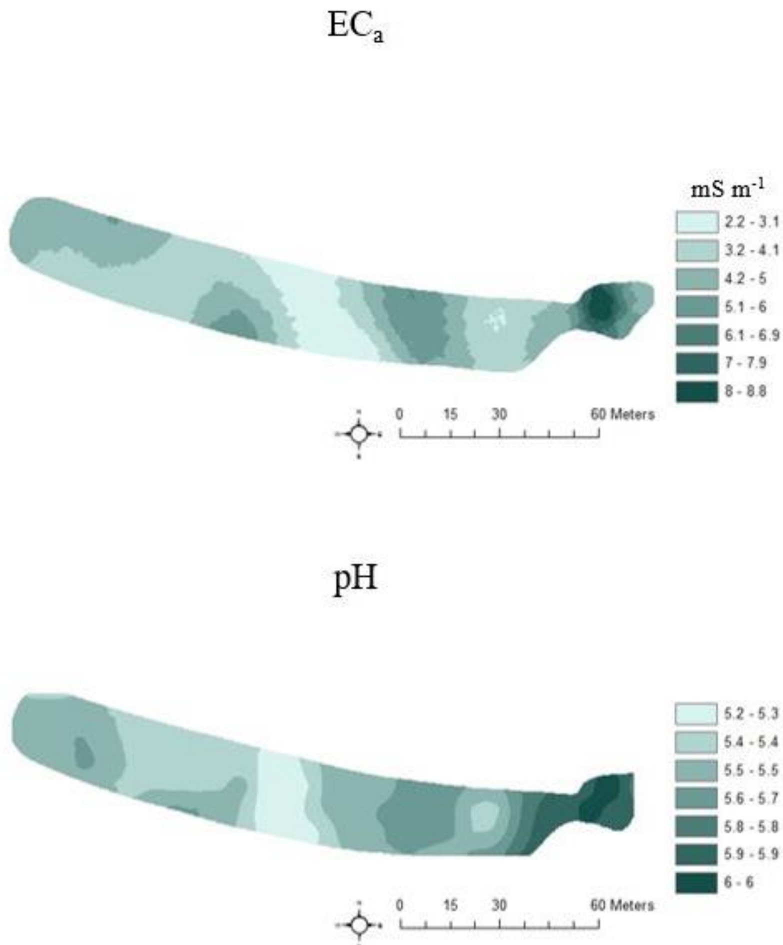

Figure 2.2. Kriged maps of apparent electrical conductivity (EC_a) and soil pH for Fairway 2 (F2) at the University of Georgia golf course in Athens, GA in 2016 (equal interval legend classifications).

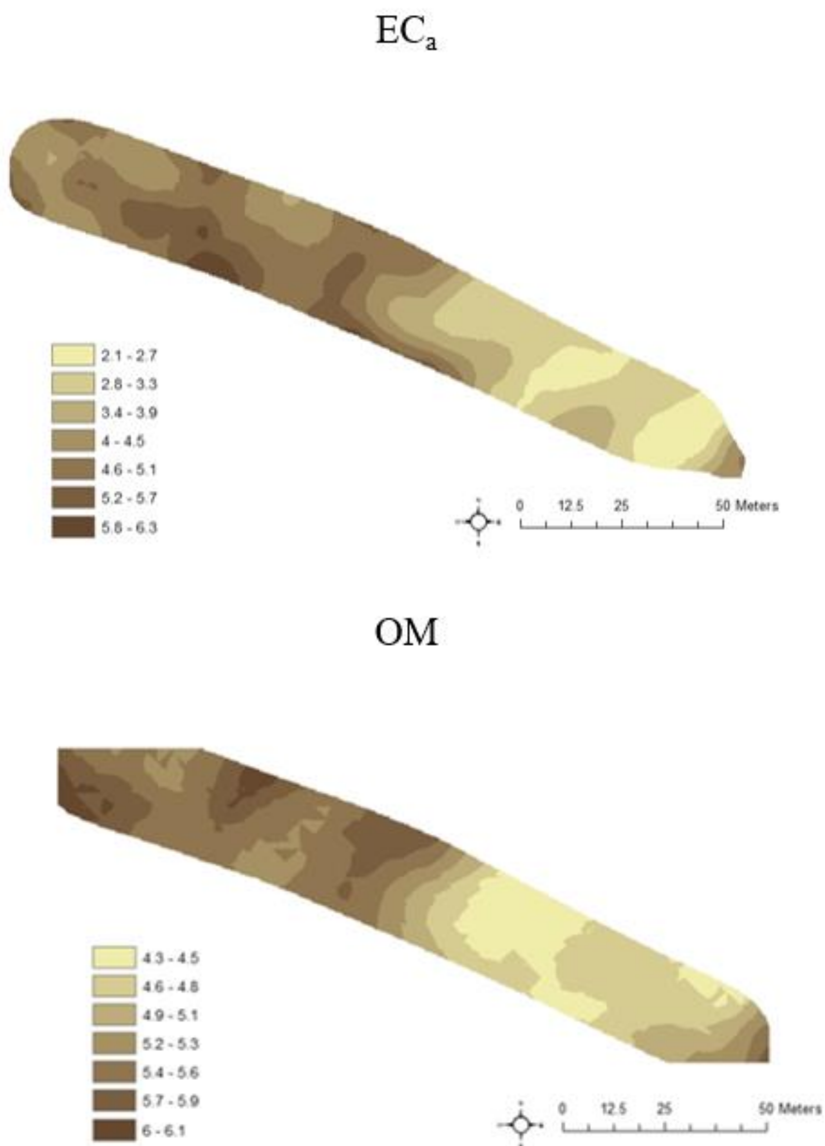

Figure 2.3. Kriged maps of apparent electrical conductivity (EC$_a$) and organic matter (OM) for Fairway 1 (F1) at University of Georgia golf course in Statham, GA in 2016 (equal interval legend classifications).

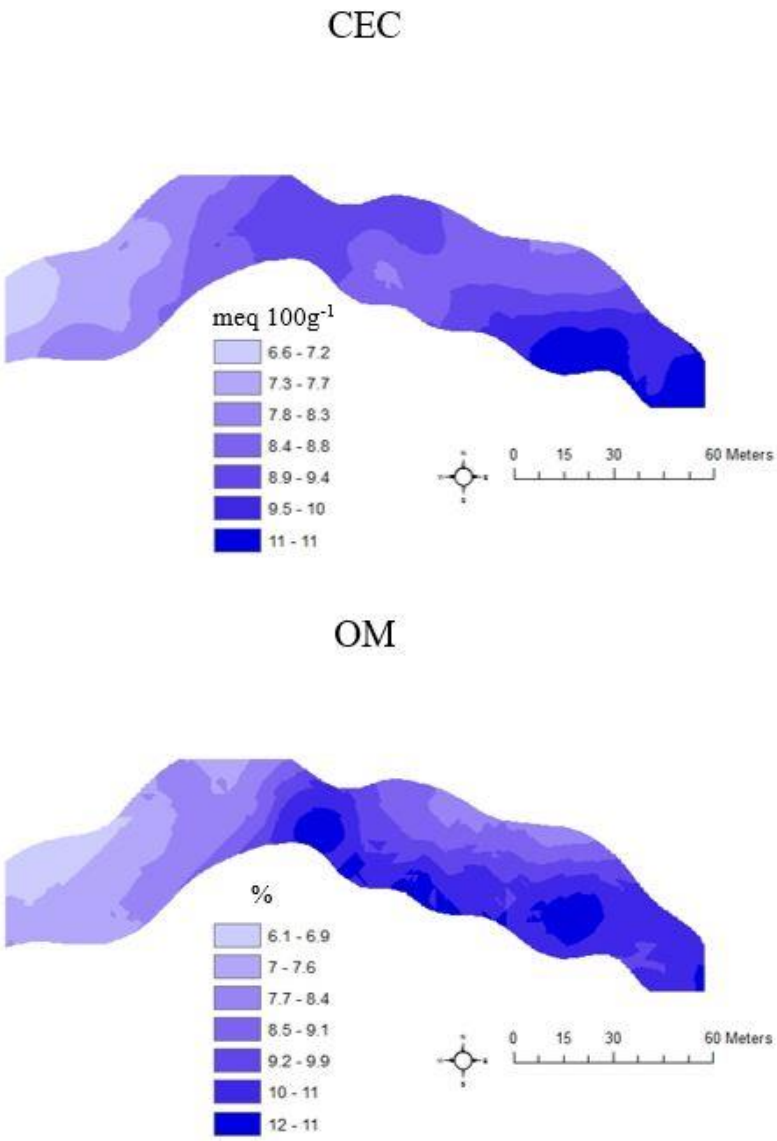

Figure 2.4. Kriged maps of cation exchange capacity (CEC) and organic matter (OM) for Fairway 5 (F5) at Georgia Club golf course in Statham, GA in 2016 (equal interval legend classification).

CHAPTER 4

EFFECTS OF MOWING FREQUENCY ON HYBRID BERMUDAGRASS CLIPPING COMPOSITION AND NITROGEN TRANSFORMATIONS[2]

[2] Grubbs, R.A., G.M. Henry, and M.L. Cabrera. For submission to *Soil Science Society of America Journal*.

Abstract

Understanding the role of clipping biomass in turfgrass system nutrient budgets is critical to establishing best fertility practices and improving nitrogen-use efficiency (NUE) in turfgrass systems. The objective of this study was to evaluate the effect of mowing frequency on clipping tissue composition [carbohydrates (CHO), cellulose, lignin and nitrogen (N)], N mineralization and NH_3 volatilization from decomposing 'TifTuf' bermudagrass (*Cynodon dactylon x C. transvaalensis*) clippings applied to the soil surface. Turfgrass clippings were collected from two research facilities (ATREC and Riverbend) at 3, 7, 10, and 14-day mowing intervals using a rotary push mower set to a height of 5.7 cm to simulate home lawn height. A subsample of clippings from each plot was ground and analyzed using near-infrared spectroscopy to determine tissue characteristics. Soil from each location was packed into polyvinyl chloride cylinders, adjusted to -0.33 MPa, treated with grass clippings on the surface or left unamended, and incubated at 28°C for 90 d. Cumulative evolved NH_3 was trapped, and inorganic N was extracted from each cylinder and analyzed colorimetrically after 90 d. No clear relationship was established between mowing frequency and tissue composition. Multiple regression models revealed weak relationships between tissue composition and total nitrogen mineralized. Significant constituents varied by location (cellulose and lignin at ATREC and N at Riverbend). Total clipping biomass deposited on the soil surface positively correlated with increased NH_3 volatilization losses indicating that more frequent mowing will result in fewer gaseous losses, and may improve overall NUE.

Introduction

Increased urbanization has had a significant effect on ecosystem structure and biogeochemical cycling (Cheng and Grewal, 2009, van Delden et al., 2016). Anthropogenic activities, including the development of residential properties and the establishment of home lawns can lead to the removal of top soil and a disruption of the soil profile that limits nutrient cycling (Cheng and Grewal, 2009). Because of this, urban soils may require supplemental fertility to meet nitrogen (N) requirements needed to support healthy, viable turfgrass growth (Carey et al., 2012). Nitrogen inputs have been found to exceed demands in urban ecosystems by as much as 51% (Fissore et al., 2012). Much of this has been attributed to fertilizer use on home lawns. Over-fertilization has several environmental consequences including contamination of urban air and ground water through nitrate (NO_3^-) leaching, and emission of greenhouse and ozone depleting gasses including N_2O, NO_x, and NH_3 (Barton and Colmer, 2006, Carrow et al., 2001, Qian et al., 2003).

Because turfgrass systems are so heavily concentrated around the urban landscape, researchers believe that turfgrass may be a significant contributor to nitrate (NO_3^-) contamination of urban groundwater resources (Flipse et al., 1984, Petrovic and Easton, 2005). Nitrate contamination in groundwater has been linked to a number of health concerns including methemoglobinemia in infants (Vigil et al., 1965, Fan and Steinberg, 1996) and subclinical hypothyroidism in women (Aschebrook-Kilfoy et al., 2012). Another loss pathway is through ammonia (NH_3) volatilization, which has been linked to atmospheric deposition (Rao et al., 2014) and eutrophication of surface water (Boyd, 2015). Research on NH_3 volatilization from turfgrass systems has been singularly concerned with immediate losses following applications of urea fertilizers (Henning et al., 2013, Stiegler et al., 2011), with little to no consideration of gaseous losses from clipping residue. However, research in pasture systems has found that volatilization from residue can be more substantial when residue is fresh and is not soil-incorporated (De Ruijter et al., 2010). More gaseous N losses may be observed in turfgrass systems in which residues remain on a thatch layer when compared to systems where residues come into direct contact with the soil surface.

Mowing practices directly impact nitrogen cycling in turfgrass systems, as fresh grass clippings can contain between 25 and 60% of all applied N (Carrow, 2001). Several studies have been conducted to explore the effect of clipping return to and removal from turfgrass systems (Qian et al., 2003, Kopp and Guillard, 2002, Heckman et al., 2000, Kauer et al., 2013, Liu and Hull, 2006). Clipping return has been found to reduce N fertilizer needs by 30% (Starr and DeRoo, 1981) to 75% (Heckman et al., 2000). Additionally, modeling of biogeochemical cycling in turfgrass systems indicate that consistent, long-term clipping return facilitates increased soil carbon (C) and N sequestration, improving overall sustainability of turfgrass systems (Qian et al., 2003). However, these findings are not always consistent, as some studies have found a negative or absent effect of clipping return on dry matter yield and soil N in the absence of N fertilizers (Kauer et al., 2013). Nitrogen recovery following clipping decomposition can be affected by multiple factors including genetic variability (Liu and Hull, 2006), temperature and soil moisture (Kauer et al., 2012, Kauer et al., 2013), N fertilization, and mowing practices (Shi et al., 2006).

Minimal to no research has explored whether mowing frequency would impact clipping decomposition and N cycling. Mowing frequency in turfgrass research has primarily focused on improving control of foliar diseases such as Dollar spot (*Sclerotinia homeocarpa* F.T. Benn)

(Putman and Kaminski, 2011, Delvalle et al., 2011); however, Shi et al. (2016) theorized that more frequent mowing (1 – 3 times per week) may result in more stable N transformations in turfgrass systems due to the overlap in fresh residue decomposition.

Abiotic and biotic stress has been found to alter cell wall structure (Le Gall et al., 2015, Tenhaken, 2014) and plant proteome composition (Kosová et al., 2011). Mowing is a mechanical stress imposed on the plant that can affect chlorophyll content, shoot succulence and carbohydrate storage throughout the plant (Fry and Huang, 2004). While some research has evaluated the effect of cutting frequency on forage quality and tissue composition of forage grasses (Burton et al., 1963, da Silveira Pontes et al., 2010, Rousk et al., 2009), minimal to no research has evaluated the effect of mowing frequency on the tissue composition of turfgrass clippings. Previous studies have primarily evaluated turfgrass cell wall constituents (carbohydrates, cellulose and lignin) in relation to wear tolerance (Trenholm et al., 2001, Trenholm et al., 2000, Brosnan et al., 2005, Shearman and Beard, 1975). The objective of this study was to explore the impact of mowing frequency on clipping composition, N mineralization, and NH_3 volatilization in order to determine whether changes in mowing frequency may improve NUE in turfgrass systems.

Materials and Methods

Site Descriptions and Tissue Collection

Research was conducted in the late summer and early fall of 2015 and 2016 in Athens, GA. Field plots were located at two University of Georgia research facilities in Athens, GA: (1) the Athens Turfgrass Research and Education Center (ATREC) and (2) the Riverbend Rhizotron facility (Riverbend). TifTuf hybrid bermudagrass (*Cynodon dactylon x C. transvaalensis*) was established at each location in the summer of 2014 and allowed one year to grow-in prior to trial initiation. Soil properties (texture, pH, and organic matter) for each location were determined by the UGA Agricultural and Environmental Services labs each year (Table 3.1).

Field plots were laid out in a randomized complete block design with four replications and with individual plots (1.6 x 1.4 m) separated by 0.5-m aisles to prevent clipping contamination across plots. A Honda Twin-Blade 3-in-1 rotary push mower (American Honda Motor Co., Inc., Gardena, CA) was set to a height of 5.7 cm to simulate home lawn height. Four mowing intervals of 3, 7, 10, and 14 days were implemented as treatments. Turfgrass clippings were harvested in the sixth week following trial initiation so that plots were mowed at designated mowing intervals for a consistent period of time prior to analysis. This allowed for greater understanding of the role of mowing frequency on tissue composition through repeated and consistent mechanical stress. At 6 weeks, plots had been mowed a total of 13 times (3-d), six times (7-d), 4 times (10-d), or 3 times (14-d). Clippings were weighed to determine total biomass output per plot (g m^{-2}). Fresh grass clippings were partitioned into two subsamples, one large (>100-g) for incubation and one small (~50-g) for dry weight determination and tissue analysis. Grass clippings separated for incubation were allowed to air-dry for approximately 48 hours before incubation.

Soil Preparation and Incubation Procedure

Air-dried clippings were incubated for 90 days at the UGA turfgrass science research lab in Athens, GA to determine cumulative N mineralization and NH_3 volatilization from clippings collected at each mowing interval. Soil was collected from each location and air-dried for 5 to 7 days before being passed through a 2-mm sieve. Soil properties [organic matter (OM), pH, texture, NO_3^- and NH_4^+] were determined for each location (Table 3.1).

For each incubation, 100 g of dry soil was packed into 5.08-cm diameter polyvinyl chloride (PVC) cylinders (10 cm long) and adjusted to -0.33 MPa, which was equivalent to a volumetric water content (VWC) of approximately 0.21 cm^3 H_2O cm^{-3}. Control columns were packed without grass to account for N mineralization from the soil. Grass clippings from individual treatments plots were placed directly onto the soil surface in each cylinder in quantities proportionate to in-situ area density following mowing. For the duration of the 90-d incubation period, each cylinder was sealed in a 1-L glass container and placed in a controlled environment chamber at a constant temperature of 28°C. Jars were aerated at regular intervals (3-minute intervals daily for the first 7 days, followed by 3 minutes every 3 days for the remainder of the experiment) to prevent accumulation of CO_2 that may disrupt microbial activity. Cumulative evolved NH_3 was trapped in 30 mL of 0.1 N H_2SO_4 over the 90-d incubation period. The trapping capacity of the NH_3 trap was sufficient to capture up to 42 mg N, Upon termination of the experiment, inorganic N (NO_3^- and NH_4^+) was extracted from individual cylinders using a 1 M KCl solution (1:8, soil to KCl ratio). Subsequently, NO_3^-—N (soil extraction) and NH_4^+—N (soil extraction and acid traps) (mg L^{-1}) were determined colorimetrically using an Alpkem AutoAnalyzer (Mulvaney, 1996).

Tissue Analysis

The 50-g clipping subsample was oven-dried at 65°C for 48 hours to determine initial soil moisture (g H_2O g^{-1} dry biomass) and total dry biomass (g m^{-2}). Dry clippings were subsequently ground using a SPEX 8000 Mixer/Mill (SPEX SamplePrep, Metuchen, NJ) to be analyzed using near-infrared (NIR) spectroscopy to determine tissue characteristics. Tissue analysis was conducted in the fall of 2016 at the University of Georgia Agricultural and Environmental Services Laboratories in Athens, GA. Scanning of dried and ground turfgrass clippings was performed using a NIRSystem model 6500 near-infrared scanning monochromator (FOSS North America, Eden Prairie, MN) in the reflectance mode. Clippings were scanned from 400 to 2498 nm to collect spectra every 2 nm. The instrument was equipped with a combination of silicon and lead sulfide detectors. The procedure used subsamples of the homogenized samples, packed in ring cups (Part# IH-0386, FOSS North America) as follows. The cup was first overfilled, and the excess was removed by scraping it away, leaving the cup full. This procedure resulted in approximately 5-g samples being scanned (around 10-mm depth). The packed cup was held on a transport module and 32 successive scans were carried out covering the wavelengths from 400 to 2498 nm at 2 nm intervals to give a 1049 data points per sample. As a control, 16 scans over the internal standard ceramic disk were made before and after the samples. The reflectance energy readings were referenced to corresponding readings from an internal ceramic disk. The recorded spectrum of each sample was the average of 32 successive scans. All spectral data were recorded as the logarithm of the reciprocal of reflectance (log 1/R, R: reflectance). The scanning procedure could be completed in 1.5 min per sample, once the NIR spectroscopy instrument was warmed up, and satisfactory instrument performance was confirmed through instrument response, photometric repeatability (noise) and wavelength accuracy tests, and check cell scan. Absorption of radiation in the region of 400–2498 nm, the visible plus near-infrared region, was used to predict forage quality using the calibration equation for grass hay “16GH50-2.EQA” developed and distributed by NIRS Forage and Feed Testing Consortium.

Data Analysis

Total N mineralized was calculated as a sum of inorganic N (ppm) trapped as NH_3, and N extracted from the soil column as NO_3^- and NH_4. Both N mineralized and NH_3-N volatilized were expressed as a percentage of total organic N (TN) applied with clippings (% NMin and % NH_3-N, respectively), and area density (g m^{-2}) for total nitrogen mineralized (TNM) and total ammonia volatilized (TAV). Tissue N was expressed as a % of total clipping dry matter, while carbohydrates, hemicellulose, cellulose and lignin were expressed as proportions of total C applied (totaling to 100%).

Due to a significant effect of year, an analysis of variance (ANOVA) was used to test mowing interval effects on total dry clipping biomass (DCBM), total organic nitrogen (TN) deposited as clippings, %NMin, TNM, %NH_3-N, and TAV for each location and year individually (SAS Institute, 2009). A second ANOVA was also performed to test mowing interval effect on tissue composition (% N, carbohydrates, cellulose, and lignin). Fisher’s least significant difference (LSD) procedure was used to compare treatment means at the $P = 0.05$ significance level. Multiple linear regression models were fit for ATREC and Riverbend to predict %NMin based on CHO, cellulose (hemicellulose and cellulose), lignin and nitrogen content using the linear model (‘lm’) function in RStudio version 3.2.1. Final models for each year and location were selected based on significance of individual parameters (Tables 6 and 7). There were no significant effects of individual tissue components on %NMin found in the 2015 Riverbend data. A homogeneity of variance (HOV) was performed on %NH_3-N to determine whether data could be pooled across years for individual locations. Subsequently, simple linear regression models were plotted for ATREC and Riverbend data to predict %NH_3-N loss from total DCBM deposition using SigmaPlot 12.0 Scientific Data Analysis and Graphic Software (Systat Software, San Jose, CA).

Results

Initial soil properties [texture, pH, organic matter (OM), and inorganic N] were determined for each location and each year (Table 3.1). Soil texture was determined to be a sandy clay loam at ATREC and a sand at Riverbend. Soil pH was acidic (<6) at both locations, but slightly more acidic at Riverbend in 2015 and 2016 (5.22 and 4.93, respectively) than at ATREC (5.57 and 5.42, respectively). Organic matter content was greater at ATREC in both 2015 and 2016 (21.1 and 23.1 g kg^{-1}), respectively) than at Riverbend (1.92% in 2015 and 1.15% in 2016).

Clipping Yield and Tissue Composition

Yield data for dry clipping biomass (DCBM) collected at ATREC and Riverbend are presented in Table 3.2. Mean DCBM collected in 2015 was lowest at the shortest mowing interval (3 days) at ATREC and Riverbend (49.3 g m^{-2} and 65.4 g m^{-2}, respectively), and highest at the longest mowing interval (14 days) for both locations (158 g m^{-2} at ATREC and 178 g m^{-2} at Riverbend). Clipping yield for intermediate mowing intervals (7 and 10 days) also increased at both locations when compared to the shortest mowing interval. Mean DCBM collected in 2016 was lowest at the 3-d mowing interval for ATREC (54.7 g m^{-2}), but statistically similar across 3, 7 and 10-d mowing intervals for Riverbend. As in 2015, the highest mean DCBM was observed at the 14-d mowing interval at both ATREC and Riverbend.

No significant differences were observed in tissue N for 2015 ATREC and Riverbend data or for 2016 ATREC data. In 2016, mean N composition was 28 g kg^{-1} at ATREC and 34 g kg^{-1} at Riverbend in 2015, dropping slightly to 27 g kg^{-1} at ATREC. For Riverbend in 2016, N in dry tissue was lowest at 3- and 14-d mowing intervals (30 g kg^{-1}), and highest at the 10-d mowing intervals (35 g kg^{-1}).

In 2015, no significant differences were observed in mean tissue carbohydrates (CHOs) between mowing intervals at ATREC in 2015 (Table 3.2). Mean tissue CHO was lowest for 3-day mowing interval at Riverbend (30.0%), but remained similar for 7, 10, and 14-d mowing (Table 3.2). Highest mean tissue CHO were observed at the 7-d mowing interval at ATREC (28.2%), and the 10-d mowing interval at Riverbend (32.8%). Lowest mean tissue CHO were observed at the 14-d mowing interval at ATREC (26.4%), but remained relatively similar at the 3 and 10-d mowing intervals (27.2% and 27.3%, respectively). Mean CHOs for 3, 7, and 14-d mowing intervals at Riverbend were not significantly different.

In 2015, no significant differences were observed in cellulose content across mowing treatments at ATREC (Table 3.2). At Riverbend, mean cellulose content was highest at the 3-d mowing interval (63.7), but was not significantly different between 7, 10, and 14-d mowing intervals. In 2016, mean cellulose content in ATREC tissue was highest at the 14-d mowing interval (68.3%) and lowest at the 7-d mowing interval (67.2%). Mean values for 3-d and 10-d mowing intervals were statistically similar. Mean cellulose content at Riverbend was highest at the 3-d mowing interval (67.0%), and lowest at the 10-d mowing interval with significant differences between 7-d and 14-d mowing intervals.

