Fall 2014

Defining Management Strategies To Maximize Net Soil Carbon And Nitrogen Retention In Turfgrass Systems

Quincy D. Law
Purdue University

Recommended Citation

Law, Quincy D., "Defining Management Strategies To Maximize Net Soil Carbon And Nitrogen Retention In Turfgrass Systems" (2014). *Open Access Theses*. 341.
https://docs.lib.purdue.edu/open_access_theses/341

Graduate School Form 30
(Revised 08/14)

PURDUE UNIVERSITY
GRADUATE SCHOOL
Thesis/Dissertation Acceptance

This is to certify that the thesis/dissertation prepared

By Quincy D. Law

Entitled
DEFINING MANAGEMENT STRATEGIES TO MAXIMIZE NET SOIL CARBON AND NITROGEN RETENTION IN TURFGRASS SYSTEMS

For the degree of Master of Science

Is approved by the final examining committee:

Aaron J. Patton

Cale A. Bigelow

Yiwei Jiang

Ronald F. Turco

To the best of my knowledge and as understood by the student in the Thesis/Dissertation Agreement, Publication Delay, and Certification/Disclaimer (Graduate School Form 32), this thesis/dissertation adheres to the provisions of Purdue University's "Policy on Integrity in Research" and the use of copyrighted material.

Approved by Major Professor(s): Aaron J. Patton

Approved by: Joseph M. Anderson 12/05/2014

Head of the Department Graduate Program Date

DEFINING MANAGEMENT STRATEGIES TO MAXIMIZE NET SOIL CARBON AND NITROGEN RETENTION IN TURFGRASS SYSTEMS

A Thesis
Submitted to the Faculty
of
Purdue University
by
Quincy D. Law

In Partial Fulfillment of the
Requirements for the Degree
of
Master of Science

December 2014
Purdue University
West Lafayette, Indiana

For my parents, whose boundless love, support, and guidance made this possible.

ACKNOWLEDGEMENTS

First and foremost, I’d like to thank my major professor, Dr. Aaron Patton. Without you, graduate school would have never been a reality. Your patience, understanding, and mentorship is truly unmatched. I’d also like to thank the rest of my committee members: Drs. Cale Bigelow, Yiwei Jiang, and Ron Turco. Thank you for your teaching, feedback, and direction.

TABLE OF CONTENTS

APPENDICES

ABSTRACT

Law, Quincy D. M.S., Purdue University, December 2014. Defining Management Strategies to Maximize Net Soil Carbon and Nitrogen Retention in Turfgrass Systems. Major Professor: Aaron Patton.

Soil carbon (C) sequestration has been proposed as a method to reduce atmospheric carbon dioxide (CO_2). Managed turf areas are both a source and a sink for greenhouse gases (GHGs) including CO_2, methane (CH_4), and nitrous oxide (N_2O), among others. Management practices, including turfgrass selection and mowing, influence the amount of C and N stored in the soil, as well as the direct and indirect GHG emissions. Thus, the objective of this research was to determine how turfgrass selection (both species and cultivar) and mowing practices (such as frequency and grass clipping management) influence the annual mowing requirements and dry matter yield, soil C and N accumulation, and GHG flux (CO_2, N_2O, and CH_4) in a turfgrass system. Planting slower growing turfgrasses resulted in fewer annual mowing events: Kentucky bluegrass (*Poa pratensis* L.) required fewer annual mowing events than tall fescue (*Schedonorus arundinaceus* Schreb.), and slow-growing cultivars needed to be mown less than the moderate-growing cultivars, which were mown fewer times than the fast-growing cultivars. Mowing by the one-third rule and collecting grass clippings also reduced mowing requirements. However, the faster growing species (i.e. tall fescue) and cultivars had higher annual dry matter yields, and returning grass clippings also increased yield. The same practices that increased dry matter yield, except for growth rate, also increased labile and total soil C concentrations. Furthermore, returning grass clippings increased leaf tissue N concentration as well as total soil N concentration. Tall fescue had a greater CO_2 flux than Kentucky bluegrass, and returning grass clippings had a greater CO_2 flux than collecting clippings, which occurred on five and one of the six collection dates, respectively. Nitrous oxide flux differed for growth rate on one collection date, though it was likely due to a fertilizer response. There was not a measurable CH_4 flux. The results of this study highlight the importance of turfgrass selection and mowing practices on the C and N dynamics and biogeochemical cycling in a turfgrass system. All turfgrasses and management practices resulted in a system-wide net C sink, though the magnitude of the sink varied by management strategy.

CHAPTER ONE – LITERATURE REVIEW

Turfgrasses make up roughly 50 of the 10,000 plant species within the Poaceae family (Christians, 2011; Watson and Dallwitz, 1992), which are monocotyledonous flowering plants. Turfgrasses are able to form a high density under the continuous defoliation from mowing. Their benefits are exemplified in three basic uses: function, recreation, and aesthetics (Beard and Green, 1994).

Benefits of Turf

Functional benefits of turfgrasses include soil conservation and improvement, groundwater recharge, improved surface water quality, heat dissipation, firebreaks, and reduced pests. By reducing sediment losses (Gross et al., 1991) and adding organic matter to the soil through the turnover of roots and other plant tissues (Beard and Green, 1994), turfgrassess can both conserve and improve soil. Turfgrass plants increase the hydraulic resistance of moving water, thereby reducing runoff (Ree, 1949); coupled with increased soil infiltration (Gross et al., 1991), turfgrasses assist in groundwater recharge.

Turfgrasses also benefit the atmosphere through the absorption of pollutants, but they can emit them as well. Managed turf areas are both a source and a sink for carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), nitric oxide (NO), and nitrogen dioxide (NO_2), as well as non-greenhouse pollutants (Stier et al., 2013). Additionally, a mown lawn provides a cooling effect through heat dissipation (Beard and Green, 1994) creates a firebreak (Younger, 1970), and offers a less favorable habitat for unwanted nuisance insects and disease vectors (Clopton and Gold, 1993).

The use of turfgrass on golf courses, sports fields, parks, and home lawns is considered recreational. Turfgrasses provide a cushioning effect that reduces injuries to participants when compared with poorly or nonturfed soils, especially in contact sports such as football, rugby, and soccer (Gramckow, 1968). Furthermore, Rogers and Waddington (1992) demonstrated the substantial benefit of a properly managed, quality turf in reducing the hardness of sports fields. Additionally, turfgrass tolerates traffic and reduces surface hardness compared to other ground covers like large crabgrass (*Digitaria sanguinalis*) and white clover (*Trifolium repens*)(Brosnan et al., 2014). The third use, aesthetic, is represented by a Harris-Life survey that indicated one of the things 95% of the respondents wanted most around them was green grass and trees (Hooper, 1970).

Two turfgrass species commonly used in Indiana home lawns are Kentucky bluegrass (*Poa pratensis* L.) and tall fescue (*Lolium arundinaceum* (Schreb.) Darbysh. = *Schedonorus arundinaceus* (Schreb.) Durmort., formerly *Festuca arundinacea* Schreb. var. *arundinacea*).

Kentucky Bluegrass

Kentucky bluegrass was considered to be the principle lawn grass of Indiana in the 1920's (Deam, 1929), and it is currently the most widely used cool-season turfgrass in the United States (Christians, 2011). It is possible that Kentucky bluegrass is native to

North America; however, tall fescue was probably native to Eurasia and has since been naturalized in North America (Beard, 2013). Kentucky bluegrass forms a dense, attractive turf sward when supplied with sufficient water (Meyer and Funk, 1989; Christians, 2011). Like all members of the *Poa* genus, Kentucky bluegrass has a boat-shaped leaf tip and folded vernation. It is a medium-textured, rhizomatous grass (Beard, 1973), and the rhizome development can be quite extensive. Lobenstein (1962) observed 6 to 18 meters of rhizomes produced from an original shoot in a 5 month period. As such, Kentucky bluegrass has excellent recuperative and vegetative reproduction capabilities (Christians, 2011), as well as good sod strength (King et al., 1982).

With soft, smooth leaves (Beard, 1973), Kentucky bluegrass mows more cleanly than tougher-bladed grasses, such as perennial ryegrass (*Lolium perenne* L.)(Christians, 2011). It is able to tolerate droughty conditions by going into summer dormancy (Beard, 1973; Christians, 2011) and exhibits excellent cold tolerance (Gudleifsson et al., 1986; Limin and Fowler, 1987; Sarkar et al., 2009). Furthermore, Kentucky bluegrass can thrive in markedly different habitats due to its capability to develop numerous ecotypes (Torrecilla and Catalán, 2002; Beard, 2013).

Kentucky bluegrass is highly polyploidy (Beard, 1973), can have 24 to 124 chromosomes (Turgeon, 2008), and reproduces apomictically (Meyer and Funk, 1989). The color, texture, density, growth habit, adaption, cultural requirements, close-mowing tolerance, and disease resistance can vary considerably within the species (Beard, 1973; Turgeon, 2008). Due to and based on these differences, Kentucky bluegrass has been classified into categorical types (Murphy et al., 1997). These types include: Compact, Compact-Midnight, Compact-American, Julia, Bellevue, Mid-Atlantic ecotype, High

Density (formerly Aggressive), Shamrock, Other, BVMG (Baron, Victa, Merit, Gnome), Common (Eurasian Midwest), and Texas × Kentucky Hybrids (*Poa arachnifera* Torr. × *P. pratensis*)(Murphy et al., 1997; Bonos et al., 2000, 2002; Turgeon, 2008; Shortell et al., 2009; Honig and Brilman, 2012). By categorizing the types of Kentucky bluegrass, turfgrass managers can select genotypes with particular morphological and agronomic traits to blend cultivars with complementary characteristics (Shortell et al., 2009).

Kentucky bluegrass is not without its weaknesses, though. With a shallow root system (Gist and Smith, 1948), it has a relatively high demand for water to remain green and prevent summer-induced drought dormancy (Beard, 1973; Christians, 2011). Kentucky bluegrass also has a poor shade tolerance (Beard, 1965; Wood, 1969). However, cultivars can vary in their tolerance to drought (Richardson et al., 2008) and shade (Taylor and Schmidt, 1977; Christians, 2011), as well as their rooting depth, root mass and distribution, shoot-to-root ratio, and dry matter yield (Burt and Christians, 1990).

Tall Fescue

Tall fescue is a turfgrass species native to Europe and adjacent regions that was introduced into the United States during the 1800s (Meyer and Funk, 1989). Cultivated on approximately 12 to 14 million ha (Buckner et al., 1979), tall fescue is a coarse-textured, bunch-type grass that is able to grow in a wide range of conditions (Beard, 1973; Turgeon, 2008). Its leaves have a pointed tip and prominent veins on the upper side. Tall fescue has a good tolerance of heat, drought, and wear (Christians, 2011), as well as shade (Turgeon, 2008) and salinity (Alshammary et al., 2004).

Compared to other popular cool-season species, tall fescue possesses a deeper rootzone that provides its good drought tolerance (Meyer and Funk, 1989). The species can persist with reduced soil fertility (Wilkinson and Mays, 1979) and in acidic soils (Turgeon, 2008). Tall fescue also has a good overall tolerance to insects compared to other cool-season grass species, and it can germinate faster than Kentucky bluegrass (Beard, 1973) – in as few as 6 days with warm soils (Meyer and Funk, 1989). Certain cultivars contain endophytic fungi, which can form a symbiotic relationship and improve the environmental and pest stress tolerance of the grass plant (Clay, 1990).

Tall fescue is a hexaploid with 42 chromosomes (Kleijer, 1987; Turgeon, 2008). Similar to Kentucky bluegrass, tall fescue cultivars have been categorized into types based on differences in texture, color, density, disease susceptibility, and tolerance to heat and drought. Those include: forage-types, improved turf-types, dwarf-types, and intermediate semi-dwarf-types (Meyer and Funk, 1989; Turgeon, 2008). Despite small rhizomes in some cultivars, tall fescue is classified as a bunch-type grass (Christians, 2011), and therefore, its recuperative capacity is limited. Additionally, tall fescue is not as cold-hardy as Kentucky bluegrass (Meyer and Funk, 1989), has a poor mowing quality, and is considered a high water user (Christians, 2011). Conversely, drought tolerance varies between cultivars, and those having high shoot to root ratios generally exhibit greater drought tolerance (Karcher et al., 2008).

Soil Carbon and Nitrogen Sequestration

Soil organic matter consists of plant and animal residues at various stages of decay (Gaussoin et al., 2013). These organic residues contain nutrients, including carbon

(C) and nitrogen (N), that are mineralized and released into the soil. As previously mentioned, turfgrasses can add organic matter to the soil profile. The process by which atmospheric C is captured by the plant during photosynthesis and stored in the soil as organic matter is known as C sequestration. Increased soil organic C benefits include more stable soil aggregates, decreased risk of runoff and erosion, and improved water infiltration (Angers and Carter, 1996), as well as decreasing bulk density through soil structure improvement (Blevins et al., 1983). Add itionally, atmospheric CO_2 can be retained in the soil if plant growth and plant residues are managed with C sequestration in mind.

Carbon dioxide, N_2O, and CH_4 are greenhouse gases (GHGs) of concern to our environment because of their contribution to climate instability (Follett et al., 2011). GHGs are named such due to their “greenhouse effect” in which they absorb thermal radiation from Earth’s surface and re-radiate it back to Earth, resulting in elevated temperatures (Follett et al., 2011). The atmospheric concentrations of CO_2, N_2O, and CH_4 have all increased since 1750 due to human activity (Stocker et al., 2013). The current level (i.e. May 2014 average) of atmospheric CO_2 (402 ppm)(Tans and Keeling, 2014) is 44 percent higher than estimated in 1750 (280 ppm)(Stocker et al., 2013). With the soil being the second-largest pool of carbon, one strategy to slow the atmospheric enrichment of CO_2 is to sequester it in the soil (Lal, 2004).

Any increase in the C content of soil resulting from a change in land management might be referred to as C sequestration because the additional C being held in the soil is separated from other parts of the ecosystem (Powlson et al., 2011). For C sequestration to contribute to climate change mitigation, the change in land management practice must cause a net additional transfer of C from atmospheric CO_2 to the terrestrial biosphere (Powlson et al., 2011). This can be done by increasing net photosynthesis, slowing the decomposition of soil organic C, and/or reducing C emissions through modified management practices. However, soil organic C does not accumulate indefinitely (Johnston et al., 2009), and C sequestration is reversible. Changes in land management leading to increased C in soil or vegetation must be continued indefinitely to maintain the increased C stock (Freibauer et al., 2004).

CENTURY model simulations indicate turfgrasses and their soils to be a strong sink of mineral N (Qian et al., 2003), and the amount of N in a particular soil is dependent on the climate, type of vegetation, topography, parent material, and management practices (i.e. activities of man)(Bremner, 1965). Moreover, Qian et al. (2003) revealed similar accumulation patterns between soil organic C and N. The results of Knops and Tilman (1998) further highlight the importance of soil C and N dynamics, as their results suggest that the rate of soil C accumulation is controlled by the accumulation rate of soil N. Though potential C and N mineralization can increase with turfgrass stand age (Shi et al., 2006), there is a limited capacity for the amount of organic N that can be stored in turfgrass soils (Porter et al., 1980). However, older turfgrass systems have a greater capacity conserve soil C and N due to their increased soil microbe resource use efficiency (Shi et al., 2006).

There are an estimated 16 to 20 million hectares of urban grasslands in the United States (Milesi et al., 2005; Brown et al., 2005), and urban grasslands can sequester soil organic C at a rate of 0.38-1.5 Mg C ha^{-1} yr^{-1} (Qian et al., 2010; Townsend-Small and Czimczik, 2010; Zirkle et al., 2011). A model created by Zirkle et al. (2011) estimated that an average home lawn in the United States has the potential to sequester between 20.3 and 163.4 kg C lawn^{-1} yr^{-1}. Furthermore, CENTURY Model simulations near Denver and Fort Collins, CO indicate that turfgrass systems can serve as a C sink for an estimated 30 to 40 yr after establishment, with 23-32 Mg ha^{-1} soil organic C sequestered in the 0 to 20 cm soil depth over a 30 year period (Bandaranayake et al., 2003). Low maintenance areas of golf courses, such as rough areas maintained similar to lawns, have also been shown to have a net C sequestration (Gutleben et al., 2010).

Greenhouse Gas Flux

Plant and soil respiration are natural processes that release CO_2 into the atmosphere and detract from the net C fixation and subsequent sequestration of an ecosystem. Plant respiration provides plants with the energy to produce and sustain biomass and acquire nutrients, and CO_2 is the physiological by-product of plant respiration. Soil respiration is the release of CO_2 due to the decomposition of organic matter by soil organisms, which in turn releases nutrients into the soil. These two types of respiration, plant and soil, are responsible for a portion of the CO_2 released from a turfgrass system and together make up its CO_2 flux. Turfgrass respiration rates differ both between (Watschke et al., 1973; Huylenbroeck and Bockstaele, 1999) and within species (Wilson, 1975; Huylenbroeck and Bockstaele, 1999), as well as amongst different plant tissues from the same plant (Moser et al., 1982). Furthermore, management practices such as mowing have been shown to influence turfgrass respiration rates (Liu and Huang, 2003). The soil's physical environment (i.e. temperature and moisture), quantity and quality of C substrate, and the microbial community are three factors that control the decomposition of organic matter and the subsequent release of CO_2 via soil respiration (Chapin et al., 2002). An estimated 64 to 72 Pg C yr^{-1} is respired from terrestrial soil on a global scale (Raich and Schlesinger, 1992).