No significant differences were observed in lignin content at ATREC in 2015. Highest and lowest mean lignin contents at Riverbend in 2015 were found at 3-d (6.3%) and 10-d (5.5%) mowing intervals, respectively. Lignin contents for tissue collected at 7-d and 14-d mowing intervals were similar. In 2016, mean lignin content in tissue collected at ATREC was highest at 14-d (5.3%), lowest at 7-d (4.6%) mowing intervals, and similar at 3-d and 10-d mowing intervals. Mean lignin content found in 2016 Riverbend tissue was lower at the 10-d mowing interval (3.9%), but similar at 3, 7, and 14-d mowing intervals.

Nitrogen Mineralization and Ammonia Volatilization

For each year, mean TN deposited was the highest for the longest mowing interval (14-d) at both ATREC (4.5 g m^{-2} in 2015 and 3.3 g m^{-2} in 2016) and Riverbend (6.0 g m^{-2} in 2015 and 4.4 g m^{-2} in 2016). Conversely, mean TN was the lowest for the shortest mowing interval (3-d) at ATREC (1.4 g m^{-2} in 2015 and 1.5 g m^{-2} in 2016) and Riverbend (2.2 g m^{-2} in 2015 and 1.6 g m^{-2} in 2016). Mean TN deposited at intermediate mowing intervals remained relatively similar for both 7 and 10-d mowing intervals at ATREC and Riverbend each year.

In 2015, mean %NMin was highest for ATREC clippings collected at 3-d and 7-d mowing intervals in 2015 (91.4% and 75.2%, respectively), and 7 and 14-d mowing intervals at Riverbend (76.3% and 68.7%, respectively). Conversely, mean %NMin was lowest for ATREC clippings collected at 10-d and 14-d mowing intervals (27.1% and 27.0%, respectively) and Riverbend clippings collected at 3-d and 10-d mowing intervals (45.6% and 54.4%, respectively). Corresponding TNM (g N m^{-2}) from ATREC clippings in 2015 was highest for the 7-d mowing interval (1.5 g m^{-2}) and lowest at the 10-d mowing interval (0.7 g m^{-2}). Nitrogen mineralized from ATREC clippings collected at 3 and 14-d mowing intervals was similar (Table

3.3). Mean TNM from Riverbend clippings was significantly different for all mowing intervals with highest value observed at the 14-d mowing interval (4.1 g m^{-2}) and lowest at the 3-d mowing interval (1.0 g m^{-2}).

In 2016, mean %NMin was highest at the 10-d mowing interval from both ATREC and Riverbend (-1.9% and 83.9%, respectively) and lowest for clippings collected at the 3-d mowing interval (-33.3% at ATREC and 26.0% at Riverbend). Mean %NMin was relatively similar for ATREC clippings collected at 7 and 14-d mowing intervals, but was significantly different for Riverbend clippings (Table 3.3). No significant differences were found in mean TNM from ATREC clippings collected at 3, 7, 10, and 14-d mowing intervals. Mean TNM was highest for Riverbend clippings collected from longer mowing intervals (2.2 g m^{-2} and 2.6 g m^{-2} for 10 and 14-d mowing intervals, respectively), and lowest for clippings collected at shorter mowing intervals (0.4 g m^{-2} and 0.9 g m^{-2} for 3 and 10-d mowing intervals, respectively).

Multiple linear regression models to predict %NMin based on tissue constituents in turfgrass clippings collected from ATREC and Riverbend are presented in Tables 4 and 5, respectively. Model output for ATREC revealed that the estimates for cellulose and lignin were significant (P <0.001) at predicting %NMin across both 2015 and 2016 (adjusted r^2 = 0.37). Estimates for N were significant at predicting %NMin for Riverbend (adjusted r^2 = 0.24).

Means separation for ammonia volatilization in response to mowing interval are presented in Table 3.3. Mean NH_3-N loss as percentage of total nitrogen mineralized was highest for clippings collected from the 14-d mowing interval at ATREC and Riverbend both years (1.42% and 1.19% at ATREC, and 3.97%, and 3.56% at Riverbend in 2015 and 2016, respectively). Mean %NH_3-N was similar for ATREC clippings collected at 3, 7, and 10-d mowing intervals in

2015. Likewise, values were similar ATREC clippings collected at 7 and 10-d mowing intervals in 2016, but were lower for clippings collected at the shortest mowing interval (0.39%). Mean %NH_3-N loss was lowest for Riverbend clippings collected at the 3-d mowing interval in 2015 (-0.41%) and the 3 and 7-d mowing intervals in 2016 (1.56% and 1.75%, respectively). Simple linear regression models to predict %NH_3-N from DBCM (g m^{-2}) at ATREC and Riverbend are presented in Figure 1. Both models showed similar positive linear trends with a moderate goodness-of-fit (r^2 = 0.44 at ATREC and r^2 = 0.45 at Riverbend).

Discussion

Under steady light and temperature conditions, %NMin in this study was not significantly affected by total DCBM deposition. Regular mowing represents a significant N loss from turfgrass, as clippings may contain between 25 and 60% of total plant N (Carrow, 2001). To offset the effects of N loss following mowing, supplemental fertility is generally required; however, these rates may be reduced in systems were clippings are being returned. Moderately to highly-managed warm-season turfgrasses such as bermudagrass are typically fertilized with between 2.4 and 4.9 g N m^{-2} per month of active growth (1 lb N 1000 ft^{-2}) (Carrow, 2001). If it is assumed that one month is equivalent to approximately 30 days, then mean N requirements for a 90-d growing period would be 7.2 to 14.4 g N m^{-2}. Over the 90-d incubation period in this study, between -0.5 and 4.1 g N m^{-2} mineralized from grass clippings across various mowing treatments, accounting for a significant portion of total N required for turfgrass growth. Throughout the course of this study, between 26.0 and 91.4% of total N in clippings mineralized over the 90-d period in systems where significant N immobilization did not occur, indicating that supplemental fertility may be significantly reduced in turfgrass systems where clippings are replaced and N is recycled.

While both locations were established 1 year prior to trial initiation, ATREC had been excavated and leveled as part of a development project, removing top soil prior to turfgrass planting. The Riverbend location had been an established turf stand for many years, and was resurfaced to complete this trial. While inorganic soil N values were comparable for each location at the start of each year, TNM in control soils following the 90-d incubation period indicated either greater organic N, or more favorable conditions for NMin in Riverbend soil. Negative mineralization and volatilization values for ATREC in 2016 point to some degree of N immobilization throughout the 90-d incubation period. This may have been a function of plant residues in the soil from the year before with a higher C:N ratio which resulted in net N immobilization by soil microbes. In systems where N immobilization occurs, supplemental fertility requirements may be higher to maintain aesthetic quality.

In contrast to %NMin, NH_3 volatilization appeared to have a moderately strong linear relationship with the amount of DCBM (g m^{-2}) deposited on the soil surface (Fig. 1). Few studies have reported the effect of total biomass on NH_3 volatilization rates, but instead have focused primarily on the role of N content and C:N ratio in determining volatilization losses (Whitehead and Lockyer, 1989, Whitehead et al., 1988). Losses ranging from -0.41% to 3.97% were observed over the 90-d incubation period in this study. In a study measuring NH_3 volatilization over a 119-day period, De Ruijter et al. (2010) reported losses of approximately 15.9% of total N in surface-applied grass clippings. Whitehead and Lockyer (1989) reported similar losses of approximately 10% from surface-applied perennial ryegrass clippings containing 2.98% tissue N over a 28-d period. Smaller losses in this study may partially be due to experimental design, as minimal air flow may have reduced NH_3 volatilization when compared to wind tunnels (Whitehead and Lockyer, 1989) and volatilization chambers in an open-air shelter (De Ruijter et al., 2010). Previous studies were also designed to simulate pasture conditions where grass clipping deposition would be significantly higher than that observed in a conventional turfgrass system. De Ruijter et al. (2010) compared surface-applied crop residues with soil-incorporated crop residues and found that NH_3 volatilized from soil-incorporated residues was insignificant. During decomposition, plant residues are first hydrolyzed to amino acids and then converted to NH_4^+ by microorganisms where they are susceptible to volatilization losses, particularly when left on the soil surface. Greater DCBM area density would mean reduced contact between clipping residue and the soil surface, increasing susceptibility to volatilization loss.

Total DCBM generally increased with increasing mowing interval such that more clippings were collected from plots mowed less frequently. This trend suggests that NH_3 volatilization may be reduced by mowing more frequently; however, DCBM differences were less pronounced between intermediate mowing intervals (7 and 10 days) at Riverbend in 2015 and ATREC in 2016, and short to intermediate mowing intervals at Riverbend in 2016 (3, 7, and 10 days). This indicates a potential lull in plant growth approximately 3 to 7 days after cutting, followed by a spike in growth between 10 and 14 days after cutting. It is unclear whether this trend was observed due to environmental effects or physiological processes in the plant. Law et al. (2016) found that mowing requirements are influenced by a number of factors including turfgrass selection and clipping management. Additional studies have reported both species (Poorter and Remkes, 1990) and varietal (Trenholm et al., 1998, Wilhelm and Nelson, 1978) differences in relative growth rates of turfgrass species. Mowing can contribute considerable carbon emissions into the atmosphere (Bartlett and James, 2011). Future research should attempt to optimize mowing practices in order to simultaneously reduce carbon emissions (less frequent mowing) and reduce NH_3 volatilization (more frequent mowing) by establishing whether there are consistent patterns in growth rates that would allow for less frequent mowing without significantly greater DCBM deposition.

Multiple regression models used to predict NMin (% of TN) from tissue composition demonstrated linear relationships between tissue constituents and NMin at ATREC (Table 3.4) and at Riverbend (Table 3.5). Significant factors varied by location, but were either determined to be cellulose and lignin (ATREC) or nitrogen content (Riverbend). While there were significant differences in cell wall constituents (CHO, cellulose, and lignin) with respect to mowing interval, these differences were negligible and inconsistent across locations and years (Table 3.4). Likewise, no clear relationship could be established between mowing interval and tissue N as a percentage of total dry matter. Significant differences in N were only observed between different mowing intervals at Riverbend in 2016. In a previous study, Burton et al. (1963) found differences in plant protein in response to increased mowing intervals for coastal bermudagrass (*Cynodon dacty*lon, (L) Pers.) grown for hay production; however, mowing intervals for hay production were significantly longer (2 – 8 weeks) which may have contributed to more pronounced differences.

Tissue composition may be influenced by abiotic and biotic factors including species, soil moisture availability, shading, soil properties, and fertility practices (Le Gall et al., 2015). Differences in tissue composition across locations in this study indicates environmental factors may have played a role. In a review assessing the impact of abiotic stress on plant cell wall metabolism, Le Gall et al. (2015) asserted that abiotic stress may result in physiological responses including changes in cell wall plasticity and reinforcement of the secondary wall with hemicellulose and lignin deposition. The degree and nature of these responses is dependent on a number of factors including species, genotype, and plant age. Light affects lignin biosynthesis pathways in some species such that increased light leads to greater lignin production and deposition in the cell wall (Cabane et al., 2012). Shading from surrounding tree growth at Riverbend may have reduced biosynthesis of more recalcitrant cell wall components (cellulose and lignin), whereas ATREC had no surrounding vegetation or shading effects.

Additional sun exposure and differences in air movement due to surrounding structures and vegetation may also have impacted heat load at each location. In a study performed on sweet corn, Suwa et al. (2010) found that heat stress resulted in a notable reduction in sugar concentrations in some parts of the plant including hemicellulose and cellulose fractions of the cobs, and the hemicellulose fraction of the shank. This response was genoytype-specific, but further supported that different types of abiotic stress can alter sugar composition in plant tissue. Reductions in carbohydrate concentrations in response to heat stress were also observed by Liu and Huang (2000) in two cultivars of creeping bentgrass [*Agrostis stolonifera* L. var. *palustris* (Huds.) Farw. (syn. *A. palustris* Huds.)]. However, warm season bermudagrass (C4) cultivars have been found to respond more efficiently to heat stress in part by accumulating greater quantities of metabolites including some sugars when compared to cool-season (C3) species (Du et al., 2011). Future research should further explore the effect of heat stress on tissue composition in bermudagrass cultivars like TifTuf.

Soil properties including temperature, moisture, aeration, pH and nutrient availability would all have an impact on nitrogen mineralization and immobilization processes throughout the soil (Sims and Stehouwer, 2008). Soil texture, pH and total OM differences (Table 3.1) at each location would result in differences in soil structure, pore space, and cation exchange capacity, which would all directly affect the microbial processes responsible for the decomposition of plant material on the soil surface. Furthermore, wetting agent applications from previous research trails performed at Riverbend may have significantly altered soil chemistry, soil moisture retention, and overall volumetric water content of the soil at this location (Karnok and Tucker, 2001). Less water had to be added to Riverbend incubations than to ATREC incubations, indicating fewer fluctuations in volumetric water content for Riverbend soils throughout the duration of the experiment. Additionally, Riverbend incubations had more visible hyphal pressure from fungi throughout the study, which may have been an indication of high soil moisture and lower pH (Rousk et al., 2009). Saturated, anoxic microsites throughout even the most well-drained soils can lead to denitrification throughout the soil profile (Coyne, 2008). It is possible that the incubation of a soil treated with wetting agents may have created ideal conditions for denitrification to occur. Denitrification tends to be inhibited by more acidic soil conditions (Whitehead, 1995); however, the sandier soil at Riverbend would have a reduced buffering capacity, making it more susceptible to fluctuations in pH and soil chemistry. Denitrification may explain negative NH_3 volatilization values measured for clippings collected at the 3-d mowing interval from Riverbend in 2015 (Table 3.3). Reduced buffering capacity of the soil would also explain greater NH_3 volatilization values for Riverbend when compared to ATREC even when total DCBM deposited was comparable for both locations, as in 2016 (Table

3.3). There is often an increase in the pH of decomposing plant material, increasing the possibility of volatilization losses (Whitehead, 1995). This increase may have been more significant for clippings decomposing on a coarse-textured soil.

Clipping decomposition and corresponding N mineralization and N transformations would likely differ under in situ conditions. Kauer et al. (2012) found that weather conditions including temperature and relative humidity significantly influenced decomposition of turfgrass clippings immediately following cutting (1 – 2 weeks). Increasing temperature can also increase the rate of NH3 volatilization from decomposing grass clippings (Whitehead, 1995). Diurnal fluctuations in temperature and relative humidity can result in corresponding fluctuations in microbial activity that would be observed under steady state lab conditions. However, Kauer et. al (2012) also observed that weather conditions were less important to decomposition rates later over the studied period (3 – 8 weeks). This may indicate that differences between lab and in situ clipping decomposition may be greatest in the period immediately after cutting, but would decrease over time resulting in comparable cumulative findings.

For the purpose of this study, turfgrass clippings were placed directly onto the soil surface for incubation. In a conventional turfgrass system, mulched clippings would undergo decomposition at the canopy, thatch, and soil layers, which would significantly impact N transformations. Thatch has been defined as a tightly intermingled layer composed of living and dead tissue found between the vegetative canopy and underlying soil surface (Beard, 1972). Management of the thatch layer is important to N management in turfgrass systems, as N retention in the thatch can be very poor compared to soil (Nelson et al., 1980). In contrast to more stable urease conditions in soil, urease activity in thatch is highly variable in response to seasonal conditions (Torello and Wehner, 1983). Consequently, NH_3 volatilization from turfgrass systems may be more influenced by thatch mechanics than by underlying soil chemical and physical properties (Torello and Wehner, 1983). Leaching losses can also be great, which is detrimental in systems where rooting is more concentrated in the thatch layer (Nelson et al., 1980).

Finally, soil structure would also have a significant impact on N transformations. Hassink (1992) found that sieving and rewetting of soils causes a temporary increase in N mineralization for all soil types, particularly finer textured soils with a higher small pore fraction. Smaller pores are believed to house protected organic matter that is not readily accessible to soil microbes. Fine sieving exposes this protected organic matter, leading to an increase in NMin.

Conclusion

TifTuf bermudagrass clippings collected at 3, 7, 10, and 14-d mowing intervals from two locations (ATREC and Riverbend) were analyzed to determine the impact of mowing frequency on tissue composition. Though significant differences were observed in tissue constituents (N, CHO, cellulose, and lignin) with respect to mowing interval, these differences were relatively small and inconsistent across locations and years. No clear relationship was established between mowing frequency and tissue composition.

Clippings were incubated for 90 days on soil collected from each location to evaluate the impact of mowing frequency on nitrogen mineralization and NH_3 volatilization. Under conditions where significant N immobilization did not occur, total nitrogen mineralized represented a significant portion of N requirements in warm-season turfgrass. It was concluded that under favorable conditions, supplemental N requirements may be reduced by between 26.0

and 94.1% in systems where clippings are returned; however, these rates may vary under in-situ conditions. Immobilization was observed at the ATREC location in 2016. This was attributed to disrupted soil dynamics following site construction and deposition of plant residues from the first year of the study.

No significant relationship was observed between total DCBM and % NMin. Multiple regression models revealed weak relationships between tissue composition and TNM. Significant constituents varied by location (cellulose and lignin at ATREC and N at Riverbend). Future studies evaluating N mineralization from turfgrass clippings should consider the role of additional management practices (e.g., fertility, irrigation, and cultivation) on tissue composition, and how this ultimately affects N mineralization rates. Additionally, the role of canopy and thatch mechanics on N mineralization and N return to the soil profile should be explored.

Total DCBM on the soil surface positively correlated with increased NH_3 volatilization losses indicating that more frequent mowing will result in fewer gaseous losses, and may improve overall nitrogen-use efficiency. Future research should evaluate ways to simultaneously reduce volatilization losses while also minimizing carbon emissions from frequent mowing.

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Table 3.1. Soil properties for turfgrass systems at two locations prior to trial initiation for 2015 and 2016 at the ATREC and Riverbend locations in Athens, GA

	Soil Texture	**Year**	**Soil pH (1:1)**	**OM (g kg^{-1})**	**Total Inorganic Soil N (mg N kg^{-1} soil)**
ATREC	Sandy Clay Loam	2015	5.57	21.1	0.9
		2016	5.42	23.1	1.0
Riverbend	Sand	2015	5.22	19.2	0.8
		2016	4.93	11.5	1.1

Table 3.2. Mean dry clipping biomass (DCBM), nitrogen (N), carbohydrates (CHO), cellulose and lignin in clipping tissue collected from different mowing intervals (MIs, 3, 7, 10, or 14 days) at the Athens Turfgrass Research and Education Center (ATREC) and Riverbend rhizotron facility in Athens, GA during the summers of 2015 and 2016.

MI	DCBM		N		CHO		Cellulose		Lignin	
(d)	(g m^{-2})		(g kg^{-1} total DM)		(% Total carbon DM)					
2015 ATREC										
3	49.3	d	28		27.9		66.0		6.1	
7	73.6	c	28		27.2		66.6		6.2	
10	78.7	b	27		26.8		67.1		6.1	
14	158.0	a	27		28.1		66.0		5.9	
2015 Riverbend										
3	65.4	c	33		30.0	b	63.7	a	6.3	a
7	121.7	b	34		32.2	a	61.9	b	5.9	ab
10	117.9	b	35		34.2	a	60.4	b	5.5	b
14	178	a	34		33.4	a	61.1	b	5.6	ab
2016 ATREC										
3	54.7	c	28		27.2	ab	68.1	ab	4.7	ab
7	92.7	b	28		28.2	a	67.2	b	4.6	b
10	92.7	b	27		27.3	ab	67.5	ab	5.2	ab
14	127.5	a	26		26.4	b	68.3	a	5.3	a
2016 Riverbend										
3	53.3	b	30	b	28.1	b	67.0	a	5.0	a
7	66.2	b	32	ab	29.3	b	66.1	ab	4.6	a
10	75.6	b	35	a	32.8	a	63.3	c	3.9	b
14	144.4	a	30	b	29.1	b	65.7	b	5.2	a

For each location and year, means in a column followed by the same letter are not significantly different at a p <0.05 based on Fischer's Protected LSD.

Table 3.3. Total nitrogen (TN), % nitrogen mineralization (NMin), total nitrogen mineralized (TNM), % NH3-N volatilization, and total ammonia volatilized (TAV) for clippings collected at 3, 7, 10, or 16-d mowing intervals (MIs) from the Athens Turfgrass Research and Education Center (ATREC) and Riverbend rhizotron facility in Athens, GA in the summers of 2015 and 2016.

MI (d)	**TN** ($g\ N\ m^{-2}$)	**NMin** (% of TN)		**TNM** ($g\ N\ m^{-2}$)		**NH_3-N** (% of TN)		**TAV** ($mg\ NH_3\text{-}N\ m^{-2}$)	
				Atrec 2015					
3	1.4	91.4	a	1.3	ab	0.56%	b	8.27	b
7	2.2	75.2	a	1.5	a	0.67%	b	18.3	b
10	2.1	27.1	b	0.7	b	0.71%	b	16.1	b
14	4.5	27.0	b	1.3	ab	1.42%	a	67.1	a
				Riverbend 2015					
3	2.2	45.6	b	1.0	d	-0.41%	d	-7.5	d
7	4.2	76.3	a	3.2	b	3.12%	b	130.1	b
10	4.2	54.4	b	2.3	c	1.50%	c	62.2	c
14	6	68.7	a	4.1	a	3.97%	a	235.0	a
				Atrec 2016					
3	1.5	-33.3	b	-0.5		0.39%	b	5.5	b
7	2.6	-9.4	ab	-0.2		0.69%	ab	19.7	ab
10	2.5	-1.9	a	0.0		0.67%	ab	16.7	b
14	3.3	-17.7	ab	-0.6		1.19%	a	42.3	a
				Riverbend 2016					
3	1.6	26.0	d	0.4	b	1.56%	c	25.2	c
7	2.1	42.6	c	0.9	b	1.75%	c	37.5	bc
10	2.6	83.9	a	2.2	a	2.64%	b	74.6	b
14	4.4	59.3	b	2.6	a	3.56%	a	156.3	a

*For each location and year, means followed by the same letter are not significantly different at a p <0.05 based on Fischer's Protected LSD.

Table 3.4. Multiple linear regression models for the Athens Turfgrass Research and Education Center [ATREC; native soil (sandy clay loam)] in Athens, GA during the summers of 2015 and 2016 to predict nitrogen mineralization[a] based on cellulose and lignin deposited as clipping tissue[b].

	ATREC			
Coefficient	**Estimate**	**Std. Error**	***t***	**p-value**
Intercept	0.484	0.148	3.274	0.003**
Cellulose	-0.105	0.023	-4.491	<0.001***
Lignin	1.141	0.262	4.352	<0.001***
Adjusted r^2 = 0.37				

*, **, *** Significant p <0.05, 0.01, and 0.001, respectively

[a]Nitrogen mineralization is cumulative N mineralized following a 90-d incubation and is presented as a percentage of total N deposited as clippings.

[b]Near-infrared (NIR) spectroscopy was used to determine tissue characteristics. Tissue analysis was conducted in the Fall of 2016 at the University of Georgia Agricultural and Environmental Services Laboratories in Athens, GA.

Table 3.5. Multiple linear regression models for the Riverbend Rhizotron facility [Riverbend; sand-capped] in Athens, GA during the summer of 2016 to predict nitrogen mineralization[a] based on total nitrogen deposited as clipping tissue[b].

Riverbend 2016				
Coefficient	**Estimate**	**Std. Error**	***t***	**p-value**
Intercept	0.352	0.074	4.731	<0.001***
Nitrogen	0.065	0.020	3.242	0.003**
Adjusted r^2 = 0.24				

*, **, *** Significant $p < 0.05$, 0.01, and 0.001, respectively

[a]Nitrogen mineralization is cumulative N mineralized following a 90-d incubation and is presented as a percentage of total N deposited as clippings.

[b]Near-infrared (NIR) spectroscopy was used to determine tissue characteristics. Tissue analysis was conducted in the Fall of 2016 at the University of Georgia Agricultural and Environmental Services Laboratories in Athens, GA.

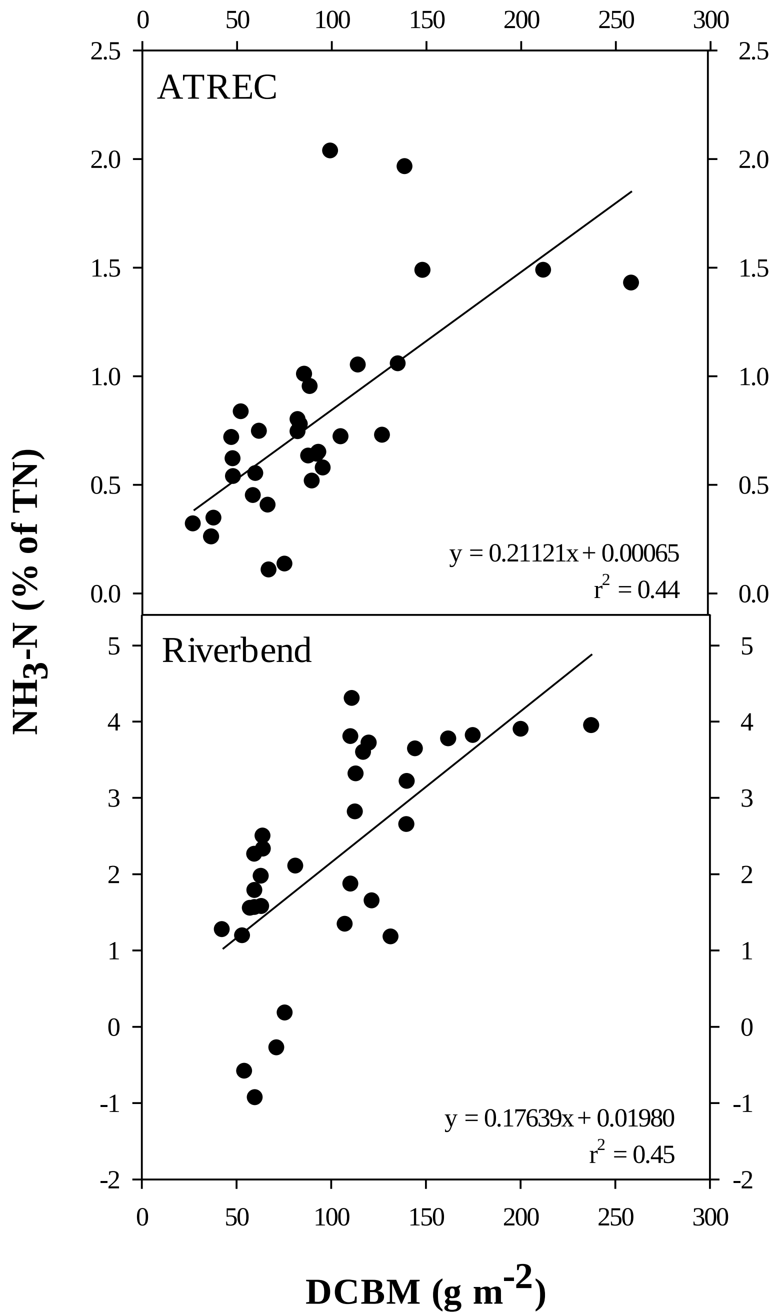

Figure 3.1. Relationship of Dry Clipping Biomass (DCBM) and ammonia volatilized as percentage of total N applied with clippings at ATREC and Riverbend sites.