Though the atmospheric concentration of N_2O is much less than that of CO_2 (Follett et al., 2011), the global warming potential of N_2O is over 300 times that of CO_2 (Stocker et al., 2013), and N_2O emissions are predicted to increase by 5% between 2005 and 2020 (U.S. Department of State, 2007). Nitrous oxide is produced through the natural processes of nitrification and denitrification, which are part of the N cycle (EPA, 2010). Soil bacteria utilize inorganic N as either an energy source or an electron acceptor in aerobic and anaerobic conditions, respectively (Sylvia et al., 2005). Ecological drivers of nitrification and denitrification, such as the availability of N and oxygen, influence N_2O production, and common turfgrass management practices (e.g. N fertilization and irrigation) directly influence the aforementioned ecological drivers (Bremer, 2006). Given that N_2O is a byproduct of fuel combustion (EPA, 2010), the fuel combusted to manage turfgrass is another anthropogenic source of N_2O emissions. Nitrous oxide flux has been correlated with N mineralization (Matson and Vitousek, 1987), N fertilization (Mosier et al., 1991; Bremer, 2006), and the cultivation of grasslands (Mosier et al., 1991). Given that turfgrass species have the potential to influence N cycling via changes in N mineralization and nitrification (Wedin and Tilman, 1990) turfgrass selection may be an important factor in reducing N_2O losses from turf. Furthermore, Lewis (2010) reported lower N_2O emissions in zoysiagrass (*Zoysia japonica* Steud.) compared to bermudagrass (*Cynodon dactylon* L. Pers. × *C. transvaalensis* Burtt-Davy), though this may have been due to bermudagrass receiving twice the amount of N fertilization. Grass clippings management has also been shown to influence N_2O flux in a turfgrass system, but the influence appeared to be dependent on the aerobic status of the soil (Li et al., 2013).

Soils can both produce and consume CH_4, even simultaneously, under the correct soil conditions (Sylvia et al., 2005). Methane is produced by obligate anaerobic bacteria known as methanogens (Whitman et al., 1992). Conversely, a group of bacteria known as methanotrophs oxidize CH_4 in aerobic conditions and use it as a carbon and energy source (Sylvia et al., 2005), and this group of bacteria make up the largest natural biological sink of CH_4 (Dutaur and Verchot, 2007). However, high soil inorganic N concentrations (Steudler et al., 1989; Mosier et al., 1991), cultivation (Mosier et al., 1991), and overly high or low soil moisture (Smith et al., 2000) inhibit the microbial consumption of CH_4, which are all factors affected by common turfgrass management practices (i.e. fertilization, aerification, and irrigation). The uptake of CH_4 has also been shown to be inversely related to N_2O emissions (Mosier et al., 1991), which highlights the importance of management practices that influence the flux of these two gases. By causing a simultaneous increase in N_2O emissions and decrease in CH_4 consumption, management practices that affect this inverse relationship have an even greater potential to influence GHG concentrations.

The intensity of turfgrass management influences both the total amount of C and N sequestered and the CO_2 and N_2O released via emissions resulting from certain management practices. Intensely managed turf that has increased fertilization, irrigation, and mowing can increase C and N stored in the soil (Golumbiewski, 2006). Furthermore, it has been shown that by producing a greater amount of biomass with the use of irrigation and fertilizer, the soil organic C pool can be increased (Lal et al., 1999). However, fuel-driven machinery and inputs, such as lawn mowers, irrigation pumps, and chemical fertilizers, have C emissions tied to their use and production.

Mowing

A large portion of a typical turfgrass maintenance budget is devoted to mowing equipment, fuel, and labor due to the frequent mowing turfgrass requires (Turgeon, 2008), and it has been shown that frequent mowing is an important aspect to maintaining high quality turf (Trappe et al., 2011). Most residential lawn mowers are gasoline powered (Davis and Truett, 2004), and the CO_2 emitted from the fuel consumption in the maintenance of turfgrass is estimated at about 24% of the organic C stored in ornamental lawns (Townsend-Small and Czimczik, 2010). Mowing frequency can also have a greater impact on C emissions that fertilization (Allaire et al., 2008). However, the annual C emissions associated with N fertilizer production, transportation, and application can be up to four times greater than the annual increase in soil organic C (Powlson et al., 2011). Due to this, Townsend-Small and Czimczik (2010) noted that urban grass areas sequester C only when managed conservatively and not when managed intensely with frequent mowing, irrigation, and fertilization.

Busey and Parker (1992) reported the time required for turfgrass maintenance was 1.08 hours 100 m^{-2} yr^{-1}, with mowing being the most common cultural practice applied to turfgrasses. Falk (1976) was able to mow a 110 m^2 cool-season turfgrass lawn in Walnut Creek, CA every week or two, except for once a month during the winter, from September 1972 to September 1973 with 4.73 L of gasoline and in a total of less than 5 h.

Despite the desirable appearance achieved afterwards, mowing is actually a plant stress (Christians, 2011; Howieson and Christians, 2008). By removing leaf tissue that turfgrasses use to acquire solar energy, mowing limits photosynthesis and C assimilation (White, 1973). Furthermore, the regrowth and initiation of new leaf tissue after mowing is necessary to develop the photosynthetic leaf area required for producing carbohydrates (Parsons et al., 1983).

Increased catabolism and decreased levels of fructans, which are important storage polysaccharides in the stems bases of many species of cool-season grasses, have been observed in response to defoliation (Morvan-Betrand et al., 2001; Volenec, 1986). Howieson and Christians (2008) not only observed temporary decreases in the levels of fructan and glucose in creeping bentgrass (*Agrostis stolonifera* L.) due to mowing, but a reduced efficiency of photosystem II as well. The duration of reduction of both the fructan levels and the efficiency of photosystem II were greatest in grasses that were double-cut, suggesting that multiple cuttings may be more damaging to plant vigor than single cutting. The plant injury caused by mowing can also influence the susceptibility of turf to infection by foliar pathogens (Putman and Kaminski, 2011). Hence, an increased mowing frequency may cause greater harm to the turfgrass plants, as well as generate greater emissions.

Turfgrass health is not only negatively affected by mowing too frequently, but not often enough as well. Crider (1955) revealed that the removal of 50 percent or more of the aboveground tissue can halt turfgrass root growth, and the duration of root growth stoppage will increase as a greater percentage of aboveground tissue is removed. Furthermore, root growth stoppage increased with repeated mowings. Thus, as a compromise between the removal of too much tissue and mowing too often, many extension publications recommend to mow frequently enough as to not remove more than one-third of the leaf blade in a single mowing, which is often referred to as the "one-third rule" (Reicher et al., 2006; Patton and Boyd, 2007). As an example, if a lawn mower is set to cut to a height of 8 cm, it is necessary to mow the grass when it reaches a height of 12 cm.

When following the one-third rule, mowing frequency is based upon the growth rate of the turf. Poorter and Remkes (1990) reported differences in the relative growth rate of different turfgrass species. Therefore, species selection is an important aspect of a turf sward's mowing requirement. Additionally, Wilhelm and Nelson (1978) showed growth rates can differ not only between grass species, but within, as they saw greater leaf elongation rates for high-yielding varieties of forage-type tall fescue than low-yielding varieties. As a result of this reduced leaf elongation, the selection, establishment, and use of slower-growing turfgrass cultivars could help reduce the mowing needs of grassed areas and therefore reduce C emissions from gasoline mowers and help increase net C sequestration of urban grasslands.

Regrowth is also important for the mowing frequency of a turf sward because the faster plants are able to regrow, the more often they will need to be mown. Turfgrass regrowth is correlated to not only the residual leaf area after mowing, but the carbohydrate reserves in the verdure as well, with carbohydrate food reserves being influential in stimulating regrowth for up to 25 days following defoliation (Ward and Blaser, 1961). As such, it is important to consider what portion of the leaf tissue will be removed, what leaf tissue will remain, and the carbohydrate reserve status of the turf.

In addition to mowing frequency, grass clippings management is another important and often overlooked aspect of mowing. The practice of returning grass clippings was previously thought to contribute to thatch accumulation, and, as a result, clippings were oftentimes collected. Furthermore, grass clippings can be collected to prevent the unsightly clumps of grass clippings when wet and/or long turf is mown. Previous estimates in the 1990s were that up to 15 to 20 percent of residential waste may be composed of grass clippings during periods of active growth (Graper and Munk, 1994). However, this number has since decreased. In 2012, yard trimmings, which include tree litter in addition to grass clippings, made up an estimated 8.7 percent of the United States' municipal solid waste after recycling and composting had occurred (EPA, 2014).

This decrease in landfilled grass clippings and subsequent increase in clippings being returned to turf swards has occurred for a multitude of reasons. Twenty-five states, including Indiana, have banned yard trimmings from landfills (Van Haaren et al., 2010). The fear of thatch production due to returning grass clippings has also been dismissed, as it has been shown to be a non-factor (Beard, 1976; Haley et al., 1985; Johnson et al., 1987) due to the rapid decomposition of grass clippings (Kopp and Guillard, 2004). In fact, there are numerous documented benefits of returning grass clippings. Heckman et al. (2000) returned grass clippings to a Kentucky bluegrass lawn with a mulching mower and found that returning clippings improved the color of turfgrass compared with removing clippings; they also observed cutting N fertilization in half did not decrease turfgrass color when clippings were returned. A response from N due to returning grass clippings has even been observed in as few as 14 days (Beard, 1976). Other researchers have noted increases in N use efficiency (Kopp and Guillard, 2002), N uptake (Starr and DeRoo, 1981), and overall dry matter yield (Kopp and Guillard, 2002; Bigelow et al., 2005) as benefits of returning grass clippings. Returning grass clippings to a turfgrass system over an extended period of time (>25 yr) has been modeled to cut N requirements in half (Qian et al., 2003).

Returning grass clippings may contribute towards increasing C sequestration as well. By increasing the soil C input via enhanced turfgrass productivity, returning grass clippings may indirectly affect the amount of C decomposed and eventually sequestered (Yao et al., 2009). Kauer et al. (2013) reported that returning plant residues (i.e. grass and clover clippings) increased the organic C content in the soil top layer compared to when the residues were removed. Estimates of an 11 to 59 percent increase in soil C sequestration over a 10 to 50 yr period due to returning grass clippings in fertilized turf (75 to 150 kg N ha^{-1} yr^{-1}) has been reported (Qian et al., 2003).

There are negative consequences to returning grass clippings to a turfgrass sward, though. By producing a greater dry matter yield (Kopp and Guillard 2002; Bigelow et al., 2005), mowing requirements may be increased. Furthermore, Kopp and Guillard (2005) observed nitrate losses more than double when grass clippings were returned compared to when clippings were collected, and the losses became greater as N rate and irrigation increased. Returning grass clippings on the turf has also been shown to increase the severity of brown patch (*Rhizoctonia solani*), but it can reduce dollar spot infestations (*Sclerotinia homoeocarpa*) as well (Dunn et al., 1996). Despite the disadvantages, the benefits of returning grass clippings justify the practice.

The height of cut is another important element of mowing. Juska and Hanson (1961) revealed cutting height can have a greater negative influence on rooting than cutting frequency. Turfgrass has the capacity to root deeper at greater mowing heights, which gives the stand access to water further down in the soil profile. High mowing (i.e., 8.8 cm) has also been shown to be of greater integrated pest management importance than N fertility or low-rate herbicide use in maintaining coverage and reducing smooth crabgrass [*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.] encroachment in ‘Rebel II’ tall fescue (Dernoeden et al., 1993). Furthermore, Biran et al. (1981) saw increasing chlorophyll per unit weight in grass clippings as the height of cut raised. However, it has been documented that water consumption increases with cutting height (Biran et al., 1981), which is partly due to taller mown plants having deeper roots and therefore access to more water.

Given this knowledge base, research was initiated to answer unknown questions about the influence and subsequent effects of turfgrass species and cultivars in conjunction with common lawn mowing practices on annual mowing requirements, soil C, N, and GHG flux.

Objectives

Thus, the objectives of this research were to determine 1) Kentucky bluegrass and tall fescue mowing requirements and dry matter yield as influenced by growth rate, mowing frequency, and grass clippings management, 2) the labile soil C, total soil C, and total soil N accumulation of Kentucky bluegrass and tall fescue cultivars with differing growth rates under different grass clippings management practices, and 3) the impact of turfgrass species, growth rate, and grass clippings management on greenhouse gas flux.

Hypotheses and Predictions

Mowing requirement and dry matter yield will likely differ amongst turfgrass species, mowing frequency, and grass clippings management. Mowing requirements, especially when the frequency is based upon the one-third rule, are predicted to be correlated with experimental factors that result in increased plant growth. Returning grass clippings has already been shown to increase dry matter yield (Kopp and Guillard, 2002; Bigelow et al., 2005), and yield differences have been noted both between (Taylor and Templeton, 1976) and within (i.e. cultivars)(Wilhelm and Nelson, 1978) turfgrass species. Greater dry matter yields have been noted for tall fescue and its faster-growing cultivars when compared to Kentucky bluegrass and slower-growing tall fescue cultivars, respectively (Taylor and Templeton, 1976; Wilhelm and Nelson, 1978). As such, it is predicted that returning grass clippings, faster growing cultivars, and tall fescue will increase mowing requirements in this experiment. Mowing based on the calendar rather than growth is also likely to increase mowing requirements, as there is only one period (i.e. spring) of rapid growth for cool-season grasses during the growing season in which mowing based on the one-third rule would be more frequent than a weekly mowing, which is a commonly scheduled mowing increment.

Soil C and N will vary amongst treatments, especially grass clippings management. Factors that increase biomass production will likely also increase soil C accumulations (Lal et al., 1999), so it is predicted that the experimental factors that increase biomass will also increase labile soil C. Using yield as an indicator biomass production, faster growing cultivars, and tall fescue will increase soil C concentrations. These predictions are in line with previous research, as returning grass clippings has already been shown to increase soil organic C (Qian et al., 2003), and turfgrass species have been shown to have differing soil organic C accumulations (Qian et al., 2010). Changes in total C and soil organic matter are less likely to occur than changes in labile soil C, as the experiment was only conducted for 2 yr and these analyses are not as sensitive as labile soil C. Due to the fertilization effect of returning grass clippings (Heckman et al., 2000), the practice is predicted to increase soil N concentrations.

Greenhouse gases will likely differ amongst treatments. Given that the cycling of nutrients affects the release of GHGs from an ecosystem, factors that influence the mass balance of certain nutrients within an ecosystem, such as C and N, will likely result in differences in their GHG flux. Returning grass clippings to a turf sward has been shown to influence C and N dynamics and therefore will likely influence the release of CO_2, N_2O, and CH_4 as well. It is predicted that returning grass clippings will increase the CO_2 and N_2O emitted and decrease the CH_4 consumed in this experiment, though differences in CO_2 flux are most likely. Turfgrass respiration rates differ both between (Watschke et al., 1973; Huylenbroeck and Bockstaele, 1999) and within species (Wilson, 1975; Huylenbroeck and Bockstaele, 1999), as well as amongst different plant tissues from the same plant (Moser et al., 1982). Furthermore, management practices such as mowing have been shown to influence turfgrass respiration rates (Liu and Huang, 2003). Tall fescue, due to its greater growth, is predicted to have a greater CO_2 flux. Additionally, since tall fescue will likely have a faster growth and greater nutrient cycling, it is predicted to have a greater N_2O flux and lesser CH_4 consumption thank Kentucky bluegrass.

References

Allaire, S.E., C. Dufour-L'Arrivée, J.A. Lafond, R. Lalancette, and J. Brodeur. 2008. Carbon dioxide emissions by urban turfgrass areas. Canadian Journal of Soil Science 88:529-532.

Alshammary, S., Y. Qian, and S. Wallner. 2004. Growth response of four turfgrass species to salinity. Agricultural Water Management 66(2):97-111.

Angers, D.A., M.R. Carter. 1996. Aggregation and organic matter storage in cool, humid agricultural soils. In: M.R. Carter and B.A. Stewart, editors, Structure and organic matter storage in agricultural soils. Advances in Soil Science. CRC Press, Boca Raton, FL. p. 193-211.

Bandaranayake, W., Y.L. Qian, W.J. Parton, D.S. Ojima, and R.F. Follett. 2003. Estimation of soil organic carbon changes in turfgrass systems using the CENTURY model. Agronomy Journal 95:558-563.

Beard, J.B. 1965. Factors in the adaption of turfgrass to shade. Agronomy Journal 57:457-459.

Beard, J.B. 1973. Turfgrass: Science and Culture. Prentice-Hall, Englewood Cliffs.

Beard, J.B. 1976. Clipping disposal in relation to rotary lawn mowers and the effect on thatch. Journal of the Sports Turf Research Institute 52:85-91.

Beard, J.B. 2013. Origins of North American turfgrasses. In: J.C. Stier, B.P. Horgan, and S.A. Bonos, editors, Turfgrass: Biology, use, and management. Agronomy Monograph 56. ASA, CSSA, and SSSA, Madison, WI. p. 1-35.

Beard, J.B., and R.L. Green. 1994. The role of turfgrasses in environmental protection and their benefits to humans. Journal of Environmental Quality 23:452-460.