CHAPTER 5

MAKING THE GRASS 'GREENER': AN EVALUATION OF HOME OWNER BEHAVIOR AND THE INTERNAL FORCES THAT DRIVE DECISION-MAKING ON THE LAWN[3]

[3] Grubbs, R.A., G.M. Henry, and J.J. Thompson. For submission to *Environmental Psychology*.

Abstract

Conventional, high-input management of turfgrass home lawns has generated increasing concern about short- and long-term environmental consequences and public health risk. Prior research on homeowner decision-making with respect to the lawn has found that behaviors are driven by several factors including biophysical demands of turfgrass, political and economic forces, and societal pressure. The purpose of this study was to investigate the role of internal drivers—such as values, identity, and emotion—in homeowner decision-making. Sixteen homeowners (across fourteen households) in North Georgia participated in a mixed-methods study to capture existing lawn care behaviors and attitudes about the lawn and lawn management. Participants completed two 60-minute walking interviews (approximately 6 months apart) on their lawns to discuss time spent working and playing on their lawns. Three primary internal drivers influencing lawn-care decisions were identified in the data: personal identity, social identity, and affective attachments to the lawn. We present a series of vignettes to illustrate how these internal drivers may influence lawn care behavior. Our data indicates that these internal drivers are not unidimensional; rather they co-exist and may operate in tension with one another to produce different, sometimes contradictory behaviors. Future research should consider the role of internal drivers in designing outreach and education tools for producing pro-environmental lawn care behaviors.

Introduction

Turfgrass lawns are an iconic part of the American landscape, providing a place to recreate, socialize, and connect with nature (Blaine, Grewal, Robbins, & Clayton, 2012). The “ideal” lawn has been described as “a plot with a single type of grass with no intruding weeds, kept mown at a height of an inch and a half, uniformly green, and neatly edged” (Jenkins, 2015). This aesthetic has become such an integral part of the suburban landscape that it is both expected and desired across the country regardless of ecosystem or climate (Robbins, 2007). Political ecologist Paul Robbins asserts that the home lawn has become a symbol of political and economic forces, as well as a strategy for producing obedient and responsible citizens (2007). Originating as a pre-Revolutionary design feature indicative of English landscapes, the lawn has evolved to epitomize a national identity: individual accomplishment, prosperity, and responsibility. While the singular home lawn reflects the socioeconomic status and moral sensibilities of the individual, the continuity of an unfenced, pastoral landscape represents a commitment to community.

Tensions between the cultural and symbolic value of the home lawn and the awareness of the financial and environmental costs of lawn management have made the lawn increasingly controversial. In 2002, the turfgrass and lawn-care industry in the United States generated a total estimated revenue of $57.9 billion, with approximately $8.0 billion attributed to lawn equipment manufacturers, $9.1 billion to lawn-care goods, and $19.8 to lawn-care services (Haydu, Hodges, & Hall, 2006). Management regimes designed to maintain ideal turfgrass aesthetics consume large amounts of water (Kjelgren, Rupp, & Kilgren, 2000), contribute to urban groundwater pollution through nutrient runoff and groundwater leaching (Barton & Colmer, 2006), and can cause physical harm through exposure to common pesticides (Karr, Solomon, & Brock-Utne, 2007). Yet turfgrass systems may also offer a number of ecosystem services including phytoremediation of contaminated soils, absorption and sequestration of environmental pollutants, soil erosion control, and temperature moderation (Beard & Green, 1994;).

Robbins (2007) found that ‘lawn people’ will go against their own pro-environmental inclinations to produce the ideal lawn, even when it contradicts what they know and believe about environmental impact. The term ‘pro-environmental’ has been defined as any behavior intended to minimize a negative impact on the environment (Kollmuss & Agyeman, 2002). Attitudes in their strictest sense are malleable and narrow in scope (Gatersleben, Murtagh, & Abrahamse, 2014). For example, a person may be have a positive attitude towards reducing pesticide use on the lawn, but this may not correlate to other pro-environmental behaviors such as watering the lawn less frequently. In a study performed in Ohio, Blaine et al. (2012) found many homeowners do not consider the possible impact of lawn chemicals on their local water sources, and do not even question what chemicals are being applied by their lawn care services. This aligns with Robbins’s finding that many homeowners seem to view their lawn as independent from the larger environment. Though there are cases in which environmental attitudes are cited by homeowners as important (e.g., Eisenhauer et al., 2016), other priorities may override these values to produce unexpected behavioral outcomes (Robbins, 2007).

The conflict between environmental attitudes and action has been referred to as the ‘attitude-behavior gap’ (Kollmuss & Agyeman, 2002). Proposed explanations for the attitude-behavior gap include an individual’s experience in relation to environmental action (direct vs. indirect), normative influences (i.e., social norms, cultural traditions, etc.), temporal discrepancy (changes in attitude over time), and methods of measuring attitude and behavior that may distort the scope of the discrepancy (Rajecki, 1982).

Previous Studies on Lawn Behavior

In recent years, a number of qualitative studies have attempted to evaluate lawn care behavior with the long-term goal of improving communication and affecting change. Most studies found that the decisions homeowners make regarding the lawn were not determined by one factor, but by some combination of factors including sociodemographics, social pressure, and perceptions of cost.

Affluent neighborhoods may be more *or* less environmental depending on the neighborhood's identity and expectations around the lawn. Some studies corroborated Robbins's claim that homeowners with higher education, greater income, and whose homes had greater value tended to use more lawn chemicals (e.g., Blaine et al., 2012). However, Law, Band, and Grove (2004) found that the relationship between socioeconomic status and lawn inputs is non-monotonic, with middle-income households applying nitrogen fertilizers at the highest rates. Homeowners often feel a responsibility to positively contribute to the neighborhood by choosing lawn care practices that mirror their neighbors' and produce a homogeneous aesthetic (Blaine et al., 2012). This comradery can be a strong motivating factor for encouraging lawn maintenance, but may also be a barrier for creativity and independent thought.

In many neighborhoods, there is a fear that the failure to uphold a certain quality or standard will be met with criticism and judgment (Dzidic & Green, 2012). Carrico et al. (2013) contends that neighborhoods with greater home values and higher mean incomes exert the greatest social pressure on residents, and this pressure is what influences behavior more than socio-demographics alone. Social pressure may be particularly strong in neighborhoods regulated by a homeowner's association (HOA) or covenant (Fraser, Bazuin, Band, & Grove, 2013).

An additional barrier to adopting pro-environmental landscapes has been the perception of cost (Eisenhauer, Brehm, Stevenson, & Peterson, 2016). Though low-cost alternatives such as incorporation of groundcovers and native plant species are available, these are generally not well-known by homeowners (Robbins, 2007). Instead, strategic marketing of organic and alternative products by the lawn care industry perpetuate a bourgeois environmentalism (Baviskar, 2003), in which 'morally responsible', low-risk alternatives to conventional lawn management are presented as a luxury option.

Previous research on lawn care behavior has primarily focused on the identification and understanding of "external drivers" or "the political and moral economy and the biophysical demands of monocultural turfgrass" (Harris, Martin, Polsky, Denhardt, & Nehring, 2013). Very few studies have explored the lived experiences of homeowners, which can be central to understanding neighborhood dynamics and shaping lawn management practices (Harris et al., 2013). A more powerful approach to impacting decision-making may be through the engagement of internal drivers, which we define as a person's core values, identity, and affective attachments that influence decision-making. This study takes an in-depth, qualitative approach to investigate the internal drivers that influence lawn care behavior in an effort to design more effective outreach and communication promoting pro-environmental lawn management practices.

Material and Methods

Our primary research objective to investigate the internal drivers of lawn care behavior was best served through a qualitative examination of participants' lived experience on their lawn, and the gap between their environmental attitudes and behaviors. Qualitative research facilitates the opportunity to investigate experience, meaning, and process in context rather than in a decontextualized, experimental, or lab setting. It does this by examining how participants experience or make sense of the events or situations being studied, the processes by which events take place, and the social context within which participants act (Maxwell, 2013). This study was part of a larger mixed-methods research project in which participants completed two 60-minute interviews and a weekly survey throughout the summer[4]. The University of Georgia Institutional Review Board approved this study, and all participants gave informed consent.

Participants

In early spring of 2015, homeowners in Athens-Clarke County, GA or adjacent counties (Bogart, Oconee, and Jackson Counties) were recruited via flyer and email materials distributed through select neighborhood listservs and social media pages. Some participants were also recruited via word-of-mouth in an attempt to build a sample diverse in age, gender, marital status, and race or ethnicity. Our final participant pool included 16 individuals (eight women and eight men) from 14 different households[5] (Table 1). Participants ranged in age from 35 to 60 years. Our final sample was predominantly white with only two non-white participants. Though our sample was not as diverse as we may have liked, it does resemble homeowner demographics for the Athens area[6]. During the recruitment process, we sought a 2-to-1 ratio of homeowners that managed their own lawns and homeowners that hired a professional lawn service; however, over the course of the study, some participants changed groups.

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[4]To collect real-time data on participants changing attitudes and behaviors, participants were asked to complete a brief (5 minute), weekly (for 20 weeks) survey regarding lawn management behaviors, recreational activity, and motivating behaviors. Survey results will be reported elsewhere.

[5]Despite several attempts, we were unable to schedule a final interview with one participant (Sylvia); however, the data from her first interview was included in our data analysis.

[6]As of 2010, white citizens represented an 84.9% share of home purchase loans in the Athens area, with black citizens accounting for 8.0%, and Hispanic, Asian/Pacific Islander, and American Indian citizens each accounting for less than 5.0% each.

Table 1 - Details of the participants interviewed (*N* = 14)

	Participant*	Age/Gender	Self/Service	Participant Description (employment status; family; additional information)
1	James	35/M	Both	Employed f/t; divorced, living with a long-term partner in an older, well-established neighborhood. Three dogs, no children.
2	Lauren	35/F	Service	Self-employed p/t; works from home; married with two children and two dogs.
3	Frank	37/M	Self	Employed f/t; married with two children and two dogs.
4	George	37/M	Self	Employed f/t; married with no children and no pets.
5	Lisa	38/F	Service	Stay-at-home parent; married with three children and one dog.
6	Samantha	39/F	Self	Employed p/t; married with two children and one dog.
7	Morgan	41/F	Both	Stay-at-home parent; married with two children and several pets (dogs, cats, and chickens).
8	Robert	42/M	Self	Employed f/t; married with one child and two dogs.
9a	Nina	45/F	Service	Employed f/t; married with four children and no pets.
9b	Ted	45/M	Service	Employed f/t; married with four children and no pets.
10	Silvia	48/F	Self	Employed f/t; single with one child.
11a	Beth	56/F	Both	Self-employed f/t; works from home; married with two adult children.
11b	Michael	56/M	Both	Employed f/t; married with two adult children.
12	Andrea	58/F	Both	Employed f/t; single with one dog and regular visits from grandchild.
13	Jake	59/M	Self	Retired; married with one dog.
14	Lawrence	56/M	Self	Employed f/t; single with roommate and no pets.

*Pseudonyms were selected for each participant to protect confidentiality

Interviews

We conducted two semi-structured walking interviews with each participant in their home yard/lawn. Our intentions in conducting interviews in this manner were three-fold. First, semi-structured interviews facilitate opportunities to loosely guide the direction of the conversation while leaving space for conversations to follow the priorities of the interviewees (Fylan, 2005). This allowed us to not only learn what participants were doing to their lawn, but also to understand the way participants make sense of their own behavior, and how that ultimately influences their management decisions. Many of our questions were driven by a desire to understand 'why,' and semi-structured interviews offer the most effective method for establishing 'why' in response to specific behaviors, emotions, or perceptions (Fylan, 2005).

Second, walking interviews create a unique opportunity for interviews to be spatially focused, and provide a productive setting for participants to connect with the environment they are talking about (Evans & Jones, 2011). This allows for a greater understanding of the context within which participants act, and how the physical space may influence that action.

Finally, we conducted the two interviews six months apart to explore how behavior and attitudes change over time (i.e., 'temporal discrepancy'). The first interview (mid-Spring) was designed to establish a baseline of participant management practices, leisure and recreation habits, and general attitudes about the lawn and lawn management. Second interviews (mid-Fall) were more participant-specific and focused on key issues that emerged in the first set of interviews and weekly surveys (e.g., time spent on the lawn over the summer, changes in attitude and behavior across the season, and alignment between the interviews and surveys). Again, the semi-structured nature of the second interview allowed participants to elaborate on different events and actions that occurred over the study period.

Data Analysis

Interview responses were transcribed verbatim, and imported into software to facilitate coding and qualitative analysis (ATLAS.ti Scientific Software Development GmbH, Version 8.0). Our analysis strategy combined inductive and deductive coding methods to organize the interview data. To facilitate an initial comprehensive overview of the data, the data was structurally coded according to the interview question (Saldaña, 2015). Next, we developed an initial codelist based on themes gleaned from the literature on attitudes and behaviors in relation to the lawn (e.g., environmental values, neighbor relationships, cultural norms/expectations, general management practices, and biophysical demands). After reviewing the raw data, this list was modified to reflect additional concepts present in our data (e.g., affective language, internal expectations, sensual language, and memories/sentimentality). The first author then indexed the entire dataset using this refined code list, and had our coding cross-checked by peers with experience in qualitative analysis. Communication with JJT was ongoing for the duration of the project to discuss the data, code lists and coding strategies, interpretation of the data, and decisions for how to proceed with data analysis.

Results and Discussion

Three primary themes emerged from this dataset: (1) the role of personal identity/core values, (2) the role of social identity/neighborhood responsibility, and (3) affective attachments to the lawn and lawn management. In this section, we present a series of vignettes drawn from our data to illustrate these themes and demonstrate how they can influence management decisions. We discuss their implications for outreach and communication below.

Vignette I: Personal Identity and Constructs of Self

Personal identity has been defined as "a sense of self built up over time as the person embarks on and pursues projects or goals that are not thought of as those of a community, but as the property of the person. Personal identity thus emphasizes a sense of individual autonomy rather than of communal involvement" (Hewitt, 2010). As such, personal identity is separate from role and group-based identities. Hitlin (2003) proposed that personal identity is driven by “deeply personal but socially patterned and communicated” values unique to each individual, and that understanding these values is critical to understanding personal identity. Developing a greater understanding of the relationship between personal identity and the lawn is critical to identifying the way constructs of self can influence lawn care decision-making and the willingness to adopt pro-environmental behaviors.

Andrea

Andrea is a single career woman who actively identifies as pro-environmental. Her ideal lawn is “sustainable” which she further defines as “low-maintenance.” Of all of the participants in the study, Andrea’s yard is the closest to embodying Robbins’s idea of an alternative lawn. Her property is largely dedicated to groundcovers, a small blueberry garden, and trees/shrubbery. In the front yard, she has kept an area of perennial ryegrass and “weeds” that are mowed every 2-4 weeks. She explains that because she is in a “traditional neighborhood”, she does not feel that she can completely forego a lawn, because “it’s not going to look good.” She adds that while she loves grass and feels that traditional lawns are beautiful, she simply does not believe they are good for the environment.

Andrea is the only participant in the study whose strong environmental identity drives the bulk of her actions in her yard. Andrea’s lawn is noticeably longer and more unkempt than the surrounding lawns. She is cognizant of this, and the way her lawn contrasts with some of her neighbors', but she is willing to make aesthetic compromises in support of her strong environmental values. She explains,

> Most of my neighbors cut their grass once a week. Honestly, I just feel like that's a lot of pollution with those lawn mowers. They're not like cars. Lawn mowers pollute very heavily. So, I would rather have my lawn look bad and a little messy for two weeks, and cut it every two or three weeks, because I care more about the environment than about how it looks.

Andrea's biggest challenge is finding the time to maintain the lawn the way that she would like. Though part of her personal identity is rooted in being an environmentalist, another core part of Andrea's identity stems from her career. Andrea values a strong work ethic, and chose a career that is very demanding of her time and energy. While she explains that she used to take time off in the spring and fall each year to invest in her lawn, personal and professional obligations have prevented that in recent years. As a result, she has grown to feel overwhelmed by the prospect of maintaining what she has, let alone continuing her on-going project of gradually incorporating more alternative groundcovers. Andrea has also found it difficult to keep the weeds out of her groundcovers, and she feels like the aesthetic appeal has suffered.

In the first interview, Andrea explained that she relied on a service during the summer to help with mowing, weeding, and trimming the shrubbery. However, over the course of the study, the surveys revealed that Andrea was doing more of the maintenance herself. In the second interview, she explained that the service she had used for years was no longer dependable. This further contributed to Andrea's frustration both with the overall appearance of her yard as well as the task of maintaining it.

Despite Andrea's strong environmental identity, she is unable to maintain her ideal yard due to constraints on her time and resources. Though she does not seem willing to compromise her environmental values (i.e., use herbicides to control the weeds), the lawn has now become more a place of anxiety for her, representing all that she is unable to accomplish.

Vignette II: Social Identity and Neighborhood Responsibility

We define social identity as an individual's identity according to their social classification to various groups such as their gender, religious affiliation, or membership to various social organizations (Ashforth & Mael, 1989). An individual may have several discrete, yet interrelated social identities that become salient or more pronounced based on unique situations or circumstances (Hogg, Terry, & White, 1995). In general, the formation of social identities serves two primary functions (1) to give structure and order to a particular social environment for the individual and (2) to enable the individual to define themselves within their social environment(s) (Ashforth & Mael, 1989).

Gardening practices "can describe more generalized aspects of social identity," meaning that the landscape can represent one's sense of duty to the neighborhood, their social status, and their willingness to conform to social norms in order to reinforce this sense of belonging (Clayton, 2007). In this regard, the degree of social attachment to the neighborhood and the importance of one's social identity in making decisions on the lawn may vary according to neighborhood characteristics and socio-demographics, as well as one's length of residence, ownership, and long-term plans to stay in the neighborhood (Riger & Lavrakas, 1981). In our study, several participants cite their desire to fit in and please their neighbors as an important priority in making lawn management decisions; however, we found that different neighborhood priorities drove different behavioral responses.

Samantha

Samantha lives with her husband and two children in a historic neighborhood with very few grass lawns. She describes her ideal lawn as being “easily maintained” and “easily played upon or used for recreation.” Samantha was quick to identify herself as a Master Gardener and shared that though she has always been “more fond of gardens” and plants to eat, she has been surprised by how much she enjoys the lawn. For Samantha, the lawn has become a place through which she not only connects with her own family, but also experiences a social bondedness to her neighborhood.

> Most of our neighbors that have young children do not have grass. They are always welcome to come and play in our yard, and they do which is really nice. There's a little girl across the street that she and her friends will come and play in the yard. They'll set up a picnic blanket and have a pretend picnic. We have other friends on the other side that come and play croquet on Sundays. We might not even be here, but they'll use the lawn.

Samantha has assumed a role of providing her lawn as a space for community and social connectedness, and expresses that she is “not willing to use pesticides or herbicides” because she wants the kids to feel “welcome.” From Samantha’s perspective, the use of pesticides, herbicides, and synthetic fertilizers would make the yard unsafe for children and pets by exposing them to potentially harmful chemicals while they play on the grass. Samantha’s sense of social responsibility to her neighborhood prompted her to assume the role of primary decision-maker on her lawn. She explained, “I knew I did not want to use any other chemicals on it that were not organic and that could be potentially harmful to animals or people. And I also didn't want to put a lot of money into nursing it.”

Though Samantha's behaviors clearly identify as pro-environmental, they are predominantly driven by her sense of duty to her family and neighborhood rather than her environmental values. In her first interview, she said that she was not willing to water the lawn once it is established; however, throughout the course of the summer, she compromised by hand-watering sections that were struggling. "It was just really nice to have the grass in the summer. Even when it was super-hot, the house shaded pretty much all of the grass. We just were enjoying it so much, that we said we were going to water it."

When asked whether she did this for more aesthetic or recreational reasons, Samantha elaborated, "Yeah, not really for how it looked. It was just that we didn't want a dust bowl out here. The grass was actually doing some good for the kids playing on it, so we wanted to keep it strong." This demonstrates Samantha's willingness to make tradeoffs on the lawn, if she feels they serve the needs of her family and community.

Vignette III – Emotional/Affective Connections

Pooley and O'Connor (2000) found that affect can be a significant predictor of environmental attitudes, and that understanding how an individual feels about a particular environmental subject is critical to designing effective outreach. A person's attachment to a place can be deeply rooted in their feelings about their personal experiences there or even how they feel about nature itself and the physical features of the space (Scannell & Gifford, 2010). Several participants in our study exhibited an affective connection with their lawn that could be emotional, sensual, and nostalgic. We also touch on examples of more 'negative' sentiments towards the lawn and the way that this drives an apathy and occasional resentment toward lawn management.

Michael and Beth

Beth and Michael have a large, sprawling property in an affluent neighborhood. They have two grown children who are no longer at home, and two active dogs. While Michael describes his ideal lawn as “No weeds”, Beth explains she doesn’t really mind the weeds so much “as long as everything is green.” She goes on to explain, “Because I come from a green area, and I want it to be lush and green.” Much of Beth’s connection to the lawn itself and her expectations of how it should look appear rooted in her affective experience. Her discourse indicates that she truly loves the lawn:

> I like the sense of accomplishment when it’s done, but I also like the time when I’m doing it because it’s peaceful. It’s relaxing, and it helps me organize my thoughts a lot of times. I have meditation and prayer during those times, and it just makes me feel like I’m connected to something.

Though they use a service seven times a year to apply herbicides and fertilizers to the lawn, they do the bulk of the maintenance themselves (e.g., mowing, irrigating, aerifying, edging, pruning and some hand-weeding). When we asked why they choose to do the work themselves, they responded differently.

Beth: Because we enjoy it.

Michael: Because we’re cheap.

Michael and Beth come from different backgrounds that have influenced their perceptions of a lawn and lawn management. Michael did not have a lawn growing up. They lived in an apartment and “never owned a house.” His first lawn was the one he and Beth shared at their first home together. Beth, on the other hand, grew up in a close-knit neighborhood where she began working on the lawn when she was eight years old. She reflected,

> Mowing the lawn at our house was always a family affair, because my cousins lived in all the houses down the street. So, all the moms and all the kids would go out and do the yards one day a week all together. We would mow everybody's lawn up and down the street.

While Michael expresses more practical concern about the cost of lawn, he uses sensual language throughout the interview. When asked about his fondest memory from the summer, he says, "I just like walking out there barefoot. I feel grounded. You feel like you're really attached to the earth, especially when the grass is green and moist. It's really good."

His sentiments toward the lawn seem largely driven by Beth's love for it, and the memories that they have formed around it together in their marriage. This prompts him to make some tradeoffs to please Beth, particularly when it comes to using more water for irrigation that he implies he may not make on his own.

Converging Themes

In some participants, no single theme emerged as more dominant. Rather, multiple themes intersected to drive lawn care behavior and decision-making.

Lawrence

Lawrence is a single male living in a home with no children or pets. He is an Afro-Carribean immigrant, and the only participant in this study who did not grow up in the U.S. Lawrence's ideal lawn is "green and weedless." In order to maintain this, he describes his efforts as a "full-time job" in which he waters, prunes, edges, mows, fertilizes, and kills the weeds. He also describes his own method for experimentation in the yard:

> When I bought this [property], these guys used the least of the least for landscaping. So, I bought 500 shrubs. I buy three of something and I plant one there, plant one there and

plant one there, and I see how it does. I realize, okay, this one needs more sun or less shade or whatever it is, so I start transplanting stuff.

The time Lawrence spends managing the lawn in this way facilitates opportunities for a deeper, more personal connection with the outcome. He explains, “You see the effort you put in it and you see the results. You reap what you sow.” Though he has forged a bond with his yard through years of investment and hard work, he is less driven by sentiment or nostalgia than participants raised with memories of and exposure to the American lawn. His internal drive is more significantly motivated by both his personal and social identities. Lawrence’s personal identity is deeply rooted in being a hard worker. In addition to his full-time job as a director of client services for a local government entity, Lawrence has two part-time jobs, pointing to this strong work ethic. He measures his success and achievement by the degree and quality of his work, and this extends to his relationship with the lawn.