Bigelow, C.A., D.W. Waddill, and D.R. Chalmers. 2005. Turf-type tall fescue lawn turf response to added clippings. International Turfgrass Society Research Journal 10:916-922.

Biran, I., B. Bravdo, I. Bushkin-Harav, and E. Rawitz. 1981. Water consumption and growth rate of 11 turfgrasses as affected by mowing height, irrigation frequency, and soil moisture. Agronomy Journal 73:85-90.

Blevins, R.L., M.S. Smith, G.W. Thomas, and W.W. Frye. 1983. Influence of conservation tillage on soil properties. Journal of Soil and Water Conservation 38:301-305.

Bonos, S.A., W.A. Meyer, and J.A. Murphy. 2000. Classification of Kentucky bluegrass genotypes grown as spaced-plants. HortScience 35:910-913.

Bonos, S.A., W.A. Meyer, and J.A. Murphy. 2002. Choose Kentucky bluegrass types to develop improved blends. Turfgrass Trends. Available at http://archive.lib.msu.edu/tic/golfd/article/2002febT11.pdf (verified 12 August 2013).

Bremer, D.J. 2006. Nitrous oxide fluxes in turfgrass. Journal of Environmental Quality 35:1678-1685.

Bremner, J.M. 1965. Organic nitrogen in soils. In: W.V. Bartholomew and F.E. Clark, editors, Soil nitrogen. Agronomy Monograph 10. ASA, CSSA, and SSSA, Madison, WI. p. 93-145.

Brosnan, J.T., K.H. Dickson, J.C. Sorochan, A.W. Thoms, and J.C. Stier. 2014. Large crabgrass, white clover, and hybrid bermudagrass athletic field playing quality in response to simulated traffic. Crop Science 54:1838-1843.

Brown, D.G., K.M. Johnson, T.R. Loveland, and D.M. Theobald. 2005. Rural land-use trends in the conterminous United States, 1950-2000. Ecological Applications 15:1851-1863.

Buckner, R.C., J.B. Powell, and RV. Frakes. 1979. Historical development. In: R.C. Buckner and L.P. Bush, editors, Tall fescue. Agronomy Monograph 20. ASA, CSSA, and SSSA, Madison, WI. p. 1-8.

Burt, M.G., and N.E. Christians. 1990. Morphological and growth characteristics of low- and high-maintenance Kentucky bluegrass cultivars. Crop Science 30:1239-1243.

Busey, P., and J.H. Parker. 1992. Energy conservation and efficient turfgrass maintenance. In: D.V. Waddington, R.N. Carrow, and R.C. Shearman, editors, Turfgrass. ASA, CSSA, and SSSA, Madison, WI.

Chapin III, F.S., M.C. Chapin, P.A. Matson, and P. Vitousek. 2011. Principles of terrestrial ecosystem ecology. Springer, New York.

Christians, N.E. 2011. Fundamentals of Turfgrass Management. 4th ed. John Wiley & Sons, Hoboken.

Clay, K. 1990. Fungal endophytes of grasses. Annual Review of Ecology and Systematics 21:275–297.

Clopton, R.E., and R.E. Gold. 1993. Distribution and seasonal and diurnal activity patterns of *Eutrombicula alfreddugesi* (Acari: Trombiculidae) in a forest edge ecosystem. Journal of Medical Entomology 30:47-53.

Crider, F.J. 1955. Root-growth stoppage resulting from defoliation of grass. USDA Technical Bulletin. 1102. U.S. Government Printing Office, Washington, DC.

Davis, S.C., and L.F. Truett. 2004. Off-highway transportation-related fuel use. ORNL/TM-2004/92. Oak Ridge National Laboratory, Oak Ridge, TN.

Deam, C.C. 1929. Grasses of Indiana. W.B. Burford Printing Company, Indianapolis.

Dernoeden, P.H., M.J. Carroll, and J.M. Krouse. 1993. Weed management and tall fescue quality as influenced by mowing, nitrogen, and herbicides. Crop Science 33:1055-1061.

Dunn, J.H., D.D. Minner, B.F. Fresenburg, and S.S. Bughrara. 1996. Clippings disposal and fertilization influence disease in perennial ryegrass turf. HortScience 31:1180-1181.

Dutaur, L., and L.V. Verchot. 2007. A global inventory of the soil CH_4 sink. Global Biogeochemical Cycles 21:GB4013.

EPA. 2010. Methane and nitrous oxide emissions from natural sources. U.S. Environmental Protection Agency, Washington, DC, USA.

EPA. 2014. Municipal solid waste generation, recycling, and disposal in the United States: Facts and figures for 2012. U.S. Environmental Protection Agency, Washington, DC, USA.

Falk, J.H. 1976. Energetics of a suburban lawn ecosystem. Ecology:141-150.

Follett, R., S. Mooney, J. Morgan, K. Paustian, L.H. Allen Jr, S. Archibeque, J.M. Baker, S.J. Del Grosso, J. Derner, and F. Dijkstra. 2011. Carbon sequestration and greenhouse gas fluxes in agriculture: Challenges and opportunities. Council for Agricultural Science and Technology (CAST), Ames.

Freibauer, A., M.D.. Rounsevell, P. Smith, and J. Verhagen. 2004. Carbon sequestration in the agricultural soils of Europe. Geoderma 122:1–23.

Gaussoin, R.E., W.L. Berndt, C.A. Dockrell, and R.A. Drijber. 2013. Characterization, development, and management of organic matter in turfgrass systems. In: J.C. Stier, B.P. Horgan, and S.A. Bonos, editors, Turfgrass: Biology, use, and management. Agronomy Monograph 56. ASA, CSSA, and SSSA, Madison, WI. p. 425-456.

Gist, G.R., and R.M. Smith. 1948. Root development of several common forage grasses to a depth of eighteen inches. Agronomy Journal 40:1036–1042.

Golubiewski, N.E. 2006. Urbanization increases grassland carbon pools: Effects of landscaping in Colorado's Front Range. Ecological Applications 16:555-571.

Gramckow, J. 1968. Athletic field quality studies. Cal-Turf Inc., Camarillo, CA.

Graper, D. and S. Munk. 1994. Cut it high… let it lie. Extension Extra 6030. South Dakota State University, Brookings, SD.

Gross, C.M., J.S. Angle, R.L. Hill, and M.S. Welterlen. 1991. Runoff and sediment losses from tall fescue under simulated rainfall. Journal of Environmental Quality 20:604-607.

Gudleifsson, B.E., C.J. Andrews, and H. Bjornsson. 1986. Cold hardiness and ice tolerance of pasture grasses grown and tested in controlled environments. Canadian Journal of Plant Science 66:601-608.

Gutleben, C., D. Provendier, J. Streit, P. Bécid, and J.M. Lecourt. 2010. Carbon footprint of turfgrass maintenance: First results and identification of levers. In: A. Zuin, editor, Proceedings of the 2nd European Turfgrass Society Conference, Loire Valley, France. 11-14 Apr. 2010.

Haley, J.E., D.J. Wehner, T.W. Fermanian, and A.J. Turgeon. 1985. Comparison of conventional and mulching mowers for Kentucky bluegrass maintenance. HortScience 20:105-107.

Heckman, J.R., H. Liu, W. Hill, M. DeMilia, and W.L. Anastasia. 2000. Kentucky bluegrass responses to mowing practice and nitrogen fertility management. Journal of Sustainable Agriculture 15(4):25-33.

Honig, J.A., and L.A. Brilman. 2012. Kentucky bluegrass classification. Seed Research of Oregon, Tangent, OR.

Hooper, B. 1970. A Life poll by Louis Harris. The real change has just begun. Life 68:102-106.

Howieson, M.J., and N.E. Christians. 2008. Carbohydrate metabolism and efficiency of photosystem II in mown creeping bentgrass (*Agrostis stolonifera* L.). HortScience 43:525-531.

Huylenbroeck, V., and V. Bockstaele. 1999. Photosynthetic characteristics of perennial ryegrass and red fescue turf-grass cultivars. Grass and Forage Science 54:267-274.

Johnson, B.J., R.N. Carrow, and R.E. Burns. 1987. Bermudagrass turf response to mowing practices and fertilizer. Agronomy Journal 79:677-680.

Johnston, A.E., P.R. Poulton, and K. Coleman. 2009. Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy 101:1-57.

Juska, F.V., and A.A. Hanson. 1961. Effects of interval and height of mowing on growth of Merion and common Kentucky bluegrass (*Poa pratensis* L.). Agronomy Journal 53:385-388.

Karcher, D.E., M.D. Richardson, K. Hignight, and D. Rush. 2008. Drought tolerance of tall fescue populations selected for high root/shoot ratios and summer survival. Crop Science 48:771-777.

Kauer, K., R. Kõlli, R. Viiralt, T. Köster, M. Noormets, T. Laidna, I. Keres, A. Parol, T. Varul, and A. Selge. 2013. Effect of cut plant residues management and fertilization on the dry matter yield of swards and on carbon content of soil. Communications in Soil Science and Plant Analysis 44:205-218.

King, J.W., J.B. Beard, and P.E. Rieke. 1982. Factors affecting survival of Kentucky bluegrass sod under simulated shipping conditions. Journal American Society for Horticultural Science 107:634-637.

Kleijer, G. 1987. Cytogenetic studies of crosses between *Lolium multiflorum* Lam. and *Festuca arundinacea* Schreb. III. The generations C1, C2 and C3. Plant Breeding 99:144-150.

Knops, J.M.H, and D. Tilman. 2000. Dynamics of soil nitrogen and carbon accumulation for 61 years after agricultural abandonment. Ecology 81:88-98.

Kopp, K.L., and K. Guillard. 2002. Clipping management and nitrogen fertilization of turfgrass. Crop Science 42:1225-1231.

Kopp, K.L., and K. Guillard. 2004. Decomposition rates and nitrogen release of turf grass clippings. Available at http://www.cropscience.org.au/icsc2004/poster/2/5/2/860_koppk.htm (verified 30 June 2014). In: T. Fischer, N. Turner, J. Angus, L. McIntyer, M. Robertson, A. Borrell, and D. Lloyd, editors, New directions for a diverse planet. Proceedings of the International Crop Science Congress, 4th, Brisbane, Australia. 26 Sept.-1 Oct. 2004. Regional Inst., Gosford, Australia.

Kopp, K.L., and K. Guillard. 2005. Clipping contributions to nitrate leaching from creeping bentgrass under varying irrigation and N rates. International Turfgrass Society Research Journal 10:80-85.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304:1623-1627.

Lal, R., R.F. Follett, J. Kimble, and C.V. Cole. 1999. Managing US cropland to sequester carbon in soil. Journal of Soil and Water Conservation 54:374-381.

Lewis, J.D. 2010. Carbon, nitrogen, and water fluxes from turfgrass ecosystems. Ph.D. dissertation, Kansas State University, Manhattan, KS.

Li, X., F. Hu, D. Bowman, and W. Shi. 2013. Nitrous oxide production in turfgrass systems: Effects of soil properties and grass clipping recycling. Applied Soil Ecology 67:61-69.

Limin, A.E., and D.B. Fowler. 1987. Cold hardiness of forage grasses grown on the Canadian prairies. Canadian Journal of Plant Science 67:1111-1115.

Liu, X., and B. Huang. 2003. Mowing height effects on summer turf growth and physiological activities for two creeping bentgrass cultivars. HortScience 38:444-448.

Lobenstein, C.W. 1962. Observing bluegrasses. In: Proceedings of the 1962 Midwest Regional Turf Conference. p. 66-69.

Matson, P.A., and P.M. Vitousek. 1987. Cross-system comparisons of soil nitrogen transformations and nitrous oxide flux in tropical forest ecosystems. Global Biogeochemical Cycles 1:163-170.

Meyer, W.A., and C.R. Funk. 1989. Progress and benefits to humanity from breeding cool-season grasses for turf. In: D.A. Sleper, K.H. Asay, and J.F. Pederson, editors, Contributions from Breeding Forage and Turf Grasses. p. 31-48.

Milesi, C., S.W. Running, C.D. Elvidge, J.B. Dietz, B.T. Tuttle, and R.R. Nemani. 2005. Mapping and modeling the biogeochemical cycling of turf grasses in the United States. Environmental Management 36:426-438.

Morvan-Bertrand, A., J. Boucaud, J. Le Saos, and M.-P. Prud'homme. 2001. Roles of the fructans from leaf sheaths and from the elongating leaf bases in the regrowth following defoliation of *Lolium perenne* L. Planta 213:109-120.

Moser, L.E., J.J. Volenec, and C.J. Nelson. 1982. Respiration, carbohydrate content, and leaf growth of tall fescue. Crop Science 22:781-786.

Mosier, A., D. Schimel, D. Valentine, K. Bronson, and W. Parton. 1991. Methane and nitrous oxide fluxes in native, fertilized and cultivated grasslands. Nature 350:330-332.

Murphy, J.A., S. Bonos, and P. Perdomo. 1997. Classification of *Poa pratensis* genotypes. International Turfgrass Society Research Journal 8:1176-1183.

Parsons, A.J., E.L. Leafe, B. Collett, and W. Stiles. 1983. The physiology of grass production under grazing. I. Characteristics of leaf and canopy photosynthesis of continuously-grazed swards. Journal of Applied Ecology 20:117-126.

Patton, A.J. and J. Boyd. 2007. Mowing your lawn. University of Arkansas Cooperative Extension Publication FSA-6023.

Poorter, H., and C. Remkes. 1990. Leaf area ratio and net assimilation rate of 24 wild species differing in relative growth rate. Oecologia 83:553-559.

Porter, D.A., D.R. Bouldin, S. Pacenka, R.S. Kossack, C.A. Shoemaker, and A.A. Pucci, Jr. 1980. Studies to assess the fate of nitrogen applied to turf: Part I. Research project technical complete report. OWRT Project A-086-NY. Cornell University, Ithaca, NY.

Powlson, D.S., A.P. Whitmore, and K.W.T. Goulding. 2011. Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false. European Journal of Soil Science 62:42-55.

Putman, A.I., and J.E. Kaminski. 2011. Mowing frequency and plant growth regulator effects on dollar spot severity and on duration of dollar spot control by fungicides. Plant Disease 95:1433-1442.

Qian, Y.L., W. Bandaranayake, W.J. Parton, B. Mecham, M.A. Harivandi, and A.R. Mosier. 2003. Long-term effects of clipping and nitrogen management in turfgrass on soil organic carbon and nitrogen dynamics. Journal of Environmental Quality 32:1694-1700.

Qian, Y., R.F. Follett, and J.M. Kimble. 2010. Soil organic carbon input from urban turfgrasses. Soil Science Society of America Journal 74:366-371.

Raich, J.W., and W.H. Schlesinger. 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus B 44:81-99.

Ree, W.O. 1949. Hydraulic characteristics of vegetation for vegetated waterways. Agricultural Engineering 30:184-189.

Reicher, Z., A.J. Patton, C.A. Bigelow, and T. Voigt. 2006. Mowing, thatching, aerifying, and rolling turf. Purdue University, Cooperative Extension Service. AY-8-W.

Richardson, M.D., D.E. Karcher, K. Hignight, and D. Rush. 2008. Drought tolerance and rooting capacity of Kentucky bluegrass cultivars. Crop Science 48:2429-2436.

Rogers, J.N., and D.V. Waddington. 1992. Impact absorption characteristics on turf and soil surfaces. Agronomy Journal 84:203-209.

Sarkar, D., P.C. Bhowmik, and K. Shetty. 2009. Cold acclimation responses of three cool-season turfgrasses and the role of proline-associated pentose phosphate pathway. Journal of the American Society for Horticultural Science 134:210-220.

Shortell, R.R., W.A. Meyer, and S.A. Bonos. 2009. Classification and inheritance of morphological and agronomic characteristics in Kentucky bluegrass (*Poa pratensis* L.). HortScience 44:274-279.

Smith, K.A., K.E. Dobbie, B.C. Ball, L.R. Bakken, B.K. Sitaula, S. Hansen, R. Brumme, W. Borken, S. Christensen, and A. Priemé. 2000. Oxidation of atmospheric methane in Northern European soils, comparison with other ecosystems, and uncertainties in the global terrestrial sink. Global Change Biology 6:791-803.

Starr, J.L., and H.C. DeRoo. 1981. The fate of nitrogen fertilizer applied to turfgrass. Crop Science 21:531-536.

Steudler, P.A., R.D. Bowden, J.M. Melillo, and J.D. Aber. 1989. Influence of nitrogen fertilization on methane uptake in temperate forest soils. Nature 341:314-316.

Stier, J.C., K. Steinke, E.H. Ervin, F.R. Higginson, and P.E. McMaugh. 2013. Turfgrass benefits and issues. In: J.C. Stier, B.P. Horgan, and S.A. Bonos, editors, Turfgrass: Biology, Use, and Management. Agronomy Monograph 56. ASA, CSSA, and SSSA, Madison, WI. p. 105-145.

Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley. 2013. Climate change 2013: The physical science basis. Intergovernmental Panel on Climate Change, Working Group I Contribution to the IPCC Fifth Assessment Report. Cambridge University Press, New York.

Sylvia, D.M., J.J. Fuhrmann, P.G. Hartel, and D.A. Zuberer. Principles and applications of soil microbiology. 2nd ed. Pearson Education Inc., Upper Saddle River.

Tans, P. and R. Keeling. 2014. Trends in Atmospheric Carbon Dioxide. http://www.esrl.noaa.gov/gmd/ccgg/trends/ (verified 30 June 2014).

Taylor, T.H., and W.C. Templeton. 1976. Stockpiling Kentucky bluegrass and tall fescue forage for winter pasturage. Agronomy Journal 68:235-239.

Torrecilla, P., and P. Catalán. 2002. Phylogeny of broad-leaved and fine-leaved *Festuca* lineages (Poaceae) based on nuclear ITS sequences. Systematic Botany 27:241-251.

Townsend-Small, A., and C.I. Czimczik. 2010. Carbon sequestration and greenhouse gas emissions in urban turf. Geophysical Research Letters 37:L02707. doi: 10.1029/2009GL041675 [erratum:37:L06707. doi: 10.1029/2010GL042735].

Trappe, J.M., D.E. Karcher, M.D. Richardson, and A.J. Patton. 2011. Bermudagrass and zoysiagrass cultivar selection: Part 1, clipping yield, scalping tendency, and golf ball lie. Applied Turfgrass Science. Available at https://dl.sciencesocieties.org/publications/ats/articles/8/1/2011-0630-01-RS (verified 16 Nov. 2014).

Turgeon, A.J. 2008. Turfgrass management. 8th ed. Pearson/Prentice Hall, Upper Saddle River, NJ.

U.S. Department of State. 2007. Projected Greenhouse Gas Emissions. In: Fourth Climate Action Report to the UN Framework Convention on Climate Change. U.S. Department of State, Washington, DC, USA.

Volenec, J.J. 1986. Nonstructural carbohydrates in stem base components of tall fescue during regrowth. Crop Science 26:122-127.

Van Haaren, R., N. Themelis, and N. Goldstein. 2010. The state of garbage in America. BioCycle 51(10):16-23.

Ward, C.Y., and R.E. Blaser. 1961. Carbohydrate food reserves and leaf area in regrowth of orchardgrass. Crop Science 1:366-370.

Watschke, T.L., R.E. Schmidt, E.W. Carson, and R.E. Blaser. 1973. Temperature influence on the physiology of selected cool season turfgrasses and bermudagrass. Agronomy Journal 65:591-594.

Watson, L., and M.J. Dallwitz. 1992. The grass genera of the world. CAB International, Wallingford.

Wedin, D.A., and D. Tilman. 1990. Species effects on nitrogen cycling: A test with perennial grasses. Oecologia 84:433-441.

White, L.M. 1973. Carbohydrate reserves of grasses: a review. Journal of Range Management 26:13-18.

Whitman, W.B., T.L. Bowen, and D.R. Boone. 2006. The methanogenic bacteria. In: M. Dworkin, S. Falkow, E. Rosenberg, K. Schleifer, and E Stackebrandt, editors, Prokaryotes. Springer, New York. p. 165-207.

Wilhelm, W., and C.J. Nelson. 1978. Leaf growth, leaf aging, and photosynthetic rate of tall fescue genotypes. Crop Science 18:769-772.

Wilkinson, S.R., and D.A. Mays. 1979. Mineral nutrition. In: R.C. Buckner and L.P. Bush, editors, Tall fescue. Agronomy Monograph 20. ASA, CSSA, and SSSA, Madison, WI. p. 41-73.

Wilson, D. 1975. Variation in leaf respiration in relation to growth and photosynthesis of *Lolium*. Annals of Applied Biology 80:323-338.

Wood, G.M. 1969. Evaluating turfgrasses for shade tolerance. Agronomy Journal 61:347-352.

Yao, H., D. Bowman, T. Rufty, and W. Shi. 2009. Interactions between N fertilization, grass clipping addition and pH in turf ecosystems: Implications for soil enzyme activities and organic matter decomposition. Soil Biology and Biochemistry 41:1425-1432.

Youngner, V.B. 1970. Landscaping to protect homes from wildfires. California Turfgrass Culture 20(4):28-32.

Zirkle, G., R. Lal, and B. Augustin. 2011. Modeling carbon sequestration in home lawns. HortScience 46:808-814.

CHAPTER TWO – KENTUCKY BLUEGRASS AND TALL FESCUE MOWING REQUIREMENTS AS INFLUENCED BY GROWTH RATE, MOWING FREQUENCY, AND GRASS CLIPPINGS MANAGEMENT

Abstract

Mowing remains one of the most important and energy-intensive cultural practices in maintaining a turfgrass stand. Turfgrass systems can become a larger net carbon sink via a reduction in the number of annual turf mowing events and subsequent mower emissions. Though university extension recommendations are to mow by the “one-third” rule and return grass clippings, how these practices influence the annual mowing requirement of a turf sward remains largely unknown. Furthermore, establishing slow-growing turfgrasses has also been proposed as a way to reduce mowing requirements. As such, the objectives of this field study were to determine 1) if an alternate mowing frequency will reduce mowing requirements, 2) the influence of returning grass clippings on mowing requirements, and 3) if turfgrass species and cultivars with differing growth rates influence mowing requirements. Mowing by the one-third rule decreased mowing requirements by 31%, and returning grass clippings added an additional 1-2 mowing events yr^{-1}. Tall fescue (*Lolium arundinaceum* (Schreb.) Darbysh. = *Schedonorus arundinaceus* (Schreb.) Durmort., formerly *Festuca arundinacea* Schreb. var. *arundinacea*) required more annual mowing events than

Kentucky bluegrass (*Poa pratensis* L.)(9 and 3 more in 2012 and 2013, respectively). Growth rate (i.e. cultivar) also affected annual mowing requirements: the faster the growth rate, the greater number of annual mowing events. Tall fescue had a greater two-year cumulative dry matter yield than Kentucky bluegrass (875 vs. 522 g m^{-2}), and the fast-growing cultivars (823 g m^{-2}) had greater cumulative dry matter yields than the moderate-growing cultivars (752 g m^{-2}), which were greater than the slow-growing cultivars (566 g m^{-2}). Leaf tissue nitrogen concentrations were higher when clippings were returned and slower-growing cultivars used. The results of this study highlight the importance of turfgrass selection, mowing strategy, and grass clipping management on annual mowing requirements.

Mowing remains one of the most important and energy-intensive cultural practices in maintaining a turfgrass stand. Even with adequate moisture, fertility, and pest control, incorrect mowing of turf can be detrimental to plant growth and function. Mowing is a plant stress, even when done correctly, as it removes green tissue, thereby reducing the plant's ability to undergo photosynthesis and produce carbohydrates (Howieson and Christians, 2008). To prevent the stresses of mowing too often (Howieson and Christians, 2008) and not often enough (Crider, 1955), it is recommended to mow frequently enough as to not remove more than one-third of the leaf blade in a single mowing, which is known as the "one-third rule" (Reicher et al., 2006). However, many homeowners and lawn services mow on a schedule rather than as needed, despite extension publication recommendations to follow the one-third rule (Reicher et al., 2006; Patton and Boyd, 2007). Mowing frequency not only impacts plant health, but energetics and emissions as well. Being that most residential lawn mowers are gasoline powered (Davis and Truett, 2004), mowing more frequently results in a higher energy requirement, greater emissions, increased labor, and increased financial cost.

In addition to mowing frequency, grass clippings management is another important and often overlooked aspect of mowing. The practice of returning grass clippings was previously thought to contribute to thatch accumulation, and, as a result, clippings were oftentimes collected. Furthermore, grass clippings can be collected to prevent the unsightly clumps of grass clippings when wet and/or long turf is mown. Previous estimates in the 1990s were that up to 15 to 20 percent of residential waste may be composed of grass clippings during periods of active growth (Graper and Munk, 1994). However, this number has since decreased. In 2012, yard trimmings, which include tree litter in addition to grass clippings, made up an estimated 8.7 percent of the United States' municipal solid waste after recycling and composting had occurred (EPA, 2014).

This decrease in landfilled grass clippings and subsequent increase in clippings being returned to turf swards has occurred for a multitude of reasons. Twenty-five states, including Indiana, have banned yard trimmings from landfills (Van Haaren et al., 2010). The fear of thatch production due to returning grass clippings has also been dismissed, as it has been shown to be a non-factor (Beard, 1976; Haley et al., 1985; Johnson et al., 1987) due to the rapid decomposition of grass clippings (Kopp and Guillard, 2004). In fact, there are numerous documented benefits of returning grass clippings. Heckman et al. (2000) returned grass clippings to a Kentucky bluegrass (*Poa pratensis* L.) lawn with a mulching mower and found that returning clippings improved the color of turfgrass compared with removing clippings; they also observed cutting nitrogen (N) fertilization in half did not decrease turfgrass color when clippings were returned. A response from N due to returning grass clippings has even been observed in as few as 14 days (Beard, 1976). Other researchers have noted increases in N use efficiency (Kopp and Guillard, 2002), N uptake (Starr and DeRoo, 1981), and overall dry matter yield (Kopp and Guillard, 2002; Bigelow et al., 2005) as benefits of returning grass clippings. Returning grass clippings to a turfgrass system over an extended period of time (>25 yr) has been modeled to cut N requirements in half (Qian et al., 2003).

Another important aspect of mowing is the turfgrass plant itself. Poorter and Remkes (1990) reported differences in the relative growth rate of different turfgrass species. Varietal selection is also important, as Wilhelm and Nelson (1978) revealed that high-yielding turfgrass genotypes display greater leaf elongation rates than low-yielding genotypes. As a result, turfgrass selection is an important consideration when attempting to reduce the mowing requirement of a turf sward. This is especially true when mowing frequency is based on growth rate, as it is with the one-third rule. Regrowth is also important for the mowing frequency of a turf sward because the faster plants are able to regrow, the more often they will need to be mown. Turfgrass regrowth is correlated to not only the residual leaf area after mowing, but the carbohydrate reserves in the verdure as well, with carbohydrate food reserves being influential in stimulating regrowth for up to 25 days following defoliation (Ward and Blaser, 1961). As such, it is important to consider what portion of the leaf tissue will be removed, what leaf tissue will remain, and the carbohydrate reserve status of the turf.

Two turfgrass species commonly used in Indiana home are Kentucky bluegrass and tall fescue (*Lolium arundinaceum* (Schreb.) Darbysh. = *Schedonorus arundinaceus* (Schreb.) Durmort., formerly *Festuca arundinacea* Schreb. var. *arundinacea*). Kentucky bluegrass was considered to be the principle lawn grass of Indiana in the 1920's (Deam, 1929), and it is currently the most widely used cool-season turfgrass in the United States (Christians, 2011). Though it is known that Kentucky bluegrass leaf blades cut more cleanly and have higher mowing quality than tougher-bladed grasses such as tall fescue (Christians, 2011), the growth habit and close-mowing tolerance can vary within either species (Beard, 1973).

The objectives of this research were to determine 1) if an alternate mowing frequency will reduce mowing requirements, 2) the influence of returning grass clippings on mowing requirements and leaf tissue N concentrations, and 3) if turfgrass species and cultivars with differing growth rates influence mowing requirements.

Materials and Methods

Research was conducted at the W.H. Daniel Turfgrass Research and Diagnostic Center in West Lafayette, IN. Soil type was a Stark silt loam (fine-silty mixed mesic Aeric Ochraqualf) with a pH of 6.9, 154 kg P ha^{-1}, 398 kg K ha^{-1}, 36 g kg^{-1} organic matter. The experimental area was fallow for 2 yr preceding this experiment. In April 2011, three cultivars of tall fescue (Table 2.1) were seeded at 294 kg ha^{-1} and three cultivars of Kentucky bluegrass (Table 2.1) were seeded at 98 kg ha^{-1}. Tall fescue and Kentucky bluegrass were the species used due to their popularity as lawn grasses in temperate regions of the world. Cultivars were selected for this experiment based upon their growth in preliminary industry trials (Rose-Fricker et al., 2010) and their similar appearance and stress tolerance in previous field trials (i.e. the National Turfgrass Evaluation Program)(data not shown) in West Lafayette, IN.

The experimental area was irrigated to prevent wilt, and pests (i.e. weeds, diseases, and insects) were controlled via pesticides and/or mechanical removal to maintain uniform plots across treatments. Plots were fertilized per Purdue Extension's recommendations for a moderate maintenance cool-season lawn with regular supplemental irrigation (Bigelow et al., 2013), receiving 142 kg of N, 20 kg of P_2O_5, and 54 kg of K_2O ha^{-1} yr^{-1}. Three fertilizer applications were made annually and occurred on 14 June, 20 September, and 17 November in 2012 and 29 May, 18 September, and 19 November in 2013. The May/June applications were at a rate of 44 kg N ha^{-1} with 32%

water insoluble N, and the September applications were at a rate of 49 kg N ha^{-1} with 40% water insoluble N. The November applications were made with urea (0% water insoluble N) at a rate of 49 kg N ha^{-1}.

The experiment was a two by three by two by two factorial design (2×3×2×2) with two species, three cultivars (slow, moderate, and fast growth rates), two mowing frequencies, and two grass clippings management treatments. The experimental design was a split-plot with four complete blocks. Whole plots of species and cultivar were 6 m by 4 m in size and randomized within blocks. Mowing frequency and grass clippings collection treatments were subunits randomized within whole plots. A total of four mowing regimes were applied, which made up the split plots that were 6 m by 1 m in size. Two separate mowing frequencies based upon 1) typical homeowner mowing practices with plots mown on the same day each week, and 2) the "one-third rule" using daily measurements to determine the appropriate mowing date. Additionally, for each of the described two mowing regimes, grass clippings were either 1) removed with a rear bagging attachment, or 2) returned using a recycling mower deck. All mowing events were recorded for each split plot to total the number of annual mowings for each cultivar and mowing regime for both species.

Plots were mown at a height of 7 cm with a Troy-Bilt TriAction 53 cm wide deck walk-behind push mower (Modern Tool and Die Company, Cleveland, OH). Thus, plots mown based on the one-third rule were mown when the turf reached a height of 10.5 cm. Moreover, the weekly-mown plots were only mown if the turf had grown 1.3 cm or more since the previous mowing in order to simulate a realistic homeowner scenario in which little growth had occurred and mowing was unnecessary. Turf height was measured in three equally-spaced locations within each split plot using a TurfChek II grass height gauge (Fig. 2.1)(Turf-Tec International, Tallahassee, FL) weekly for the weekly-mown plots and daily for the plots mown by the one-third rule; if two of three measurements were at or above the target mowing height, it was mown that day. Mowing began on 20 March in 2012 and 4 April in 2013 and had ceased by 30 October in 2012 and 8 November in 2013.

To collect dry matter yield data, grass clippings from the weekly-mown plots with clippings removed were collected, kept at 60 °C until a constant weight was achieved, and weighed for each mowing event. On two occasions in 2012 (31 July and 18 September) and three in 2013 (28 May, 30 July, and 16 September) in order to compare the dry matter yields and leaf tissue N concentrations between grass clippings management strategies, clippings were also collected, dried, and weighed from the weekly-mown plots with clippings returned. After being weighed, the clippings collected on those dates from both grass clipping management strategies were ground and analyzed for total N using a FlashEA 1112 Elemental Analyzer (Thermo Fisher Scientific, Waltham, MA), which is based on the Flash Dynamic Combustion Method.

Turfgrass quality and color were visually rated each month of the growing season according to the National Turfgrass Evaluation Program's recommendations (Morris, 20XX). Turfgrass quality was rated on a 1 to 9 scale, with 1 being dead, ≥6 being considered acceptable, and 9 being ideal grass (i.e. optimum color, density, and uniformity). Color was evaluated on a 1 to 9 scale, with 1 being straw brown and 9 being dark green. Furthermore, digital images of each plot were taken with an Olympus C-3030 camera (Olympus Amercia Inc., Melville, NY) and analyzed with SigmaScan software (Systat Software, Inc., San Jose, CA) to quantify the turfgrass dark green color index (DGCI) according to methods established by Karcher and Richardson (2003).

All data were analyzed using PROC GLIMMIX (SAS Institute, Cary, NC). Means were separated using Tukey's honest significant difference test (α=0.05). The full model, including all interactions, was run for the number of mowing events, turfgrass quality using species, growth rate, mowing frequency, and grass clipping management as main effects. A partial model, including the interaction, was run for cumulative dry matter yield of the weekly-mown plots with clippings collected using species and growth rate as main effects. Lastly, the dry matter yield, leaf tissue N concentration, and DGCI for weekly-mown plots were analyzed using species, growth rate, and grass clippings management, along with their interactions, as effects.

Results

In this irrigated field experiment, mowing events were significant for all main effects (i.e. species, growth rate, mowing frequency, grass clipping management) in both 2012 and 2013 (P<0.0001). Tall fescue (2012=26, 2013=24) required more annual mowing events than Kentucky bluegrass (2012=17, 2013=21)(Table 2.2). The fast-growing cultivars required the greatest number of annual mowing events (25 both years), which was followed by the moderate-growing cultivars (23 both years), and the slow-growing cultivars required the fewest mowing events (2012=16, 2013=20)(Table 2.2). Mowing based on the one-third rule (18 both years) reduced the number of mowing events compared to weekly mowing (2012=25, 2013=27), and returning grass clippings

(2012=22, 2013=24) resulted in a greater amount of mowing events versus collecting clippings (2012=21, 2013=22)(Table 2.2).