Lawrence’s efforts are also driven by his sense of duty to the neighborhood and his corresponding social identity. “I'm thinking about my neighbors and what their guests see. You don't want somebody beside you that has overgrown yards,” he says. Additionally, as one of the only non-white residents in his neighborhood, he is keenly aware that the appearance and upkeep of his lawn may be perceived by his neighbors as a representation of his race and ethnicity. He explains, “I live in a neighborhood where there are not many African Americans, and if you see somebody at a distance, I’ve got to represent my race.” He goes on to explain that it is “particularly important” to him that people do not think that because of his race, that he is going to have a “poor looking yard and distasteful scenery.” This sense of responsibility to positively represent his race works in tandem with Lawrence’s sense of duty to his neighborhood, giving rise to a heightened awareness of how his yard is perceived. While it is in Lawrence’s nature to work hard, he admits that he may not invest the same time or energy into the space if he did not feel an innate responsibility to his neighbors.

> Maybe if I lived on a deserted island or something, I wouldn't keep it (the lawn) the way I did. But I don't want it to be unkempt for appearances. That's my main motivation. It's not like I'm thinking about how it looks all of the time, but I want it to look good for the neighbors.

Vignette Discussion

Though personal identity, social identity, and affective attachments co-exist, they operate in tension with one another to produce different, sometimes contradictory behaviors. Different themes may be more or less salient for different individuals, and may also change or shift in the same individual over time as a person's attitudes, expectations, and priorities are fluid. The following discussion further explores the three primary themes identified in this study (personal identity, social identity, and affective attachments) as they relate to lawn care behavior. Additional instructive counter-examples are pulled from the data to further illustrate specific points, and to give contrast to some of the examples presented earlier.

Personal Identity

Lawrence and Andrea both express their personal identities through their lawns. For Lawrence, the lawn embodies his strong work ethic and his desire to produce a visually stunning landscape. For Andrea, her landscape embodies her environmental values and desire to achieve a low-input lawn. Though most participants have made creative changes to their lawn, Lawrence and Andrea's are among the most dramatic: Lawrence's through his experimentation and intensive management regime, and Andrea's through the incorporation of alternative groundcovers and low-input grass species. This creative process has been previously identified as an important expression of identity and self for some homeowners (Freeman et al., 2012).

For homeowners such as these, pro-environmental outreach and education would need to appeal to this creative process and larger sense of pride and achievement of the lawn. While Andrea already has strong environmental values, methods of upholding these values that are more convenient to the busy individual are key. For Lawrence, pro-environmental behaviors must be able to support his desire to maintain a lawn that publicly represents hard work and a meticulous aesthetic. Cultural norms around how the lawn should look (i.e., green and weedless) may be more difficult to overcome in this regard.

Social Identity

Lawrence's management decisions were also strongly influenced by his social identity. He and Samantha were both driven by a strong sense of neighborhood responsibility, which is consistent with previous studies that identified the lawn as a space for engaging with community (Blaine et al., 2012; Fraser et al., 2013; Martini et al., 2014). These socio-physiological processes involved with the way people connect with their lawn have been observed before, and are sometimes discussed under the umbrella of 'neighborhood attachment' (Austin & Baba, 1990; Comstock et al., 2010). Vested interest in what the neighbors are doing has been correlated with increased chemical usage (Blaine et al., 2012; Robbins, 2007); however, different neighborhood priorities will drive different external expectations of what the ideal lawn is. Correspondingly, Samantha and Lawrence's social identities in their neighborhoods drive different environmental behaviors. Whereas Lawrence's management style is more intensive and high-input to maintain a certain visual aesthetic, Samantha's behavior is arguably pro-environmental to accommodate her perceptions of risk and safety vis-à-vis its use by others (children) in her neighborhood.

It could also be argued that Samantha arguably has the luxury of choosing to avoid chemicals because there are fewer social consequences if the aesthetic suffers. Because Lawrence is both in a neighborhood with more formal expectations (via his HOA), and simultaneously feels that he is combatting racial stereotypes, his sense of freedom to choose alternative management practices is ultimately diminished. Lawrence mentions his HOA twice in the interview in broad terms, but does not elaborate on the specific covenants that govern neighborhood expectations of how the lawn should look. His concerns around how he represents his race to his neighbors, however, were articulated early in the first interview and reinforced throughout.

In contrast, Samantha's neighborhood has a higher level of 'collective efficacy,' or "the link between mutual trust and a shared willingness to intervene for the common good of the neighborhood" (Sampson, Raudenbush, & Earls, 1997). Higher collective efficacy has been associated with greater neighborhood attachment and strong neighborhood identity. She feels that minimizing chemical exposure is a neighborhood priority—a consensus reached through various dialogues with neighbors. Reducing chemical usage is Samantha's way of engaging in positive citizen participation. This is an instructive counterexample to previous studies finding that the degree to which children and pets play on the lawn or "lawn exposure" correlated with increased use of synthetic fertilizers, regardless of environmental perceptions (Carrico et al., 2013). Results from such studies indicate that tradeoffs may be made not only to maintain aesthetics, but also to support recreational activity. In our study, this tradeoff was observed in another mother, Lauren, who described using chemicals to minimize brush in the yard that attracted snakes, insects, and prevented play for her children:

> I want my grass green. That sounds awful, but you paid a lot of money to get it in here to have the lawn for them to play with. We're not trying to do anything bad to the environment, but I realize I am putting chemicals out there.

Lauren feels the risk of natural hazards in the lawn outweigh the risk of chemical exposure that trouble Samantha.

As Dzidic and Green (2012) suggested, shifting priorities at the neighborhood level could have a dramatic effect for homeowners like Lawrence who are concerned about what the neighbors think. If the community priority is to produce the lawn that is the most ‘natural’ or ‘green’, Lawrence’s core values might drive him to put his efforts into meeting this new objective. In a study evaluating the transmission of new lawn management information among neighbors, Martini, Nelson, and Dahmus (2014) found that attendance at group discussions, individual social connectedness, length of homeownership, and the presence of children all contributed to increased sharing of best management practices among neighbors.

Affective Attachments

Michael and Beth’s relationship with the lawn appeared rooted in sentimentality and sensual functions of memory and experience. For Beth, this stems from pleasant childhood experiences and the lawn serving as a space to bond with family and self. Michael primarily identifies with more recent memories, particularly those shared with his wife.

Beth’s language draws upon more affective language and elements of ‘topophilia’, or the emotional bond between a person and place (Tuan, 1990). This is further defined as “fleeting visual pleasure, the sensual delight of physical contact; the fondness for place because it is familiar, because it is home and incarnates the past, because it evokes pride of ownership or of creation; joy of things because of animal health and vitality” (Tuan, 1990). While most participants may exhibit elements of this to some degree, Beth and Michael's discourse most embodies it more completely.

Beth's management decisions seek to preserve some natural elements of the space, while simultaneously recreating the lush, green grass of her childhood. She demonstrates a willingness to use synthetic fertilizers, occasional pesticides, and supplemental irrigation to construct her ideal lawn. Where shifts in neighborhood priorities or attempts to change the environmental knowledgebase may work in changing behavior for some, it would not address Beth's deeper internal drivers. Rather, an appeal to Beth's emotions and sentimentality towards the lawn may prove more effective. This approach has already been utilized by the lawn care industry through strategic marketing campaigns presenting images of families playing on a lush, green lawn.

In contrast to Beth's nostalgia, another participant, Robert, negatively associates the yard with long Saturdays spent completing strenuous lawn care tasks delegated by his father. As a result, Robert does the bare minimum on with his lawn now. Although his management practices are inherently low-input, they are not driven by pro-environmental values, but instead by his desire to avoid yard work. Robert's lawn care behaviors may be particularly vulnerable to revision. If he had the discretionary income to hire a service, he might give little thought to the chemicals used or their impact on the environment. This mindset was observed in another participant, Lisa, who employed a service without knowing the name of the service, their regular practices on her lawn, or even what she paid them. When Lisa moved into her home with her husband and three children, they kept the service put in place by the previous owner because they knew that it would meet HOA standards. Lisa then set up automatic payments with the company, eliminating her need to think about it at all.

A more rational, economic appeal could be effective for homeowners like Robert who tend to feel indifferent or apathetic toward their lawn. Less expensive ways to manage the yard that appear to change the homeowner's "status," or promote a "less is more" message that reframes minimal inputs as desirable may draw attention from homeowners that have little vested interest in the lawn otherwise. Additionally, for homeowners like Lisa who rely heavily on a service, a greater impact may be made by engaging directly with lawn care services to encourage more pro-environmental practices.

Conclusion

Lawns present a unique interface for studying paradoxical tensions in environmental behavior. They serve as a bridge between the natural and built environment, a bridge between the individual or family and the larger social environment, as well as a connection to the larger ecosystem. This study affirms that homeowner attitudes and perceptions are strongly influenced by the deeper, internal drivers of personal identity, social identity, and affective attachments. It is our assertion that in order to close the attitude-behavior gap and effect change among homeowners, outreach and education tools must address these three drivers.

Nevertheless, the relationship between these internal drivers and pro-environmental behavior is not straightforward. For example, with social identity, external factors shape neighborhood expectations and community priorities, which, in turn, influence the nature of a homeowner's perceived responsibility. For one individual, the responsibility to maintain a safe space for community play is marked by reduced chemical usage to minimize perceptions of public health risk. For another individual, extensive inputs may be used to produce an aesthetic that upholds the overall appearance and image of the neighborhood. It is not enough to simply say that the desire to please the neighbors results in behavior that is more or less environmentally responsible. Rather, what is revealed is the opportunity to target behavior through group-oriented outreach (i.e., shifting neighborhood priorities).

This same mindset may be applied to the other internal drivers outlined in our study. Personal identity can be addressed by targeting core values and fundamental constructs of self (e.g., work ethic or environmental values). Affective attachments to the lawn and lawn management behaviors may be addressed through more nostalgic and sentimental appeals for those who are positively attached to the space, and more logical, economical appeals for those more apathetic towards the space.

Finally, it is important to acknowledge how these internal drivers intersect. In this study, one participant's personal and social identities worked in tandem to reinforce his drive to produce a perfect lawn aesthetic through high inputs. For other participants, their personal identities to be "green" may compete with their social identities to have a perfect lawn that pleases the neighbors. As has been previously suggested by other researchers, outreach and education for shifting lawn care behavior must take a multifaceted approach, appealing to a wider range of homeowners. However, rather than taking a piece-meal approach of targeting specific attitudes and behaviors, outreach should appeal to deeper internal drivers including personal identity, social identity, and emotion to create more fundamental shifts in the homeowners themselves.

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CHAPTER 5

CONCLUSIONS

This research employed a mixed-methods, interdisciplinary approach to evaluate sustainable fertility practices and explore homeowner decision-making in turfgrass management. Three individual projects were completed: 1) predicting spatial structure of soil physical and chemical properties of golf course fairways using an EC_a sensor, 2) evaluating the effects of mowing frequency on hybrid bermudagrass clipping composition and nitrogen transformations, and 3) a qualitative analysis of the internal drivers of home lawn decision-making. These three projects as a whole offered opportunities to address three areas of environmental turfgrass science including large-scale management (golf courses, sod farms, athletic fields), small-scale management (home lawns), and the design of effective outreach/education tools.

Maps generated in the first study using the EC_a device revealed strong spatial variability both across and within fairways for each location. These maps provide evidence that golf course fairways exhibit significant 'within-field' variability of properties relevant to crop management, an important criterion for the implementation of site-specific management (Plant, 2001). Though significant relationships were established between EC_a and soil properties including clay content, organic matter, and soil pH, the strength and nature of these relationships varied by fairway. This indicates that further research was warranted to determine the best protocol for using the mobile EC_a device to measure or predict the spatial structure of individual soil properties. Future research should explore the relationship between EC_a data and soil moisture, as well as the effect of temporal stability, or change over time. Principles of site-specific management could be applied to smaller turfgrass systems such as home lawns and small recreation fields. However, site-specific management is best suited for large-scale turfgrass systems where there are the greatest environmental and economic benefits.

Results from the second study, evaluating the effect of mowing frequency on clipping composition and nitrogen transformations, yielded three important overall findings. First, that no clear relationship could be established between mowing frequencies (ranging from 3 to 14 days) and clipping composition (% carbohydrates, cellulose, lignin, or nitrogen). Second, that there appeared to be a strong relationship between total biomass deposited as a function of mowing frequency and NH_3 volatilization, implying that less frequent mowing could reduce volatilization losses. Finally, that in turfgrass systems that were not prone to N immobilization, a significant percentage of N from recycled clipping tissue would mineralize into a plant-available form, reducing fertilizer needs by between 26.0 and 94.1% in systems where clippings are returned. Future research should consider diurnal fluctuations in temperature and moisture, along with canopy and thatch mechanics under in-situ conditions to determine how this could affect N mineralization when compared with this study. Clippings in this study were incubated under steady-state conditions with clippings deposited directly onto the soil surface. Findings from this study, when combined with a complimentary field study, could be used to offer simple management changes that might be employed both by large- and small-scale turfgrass managers to improve RUE and reduce overall nitrogen inputs.

Interviews and surveys conducted with 14 local households revealed that what drives homeowner decision-making with respect to the lawn and turfgrass management was complicated. Previous research has focused primarily on external drivers such as biophysical demand, politics, economics, and societal pressure; however, this study revealed that internal drivers (personal identity, social identity, and affective attachments) appear to be at the core of behavior and decision-making. In order to effectively disseminate scientific findings like those from the first two studies and affect change in turfgrass management behavior, outreach and educational tools will need to take on a multi-faceted approach. Appealing to individual identities and sensitivities is critical to competing with industry marketing, which has exploited emotional proclivities for decades. Conventional rationalist approaches that strictly regurgitate scientific information can only appeal to a particular audience, excluding the portion of the population that is driven by deeper, sometimes conflicting constructs of self.

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APPENDIX A

ADDITIONAL SPATIAL MAPS OF FAIRWAY SOIL PROPERTIES

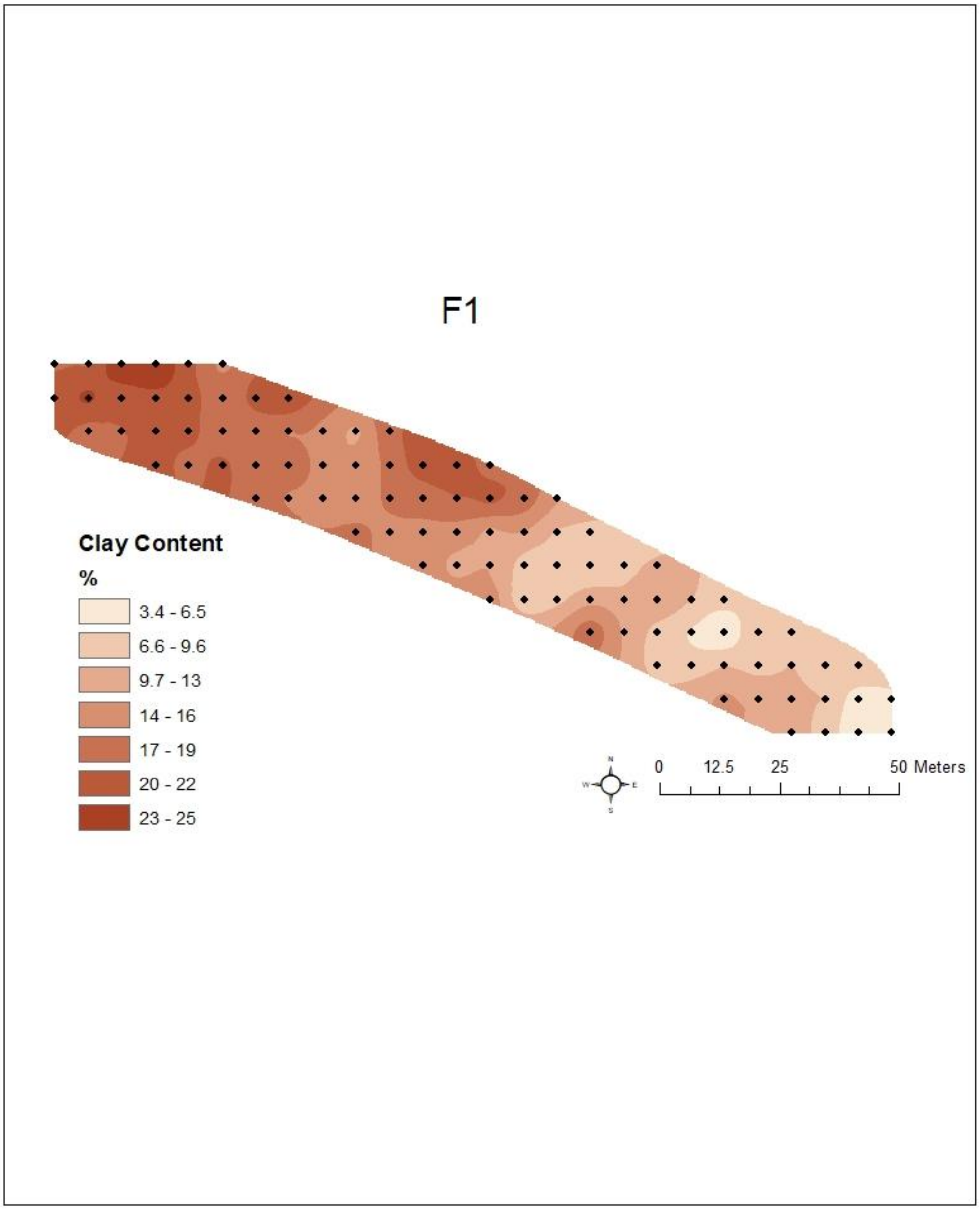

Figure A.1. Georeferenced soil sampling grid (7 m × 7 m) and corresponding kriged map of clay content (%) for Fairway 1 (F1) at the University of Georgia golf course in Athens, GA in 2016 (equal interval legend classifications).

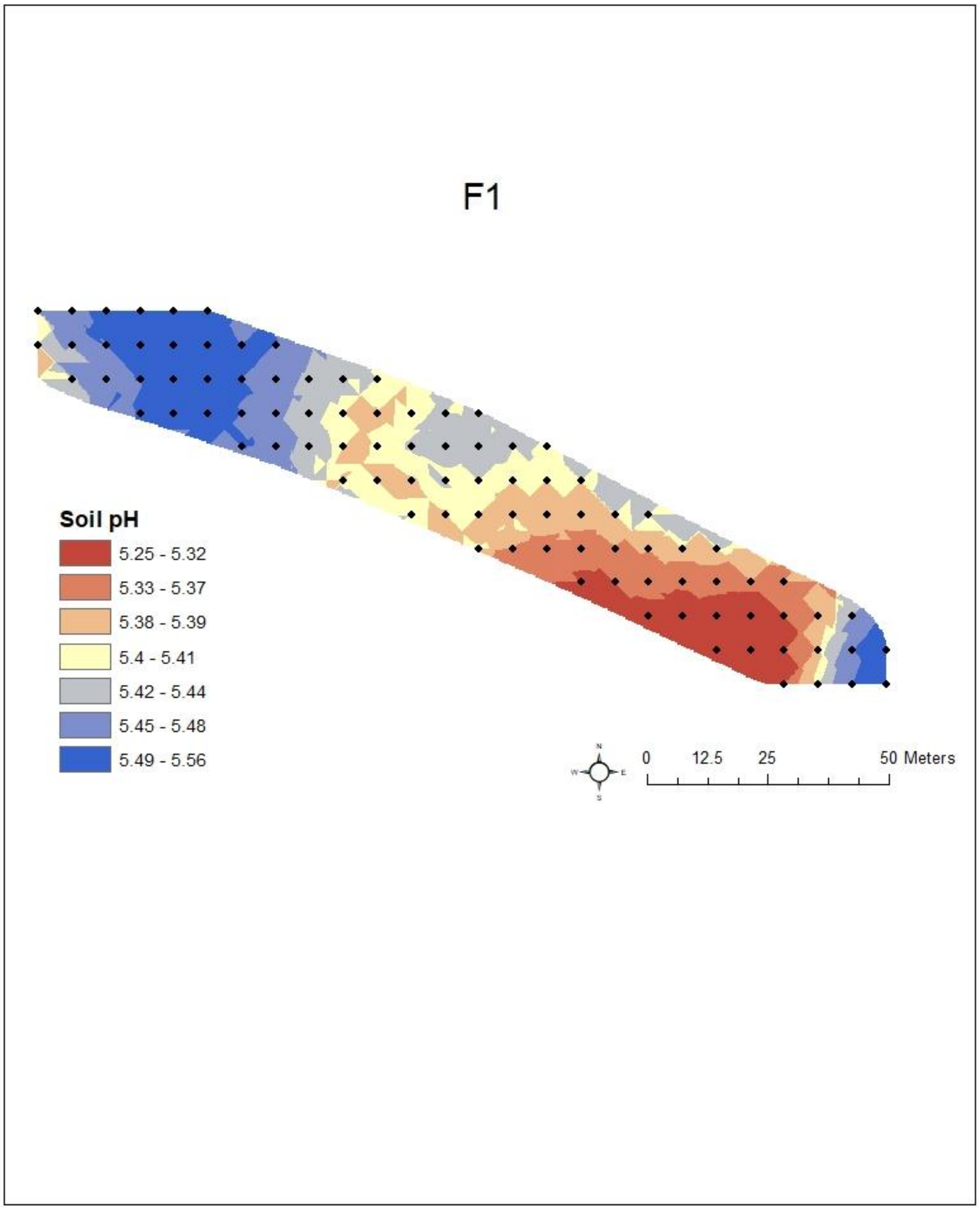

Figure A.2. Georeferenced soil sampling grid (7 m × 7 m) and corresponding kriged map of soil pH for Fairway 1 (F1) at the University of Georgia golf course in Athens, GA in 2016 (equal interval legend classifications).

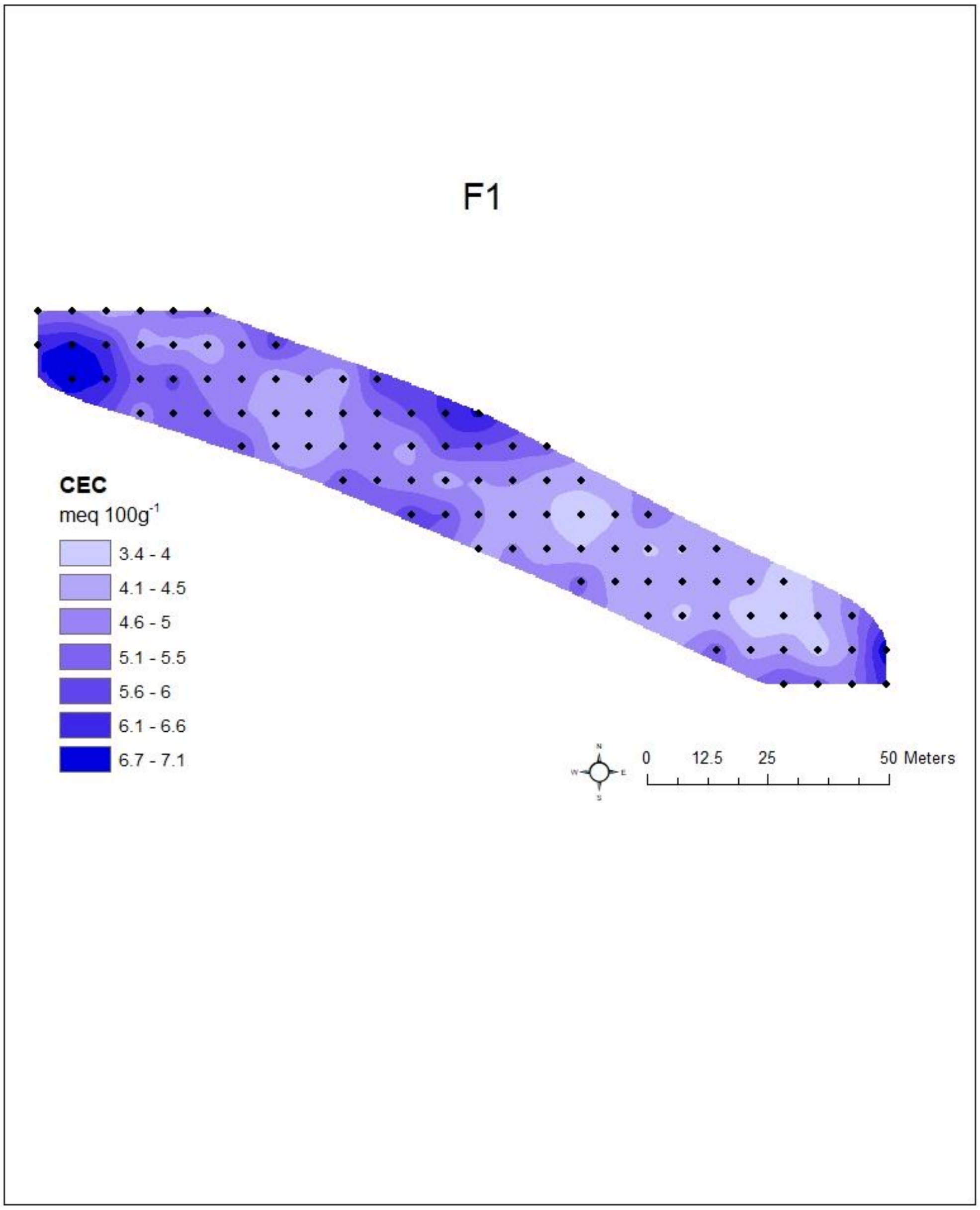

Figure A.3. Georeferenced soil sampling grid (7 m × 7 m) and corresponding kriged map of cation exchange capacity (CEC) for Fairway 1 (F1) at the University of Georgia golf course in Athens, GA in 2016 (equal interval legend classifications).