Twelve months was not long enough for the slow-growing cultivar of Kentucky bluegrass to fully establish. While coverage was complete, plants did not reach the target mowing height until 26 June 2012. Thus, the 2012 data was skewed, especially when considering the interactions. Therefore, only the 2013 treatment interactions are discussed. In 2013, all fixed effects were significant except for the species by grass clipping management and growth rate by grass clipping management interactions ($P>0.05$). When looking at the interaction of the full model of species by growth rate by mowing frequency by grass clippings management in 2013 ($P=0.0211$), the influence of mowing frequency is readily apparent. All of the weekly-mown plots, regardless of species, growth-rate, or grass clipping management, save for the slow-growing Kentucky bluegrass plots, had a greater number of mowing events (>27) than all of the plots mown by one-third rule plus the weekly mown slow-growing Kentucky bluegrass plots (≤24). The slow-growing cultivar of Kentucky bluegrass mown by the one-third rule with clippings collected had the fewest mowing events in 2013 with only 12.2 annual mowing events.

For the two year cumulative dry matter yield of the weekly-mown plots with clippings collected, species ($P<0.0001$), growth rate ($P<0.0001$), and the species by growth rate interaction ($P<0.0001$) were all significant. Tall fescue (875 g m^{-2}) had a greater dry matter yield than Kentucky bluegrass (552 g m^{-2})(Fig. 2.2). The fast-growing cultivars had the greatest dry matter yield (823 g m^{-2}), which was followed by the moderate-growing cultivars (752 g m^{-2}), and the slow-growing cultivars had the lowest yield (566 g m^{-2})(Fig. 2.3). For the interaction of species by growth rate, the fast- and moderate-growing cultivars of tall fescue had greater yields (924 and 881 g m^{-2}, respectively) than all of the Kentucky bluegrass cultivars (Fig. 2.4). However, the slow-growing cultivar of tall fescue (821 g m^{-2}) had a similar yield to that of the fast-growing Kentucky bluegrass (722 g m^{-2})(Fig. 2.4). The fast-growing cultivar of Kentucky bluegrass was also similar to the moderate-growing cultivar of Kentucky bluegrass (623 g m^{-2}), but the slow-growing cultivar of Kentucky bluegrass had the lowest yield (311 g m^{-2}) of all treatments (Fig. 2.4).

There were seasonal differences in both the number of mowing events for the one-third rule ($P<0.0001$) and dry matter yield ($P<0.0001$) in 2013 when following the meteorological calendar (i.e. spring begins on 1 March, summer on 1 June, and autumn on 1 September). Because the slow-growing cultivar of Kentucky bluegrass had not fully established by the beginning of the growing season in 2012, it did not require mowing until 26 June 2012. Thus, only the 2013 seasonal data will be discussed. When mowing by the one-third rule, summer required the greatest number of mowing events (9.0 mowing events), which followed by autumn (5.1 mowing events), and spring required the fewest (4.3 mowing events)(Table 2.3). However, these seasonal mowing events are slightly misleading, as the time between the first mowing and the beginning of summer was 39 d, summer lasted 92 d, and the time between the beginning of autumn and the final mowing was 69 d. Thus, if the data is standardized for days between mowing events for the three seasons, the statistical rankings change ($P<0.0001$). Spring had the fewest days between mowing events when following the one-third rule (9.1 d), which means that it had the greatest mowing frequency. Summer had an intermediate number of days between mowing events (10.2 d), and autumn had the greatest number of days between mowing events (13.6). Though mowing by the one-third rule had an average of 9.2 d between mowing events in the spring of 2013, there were brief periods where mowing by the one-third rule resulted in more frequent mowing events than by mowing weekly.

Dry matter yield was highest in the spring (189 g m^{-2}) and lowest in the autumn (60 g m^{-2}); summer dry matter yield fell between spring and autumn (151 g m^{-2}). There was also a notable season by species interaction for dry matter yield (P<0.0001). Spring tall fescue yield was the greatest (222 g m^{-2}), while the autumn yields for both species were lowest (64 and 56 g m^{-2} for tall fescue and Kentucky bluegrass, respectively)(Fig. 2.5). Yields for Kentucky bluegrass in the summer and spring (157 and 156 g m^{-2}, respectively) and tall fescue in the summer (144 g m^{-2}) were intermediates (Fig. 2.5).

Returning grass clippings increased dry matter yields by an average of 33% across the five dates that clippings from both of the weekly-mown plots were collected (i.e. weekly-mown plots with clippings collected and weekly-mown plots with clippings returned)(P<0.0001 for all five dates). In addition to increasing dry matter yields, returning grass clippings increased the N concentration of the grass clippings by 2.0, 7.0, 4.7, and 4.4% compared to when clippings were returned on 31 July 2012 (P=0.0157) and 28 May (P<0.0001), 30 July (P=0.0029), and 16 September (P<0.0001) in 2013, respectively (Table 2.4). Leaf tissue N concentration was also influenced by growth rate on those same four dates (P=0.0151, 0.0014, 0.0062, and 0.0029, respectively). On all four dates, the fast-growing cultivars had one of the lowest leaf tissue N concentrations, which ranged from 0.0255 to 0.0311 g N g^{-1} tissue (Table 2.4). Conversely, the slow and/or moderate growth rates had the highest leaf tissue N concentrations, which ranged from 0.0281 to 0.0340 and 0.0261 to 0.0333 g N g^{-1} tissue, respectively (Table 2.4). There were also significant species by growth rate interactions for leaf tissue N concentration on 30 July 2013 (*P*=0.0046) and 16 Sept. 2013 (*P*=0.0126)(data not shown). On both of those dates, the slow and moderate growth-rates of Kentucky bluegrass had the highest leaf tissue N concentrations, and the fast-growing cultivar of Kentucky bluegrass had the lowest. The tall fescue cultivars were always similar to at least one of the Kentucky bluegrass cultivars.

Dark green color index was strongly influenced by the inherent genetic differences, as the interaction of species by growth rate (i.e. the six cultivars) were significant on all 15 collection events (data not shown). The slow-growing cultivar of Kentucky bluegrass consistently had the highest DGCI value each month whereas the fast-growing cultivar of Kentucky bluegrass generally had the lowest DGCI value. Kentucky bluegrass had a greater DGCI than tall fescue in the early spring (i.e. May and June 2012; April and May 2013), and the opposite was true in July and August 2013. Growth rate also influenced DGCI and was significant on all 15 collection events. The general trend was that the slow-growing cultivars had the highest DGCI values, which was followed by the moderate-growing cultivars, and the fast-growing cultivars largely had the lowest DGCI. Differences for DGCI did not develop between grass clippings management practices until June 2013, but beginning that month, it was significant for five consecutive collection dates. On all five of those dates, plots where grass clippings were returned had a greater DGCI than plots where clippings were collected.

Conclusions from visual color and quality data were similar to those of DGCI (data not shown). For brevity, only DGCI is discussed.

Discussion

With all main effects and many interactions significant, it is evident that mowing requirements can be influenced by a number of factors. By selecting slow-growing turfgrasses, mowing requirements can be reduced for the life of the turf sward. However, this information is not readily available to consumers, and slow-growing cultivars can be slower to recover from injury. Mowing by the one-third rule is often recommended by turfgrass extension specialists (Reicher et al., 2006; Patton and Boyd, 2007). This rule serves as a guideline to prevent unnecessary emissions and/or reduced vigor (Howieson and Christians, 2008) from mowing too often as well as the injury from not mowing enough (Crider, 1955). In this experiment, the one-third rule reduced mowing requirements by 31% compared to when mown on a weekly basis, and this reduction was obtained without an unacceptable reduction in turfgrass quality (data not shown). Given that an average-sized home lawn in the United States is approximately 800 m^2 in size (Zirkle et al., 2011) and that it can be mown in roughly 30 min (personal observation), an average homeowner could reduce the time spent mowing their lawn by 4 hr yr^{-1} simply by following the one-third rule instead of mowing weekly. In addition to labor, a lower mowing requirement reduces fuel use and thus decreases costs and greenhouse gas emissions.

Crider (1955) found that root-growth stoppage can occur when removing between 40 and 50% or more foliage. Considering that growth rates as fast as 1.3 cm d^{-1} were observed during this study (personal observation), grasses mown by the one-third rule at a height of 7 cm have the potential to move from one-third removal into the potentially root-stopping 40 to 50% removal range in one day. Thus, turfgrass managers should closely monitor turfgrass growth if they plan to mow based on a removal rule, especially during periods of active growth. Though the practice of returning grass clippings increased the number of mowing events by about two events per year, the increased leaf tissue N concentration as well as increased soil carbon and N (Law, 2014) resulting from returning clippings offset these additional mowing events. As such, returning grass clippings should continue to be recommended.

Our dry matter yields were comparable to previously published tall fescue and Kentucky bluegrass data from the same geographic location that received similar N rates (Walker et al., 2006). Furthermore, our findings support previous research that indicate returning grass clippings increases dry matter yield (Kopp and Guillard, 2002; Bigelow et al., 2005; Starr and DeRoo, 1981). Dry matter yield increases of 15 to 55% and 79 to 254% were observed by Starr and DeRoo (1981) and Kopp and Guillard (2002) by returning grass clippings, respectively. Yield increases of 27 to 45% were obtained in our study, which received approximately 25% less N fertilizer than Starr and DeRoo (1981) and Kopp and Guillard (2002). The influence of turfgrass species and growth rate on dry matter yield was also apparent in our study, and our data supports Taylor and Templeton (1976) that tall fescue generally produces greater dry matter yields than Kentucky bluegrass. Furthermore, Wilhelm and Nelson (1978) noted greater dry matter yields for faster-growing cultivars in tall fescue, which was observed across all species in our experiment.

Increased leaf tissue N concentration as a result of returning grass clippings had already been reported by Kopp and Guillard (2002), but the effect of returning grass clippings on leaf tissue N concentration was more consistent in our study (80 vs 20% of collections) than it was for Kopp and Guillard (2002). Improvements in turfgrass color (i.e. DGCI) due to returning grass clippings agrees with Heckman et al. (2000). However, it took much longer in our experiment than three months to detect differences as Heckman et al. (2000) reported. The influence of growth rate on DGCI may be a result of leaf tissue N concentration, as the slower-growing cultivars tended to have greater tissue N concentrations. The greater tissue N concentrations in slower-growing cultivars may be a result of their reduced growth, differences in N use efficiency, or both.

Multiplying the average two year cumulative dry matter yield of all species and cultivars for the weekly-mown plots with clippings collected (714 g m^{-2}) by the average leaf tissue N concentration across the five collection dates for the same plots (0.0290 g N g^{-1} tissue), we can safely estimate that collecting grass clippings removed 20.7 g N m^{-2} over the two-year period. This value is equal to 104 kg N ha^{-1} yr^{-1}, which was approximately 73% of the annually applied N. Thus, grass clippings management plays a significant role in N cycling in turfgrass systems. To maximize the benefits of N fertilization, turfgrass managers should return grass clippings when mowing.

The results of this study highlight the importance of turfgrass selection, mowing frequency, and grass clipping management on annual mowing requirements. This research also provides specific management practices that homeowners and professional turfgrass managers can utilize to reduce their mowing requirements. Furthermore, our field research data from various species, cultivars, and mowing regimes could be adapted for use in modeling C budgets instead of the previously-used survey data for annual mowing requirements (Zirkle et al., 2011).

References

Beard, J.B. 1972. Turfgrass: Science and Culture. Prentice-Hall, Englewood Cliffs.

Beard, J.B. 1976. Clipping disposal in relation to rotary lawn mowers and the effect on thatch. Journal of the Sports Turf Research Institute 52:85-91.

Bigelow, C.A., D.W. Waddill, and D.R. Chalmers. 2005. Turf-type tall fescue lawn turf response to added clippings. International Turfgrass Society Research Journal 10:916-922.

Bigelow, C.A., J.J. Camberato, and A.J. Patton. 2013. Fertilizing established cool-season lawns: Maximizing turf health with environmentally responsible programs. Purdue University, Cooperative Extension Service. AY-22-W.

Christians, N.E. 2011. Fundamentals of Turfgrass Management. 4th ed. John Wiley & Sons, Hoboken.

Crider, F.J. 1955. Root-growth stoppage resulting from defoliation of grass. USDA Technical Bulletin. 1102. U.S. Government Printing Office, Washington, DC.

Davis, S.C., and L.F. Truett. 2004. Off-highway transportation-related fuel use. ORNL/TM-2004/92. Oak Ridge National Laboratory, Oak Ridge, TN.

Deam, C.C. 1929. Grasses of Indiana. W.B. Burford Printing Company, Indianapolis.

EPA. 2014. Municipal solid waste generation, recycling, and disposal in the United States: Facts and figures for 2012. U.S. Environmental Protection Agency, Washington, DC, USA.

Graper, D. and S. Munk. 1994. Cut it high… let it lie. Extension Extra 6030. South Dakota State University, Brookings, SD.

Haley, J.E., D.J. Wehner, T.W. Fermanian, and A.J. Turgeon. 1985. Comparison of conventional and mulching mowers for Kentucky bluegrass maintenance. HortScience 20:105-107.

Heckman, J.R., H. Liu, W. Hill, M. DeMilia, and W.L. Anastasia. 2000. Kentucky bluegrass responses to mowing practice and nitrogen fertility management. Journal of Sustainable Agriculture 15(4):25-33.

Howieson, M.J., and N.E. Christians. 2008. Carbohydrate metabolism and efficiency of photosystem II in mown creeping bentgrass (*Agrostis stolonifera* L.). HortScience 43:525-531.

Johnson, B.J., R.N. Carrow, and R.E. Burns. 1987. Bermudagrass turf response to mowing practices and fertilizer. Agronomy Journal 79:677-680.

Karcher, D.E., and M.D. Richardson. 2005. Batch analysis of digital images to evaluate turfgrass characteristics. Crop Science 45:1536-1539.

Kopp, K.L., and K. Guillard. 2002. Clipping management and nitrogen fertilization of turfgrass. Crop Science 42:1225-1231.

Kopp, K.L., and K. Guillard. 2004. Decomposition rates and nitrogen release of turf grass clippings. Available at http://www.cropscience.org.au/icsc2004/poster/2/5/2/860_koppk.htm (verified 30 June 2014). In: T. Fischer, N. Turner, J. Angus, L. McIntyer, M. Robertson, A. Borrell, and D. Lloyd, editors, New directions for a diverse planet. Proceedings of the International Crop Science Congress, 4th, Brisbane, Australia. 26 Sept.-1 Oct. 2004. Regional Inst., Gosford, Australia.

Law, Q.D. 2014. Defining management strategies to maximize soil carbon retention in turfgrass systems. M.S. thesis, Purdue University, West Lafayette, IN.

Morris, K.M. 20XX. A guide to NTEP turfgrass ratings. NTEP, Beltsville, MD.

Patton, A.J. and J. Boyd. 2007. Mowing your lawn. University of Arkansas Cooperative Extension Publication FSA-6023.

Poorter, H., and C. Remkes. 1990. Leaf area ratio and net assimilation rate of 24 wild species differing in relative growth rate. Oecologia 83:553-559.

Qian, Y.L., W. Bandaranayake, W.J. Parton, B. Mecham, M.A. Harivandi, and A.R. Mosier. 2003. Long-term effects of clipping and nitrogen management in turfgrass on soil organic carbon and nitrogen dynamics. Journal of Environmental Quality 32:1694-1700.

Reicher, Z., A.J. Patton, C.A. Bigelow, and T. Voigt. 2006. Mowing, thatching, aerifying, and rolling turf. Purdue University, Cooperative Extension Service. AY-8-W.

Rose-Fricker, C.A., C.P. Scott, M.L. Fraser, L.P. Sharp Jr., J. Frelich, and S. Staples. 2010. Improving tall fescue (*Festuca arundinacea*) and Kentucky bluegrass (*Poa pratensis*) cultivars for summer performance. In: A. Zuin, editor, Proceedings of the 2nd European Turfgrass Society Conference, Loire Valley, France. 11-14 Apr. 2010. p. 186-187.

Starr, J.L., and H.C. DeRoo. 1981. The fate of nitrogen fertilizer applied to turfgrass. Crop Science 21:531-536.

Taylor, T.H., and W.C. Templeton. 1976. Stockpiling Kentucky bluegrass and tall fescue forage for winter pasturage. Agronomy Journal 68:235-239.

Van Haaren, R., N. Themelis, and N. Goldstein. 2010. The state of garbage in America. BioCycle 51(10):16-23.

Walker, K.S., C.A. Bigelow, D.R. Smith, G.E. Van Scoyoc, and Z.J. Reicher. 2007. Aboveground response of cool-season lawn species to nitrogen rates and application timings. Crop Science 47:1225-1236.

Ward, C.Y., and R.E. Blaser. 1961. Carbohydrate food reserves and leaf area in regrowth of orchardgrass. Crop Science 1:366-370.

Wilhelm, W., and C.J. Nelson. 1978. Leaf growth, leaf aging, and photosynthetic rate of tall fescue genotypes. Crop Science 18:769-772.

Zirkle, G., R. Lal, and B. Augustin. 2011. Modeling carbon sequestration in home lawns. HortScience 46:808-814.

Table 2.1. Tall fescue (*Schedonorus arundinaceus*) and Kentucky bluegrass (*Poa pratensis*) cultivars, growth rates, experimental names, and providers.

Species	Cultivar	Growth rate†	Experimental	Provider
Tall fescue	Gazelle II	Slow	PST-5HP	Pure Seed Testing
Tall fescue	Tar Heel II	Moderate	PST-5TR1	Pure Seed Testing
Tall fescue	Endeavor	Fast	PST-5R94E	Pure Seed Testing
Kentucky bluegrass	Prosperity‡	Slow	PST-Y2K-59	Pure Seed Testing
Kentucky bluegrass	Moonshine§	Moderate	PST-1804	Pure Seed Testing
Kentucky bluegrass	Thermal blue¶	Fast	HB-129	O.M. Scotts Company

† Cultivars were selected from information on leaf elongation rate provided by Pure Seed Testing (Canby, OR).

‡ Compact-type Kentucky bluegrass classification.

§ Shamrock-type Kentucky bluegrass classification.

¶ Texas (*Poa arachnifera*) × Kentucky bluegrass hybrid.

Table 2.2. Number of annual mowing events by year, mowing frequency, grass clippings management, growth rate, and species for turf swards planted in April 2011 in West Lafayette, IN.

			2012				2013			
			Weekly		One-third rule		Weekly		One-third rule	
Cultivar	Species	Growth rate	Collected	Returned	Collected	Returned	Collected	Returned	Collected	Returned
			Mowing events (# plot^{-1})							
Gazelle II	Tall fescue	Slow	29	29	19.0	21.0	28.3	29.0	16.0	17.8
Tar Heel II	Tall fescue	Moderate	30	30	20.8	22.5	29.0	29.3	17.3	21.3
Endeavor	Tall fescue	Fast	30	30	23.3	25.0	28.8	29.5	21.0	24.3
Prosperity	Kentucky bluegrass	Slow	9	9	6.0	6.0	19.8	24.0	12.3	14.3
Moonshine	Kentucky bluegrass	Moderate	26	26	14.8	16.8	27.5	28.0	15.5	17.5
Thermal blue	Kentucky bluegrass	Fast	27	27	19.5	21.8	27.8	28.0	20.0	22.5

Table 2.3. Number of mowing events in 2013 by meteorological season (i.e. spring begins on 1 March, summer on 1 June, and autumn on 1 September), growth rate, and species for turf swards mown by the one-third rule and planted in April 2011 in West Lafayette, IN. Mowing began on 4 April and ceased on 8 November.

Cultivar	Species	Growth rate	Spring	Summer	Autumn
			----- Mowing events (# plot^{-1}) -----		
Gazelle II	Tall fescue	Slow	4.1 fg†	8.3 b	4.5 ef
Tar Heel II	Tall fescue	Moderate	4.0 fg	10.0 a	5.3 de
Endeavor	Tall fescue	Fast	5.5 cd	10.9 a	6.3 c
Prosperity	Kentucky bluegrass	Slow	3.3 g	5.9 cd	4.1 fg
Moonshine	Kentucky bluegrass	Moderate	4.3 f	8.0 b	4.3 f
Thermal blue	Kentucky bluegrass	Fast	4.4 ef	10.9 a	6.0 cd
Mean			4.3 C	9.0 A	5.1 B

† Within capitalization style (i.e. lowercase and uppercase), means followed by the same letter are not significantly different according to Tukey's honest significant difference test (α=0.05).

Table 2.4. Leaf tissue nitrogen (N) concentration as influenced by grass clippings management and turfgrass growth rate. Grasses were planted in April 2011 in West Lafayette, IN, and grass clipping management practices were initiated in 2012.

Effect	31 July 2012	18 Sept. 2012	28 May 2013	30 July 2013	16 Sept. 2013
	----------------------------	----------------------------	$g\ N\ g^{-1}$ tissue	----------------------------	----------------------------
Grass clippings management					
Collected	0.0299 b†	0.0295	0.0257 b	0.0279 b	0.0321 b
Returned	0.0305 a	0.0299	0.0275 a	0.0292 a	0.0335 a
P-value	0.0157	NS	<0.0001	0.0029	>0.0001
Growth rate					
Slow	0.0302 AB	0.0299	0.0281 A	0.0295 A	0.0340 A
Moderate	0.0314 A	0.0304	0.0261 B	0.0295 A	0.0333 A
Fast	0.0290 B	0.0288	0.0255 B	0.0268 B	0.0311 B
P-value	0.0151	NS	0.0014	0.0062	0.0029

† Within column and capitalization style (i.e. lowercase and uppercase), means followed by the same letter are not significantly different according to Tukey's honest significant difference test (α=0.05).

Fig. 2.1. TurfChek II grass height gauge (Turf-Tec International, Tallahassee, FL) used in this experiment.

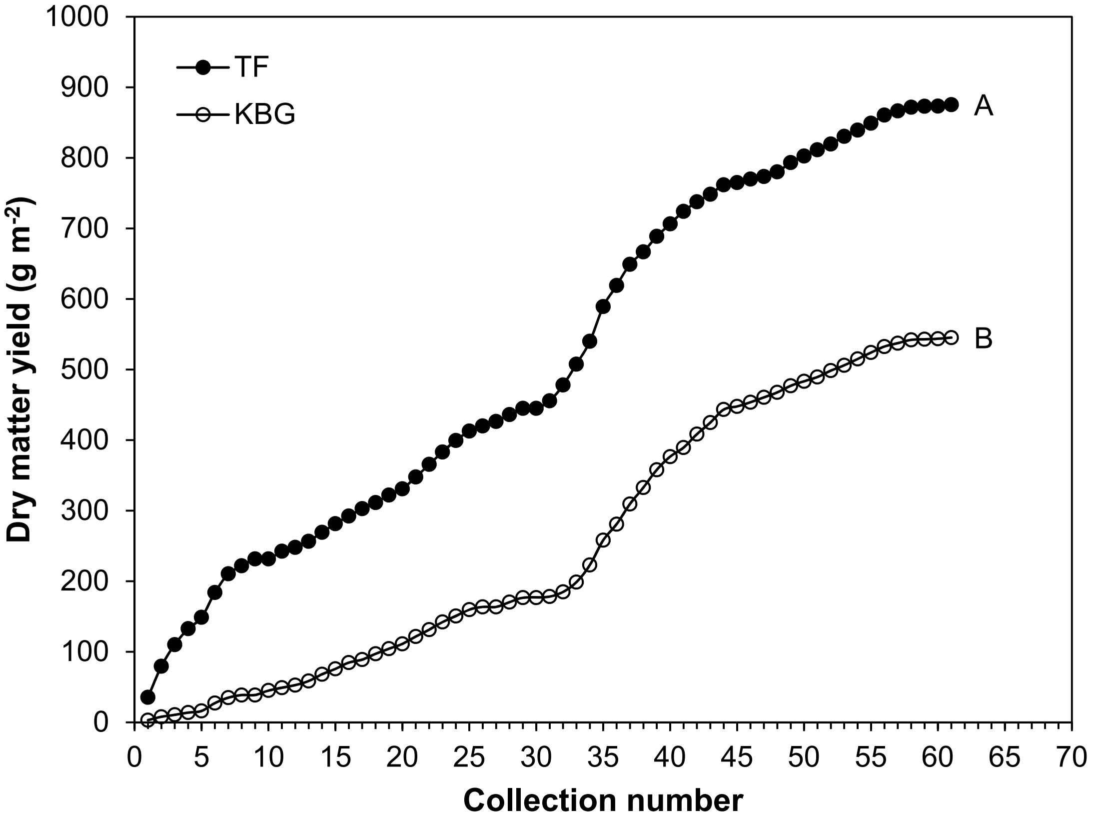

Fig. 2.2. Two year (2012 and 2013) cumulative dry matter yield for the two species used in the experiment in West Lafayette, IN. 2012 collections include 1-30, and 2013 collections include 31-61. Each data point represents the average of four blocks of three growth rates (n=12). Data lines with the same letter are not significantly different according to Tukey's honest significant difference test (α=0.05).

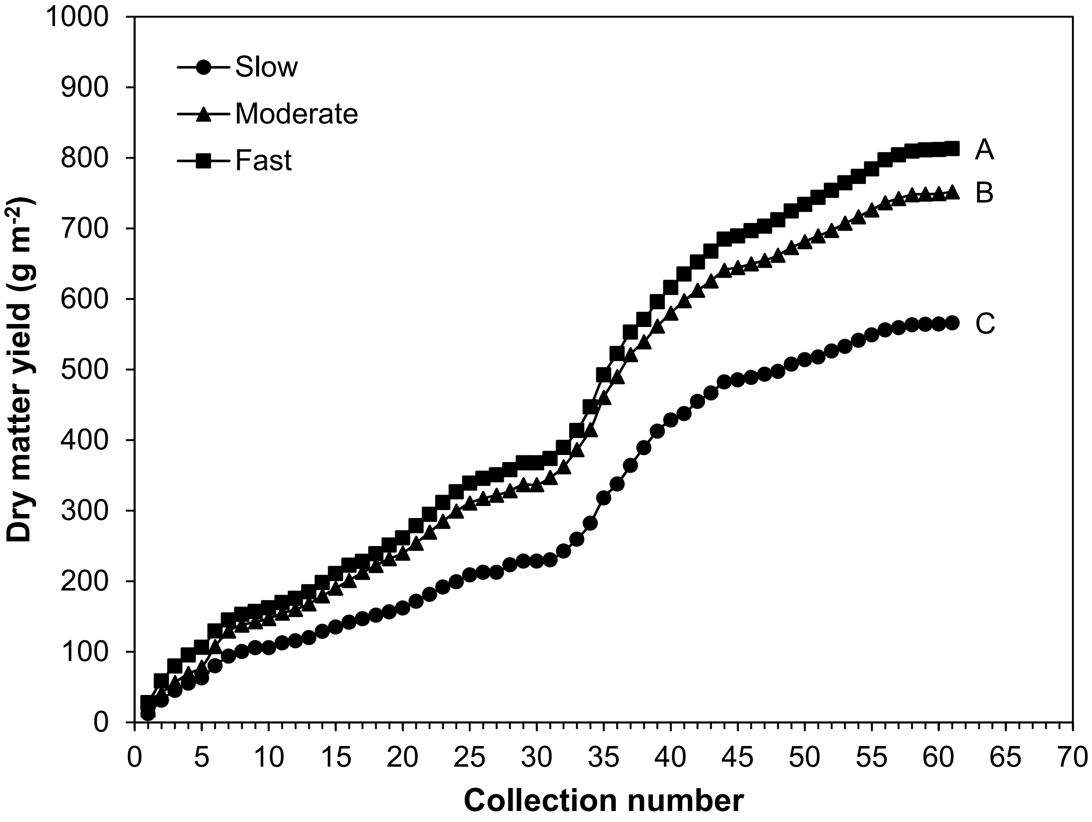

Fig. 2.3. Two year (2012 and 2013) cumulative dry matter yield for the three growth rates used in the experiment in West Lafayette, IN. 2012 collections include 1-30, and 2013 collections include 31-61. Each data point represents the average of four blocks of two species (n=8). Data lines with the same letter are not significantly different according to Tukey's honest significant difference test (α=0.05).

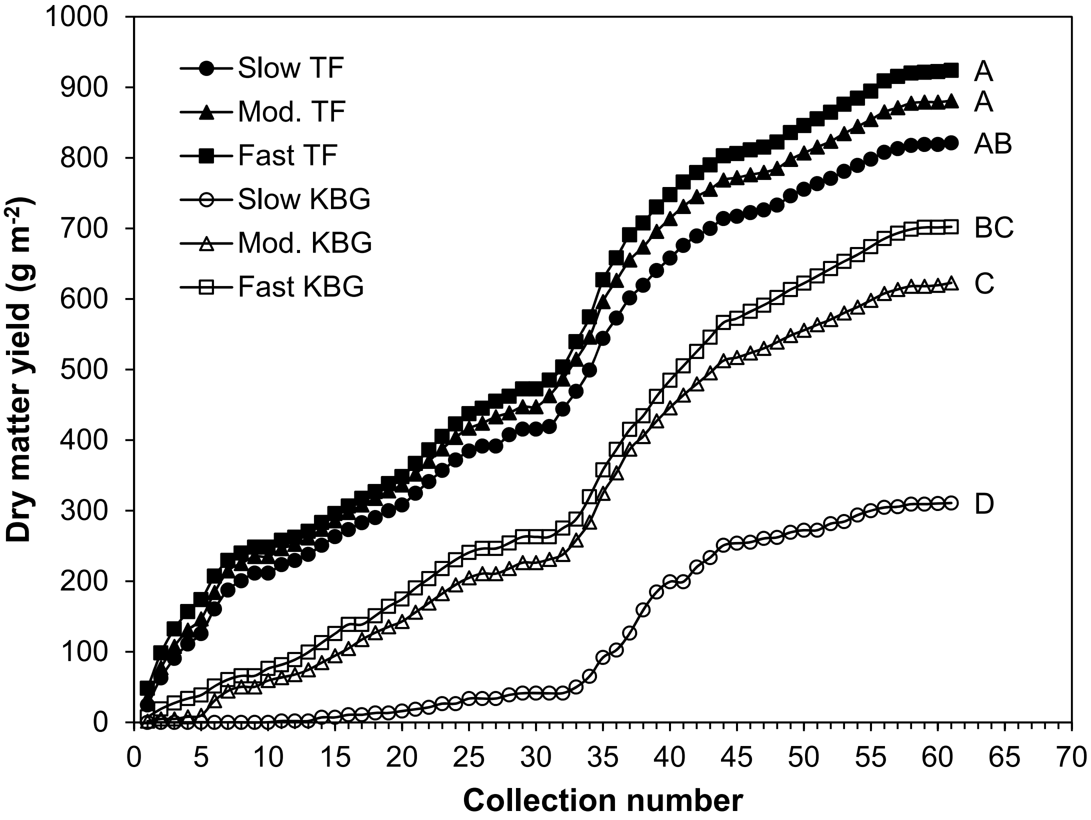

Fig. 2.4. Two year (2012 and 2013) cumulative dry matter yield for the six grasses used in the experiment in West Lafayette, IN. 2012 collections include 1-30, and 2013 collections include 31-61. Each data point represents the average of four blocks (n=4). Data lines with the same letter are not significantly different according to Tukey's honest significant difference test (α=0.05).

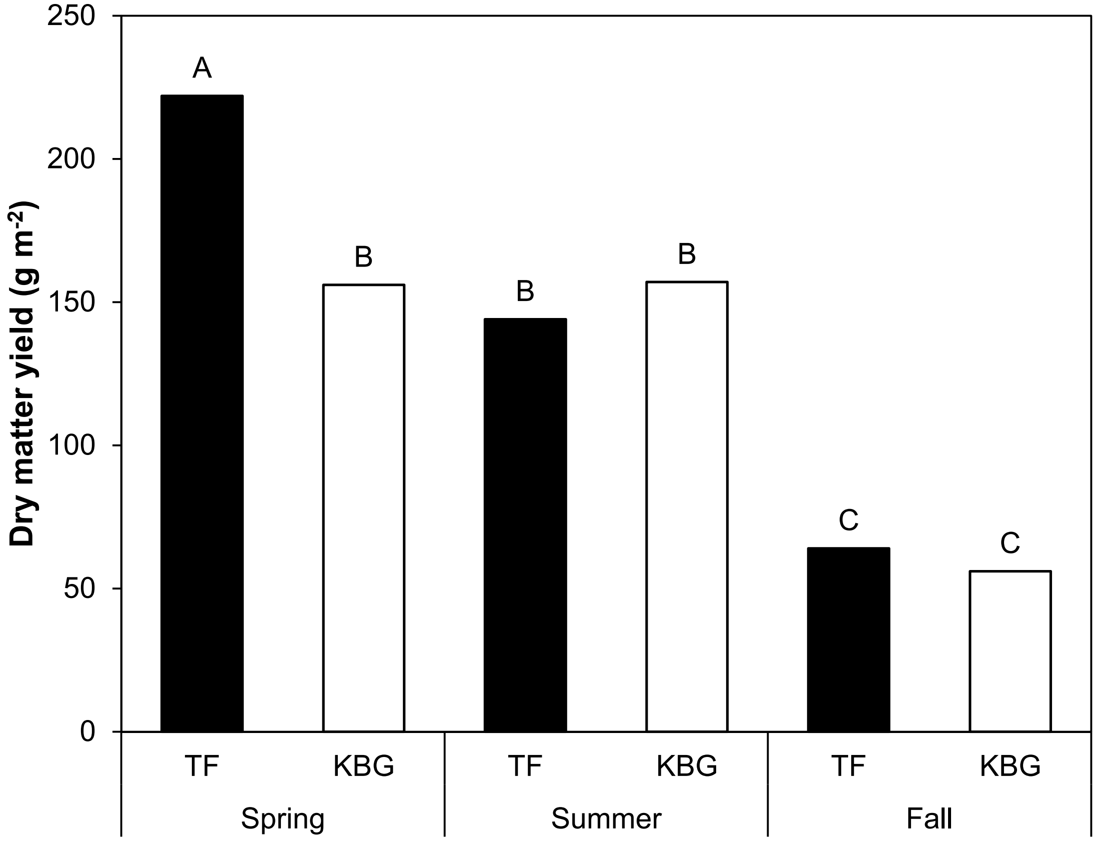

Fig. 2.5. Dry matter yield by meteorological season (i.e. spring begins on 1 March, summer on 1 June, and autumn on 1 September) and turfgrass species in 2013 in West Lafayette, IN. Each bar represents the average of four blocks of three growth rates (n=12). Bars with the same letter are not significantly different according to Tukey's honest significant difference test (α=0.05).