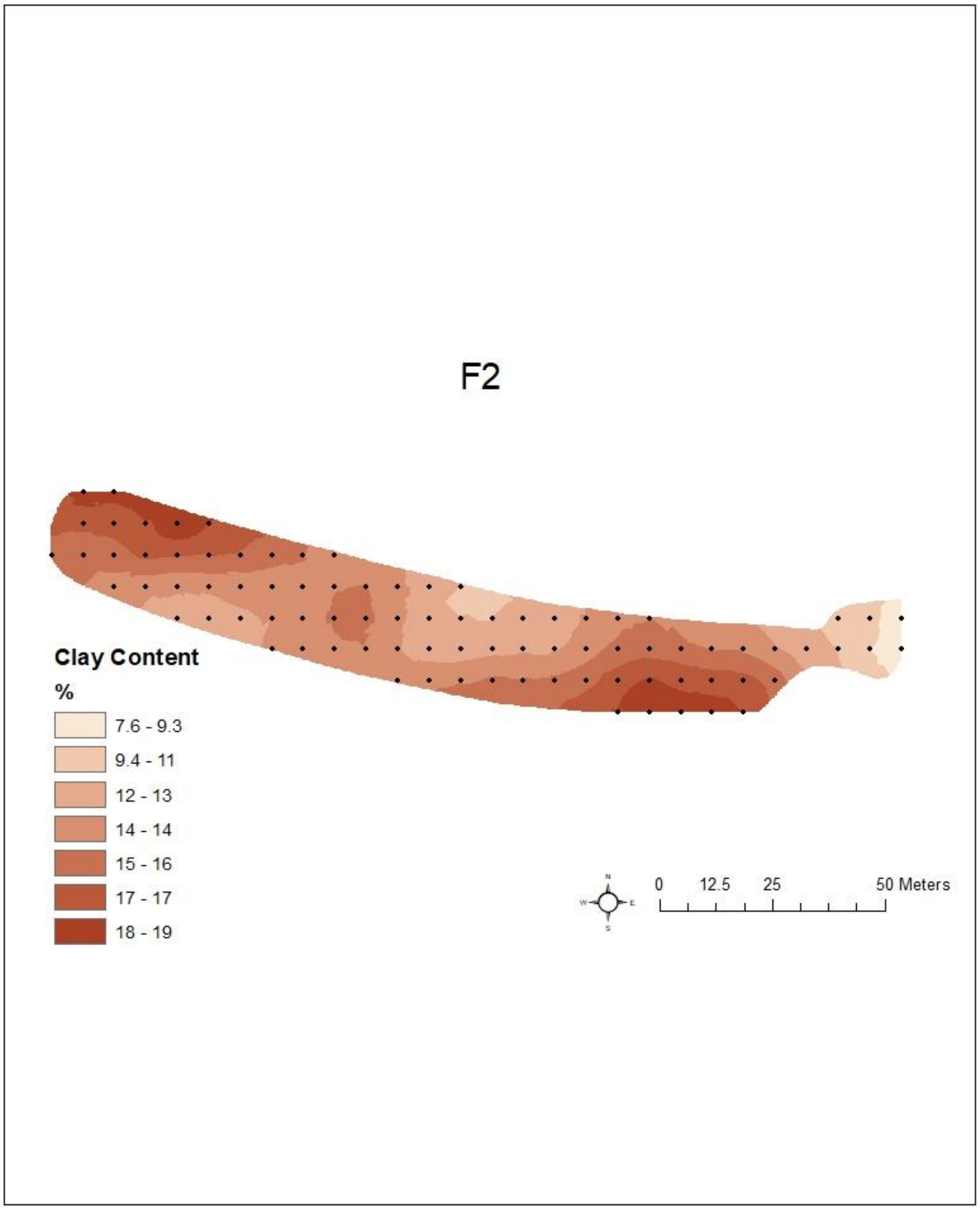

Figure A.4. Georeferenced soil sampling grid (7 m × 7 m) and corresponding kriged map of clay content (%) for Fairway 2 (F2) at the University of Georgia golf course in Athens, GA in 2016 (equal interval legend classifications).

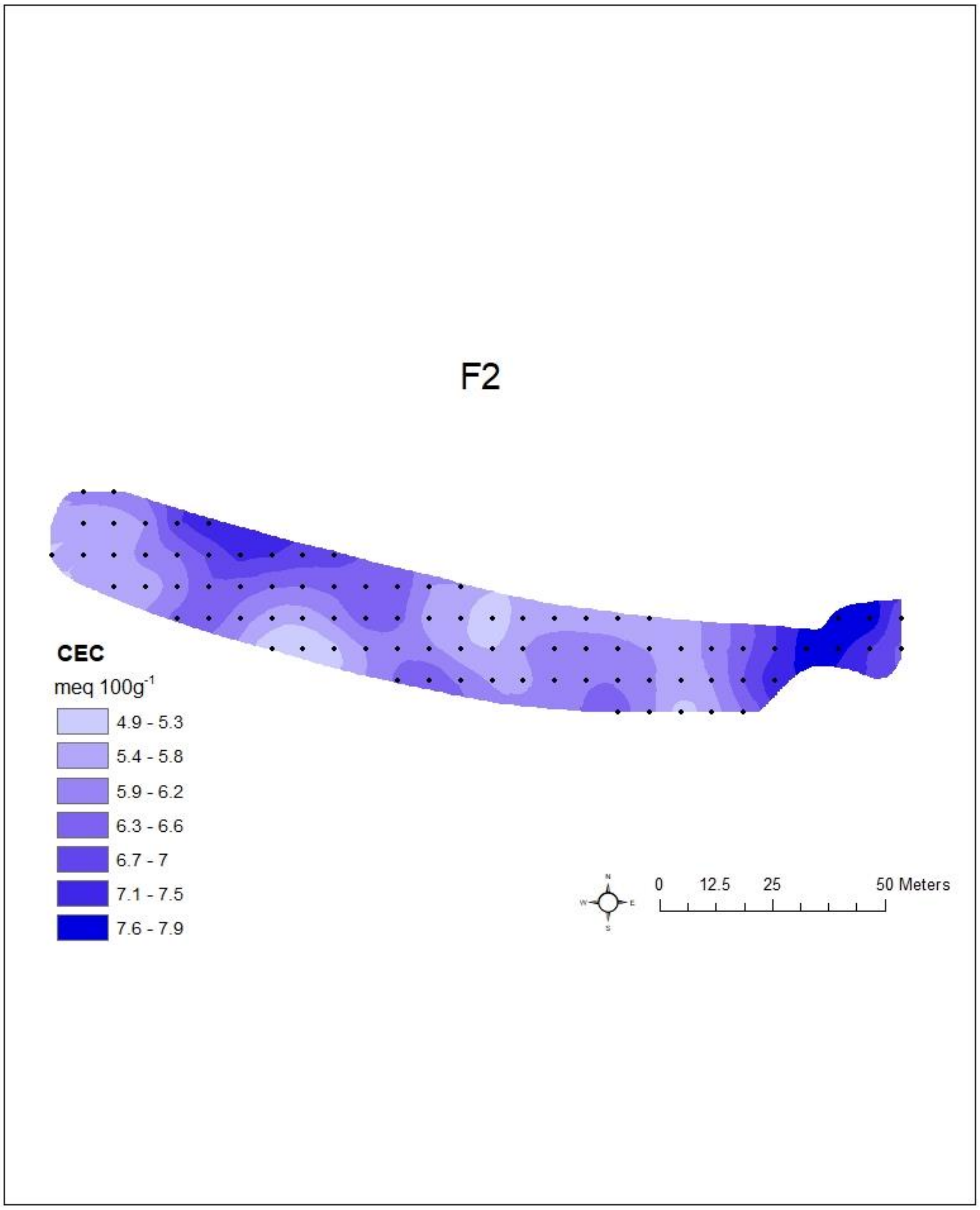

Figure A.5. Georeferenced soil sampling grid (7 m × 7 m) and corresponding kriged map of cation exchange capacity (CEC) for Fairway 2 (F2) at the University of Georgia golf course in Athens, GA in 2016 (equal interval legend classifications).

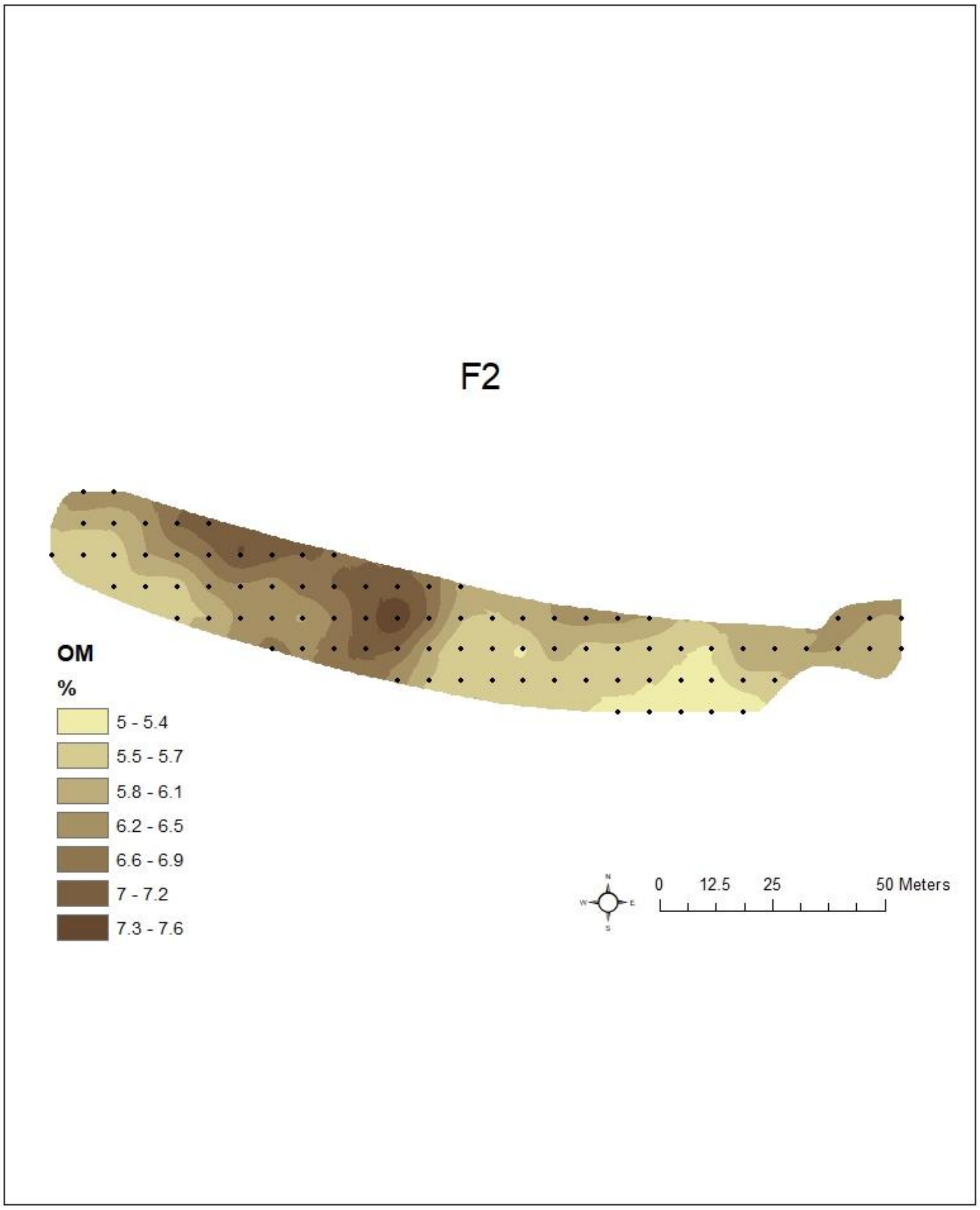

Figure A.6. Georeferenced soil sampling grid (7 m × 7 m) and corresponding kriged map of soil organic matter (OM) for Fairway 2 (F2) at the University of Georgia golf course in Athens, GA in 2016 (equal interval legend classifications).

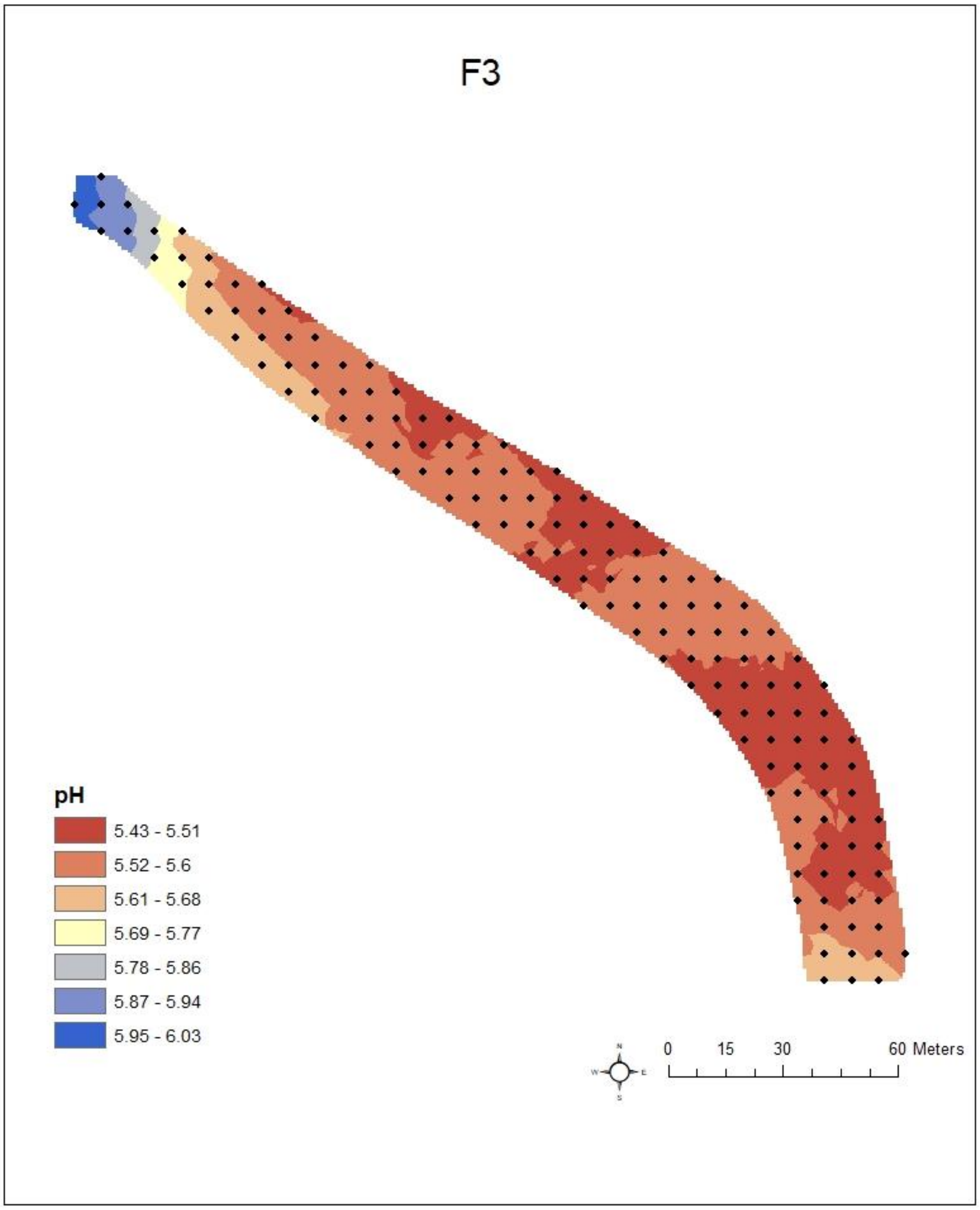

Figure A.7. Georeferenced soil sampling grid (7 m × 7 m) and corresponding kriged map of soil pH for Fairway 3 (F3) at the University of Georgia golf course in Athens, GA in 2016 (equal interval legend classifications).

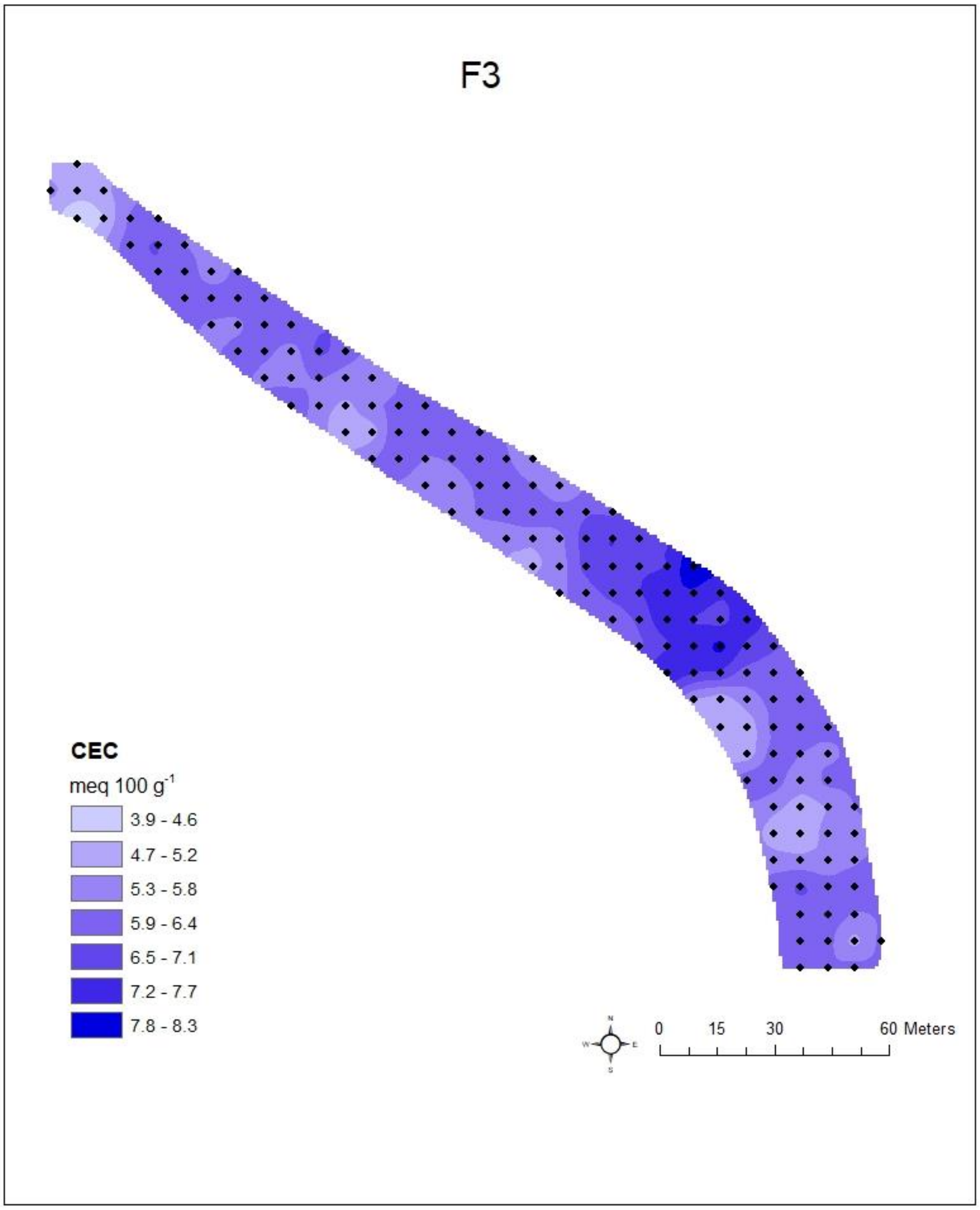

Figure A.8. Georeferenced soil sampling grid (7 m × 7 m) and corresponding kriged map of cation exchange capacity (CEC) for Fairway 3 (F3) at the University of Georgia golf course in Athens, GA in 2016 (equal interval legend classifications).

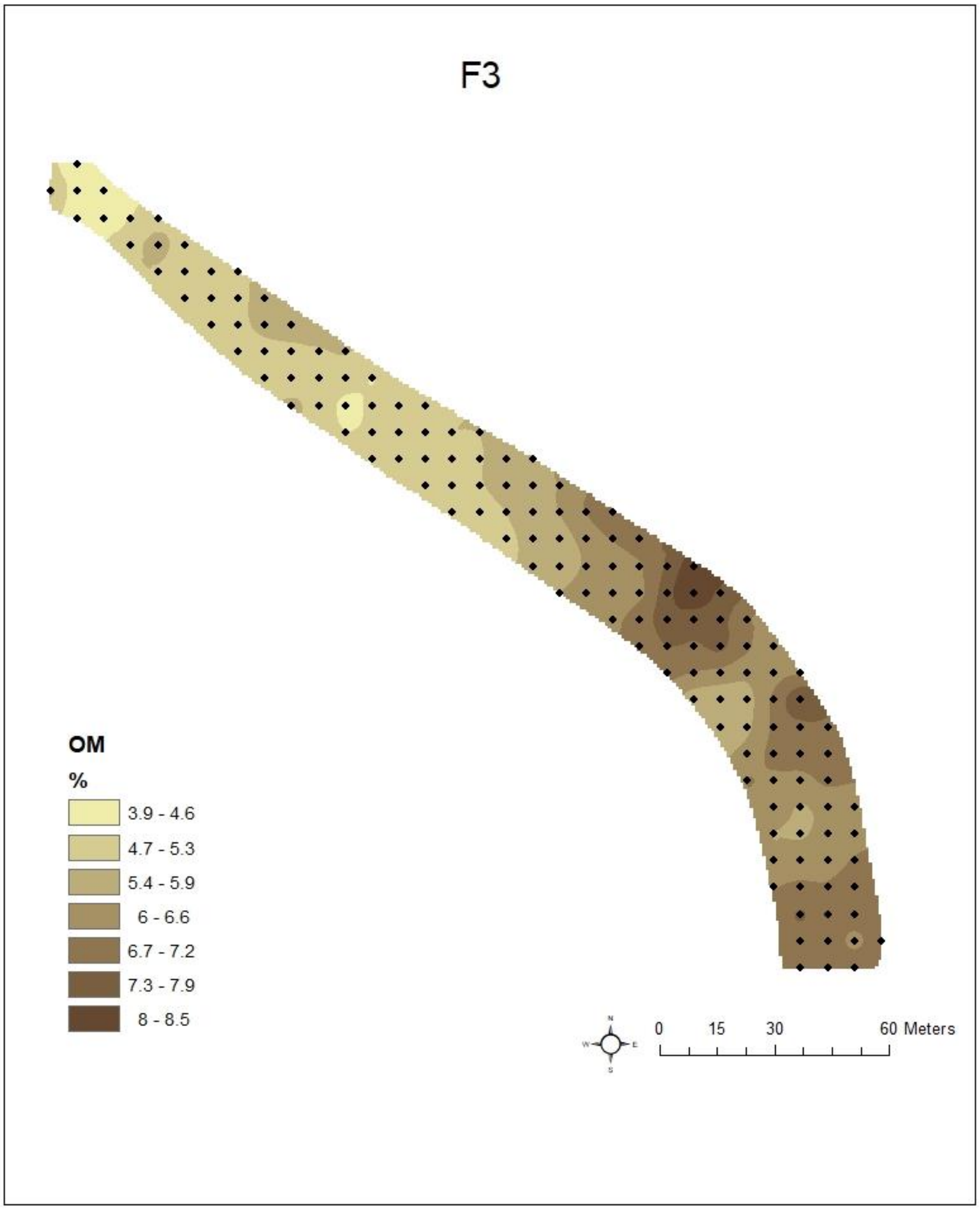

Figure A.9. Georeferenced soil sampling grid (7 m × 7 m) and corresponding kriged map of soil organic matter (OM) for Fairway 3 (F3) at the University of Georgia golf course in Athens, GA in 2016 (equal interval legend classifications).

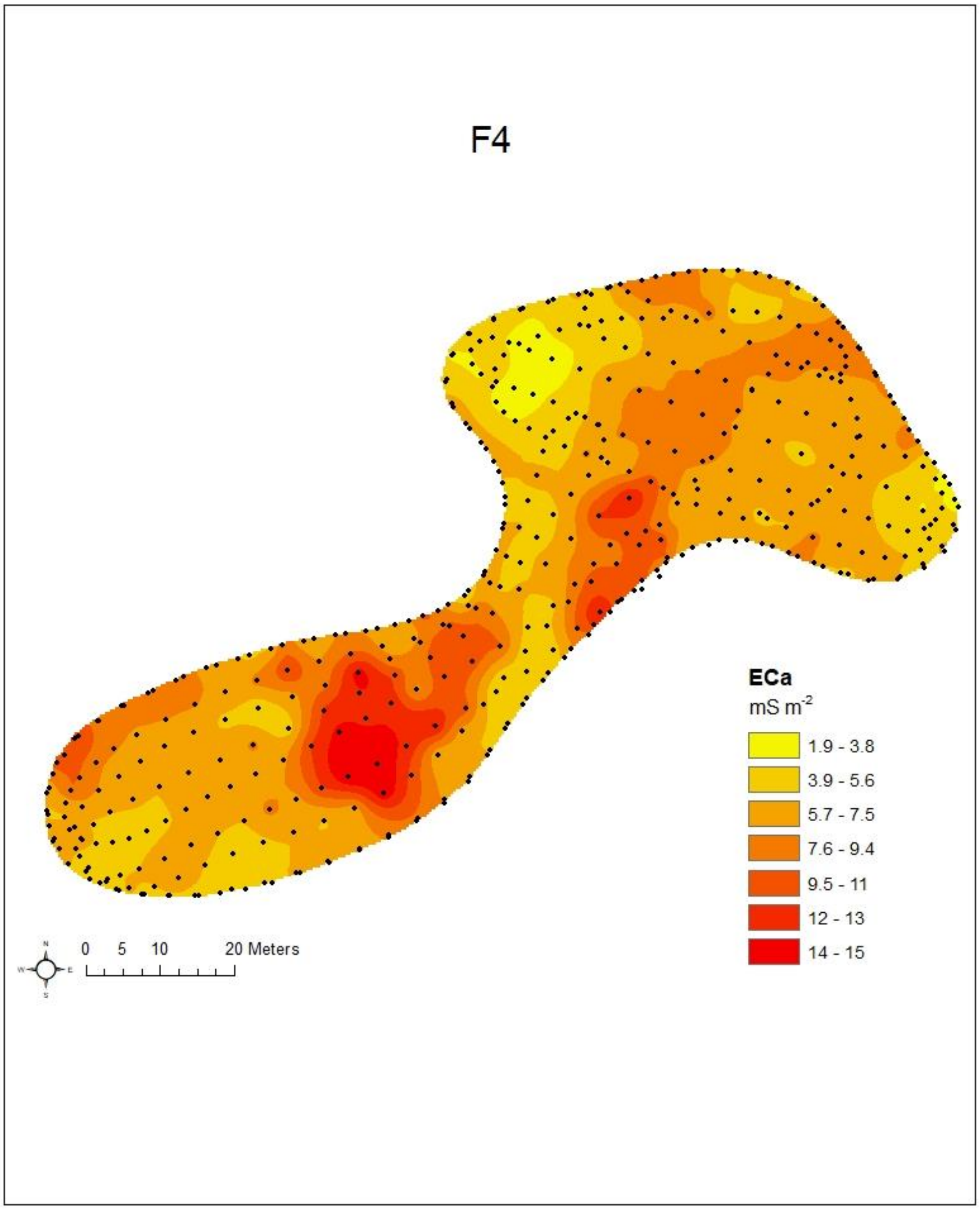

Figure A.10. Georeferenced apparent electrical conductivity (EC_a) sample points and corresponding kriged map of EC_a for Fairway 4 (F4) at the Georgia Club golf course in Statham, GA in 2016 (equal interval legend classifications).