CHAPTER THREE – SOIL CARBON AND NITROGEN DYNAMICS AS INFLUENCED BY TURFGRASS SELECTION AND GRASS CLIPPINGS MANAGEMENT

Abstract

Soil carbon (C) is made up of different pools that vary in their turnover time or rate of decomposition; labile soil C is broken down in less than 5 yr, and, due to its rapid turnover, is considered a more sensitive indicator of changes in soil quality and function than total C. Different grass species and certain management practices, such as grass clipping management, are thought to influence soil C and nitrogen (N) accumulation. Thus, the objective of this field experiment was to determine the labile soil C, total soil C, and total soil N accumulation of Kentucky bluegrass (*Poa pratensis* L.) and tall fescue (*Lolium arundinaceum* (Schreb.) Darbysh. = *Schedonorus arundinaceus* (Schreb.) Durmort., formerly *Festuca arundinacea* Schreb. var. *arundinacea*) cultivars with differing growth rates under different grass clipping management practices. Differences in labile and total soil C were realized between turfgrass species after less than 3 yr of growth post planting. Labile soil C was 9.9% higher (851 vs. 774 mg C kg^{-1} soil) and total soil C was 4.2% higher (24.8 vs. 23.8 g C kg^{-1} soil) for tall fescue than Kentucky bluegrass. After 2 yr under different mowing practices, plots where grass clippings were returned had 3.3% more labile soil C (826 vs. 800 mg C kg^{-1} soil), 3.5% more total soil C

(24.7 vs. 23.9 g C kg^{-1} soil), and 4.6% more total soil N (2.28 vs. 2.18 g N kg^{-1} soil) than those where clippings were collected. The results of this study highlight the importance of turfgrass selection and grass clipping management on soil C and N accumulation.

Carbon dioxide (CO_2) is a greenhouse gas that contributes to climate instability because it absorbs and emits infrared radiation. Emissions of CO_2 from the combustion of fossil fuels increased drastically during the 20th century (Stocker et al., 2013), and the current level (i.e. May 2014 average) of atmospheric CO_2, 402 ppm (Tans and Keeling, 2014), is 44% higher than estimated in 1750 (280 ppmv)(Stocker et al., 2013). It has been demonstrated that atmospheric CO_2 can be retained in the soil if plant growth and plant residues are managed appropriately, which is known as soil carbon (C) sequestration. Soil C sequestration has been proposed to slow the atmospheric enrichment of CO_2, as terrestrial soil is the second-largest global pool of C (Lal, 2004b), and it has the potential to offset 5 to 15% of global fossil fuel emissions (Lal, 2004a). In addition to reducing atmospheric CO_2, increasing soil organic C benefits the soil itself. Increases in soil organic C can lead to improved aggregate stability (Angers and Carter, 1996) and structure (Snyder and Vazquez, 2005), reduced run-off and erosion, and increased water infiltration and retention (Johnston et al., 2009).

There are an estimated 16 to 20 million ha of urban grasslands in the United States (Milesi et al., 2005; Brown et al., 2005), and urban grasslands can sequester soil organic C at a rate of 0.38-1.5 Mg C ha^{-1} yr^{-1} (Qian et al., 2010; Townsend-Small and Czimczik, 2010; Zirkle et al., 2011). A model created by Zirkle et al. (2011) estimated that single-family home lawns in the United States to sequester between 3.2 and 9.6 Mg of soil organic C yr^{-1}. Furthermore, CENTURY Model simulations near Denver and Fort Collins, CO indicate that turfgrass systems can serve as a C sink after establishment, with 23 and 32 Mg soil organic C sequestered ha^{-1} in the 0 to 20 cm soil depth in a 30 yr period (Bandaranayake et al., 2003). Low maintenance areas of golf courses, such as rough areas maintained similar to lawns, have also been shown to have a net C sequestration (Gutleben et al., 2010).

Any increase in the C content of soil resulting from a change in land management may be referred to as C sequestration because the additional C being held in the soil is separated from other parts of the ecosystem (Powlson et al., 2011). For C sequestration to contribute to climate change mitigation, the change in land management practice must cause a net additional transfer of C from atmospheric CO_2 to the terrestrial biosphere (Powlson et al., 2011). This can be done by increasing net photosynthesis, slowing the decomposition of soil organic C, and/or reducing C emissions through modified management practices (Follett et al., 2011). However, soil organic C does not accumulate indefinitely (Johnston et al., 2009), and C sequestration is reversible; changes in land management leading to increased C in soil or vegetation must be continued indefinitely to maintain the increased C stock (Freibauer et al., 2004).

The intensity of turfgrass management influences both the total amount of C sequestered and the CO_2 released via emissions resulting from certain management practices. Intensely managed turf that has increased fertilization, irrigation, and mowing can increase C and nitrogen (N) stored in the soil (Golumbiewski, 2006). Furthermore, it has been shown that by producing a greater amount of biomass with the use of irrigation and fertilizer, the soil organic C pool can be increased (Lal et al., 1999). Soil C storage has a direct relationship with net primary production and an inverse relationship with decomposition (Wang and Hsieh, 2002). However, fuel-driven machinery such as lawn mowers and inputs such as synthetic fertilizers have C emissions tied to their production and use, and these emissions detract from the net C sequestration.

CENTURY model simulations indicate turfgrasses and their soils to be a strong sink of mineral N (Qian et al., 2003), and the amount of N in a particular soil is dependent on the climate, type of vegetation, topography, parent material, and management practices (i.e. activities of man)(Bremner, 1965). Moreover, Qian et al. (2003) revealed similar accumulation patterns between soil organic C and N. The results of Knops and Tilman (1998) further highlight the importance of soil C and N dynamics, as their results suggest that the rate of soil C accumulation is controlled by the accumulation rate of soil N. Though potential C and N mineralization can increase with turfgrass stand age (Shi et al., 2006), there is a limited capacity for the amount of organic N that can be stored in turfgrass soils (Porter et al., 1980). However, older turfgrass systems have a greater capacity conserve soil C and N due to their increased soil microbe resource use efficiency (Shi et al., 2006).

Certain management practices, such as N fertilization, irrigation, and returning grass clippings, can contribute to increases in C sequestration. By increasing the soil C input via enhanced turfgrass productivity, returning grass clippings may indirectly affect the amount of C decomposed and eventually sequestered (Yao et al., 2009). Kauer et al. (2013) reported that returning plant residues increased the organic C content and stock in the soil top layer compared to when the residues were removed. Returning grass clippings has been estimated/modeled to increase the amount of soil C sequestered in fertilized turf (75 to 150 kg N ha^{-1}) by 11 to 59% over a 10 to 50 yr period (Qian et al., 2003).

Soil C is made up of different pools that vary in their turnover time or rate of decomposition. The addition of fresh organic residues, such as plant roots and grass clippings, makes up the labile pool. Labile soil C is broken down in less than 5 yr, and, due to its rapid turnover, is considered a more sensitive indicator of changes in soil quality and function than total C (Hoyle et al., 20XX). Conversely, the decomposition of resistant C is much slower and therefore is not as sensitive of an indicator of changes in soil C due to management practices. Permanganate oxidizable C (POXC) is a rapid and inexpensive method refined by Weil et al. (2003) to evaluate biologically active soil C, which is also known as labile soil C, as it is significantly related the particulate organic, microbial biomass, and soil organic C fractions in soil (Culman et al., 2012).

Little research has been conducted to determine differences in soil C accumulations either within turfgrass species (i.e. cultivars), and the influence of residue management practices (e.g. collecting vs. returning grass clippings) needs to be more clearly defined. Thus, the objective of this experiment was to determine the labile soil C, total soil C, and total soil N accumulation of Kentucky bluegrass (*Poa pratensis* L.) and tall fescue (*Lolium arundinaceum* (Schreb.) Darbysh. = *Schedonorus arundinaceus* (Schreb.) Durmort., formerly *Festuca arundinacea* Schreb. var. *arundinacea*) cultivars with differing growth rates under different grass clipping management practices.

Materials and Methods

Research was conducted at the W.H. Daniel Turfgrass Research and Diagnostic Center in West Lafayette, IN. Soil type was a Stark silt loam (fine-silty mixed mesic Aeric Ochraqualf) with a pH of 6.9, 154 kg P ha^{-1}, 398 kg K ha^{-1}, 36 g kg^{-1} organic matter, 597 mg kg^{-1} labile C, 17.45 g kg^{-1} total C, and 1.71 g kg^{-1} total N. The experimental area was fallow for 2 yr preceding this experiment. In April 2011, three cultivars of tall fescue (Table 3.1) were seeded at 294 kg ha^{-1} and three cultivars of Kentucky bluegrass (Table 3.1) were seeded at 98 kg ha^{-1}. Tall fescue and Kentucky bluegrass were the species used due to their popularity as lawn grasses in temperate regions of the world. Cultivars were selected for this experiment based upon their growth in preliminary industry trials (Rose-Fricker et al., 2010) and their similar appearance and stress tolerance in previous field trials (i.e. the National Turfgrass Evaluation Program)(data not shown) in West Lafayette, IN.

The experimental area was irrigated to prevent wilt, and pests (i.e. weeds, diseases, and insects) were controlled via pesticides and/or mechanical removal to maintain uniform plots across treatments. Plots were mown at a height of 7 cm with a Troy-Bilt TriAction 53 cm wide deck walk-behind push mower (Modern Tool and Die Company, Cleveland, OH) and were fertilized per Purdue Extension’s recommendations for a moderate maintenance cool-season lawn with regular supplemental irrigation (Bigelow et al., 2013), receiving 142 kg of N, 20 kg of P_2O_5, and 54 kg of K_2O ha^{-1} yr^{-1}. Three fertilizer applications were made annually and occurred on 14 June, 20 September, and 17 November in 2012 and 29 May, 18 September, and 19 November in 2013. The May/June applications were at a rate of 44 kg N ha^{-1} with 32% water insoluble N, and the September applications were at a rate of 49 kg N ha^{-1} with 40% water insoluble N. The November applications were made with urea (0% water insoluble N) at a rate of 49 kg N ha^{-1}. Mowing began on 20 March in 2012 and 4 April in 2013 and had ceased by 30 October in 2012 and 8 November in 2013.

The experiment was a two by three by two by two factorial design (2×3×2×2) with two species, three cultivars (slow, moderate, and fast growth rates), two mowing frequencies, and two grass clipping treatments. The experimental design was a split-plot with four complete blocks. Whole plots of species and cultivar were 6 m by 4 m in size and randomized within blocks. Mowing frequency and grass clipping collection treatments were subunits randomized within whole plots. A total of four mowing regimes were applied, which made up the split plots that were 6 m by 1 m in size. Two separate mowing frequencies based upon 1) typical homeowner mowing practices with plots mown on the same day each week, and 2) the "one-third rule" using daily measurements to determine the appropriate mowing date. Additionally, for each of the described two mowing regimes, grass clippings were either 1) removed with a rear bagging attachment, or 2) returned using a recycling mower deck.

Soil samples were collected to a depth of 5.1 cm on 17 May 2012, 17 Nov. 2012, and 19 Nov. 2013. For the 17 May 2012 collection, a 1.3 cm diameter soil probe was used to collect four cores from each split plot, and cores from split plots with the same grass clipping treatment were pooled for a composite sample that represented the experimental factors of species, growth rate, and grass clipping management. The 17 Nov. 2012 and 19 Nov. 2013 soil samples were collected with a 10.8 cm diameter Par Aide Lever Action Hole Cutter (Par Aide Products Company, Lino Lakes, MN) with two composite samples taken from each split plot. Sampling intensity was increased for the 17 Nov. 2012 and 19 Nov. 2013 collections in order to increase statistical power. Samples were air dried and then ground prior to soil C analysis.

Permanganate oxidizable C was used to evaluate labile soil C, as Culman et al. (2012) demonstrated that POXC is suitable to assess changes in the labile soil C pool. POXC was determined using a procedure based on Weil et al. (2003) and the protocol described by Culman (20XX). Briefly, 18 mL deionized water and 2 mL of 0.2 *M* $KMnO_4$ stock solution (creating an initial $KMnO_4$ solution concentration of 0.02 *M*) were added to 2.5 g of air-dried soil in 50 mL screw-top centrifuge tubes, which were then shaken at 240 oscillations min^{-1} for precisely 2 min. Tubes were then removed from the shaker and allowed to settle in the dark for precisely 10 min. After 10 min, two 1:100 dilutions of the supernatant were made into deionized water for each sample. Aliquots of each dilution were then transferred into cuvettes and sample absorbance was read at 550 nm with a Spectronic Genesys 10 Bio spectrophotometer (Thermo Electron Corporation, Waltham, MA). Five standard concentration solutions (0.005, 0.010, 0.015, 0.02, and 0.025 mol $KMnO_4$ L^{-1}) were created and subsequently diluted (1:100) to create a standard curve by plotting absorbance vs. original concentration. Soil and soilless standards were run with each batch of samples to ensure quality control. POXC was calculated as follows:

$$\text{POXC (mg C kg}^{-1}\text{ soil)} = [0.02 \text{ mol L}^{-1} - (\text{b} + \text{m} \times \text{Abs})] \times (9000 \text{ mg C mol}^{-1}) \times [(0.02 \text{ L})/(\text{soil wt.})]$$

where 0.02 mol L^{-1} is the concentration of the intial $KMnO_4$ solution, *b* is the intercept and *m* is the slope of the standard curve, Abs is the absorbance of the unknown soil sample, 9000 mg is the amount of C oxidized by 1 mol of MnO_4 changing from Mn^{7+} to Mn^{4+}, 0.02 L is the volume of $KMnO_4$ solution reacted, and soil wt. is the mass of the soil (kg) used in the reaction.

Soil samples were also analyzed for total soil C and N using a FlashEA 1112 Elemental Analyzer (Thermo Fisher Scientific, Waltham, MA), which is based on the Flash Dynamic Combustion Method.

All data were analyzed using PROC GLIMMIX (SAS Institute, Cary, NC). Means were separated using Tukey's honest significant difference test (α=0.05). The full model, including all interactions, was run using species, growth rate, and grass clipping management as main effects for each of the three sampling dates.

Results and Discussion

In this irrigated field experiment, statistical differences for soil labile C were only detected for the 19 Nov. 2013 sampling. On that date, both the turfgrass species (P = 0.0012) and grass clipping management (P = 0.0021) factors had statistical differences; tall fescue (851 mg C kg^{-1} soil) had greater labile soil C values than Kentucky bluegrass (774 mg C kg^{-1} soil)(Fig. 3.1), and returning grass clippings (826 mg C kg^{-1} soil) produced more labile soil C than when grass clippings were collected (800 mg C kg^{-1} soil)(Fig. 3.2). Given that labile C is a more sensitive indicator than total C (Hoyle et al., 20XX), total C and total N were only analyzed when differences in labile C were detected (i.e. 19 Nov. 2013). Total soil C was significant for the same factors with the same trends as labile C, which included turfgrass species (P = 0.0439) and grass clipping management (P = 0.0124). Tall fescue (24.8 g C kg^{-1} soil) had greater total soil C concentrations than Kentucky bluegrass (23.8 g C kg^{-1} soil)(Fig. 3.3), and returning grass clippings (24.7 g C kg^{-1} soil) had greater total soil C concentrations than collecting grass clippings (23.9 g C kg^{-1} soil)(Fig. 3.4). Grass clipping management also influenced total soil N (*P* = 0.0006); returning clippings (2.28 g N kg^{-1} soil) resulted in increased total soil N concentrations compared to when they were collected (2.18 g N kg^{-1} soil)(Fig. 3.5).

Management practices that increase biomass production lead to an increased C pool (Lal et al., 1999), which was apparent in this study. Returning grass clippings increased both the dry matter yield (Law, 2014) and the soil C pool (i.e. labile soil C and total C) compared to when grass clippings were collected, which agrees with previous research that an increased dry matter yield (Starr and DeRoo, 1981; Kopp and Guillard, 2002) and soil C content (Qian et al., 2003) can be expected when clippings are returned versus collected. The trend of increased dry matter yields resulting in greater soil C concentrations was also evident amongst the turfgrass species used in this study. Not only were the two-year cumulative dry matter yields greater for tall fescue than Kentucky bluegrass (Law, 2014), soil C concentrations (i.e. labile and total soil C) were as well. Given that C storage has a direct relationship with net primary production (Wang and Hsieh, 2002) and yield data can be used to estimate the net primary production of the Midwestern United States croplands in other cropping systems (Prince et al., 2000), it makes sense that soil C concentrations, both the labile and total soil C pools, were greater for tall fescue within species and when grass clippings were returned versus collected.

Previous research has also shown that different soil organic C sequestration rates exist between turfgrass species (Qian et al., 2010), and returning grass clippings has been estimated/modeled to increase the amount of soil C sequestered in fertilized turf (75 to 150 kg N ha^{-1}) by 11 to 59% over a 10 to 50 yr period (Qian et al., 2003). In our experiment, returning grass clippings for 2 yr increased labile and total soil C by 3.3 and 3.5%, respectively compared to when clippings were collected. Kauer et al. (2013) also reported that returning clipped plant residues increased the organic C content in the soil top layer compared to when the residues were removed, and the magnitude of the effect of returning residues differed depending on a sward's species composition. Though C accumulates more quickly when clippings are returned, C can still be sequestered when clippings are collected (Kauer et al., 2013). In our experiment, grass planted with clippings collected increased labile soil C by 34% (from 597 to 800 mg C kg^{-1} soil) and total soil C by 37% (from 17.5 to 23.9 g C kg^{-1} soil) when compared to a bare-soil area adjacent to the experiment.