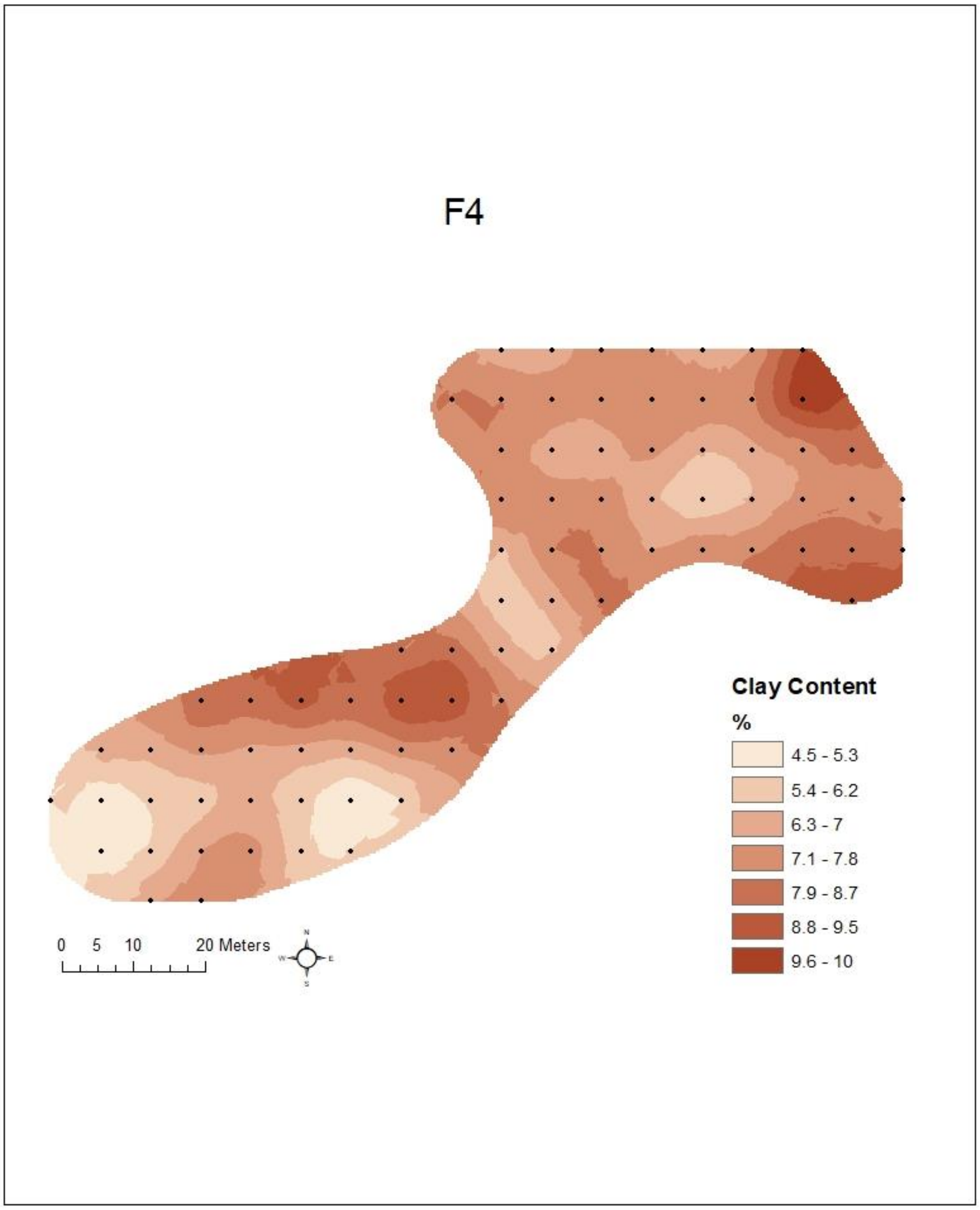

Figure A.11. Georeferenced soil sampling grid (7 m × 7 m) and corresponding kriged map of clay content for Fairway 4 (F4) at the Georgia Club golf course in Statham, GA in 2016 (equal interval legend classifications).

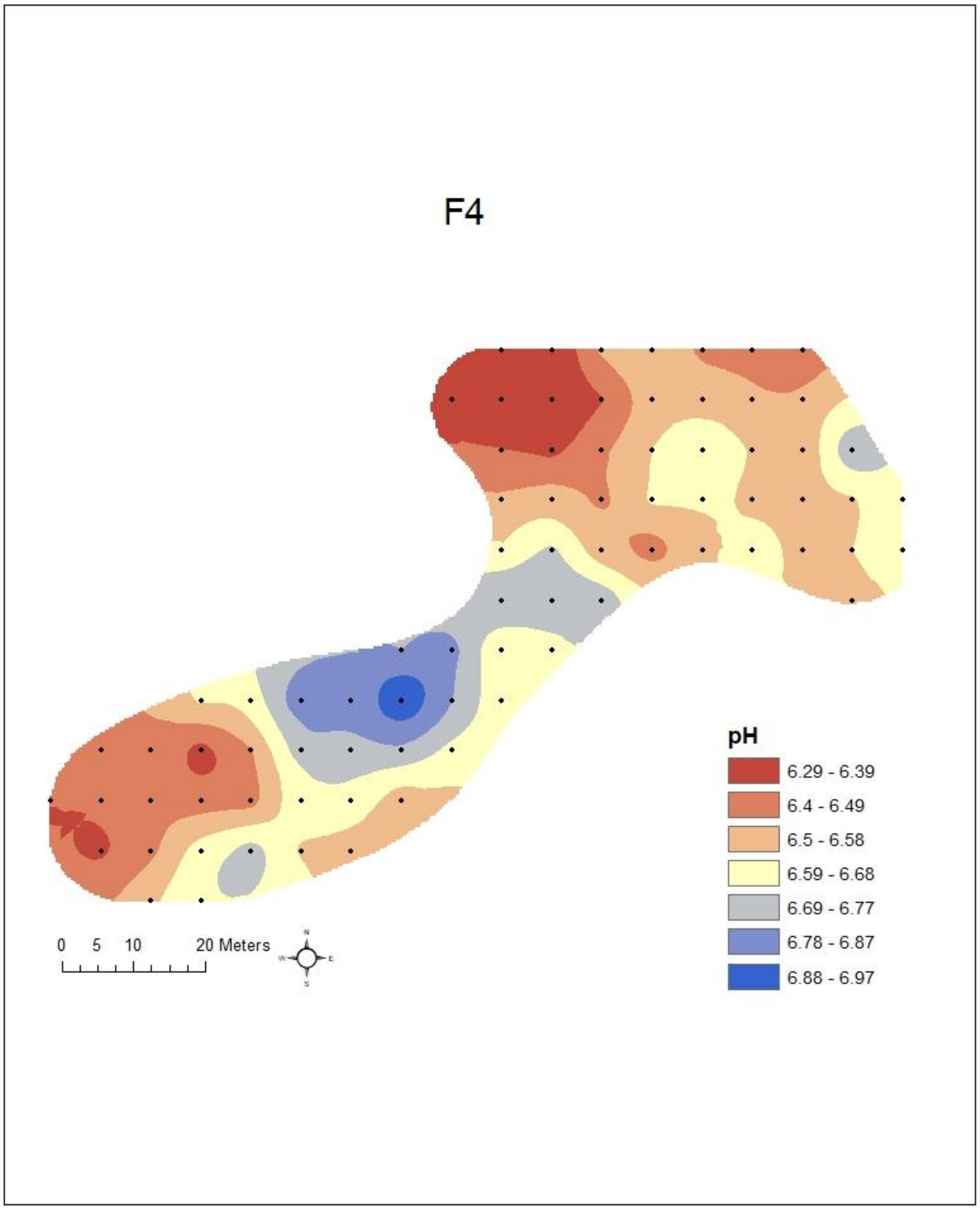

Figure A.12. Georeferenced soil sampling grid (7 m × 7 m) and corresponding kriged map of soil pH for Fairway 4 (F4) at the Georgia Club golf course in Statham, GA in 2016 (equal interval legend classifications).

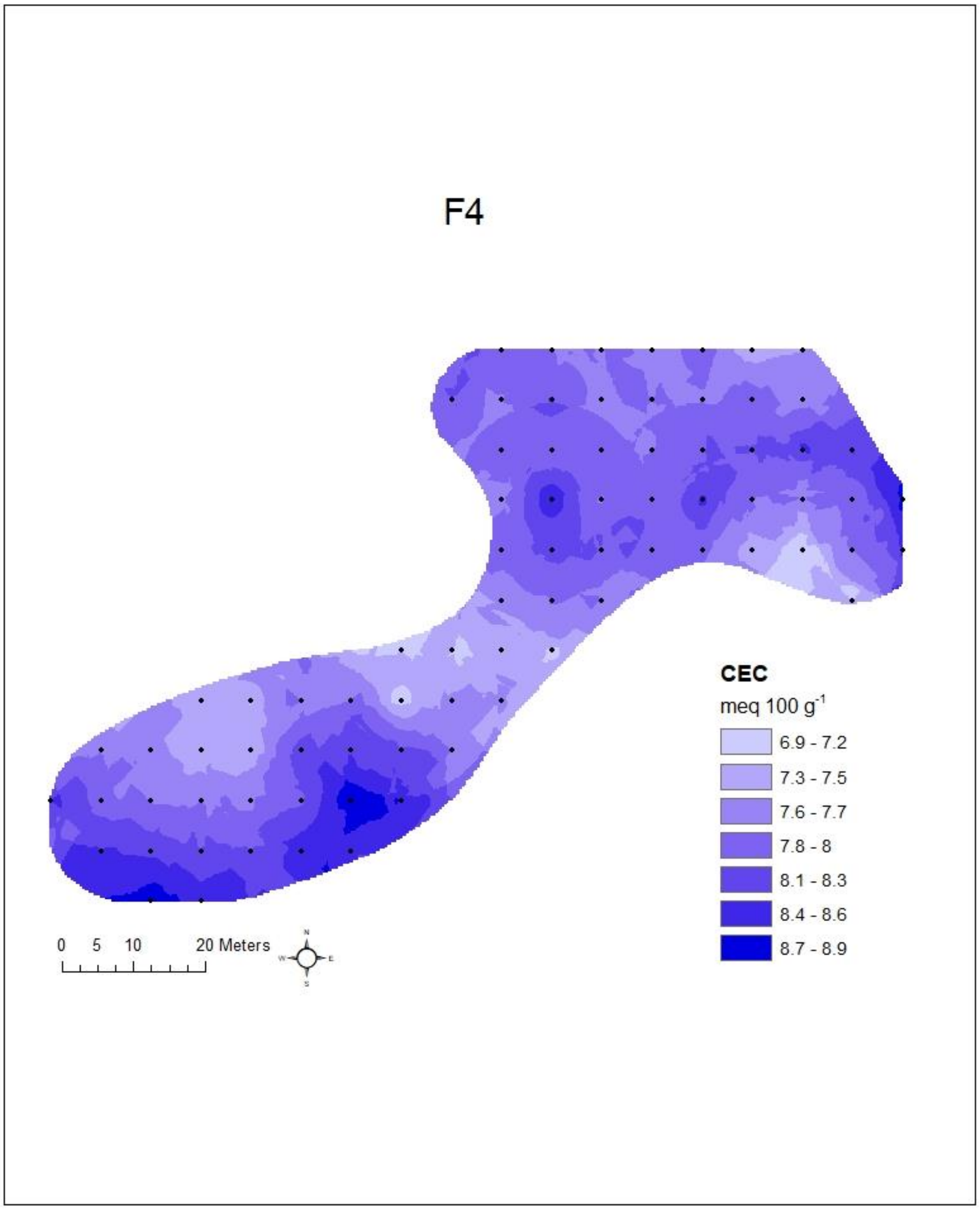

Figure A.13. Georeferenced soil sampling grid (7 m × 7 m) and corresponding kriged map of cation exchange capacity (CEC) for Fairway 4 (F4) at the Georgia Club golf course in Statham, GA in 2016 (equal interval legend classifications).

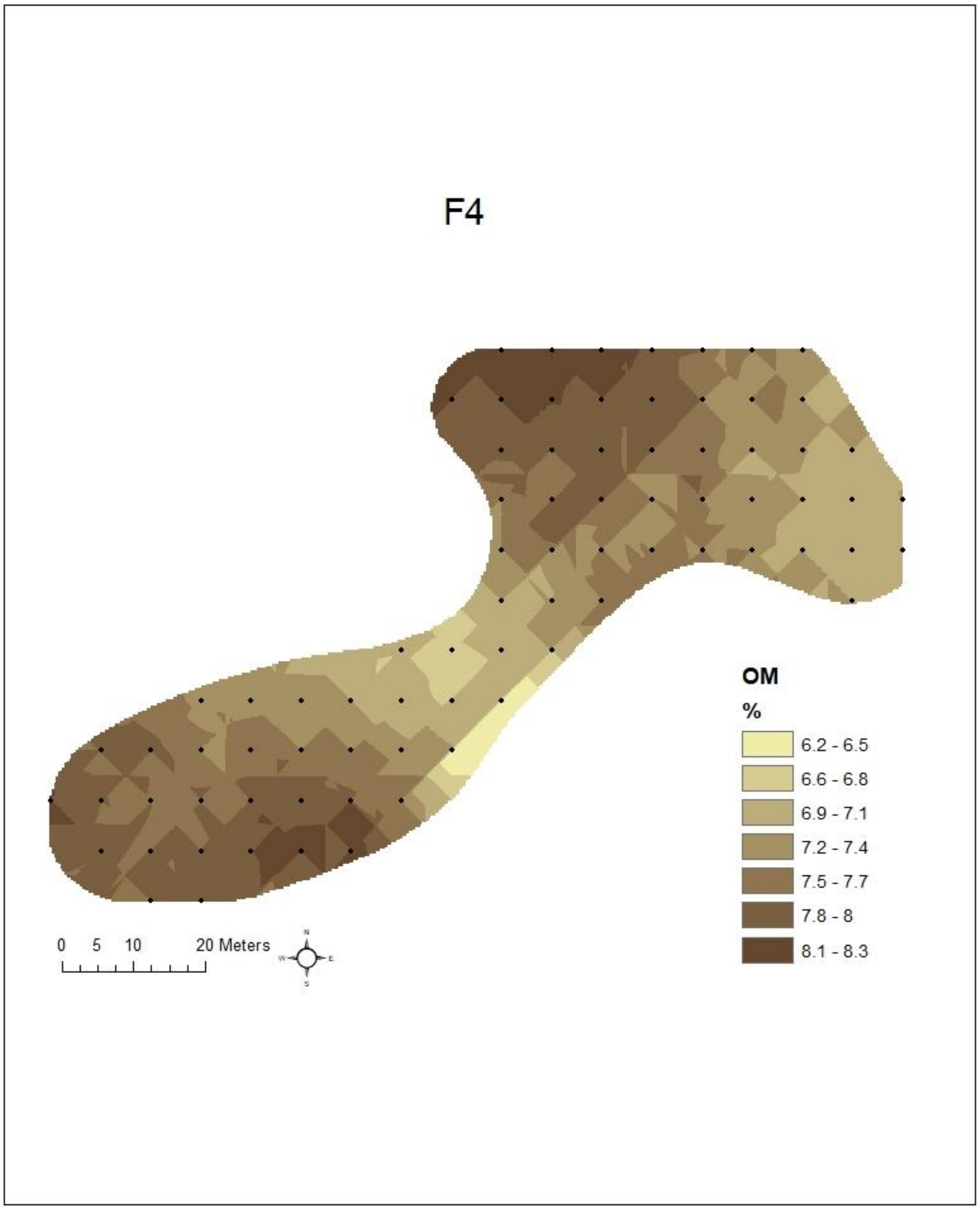

Figure A.14. Georeferenced soil sampling grid (7 m × 7 m) and corresponding kriged map of soil organic matter (OM) for Fairway 4 (F4) at the Georgia Club golf course in Statham, GA in 2016 (equal interval legend classifications).

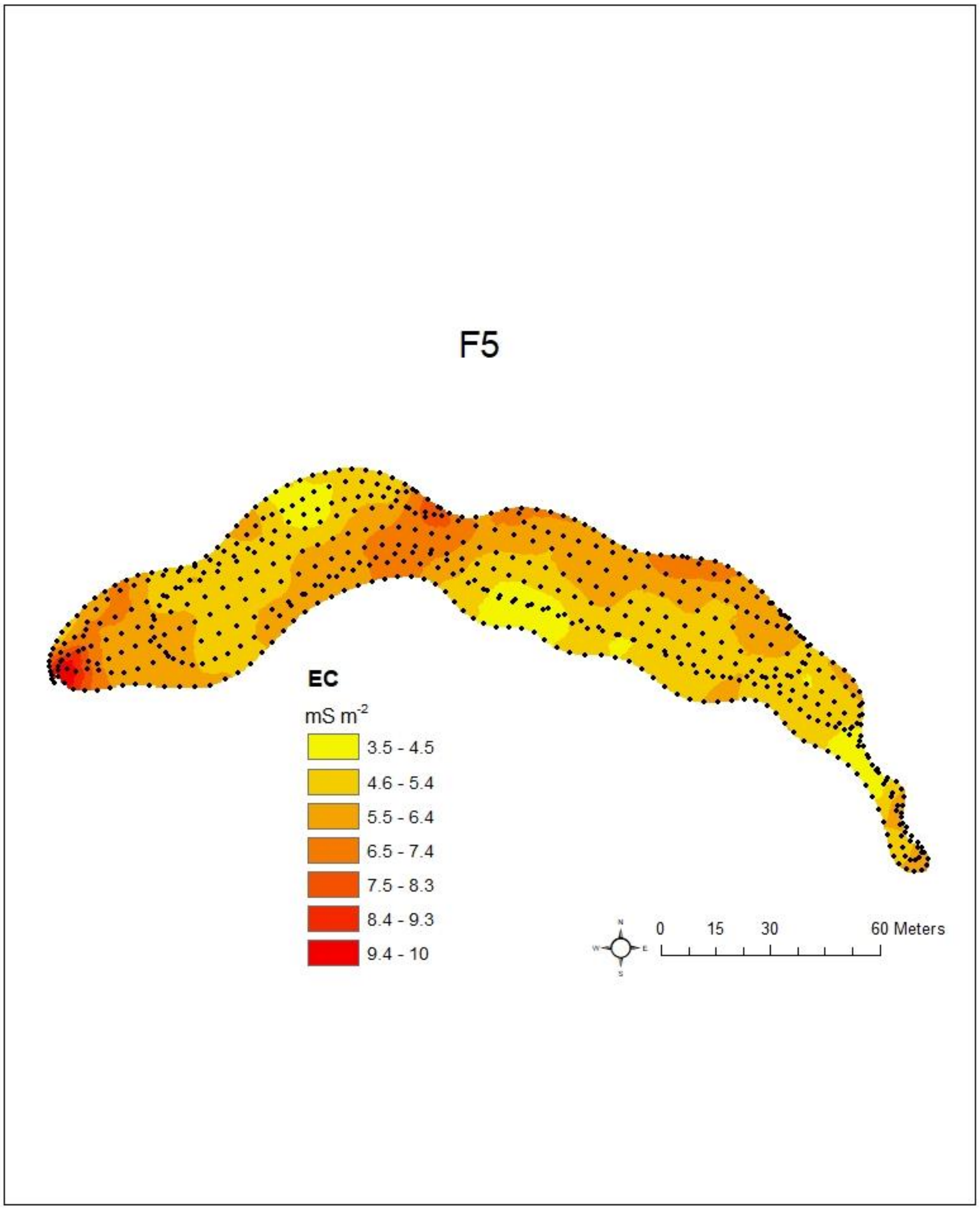

Figure A.15. Georeferenced apparent electrical conductivity (EC_a) sample points and corresponding kriged map of EC_a for Fairway 5 (F5) at the Georgia Club golf course in Statham, GA in 2016 (equal interval legend classifications).

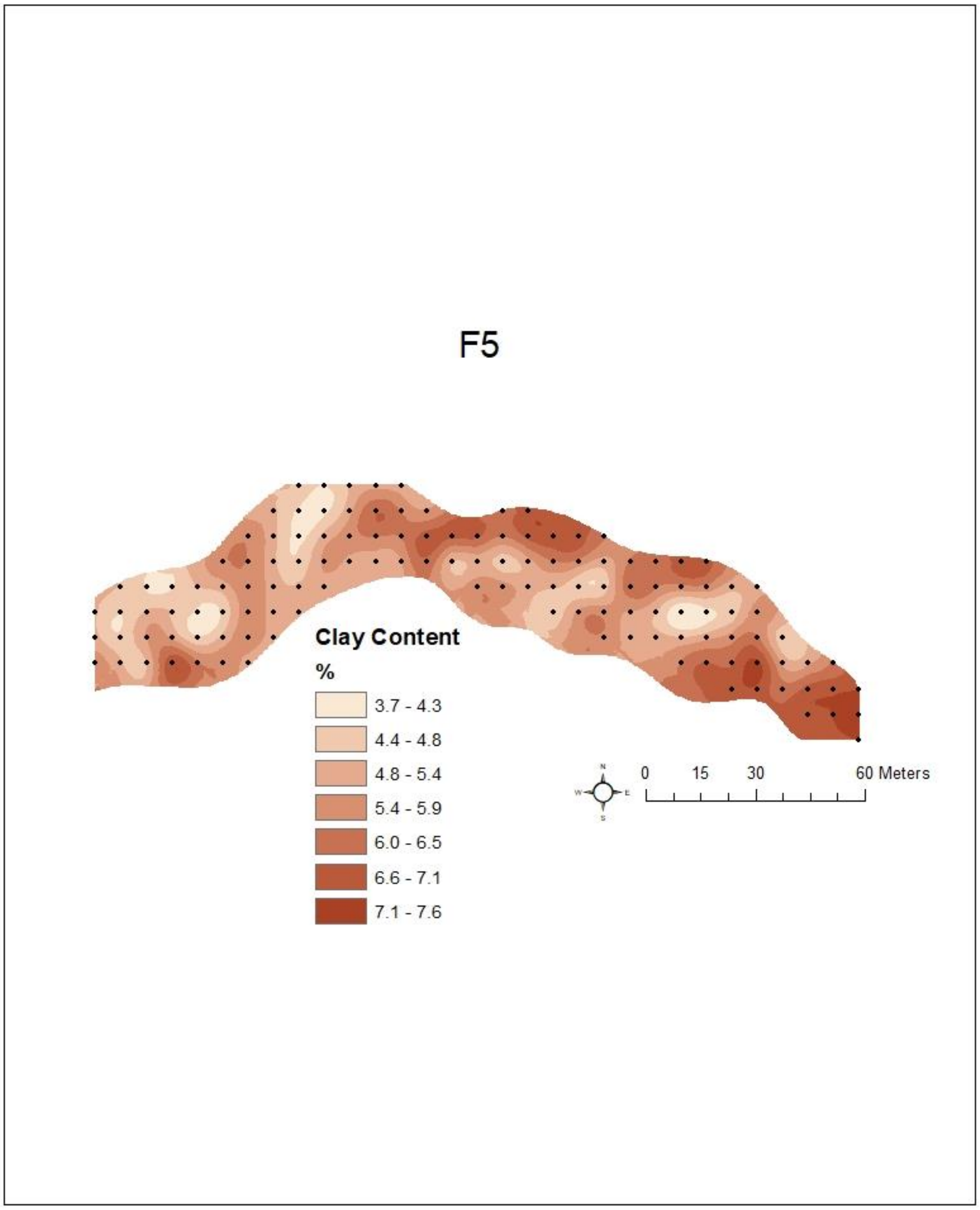

Figure A.16. Georeferenced soil sampling grid (7 m × 7 m) and corresponding kriged map of clay content for Fairway 5 (F5) at the Georgia Club golf course in Statham, GA in 2016 (equal interval legend classifications).

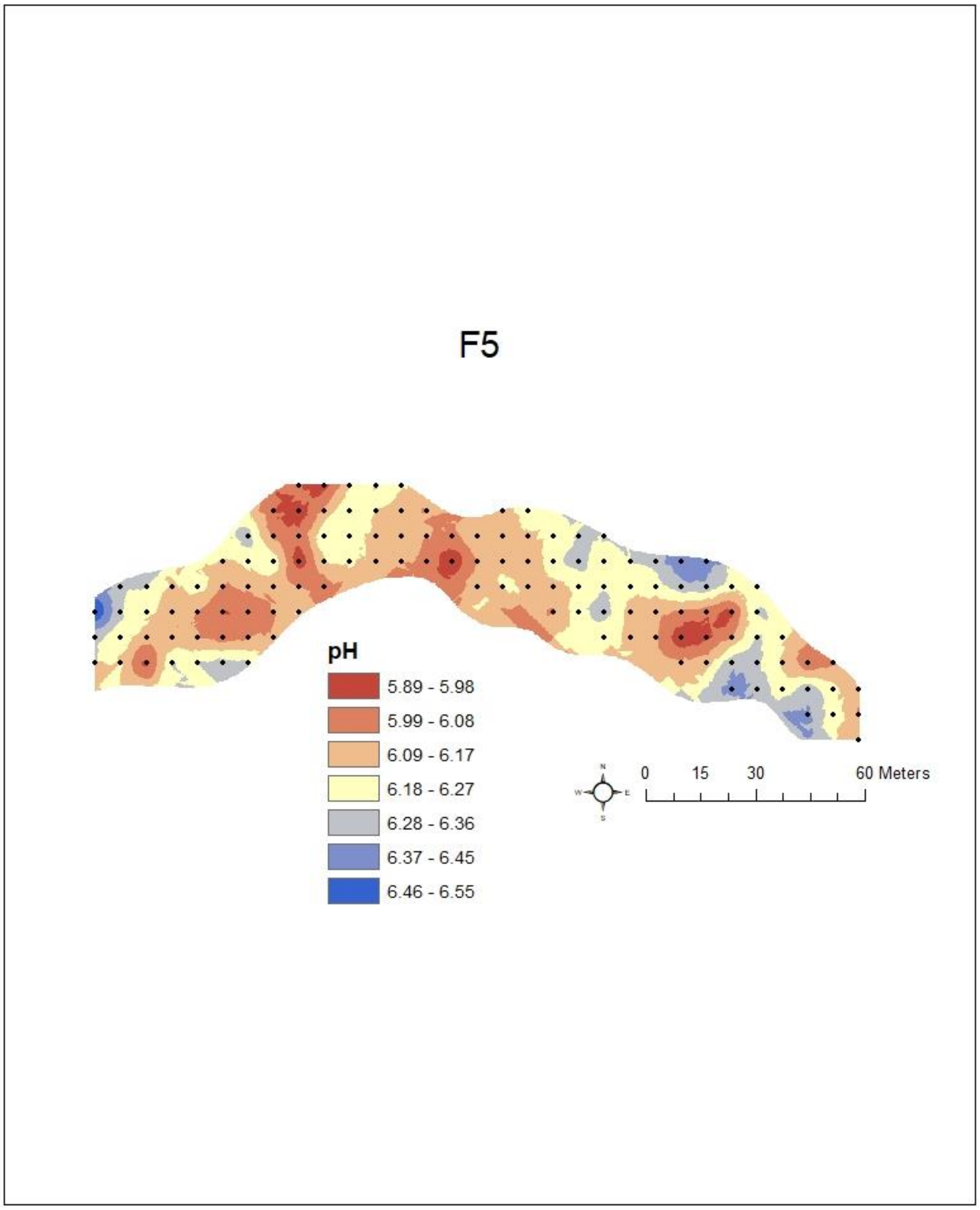

Figure A.17. Georeferenced soil sampling grid (7 m × 7 m) and corresponding kriged map of soil pH for Fairway 5 (F5) at the Georgia Club golf course in Statham, GA in 2016 (equal interval legend classifications).

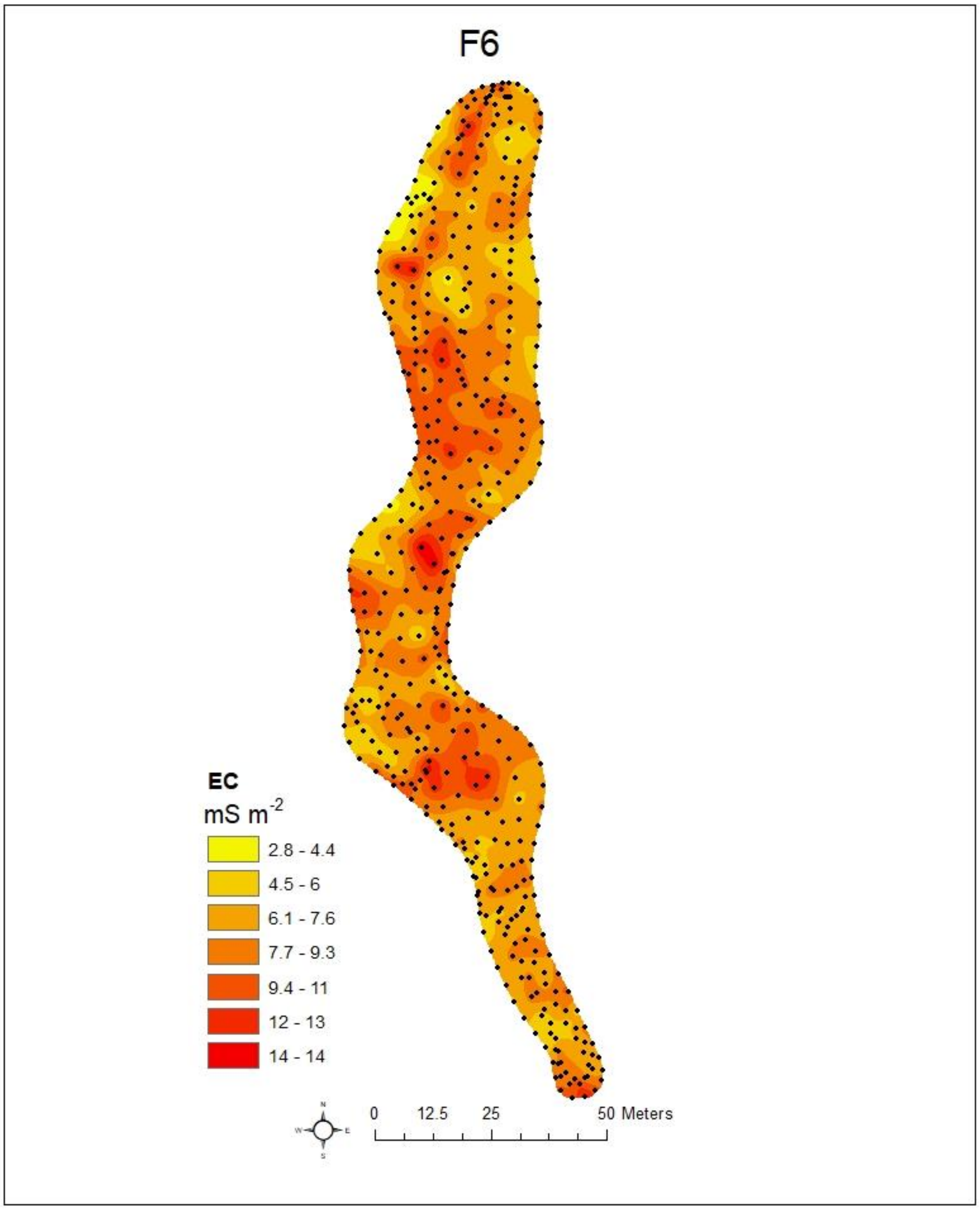

Figure A.18. Georeferenced apparent electrical conductivity (EC_a) sample points and corresponding kriged map of EC_a for Fairway 6 (F6) at the Georgia Club golf course in Statham, GA in 2016 (equal interval legend classifications).

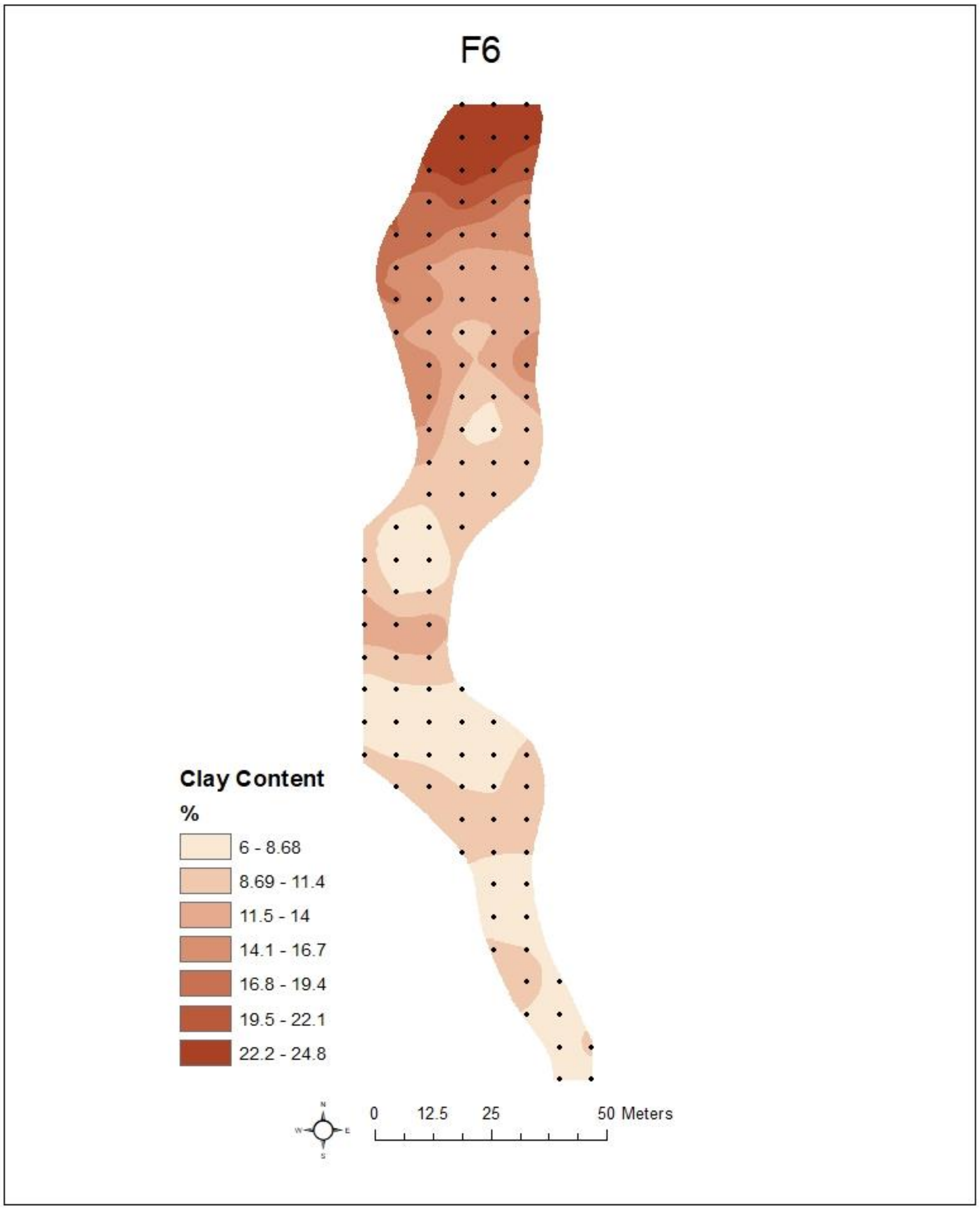

Figure A.19. Georeferenced soil sampling grid (7 m × 7 m) and corresponding kriged map of clay content for Fairway 6 (F6) at the Georgia Club golf course in Statham, GA in 2016 (equal interval legend classifications).

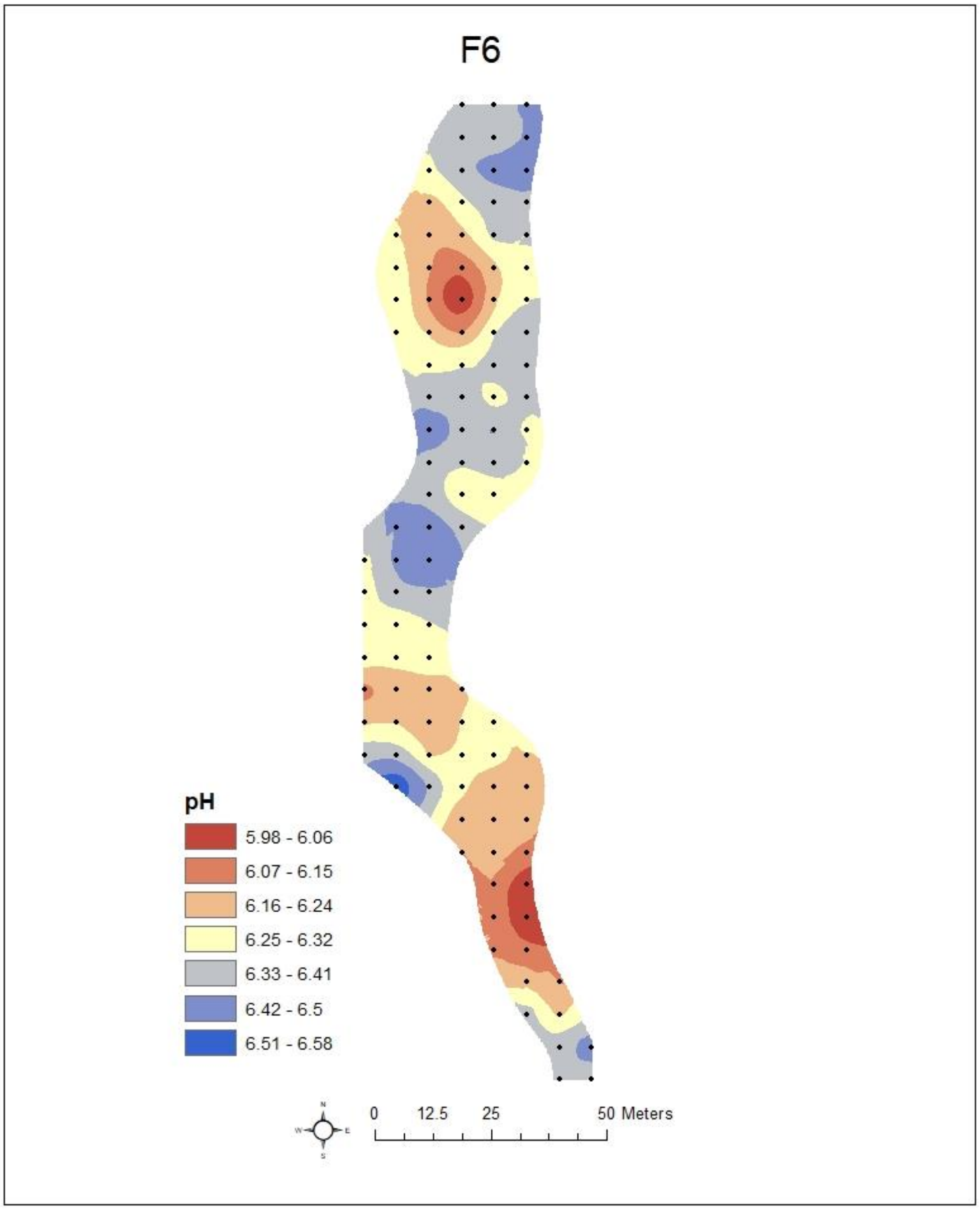

Figure A.20. Georeferenced soil sampling grid (7 m × 7 m) and corresponding kriged map of soil pH for Fairway 6 (F6) at the Georgia Club golf course in Statham, GA in 2016 (equal interval legend classifications).

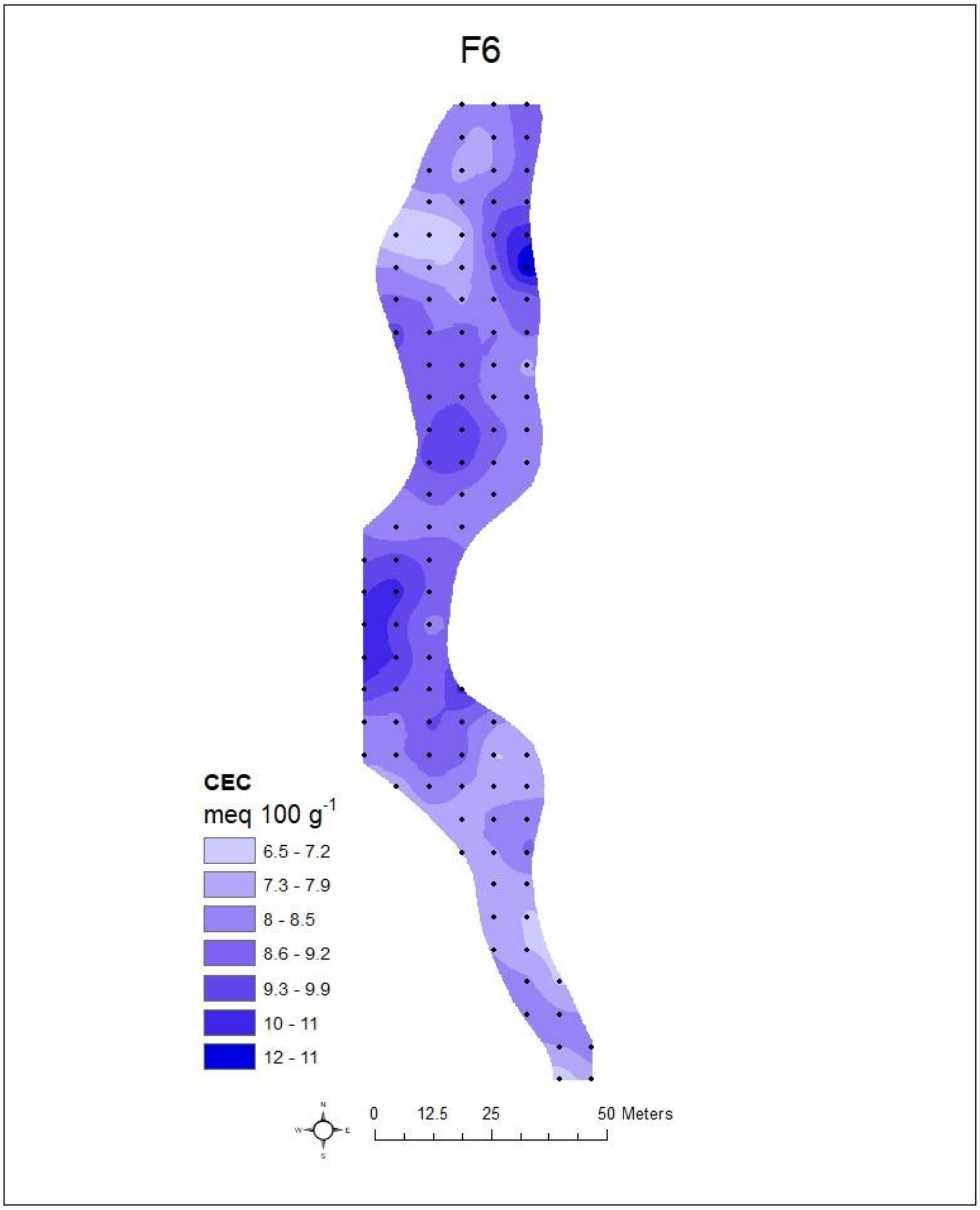

Figure A.21. Georeferenced soil sampling grid (7 m × 7 m) and corresponding kriged map of cation exchange capacity (CEC) for Fairway 6 (F6) at the Georgia Club golf course in Statham, GA in 2016 (equal interval legend classifications).

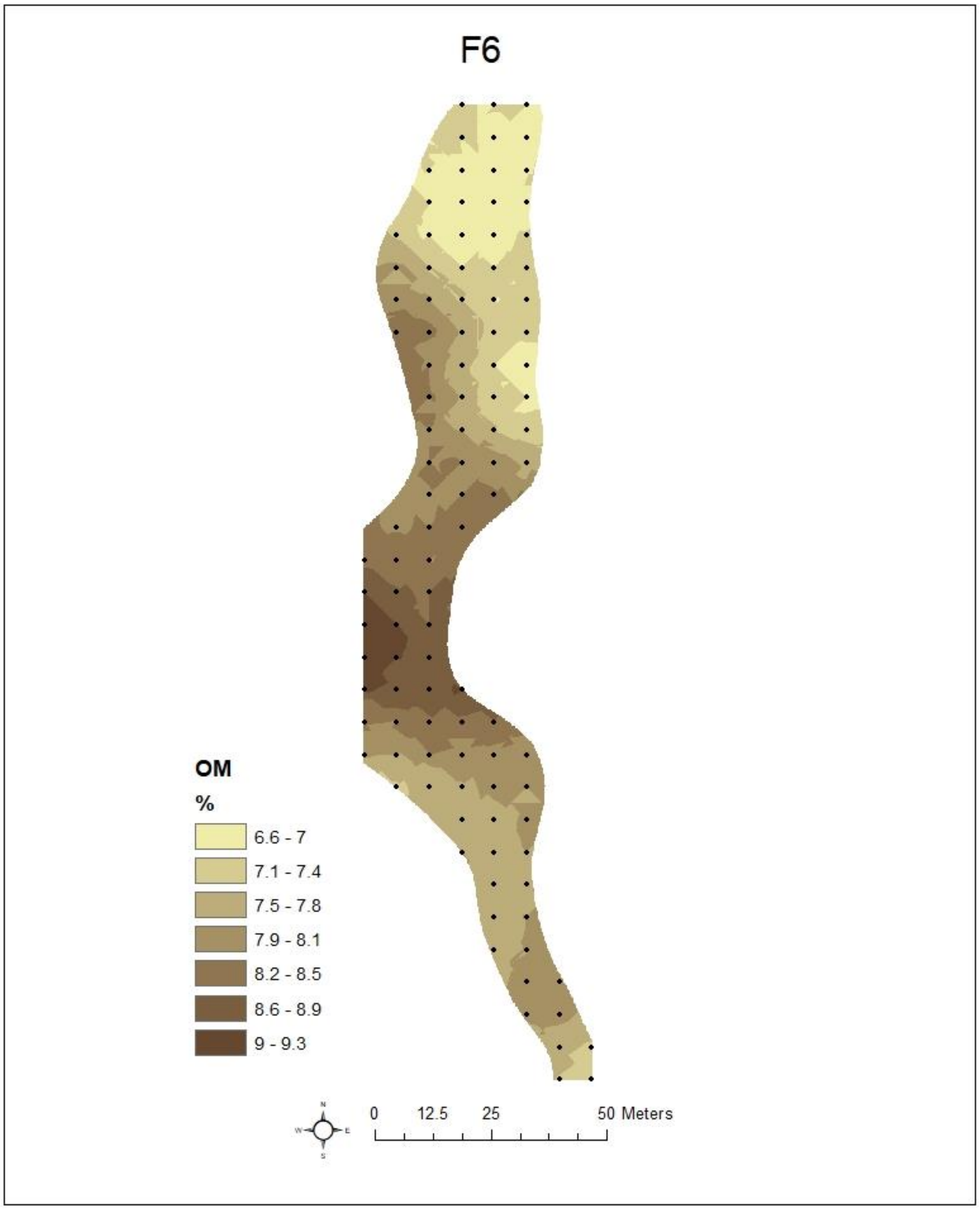

Figure A.22. Georeferenced soil sampling grid (7 m × 7 m) and corresponding kriged map of soil organic matter (OM) for Fairway 6 (F6) at the Georgia Club golf course in Statham, GA in 2016 (equal interval legend classifications).

APPENDIX B

MAKING THE GRASS 'GREENER': INTERVIEW QUESTIONS

1. **Introductory**
   a. Tell me about your household.
      i. Who lives with you?
      ii. Who cares for your lawn?
2. **Lawn Aesthetics**
   a. How would you define a lawn?
   b. When you imagine an ideal lawn, what does it look like?
   c. Do you feel like your looks ideal?
      i. Why/Why not?
      ii. How important is it to you that your lawn look ideal?
      iii. Besides yourself, who do you think it matters to most that your lawn look well-cared for?
         1. Why do you feel this way?
         2. Do you feel that their vision of a well-cared for lawn is the same or similar to yours?
            a. How is it similar? How might it differ?
         3. How much influence do you feel this person has over the way you manage your lawn?
   d. Can you show me your favorite feature in your yard or your favorite thing about the way your lawn looks?
      i. What makes it your favorite thing?
   e. Can you show me your least favorite thing about the way your lawn looks?
      i. What makes it your least favorite thing?
   f. If you had additional free time, do you think you would spend it caring for your lawn?
      i. If no, why not?
      ii. If yes, what specifically might you devote that additional time or energy to?
3. **Recreational Value**
   a. What is one of your fondest lawn memories? Tell me about it.
   b. Who uses the lawn? In what ways?
   c. How long have you owned this property?
      i. When you purchased this property, was it important that it have a lawn?
         1. Why/why not?
      ii. Do you feel that it is still that important now?
         1. If no, why not? Do you wish you did not have a lawn now?
         2. If yes, why and do you feel it is important for the same reasons?

d. How much recreational time do you spend on your lawn throughout the year now?
    i. Who spends the most recreational time in your yard?
    ii. Tell me more about that time.
    iii. How important would you say that time is both to you and to others?
    iv. Do you feel that your lawn is a good space for this purpose, or is there something you would change that would enhance your recreational experience?
        1. How often do you think about that?
    v. Tell me a time when you've felt really positively towards your lawn.
        1. Tell me more about that
    vi. Tell me a time when you've felt less positively towards your lawn.
        1. Tell me more about that

4. Lawn Management

a. Which season do you feel you do the most work in your lawn?
b. Do you know what type or species of grass do you have?
    i. Tell me.
    ii. Did you choose that species or was it chosen for you? By whom?
    iii. What are the pros/cons of this species in your experience?
    iv. How do you feel about the species you have?
c. Who is generally in charge of maintaining your lawn?
    i. For how long and how did this come to be?
    ii. Would you trust anyone else with the responsibility of maintaining your lawn?
    iii. Why/Why not?
d. What kind of work do you do?
    i. What about the other seasons? How much and what kinds of work do you do during those seasons?
e.

5. Lawn Management (lawn service company)

a. Do you use a lawn service or have others (non-household) help you with your lawn management?
    i. What do they do?
    ii. How often?
b. How do you determine what is done to your lawn?
    i. Could you walk me through how decisions are made?
c. How often does your service provider mow your lawn?
    i. Who and what determines that frequency?
d. What height do they mow your lawn at?
    i. Who/What determines that?
e. What do they do with the clippings?
    i. Who/What decides that?
f. Do they fertilize your lawn?
    i. How often?
    ii. What do they use?
    iii. Did you ask for it?

iv. How important is it to you that they fertilize?

g. Do they use pesticides?

i. For which pests?

6. Lawn Management (self-managed)

a. If not already established: Do you mow your own lawn?
  i. What sort of lawn mower do you have?
  ii. Which months would you say you're most actively mowing? (Timeframe)
  iii. During this period, approximately what is your mowing frequency?
    1. Why? What motivates this?
  iv. What height do you typically keep it mowed at?
    1. Why? What motivates this?
  v. What do you do with the grass clippings?
    1. Why?

b. Do you fertilize your lawn?
  i. If no, why not?
  ii. If yes, why?
    1. What sort of fertilizer do you choose to use?
      a. Why?
      b. Do you mind if I take a photo for reference?
      c. How do you determine…
        i. How much?
        ii. How often?
        iii. Do you follow the label or are there other reasons?
    2. Do you feel like it makes a difference when you fertilize?
      a. In what ways?

c. Do you water/irrigate your lawn?
  i. If no, why not?
  ii. If yes, why?
    1. What kind of irrigation do you use?
      a. Why?
      b. How do you determine when to irrigate?
        i. (regular schedule, weather, etc)

d. Are other things you do to care for your lawn? Tell me about them.

7. Influences and Habit Development

a. How confident do you feel in managing and making decisions in your lawn?
  i. What do you feel has contributed to that level of confidence? Or lack of confidence?

b. What sources do you rely on for lawn care information and/or advice?
  i. Tell me more about this.
  ii. When was the last time you sought out advice? Tell me about that.

c. What are your earliest experiences in working in a lawn? (Your first home? Others?)
  i. Tell me about those.

d. When was the last time you made a significant or purposeful change to the way you manage your lawn?
    i. Tell me about that change and what prompted it.
e. If someone came to you for advice on managing their lawn, what sort of advice might you give them?
    i. Have you ever given advice to someone about managing their lawn? Tell me about that.

APPENDIX C

LONGITUDINAL SURVEY COMPONENT: OVERVIEW

Objective

This study was part of a larger research project on lawn attitudes and behaviors that employed a mixed-methods approach in which participants completed two 60-minute interviews and a weekly survey throughout the summer. Previous studies have employed one-time “snap-shot” surveys in an attempt to capture lawn care attitudes and behaviors (Blaine, Grewal, Robbins, & Clayton, 2012; Groffman et al., 2016; Martini, Nelson, Hobbie, & Baker, 2015; Nassauer, Wang, & Dayrell, 2009). We feel that this approach does not adequately account for fluctuations in management behavior (e.g., changes in water use, chemical applications, and mowing frequency) that would significantly affect geospatial modeling of the environmental impact of lawn behavior. One-time surveys also fail to account for ‘temporal discrepancy,’ or changes in people’s attitudes over time (Rajecki, 1982). Temporal discrepancy has been previously identified as one possible explanation for the gap between environmental attitudes and behavior (Kollmuss & Agyeman, 2002). The objective of the survey component was to capture homeowner attitudes and behaviors towards the lawn in real-time in order to (1) examine differences within households over the course of the growing season, (2) evaluate differences/similarities across households, and (3) triangulate survey and interview data to both corroborate and interrogate findings. By this, we mean areas of alignment between the surveys and interviews may be substantiated, but areas of divergence may also be identified and investigated.

Methodology

A total of 16 participants (across 14 households) were recruited using neighborhood listservs/Facebook pages and word-of-mouth to complete a study on home lawn behaviors. Each household was asked to complete two semi-structured walking interviews in their home lawn. The interviews were designed to learn what participants were doing on their lawns, how they felt about their lawns, and how they made sense of their own behaviors and decision-making in relation to the lawn. In addition to this, each household was asked to complete a brief (3 to 5 minute) survey, weekly (for 20 weeks) survey regarding lawn management behaviors, recreational activity, and motivating behaviors. This study was approved by the University of Georgia Institutional Review Board, and all participants gave informed consent. Participants also received compensation commensurate with the number of surveys completed.

Survey questions (see APPENDIX D) covered both recreational and management activities in order to evaluate the amount of time spent on the lawn, the manner in which that time was spent, and how participants felt about that time. The survey was the same each week and participants were given an opportunity to preview the survey questions one week prior to the survey period in order to ask questions and clarify any items they felt were confusing. Weekly surveys were distributed via email at the same time every Sunday afternoon to cover the previous Monday through the current Sunday using Qualtrics survey software (Qualtrics, Provo, UT). Qualtrics provided infrastructure for creating a survey tool that was proficient at collecting and storing data in a consistent and organized manner. The survey tool was 21 questions long if complete in its entirety; however, skip logic was used to allow participants to skip portions not relevant to a particular week (i.e., fertilizer applications, mowing, etc.). Participants had approximately four days to respond to each weekly survey, but were encouraged to do so as quickly as possible with a single reminder email two days after the survey went out. Survey responses were stored for each participant in the Qualtrics system, and were subsequently exported into Microsoft Excel and Microsoft Word for data analysis.

Preliminary Findings

The maximum number of survey responses possible was 280 (14 households × 20 weeks). Over the course of the survey period, there were a total of 244 responses with a maximum weekly response by 14 households, a minimum weekly response by 10 households, and an average weekly response by 12.2 households. Initial review of the data reveals that lawn care behaviors are highly variable from week to week. Thus, "snap-shot" tools designed to collect data one time are unlikely to sufficiently capture homeowner behaviors on the lawn. To illustrate this point, we present data on the number of hours of work performed by self/household each week from three participant households (Ted and Nina, Beth and Michael, and Lawrence) (Fig. C.1). The number of hours spent on the lawn varied both across households and for individual households overtime. Group averages were also included to demonstrate that mean values obscure variability when trying to understanding individual homeowner behaviors and contributions to the environment vis-à-vis their lawn care practices.

This is significant, as understanding individual household inputs is critical to mapping the spatial distribution of homeowner behaviors and their corresponding impact on specific environmental features. For example, if several homes in one neighborhood fertilize their lawns at much higher rates than the municipal average, natural features adjacent to the neighborhood (e.g., streams, ponds, parks, or community gardens) may be more significantly affected by nutrient runoff than expected. Similarly, temporal fluctuations in behavior by a single household are also critical to understanding environmental impact of lawn care behaviors. Temporal distribution of fertilizer and pesticide inputs is important because the degree and direction of chemical displacement is often determined by weather during and immediately following application. The amount of wind or rainfall at the time of a particular application may significantly affect the degree to which a particular application impacts the larger environment.

The data also revealed that homeowners can make significant changes in management behaviors over a 6-month period. For example, in her first interview, Morgan discusses how she and her husband maintain their nearly 4-acre property on their own with a riding mower. By week seven of the survey study period, Morgan explains in the comments portion on the survey "With the husband out of town for most of June, the lawn was out of control. We hired a service to do it for us." She adds to this, almost playfully, "I now have a 'lawn guy.' I feel like I have arrived." The change in who was managing their yard and how many hours of work were performed each week is presented in Figure 2.

Participants were also given the opportunity to elaborate on what specific management practices were employed each week that work was performed. Participants could choose from a list of ten options (see APPENDIX D) including common practices such as irrigation, mowing, weeding, fertilizing, and pesticide applications. Participants also had two blank options to insert additional tasks performed on the lawn that week that were not covered by the survey options.

Three participant households (Samantha, Robert, and James) were also selected to demonstrate recreational time spent on over the 20-week survey period (Fig. C.3). Understanding how much time homeowner's dedicate to leisure and recreation on the lawn may play an important role in understanding the way lawns are valued and the degree to which a participant bonds with their lawn. Homeowners may spend more or less time on the lawn than they think, and the amount of time spent on the lawn may change over time in response to changes in attitudes and lifestyle. The survey also included a section to select who spent time on the lawn each week to capture the primary lawn users in each household. This portion included pets and lawn-care services, as these were the primary occupants on the lawn for some households.

Homeowners were given the opportunity to select various “motivating factors” each week that they performed lawn management. These factors are listed in Table C.1 in order of factors most selected by homeowners to least selected by homeowners over the 20-week survey period. Arguably those factors which were most frequently selected (Aesthetics and Weather) were greater priorities for the group in this study. Participants were given an opportunity in the second interview to elaborate on what each of these factors meant to them with respect to their lawn management decisions, and why they selected them throughout the growing season.

Finally, participants were also given an opportunity to provide three terms to describe how they felt about the time spent on their lawn each week. Several terms were used by multiple participants on several occasions, and the top 15 terms used are presented in Table C.2. Though these were the most commonly used descriptive words, several others appeared in the data that were interesting including “calming,” “joy,” “aggravating,” “lush,” “contemplative,” and “crunchy.” What is especially interesting about the terms selected is the inclusion of both affective terms and sensual terms. A person’s experience with their lawn is complex, and can be both emotional and sensory-oriented.

Potential Applications for the Data

Data collected from the survey component of this project may be used in multiple ways to provide a deeper understanding of homeowner attitudes and behavior. This study can provide a greater understanding of how different data collection methods make different contributions to lawn research by revealing areas of agreement and disagreement between survey data and interview data. The data may also be used to provide an overview of within household change over time and what this may mean for outreach dissemination and environmental modeling of home lawn inputs. Finally, the data may be used to show the degree of variability in homeowner attitudes/behaviors across even a small group of only 14 households in order to reinforce the importance of producing a versatile approach to outreach and education that addresses different homeowner attitudes and lifestyles. Individual households may have more or less consistent routines relative to one another due to their individual habits, or the employment of a service. Investigating differences in lawn behavior both within and across households is important to modeling the spatiotemporal variability in lawn management practices and their greater environmental impact.

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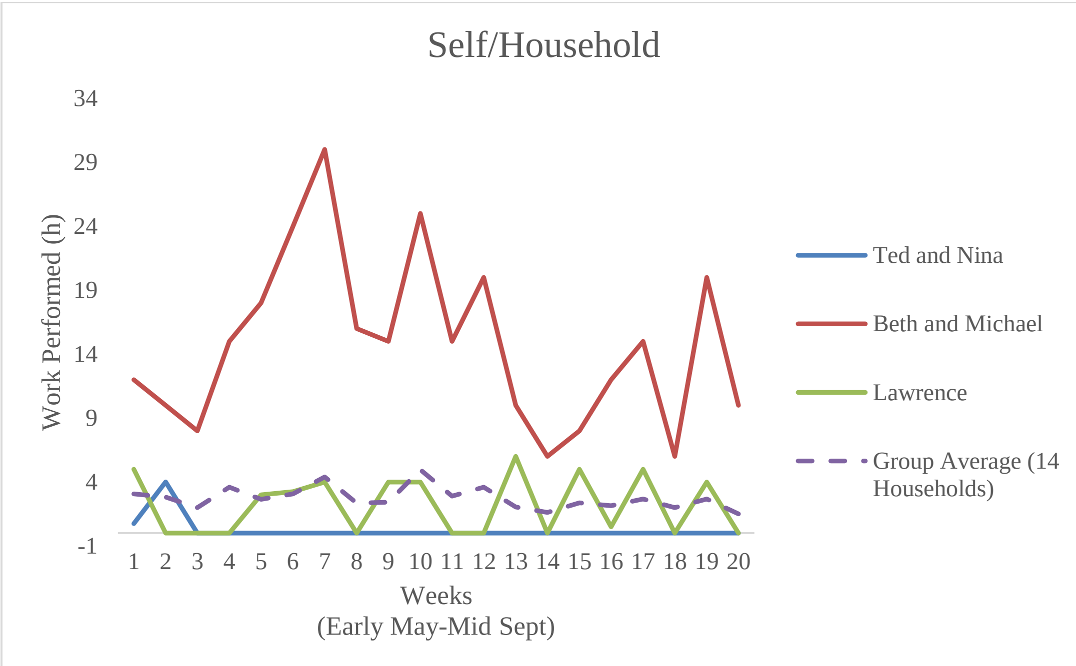

Figure C.1. Hours of work performed weekly by self/household over a 20-week survey period as reported by three participant households, as well as a weekly group average for comparison.

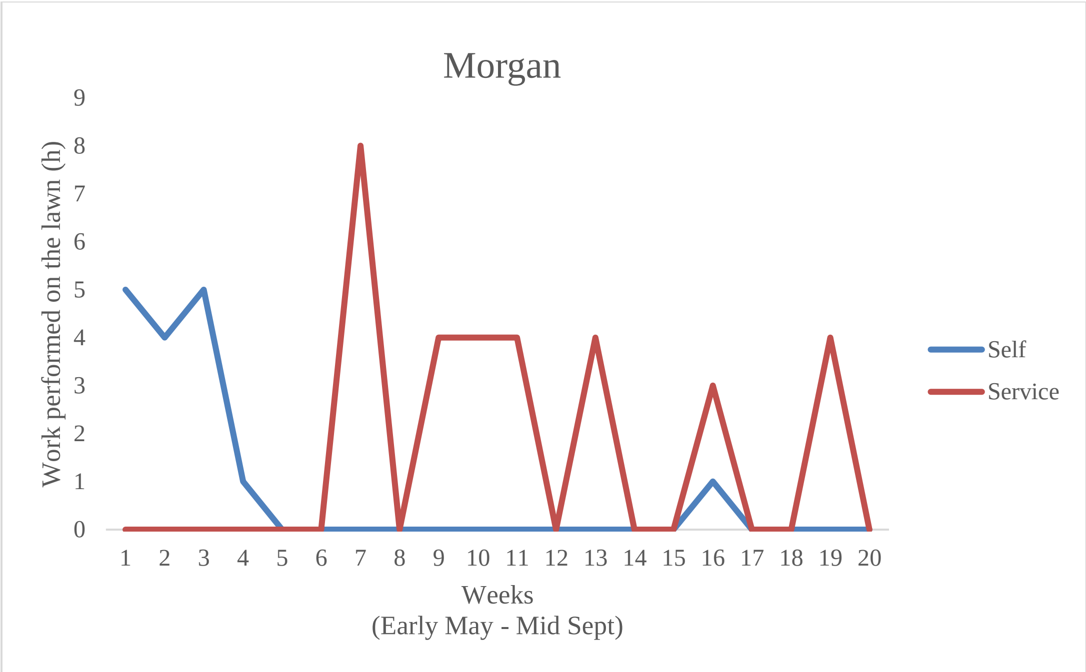

Figure C.2. Weekly work performed by self/household versus work performed by a professional service over time for one participant (Morgan).

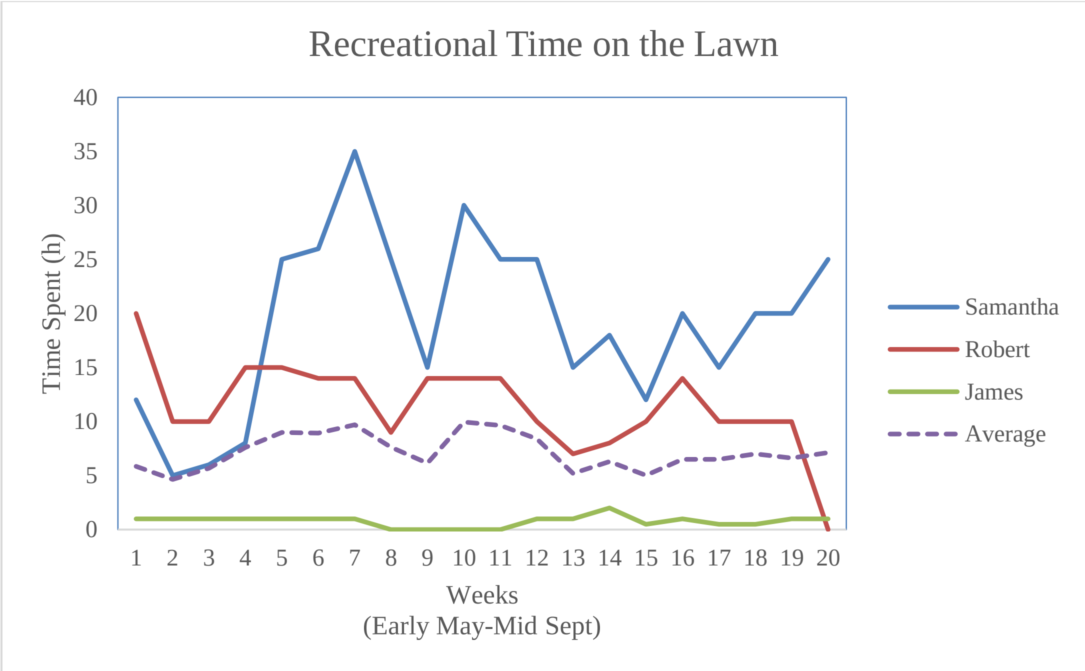

Figure C.3. Time spent for lawn recreation/leisure over a 20-week survey period as reported by three participant households, as well as a weekly group average for comparison.

Table C.1. Motivating factors for lawn management decisions selected by participants from 14 households over a 20-week survey period.[1]

Motivating Factor	Frequency
Aesthetics	165
Weather	158
Neighborhood/Community	57
Recreation	51
Family/Children	28
Environment	15
Advice	13

[1]Participants were given the opportunity to select motivating factors each week from a list.

Participants were not required to answer all questions, or complete every survey.

Table C.2. Terms used by participants from 14 different households over a 20-week survey period to describe time spent on the lawn each week.[1]

Ranking	Descriptive Term	Frequency
1	Hot	57
2	Relaxing	52
3	Fun	36
4	Enjoyable	25
5	Good	20
6	Satisfying	18
7	Humid	18
8	Pleasant	17
9	Refreshing	14
10	Peaceful	14
11	Tiring	12
12	Comfortable	10
13	Productive	9
14	Green	9
15	Dry	9

[1]Participants had the opportunity to use a total of three terms each week. Participants were not required to complete every survey, or respond to every question.

APPENDIX D

LONGITUDINAL SURVEY COMPONENT: SURVEY QUESTIONS

Q1.1 The following survey should only take 2-5 minutes to complete. Please answer this survey as soon as possible, as the answers are time-sensitive. The purpose of this survey is simply to collect information regarding your lawn activities over the past 7 days only (last Monday-current Sunday). This portion of our study is intended to collect real-time information to see how lawn care and recreation patterns change over time. There are no right or wrong answers. You may choose to not answer any questions. If you have any questions or concerns about this survey, you may contact me by phone at 972/896-4236 or email at rgrubbs@uga.edu. Thank you for taking time to complete this survey.

Q1.2 How do you feel about your lawn this week?

Q2.1 In the past 7 days (dates specified), approximately how many hours were dedicated to managing and maintaining your lawn (not recreation or leisure)? Please provide your best guess.

	Hours (1)
Work performed by myself or another member of my household. (1)	
Work performed by an outside party (hired service) (2)	

Q2.2 In the past 7 days (dates specified), has your lawn been mowed?

- ❍ Yes, my lawn was mowed by myself or another member of my household. (1)
- ❍ Yes, my lawn was mowed by a service. (2)
- ❍ No, my lawn has not been mowed. (3)
- ❍ I would prefer not to answer this question. (4)

If No, my lawn has not been mo... Is Selected, Then Skip To End of Block

Q2.3 How many times has your lawn been mowed in the past 7 days (dates specified)?

- ❍ 1 (1)
- ❍ 2 (2)
- ❍ 3 (3)
- ❍ More than 3 (4)
- ❍ I'm not sure (5)
- ❍ I would prefer not to answer this question. (6)

Q2.4 Approximately how much height did you take off of your grass each time it was mowed in the past 7 days (dates specified)?

- ❍ Less than 1/4" (1)
- ❍ 1/4"-1/2" (2)
- ❍ 1/2"-3/4" (3)
- ❍ 3/4"-1" (4)
- ❍ 1” – 1 ½” (5)
- ❍ More than 1 ½” (6)
- ❍ I'm not sure (7)
- ❍ I would prefer not to answer this question. (8)

Q2.5 What did you do with your clippings?

- ❍ Mulched (left on the lawn) (1)
- ❍ Bagged and taken away (2)
- ❍ Composted and reused elsewhere on the yard (3)
- ❍ I'm not sure (4)
- ❍ Other: (5) ____________________
- ❍ I would prefer not to answer this question. (6)

Q3.1 Has your lawn been fertilized in the past 7 days (dates specified)? This will include any material intended as a source of nutrients to your turfgrass (synthetic and natural fertilizers, organic matter, compost, weed and feed products).

- ❍ Yes, my lawn has been fertilized by myself or someone in my household. (1)
- ❍ Yes, my lawn has been fertilized by a service company. (2)
- ❍ No, my lawn has not been fertilized in the past 7 days. (3)
- ❍ I am not sure whether my lawn has been fertilized. (4)
- ❍ I would prefer not to answer this question. (5)

If No, my lawn has not been fe... Is Selected, Then Skip To End of Block

Q3.2 Briefly explain why you chose to fertilize your lawn this past week.

Q3.3 How many fertilizer products have you used in the past 7 days (dates specified)? (Includes synthetic fertilizers, weed and feed products, natural fertilizers, compost and organic matter).

- ❍ 1 (1)
- ❍ 2 (2)
- ❍ 3 (3)
- ❍ 4 (4)
- ❍ More than 4 (5)
- ❍ I'm not sure. (6)
- ❍ I would prefer not to answer this question. (7)

Q3.4 Please list any nutrient/fertilizer products that you used on your lawn in the past 7 days (dates specified). This will include both natural (manure, compost, etc) and synthetic products granular and liquid fertilizers, weed and feed, etc). If you are not sure about your product name, please write "unknown", and the researcher may contact you for additional details at a later time.

	Product Name	Did you use a rate recommended on the label?			Please provide any additional details you feel the researcher should know about this product.
	Product Name (1)	Yes (1)	No (2)	I'm not sure (3)	Comments (1)
Product 1 (1)		❍	❍	❍	
Product 2 (2)		❍	❍	❍	
Product 3 (3)		❍	❍	❍	
Product 4 (4)		❍	❍	❍	
Product 5 (5)		❍	❍	❍	

Q3.5 Please briefly explain why you did or did not use the label recommendations.

Q3.6 Please use this space to briefly share anything else you would like the researcher to know about your fertilizer practices from the past 7 days. If you have nothing to add, leave blank.

Q4.1 In the past 7 days (dates specified), which tasks have been performed on your lawn? Please select all that apply, and indicate whether they were performed by you (homeowner) or an outside party (lawn service).

	Performed by Homeowner	
	Homeowner (1)	Service (2)
Irrigation/Watering (1)	❑	❑
Fungicide Application (2)	❑	❑
Herbicide Application (3)	❑	❑
Insecticide Application (4)	❑	❑
Manual Weed Pulling/Weed Eating (5)	❑	❑
Re-surfacing (sod or sprigs) (6)	❑	❑
Cultivation (dethatching/aerification) (7)	❑	❑
Liming (8)	❑	❑
Top-dressing (9)	❑	❑
Mulching (bark and pine straw) (10)	❑	❑
Other 1 (11)	❑	❑
Other 2 (12)	❑	❑

Q4.2 Please use this space to briefly share anything else you would like the researcher to know about your general management practices from the past 7 days. If you have nothing to add, leave bank.

Q5.1 In the past seven days, which factors have influenced the way you've managed your lawn (including product selection)? Please select all that apply. REMINDER: Note that what may affect management decisions on your lawn can change on a weekly basis. You do not need to answer consistently from week to week.
Weather (1)

- ❑ Advice from others (media, experts, family, neighbors) (2)
- ❑ Responsibility to neighborhood and community (3)
- ❑ Concerns about the environment (waste, pollution, toxins, etc) (4)
- ❑ Aesthetics and appearance (5)
- ❑ Recreation and lawn use (making the lawn accessible) (6)
- ❑ Responsibility to family/children (safety) (7)
- ❑ Other (8) ____________________

Q5.2 Tap or click below to arrange the following factors according to importance in the last 7 days -- from MOST important (top) to LEAST important (bottom).

Q5.3 Please briefly explain any other factors that may have affected your lawn management decisions for the past 7 days (dates specified). If you have nothing to add, please leave blank.

Q6.1 In the past 7 days (dates specified), approximately how many hours were spent on your lawn by yourself and others for recreation and leisure. Please provide your best guess.
Time (h)

Q6.2 Who has spent time on your lawn in the past 7 days (dates specified)? Select all that apply.

- ❑ Self (1)
- ❑ Another adult that lives with me (spouse, partner, roommate) (2)
- ❑ Children that live with me (3)
- ❑ Children that do not live with me (4)
- ❑ Adult neighbors (5)
- ❑ Family that does not live with me. (6)
- ❑ Pets (7)
- ❑ Lawn Service (8)
- ❑ Other (9) ____________________
- ❑ No one was on my lawn this week. (10)

If No one was on my lawn this ... Is Selected, Then Skip To End of Survey

Q6.3 Tap or click below to arrange the following individuals according to who spent time in your yard in the last 7 days -- from MOST time (top) to LEAST time (bottom).
Q6.4 Use three words to describe how you feel about the time spent on your lawn in the past 7 days (dates specified).

1 (1)
2 (2)
3 (3)

Q6.5 Please use this space to briefly expand on your answer or share any additional thoughts that you may have for the researcher.