It should be noted, though, that the treatments with greater labile and total soil C accumulations in this experiment (i.e. tall fescue and returning grass clippings) also elicited greater mowing requirements (Law, 2014). Given that most residential lawnmowers are gasoline powered (Davis and Truett, 2004), a greater mowing requirement equates to greater C emissions that detract from the net C retained in the turfgrass system. The CO_2 released from a turfgrass system as a result of plant and soil respiration, known as its CO_2 flux, should also be considered. In this study, the same factors that increased labile soil C, turfgrass species and grass clipping management, also increased the CO_2 flux (Law, 2014). Despite the greater amount of C lost via plant and soil respiration, both tall fescue and returning grass clippings had greater labile soil C accumulations compared to Kentucky bluegrass and collecting clippings, respectively.

Returning grass clippings increased total soil N concentrations by 4.6% compared to when clippings were collected, which was similar to the influence grass clipping management had on soil C in this study (Fig. 3.6). This agrees with Qian et al. (2003), whose CENTURY model simulations revealed similar patterns between C and N accumulations from returning grass clippings (i.e. returning grass clippings increased both soil C and N sequestration). The increase in total soil N due to returning grass clippings agrees with the fact that approximately 73% of the N applied was removed when grass clippings were collected in this study (Law, 2014). The influence of grass clipping management on N dynamics is also evident through the increased N use efficiency (Kopp and Guillard, 2002), N uptake (Starr and DeRoo, 1981), and overall dry matter yield (Kopp and Guillard, 2002; Bigelow et al., 2005) obtained by returning grass clippings. Additionally, returning grass clippings to a turfgrass system over an extended period of time (>25 yr) has been modeled to cut N requirements in half (Qian et al., 2003). Our data is consistent with previous research, as both the dry matter yield and leaf tissue N concentrations were increased when clippings were returned (Law, 2014). By simultaneously increasing the quantity of organic residues returned to the system as well as the nutritional quality of those organic residues (i.e. tissue N concentration), a greater amount of N accumulated in the soil.

Though turfgrass growth rate of the cultivars within species did not affect either labile or total soil C accumulation, its importance in the C budget of turfgrass management shouldn’t be forgotten. Planting slower growing cultivars has been shown to reduce annual mowing requirements (Law, 2014), which reduces CO_2 emissions from fossil fuel powered mowers. This reduction in annual mowing events and their resulting emissions was inconsequential in terms of short-term labile and total soil C accumulation, as growth rate was not significant for labile or total soil C after three growing seasons. More time may be needed to realize differences in labile soil C amongst turfgrass growth rates, though, as growth rate did influence biomass production in the form of cumulative dry matter yield (Law, 2014), and dry matter yield was a positive indicator for the C accumulation of other factors in this experiment. As such, turfgrass growth rate should still be considered an important factor in the C budget of a turfgrass system.

There were no differences noted for any factor or interaction on either 17 May 2012 or 17 Nov. 2012 soil samplings, as two growing seasons (2011 and 2012), which included one season of mowing treatments (2012), was not long enough to observe changes in labile soil C. This agrees with Culman et al. (2012), as they noted that a 2 to 4 yr period may be required for POXC to detect changes in management practices involving tillage and inputs. However, both POXC and the Flash Dynamic Combustion Method were sensitive enough to detect changes in labile and total soil C, respectively, between turfgrass species in less than three years of growth post establishment and after only two years of grass clipping management treatments.

The results of this study highlight the importance of turfgrass selection, both species and cultivar, on net C accumulation. Furthermore, this study demonstrates the significance of grass clippings management on soil C and N accumulation. With the increased importance of C budgets related to mitigating climate change, C accrual may become a characteristic that turfgrass managers use to select which grasses to use, much like disease resistance, drought resistance, and color are used today. While there are many characteristics that are considered when selecting a turfgrass species or cultivar, tall fescue’s ability to accumulate C at a faster rate may offset its negative characteristics (i.e. coarser texture and greater mowing requirement) that lead to selecting other species, such as Kentucky bluegrass. Moreover, increasing the soil C and N accrual rates by returning clippings further supports this recommended practice, as it is another of the already documented numerous benefits of returning grass clippings.

References

Angers, D.A., M.R. Carter. 1996. Aggregation and organic matter storage in cool, humid agricultural soils. In: M.R. Carter and B.A. Stewart, editors, Structure and organic matter storage in agricultural soils. Advances in Soil Science. CRC Press, Boca Raton, FL. p. 193-211.

Bandaranayake, W., Y.L. Qian, W.J. Parton, D.S. Ojima, and R.F. Follett. 2003. Estimation of soil organic carbon changes in turfgrass systems using the CENTURY model. Agronomy Journal 95:558-563.

Bigelow, C.A., D.W. Waddill, and D.R. Chalmers. 2005. Turf-type tall fescue lawn turf response to added clippings. International Turfgrass Society Research Journal 10:916-922.

Bigelow, C.A., J.J. Camberato, and A.J. Patton. 2013. Fertilizing established cool-season lawns: Maximizing turf health with environmentally responsible programs. Purdue University, Cooperative Extension Service. AY-22-W.

Bremner, J.M. 1965. Organic nitrogen in soils. In: W.V. Bartholomew and F.E. Clark, editors, Soil nitrogen. Agronomy Monograph 10. ASA, CSSA, and SSSA, Madison, WI. p. 93-145.

Brown, D.G., K.M. Johnson, T.R. Loveland, and D.M. Theobald. 2005. Rural land-use trends in the conterminous United States, 1950-2000. Ecological Applications 15:1851-1863.

Culman, S.W. 20XX. Procedure for the determination of permanganate oxidizable carbon. Kellogg Biological Station, Long-Term Ecological Research. http://lter.kbs.msu.edu/protocols/133 (accessed 12 Nov. 2014).

Culman, S.W., S.S. Snapp, M.A. Freeman, M.E. Schipanski, J. Beniston, R. Lal, L.E. Drinkwater, A.J. Franzluebbers, J.D. Glover, A.S. Grandy, J. Lee, J. Six, J.E. Maul, S.B. Mirsky, J.T. Spargo, and M.M. Wander. 2012. Permanganate oxidizable carbon reflects a processed soil fraction that is sensitive to management. Soil Science Society of America Journal 76:494–504.

Davis, S.C., and L.F. Truett. 2004. Off-highway transportation-related fuel use. ORNL/TM-2004/92. Oak Ridge National Laboratory, Oak Ridge, TN.

Follett, R., S. Mooney, J. Morgan, K. Paustian, L.H. Allen Jr, S. Archibeque, J.M. Baker, S.J. Del Grosso, J. Derner, and F. Dijkstra. 2011. Carbon sequestration and greenhouse gas fluxes in agriculture: Challenges and opportunities. Council for Agricultural Science and Technology (CAST), Ames.

Freibauer, A., M.D.. Rounsevell, P. Smith, and J. Verhagen. 2004. Carbon sequestration in the agricultural soils of Europe. Geoderma 122:1–23.

Golubiewski, N.E. 2006. Urbanization increases grassland carbon pools: Effects of landscaping in Colorado’s Front Range. Ecological Applications 16:555-571.

Gutleben, C., D. Provendier, J. Streit, P. Bécid, and J.M. Lecourt. 2010. Carbon footprint of turfgrass maintenance: First results and identification of levers. In: A. Zuin, editor, Proceedings of the 2nd European Turfgrass Society Conference, Loire Valley, France. 11-14 Apr. 2010.

Hoyle, F.C., D.V. Murphy, and J. Sheppard. 20XX. Labile carbon. Soil Quality. https://s3.amazonaws.com/soilquality-production/fact_sheets/4/original/Biol_-_Labile_Carbon.pdf (accessed 12 Nov. 2014).

Johnston, A.E., P.R. Poulton, and K. Coleman. 2009. Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy 101:1-57.

Kauer, K., R. Kõlli, R. Viiralt, T. Köster, M. Noormets, T. Laidna, I. Keres, A. Parol, T. Varul, and A. Selge. 2013. Effect of cut plant residues management and fertilization on the dry matter yield of swards and on carbon content of soil. Communications in Soil Science and Plant Analysis 44:205-218.

Knops, J.M.H, and D. Tilman. 2000. Dynamics of soil nitrogen and carbon accumulation for 61 years after agricultural abandonment. Ecology 81:88-98.

Kopp, K.L., and K. Guillard. 2002. Clipping management and nitrogen fertilization of turfgrass. Crop Science 42:1225-1231.

Lal, R. 2004a. Soil carbon sequestration impacts on global climate change and food security. Science 304:1623-1627.

Lal, R. 2004b. Soil carbon sequestration to mitigate climate change. Geoderma 123:1-22.

Lal, R., R.F. Follett, J. Kimble, and C.V. Cole. 1999. Managing US cropland to sequester carbon in soil. Journal of Soil and Water Conservation 54:374-381.

Law, Q.D. 2014. Defining management strategies to maximize soil carbon retention in turfgrass systems. M.S. thesis, Purdue University, West Lafayette, IN.

Milesi, C., S.W. Running, C.D. Elvidge, J.B. Dietz, B.T. Tuttle, and R.R. Nemani. 2005. Mapping and modeling the biogeochemical cycling of turf grasses in the United States. Environmental Management 36:426-438.

Porter, D.A., D.R. Bouldin, S. Pacenka, R.S. Kossack, C.A. Shoemaker, and A.A. Pucci, Jr. 1980. Studies to assess the fate of nitrogen applied to turf: Part I. Research project technical complete report. OWRT Project A-086-NY. Cornell University, Ithaca, NY.

Powlson, D.S., A.P. Whitmore, and K.W.T. Goulding. 2011. Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. European Journal of Soil Science 62:42-55.

Prince, S.D., J. Haskett, M. Steininger, H. Strand, and R. Wright. 2001. Net primary production of US Midwest croplands from agricultural harvest yield data. Ecological Applications 11:1194-1205.

Qian, Y.L., W. Bandaranayake, W.J. Parton, B. Mecham, M.A. Harivandi, and A.R. Mosier. 2003. Long-term effects of clipping and nitrogen management in turfgrass on soil organic carbon and nitrogen dynamics. Journal of Environmental Quality 32:1694-1700.

Qian, Y., R.F. Follett, and J.M. Kimble. 2010. Soil organic carbon input from urban turfgrasses. Soil Science Society of America Journal 74:366-371.

Rose-Fricker, C.A., C.P. Scott, M.L. Fraser, L.P. Sharp Jr., J. Frelich, and S. Staples. 2010. Improving tall fescue (*Festuca arundinacea*) and Kentucky bluegrass (*Poa pratensis*) cultivars for summer performance. In: A. Zuin, editor, Proceedings of the 2nd European Turfgrass Society Conference, Loire Valley, France. 11-14 Apr. 2010. p. 186-187.

Snyder, V.A., and M.A. Vázquez. 2005. Structure. In: D. Hillel, J.L. Hatfield, D.S. Powlson, C. Rosenzweig, K.M. Scow, M.J. Singer, and D.L. Sparks, editors, Encyclopedia of soils in the environment. Elsevier, Amsterdam. p. 54-68.

Starr, J.L., and H.C. DeRoo. 1981. The fate of nitrogen fertilizer applied to turfgrass. Crop Science 21:531-536.

Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley. 2013. Climate change 2013: The physical science basis. Intergovernmental Panel on Climate Change, Working Group I Contribution to the IPCC Fifth Assessment Report. Cambridge University Press, New York.

Tans, P. and R. Keeling. 2014. Trends in Atmospheric Carbon Dioxide. http://www.esrl.noaa.gov/gmd/ccgg/trends/ (verified 30 June 2014).

Townsend-Small, A., and C.I. Czimczik. 2010. Carbon sequestration and greenhouse gas emissions in urban turf. Geophysical Research Letters 37:L02707. doi: 10.1029/2009GL041675 [erratum:37:L06707. doi: 10.1029/2010GL042735].

Wang, Y., and Y. Hsieh. 2002. Uncertainties and novel prospects in the study of the soil carbon dynamics. Chemosphere 49:791-804.

Weil, R.R., K.R. Islam, M.A. Stine, J.B. Gruver, and S.E. Samson-Liebig. Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. American Journal of Alternative Agriculture 18:3-17.

Yao, H., D. Bowman, T. Rufty, and W. Shi. 2009. Interactions between N fertilization, grass clipping addition and pH in turf ecosystems: Implications for soil enzyme activities and organic matter decomposition. Soil Biology and Biochemistry 41:1425-1432.

Zirkle, G., R. Lal, and B. Augustin. 2011. Modeling carbon sequestration in home lawns. HortScience 46:808-814.

Table 3.1. Tall fescue (*Schedonorus arundinaceus*) and Kentucky bluegrass (*Poa pratensis*) cultivars, growth rates, experimental names, and providers.

Species	Cultivar	Growth rate†	Experimental	Provider
Tall fescue	Gazelle II	Slow	PST-5HP	Pure Seed Testing
Tall fescue	Tar Heel II	Moderate	PST-5TR1	Pure Seed Testing
Tall fescue	Endeavor	Fast	PST-5R94E	Pure Seed Testing
Kentucky bluegrass	Prosperity‡	Slow	PST-Y2K-59	Pure Seed Testing
Kentucky bluegrass	Moonshine§	Moderate	PST-1804	Pure Seed Testing
Kentucky bluegrass	Thermal blue¶	Fast	HB-129	O.M. Scotts Company

† Cultivars were selected from information on leaf elongation rate provided by Pure Seed Testing (Canby, OR).

‡ Compact-type Kentucky bluegrass classification.

§ Shamrock-type Kentucky bluegrass classification.

¶ Texas (*Poa arachnifera*) × Kentucky bluegrass hybrid.

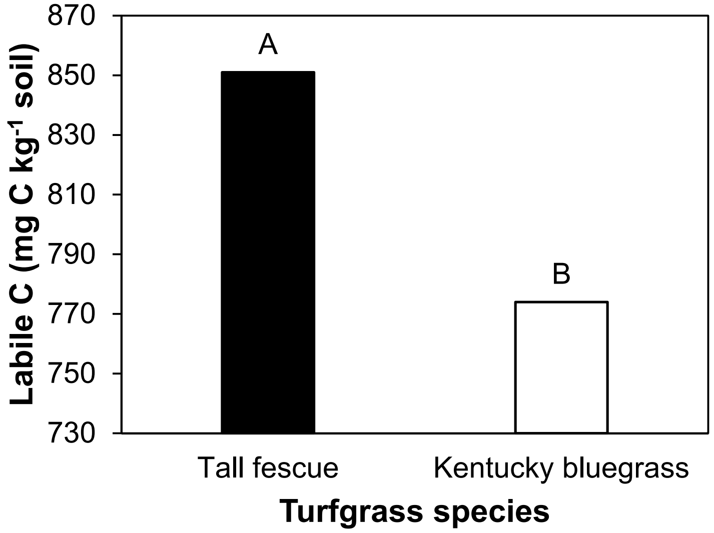

Fig. 3.1. Labile soil carbon (C) values by turfgrass species for soil samples collected to a 5 cm depth on 19 Nov. 2013 from turfgrasses planted by seed in April 2011 in West Lafayette, IN. Each bar represents the average of four blocks for two mowing frequencies by two grass clippings management practices on the three cultivars of two species (n=48). Bars with the same letter are not significantly different according to Tukey's honest significant difference test (α=0.05).

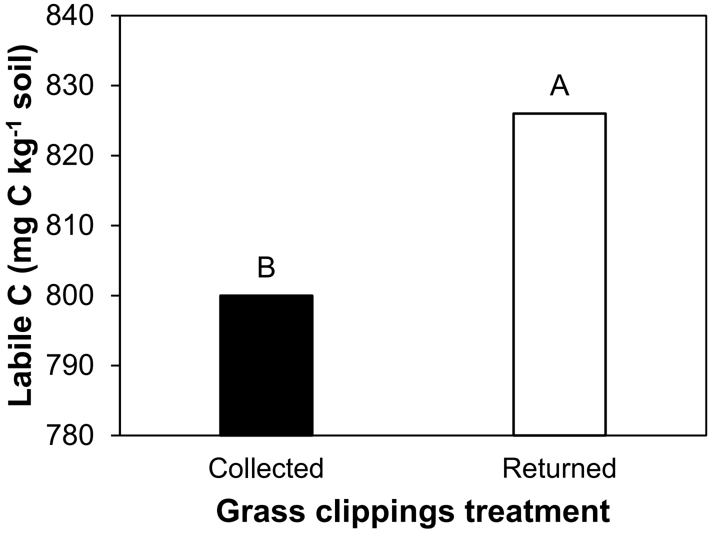

Fig. 3.2. Labile soil carbon (C) values by grass clippings management treatment for soil samples collected to a 5 cm depth on 19 Nov. 2013 from turfgrasses planted by seed in April 2011 in West Lafayette, IN. Each bar represents the average of four blocks for two mowing frequencies on the three cultivars of two species (n=48). Bars with the same letter are not significantly different according to Tukey's honest significant difference test (α=0.05).

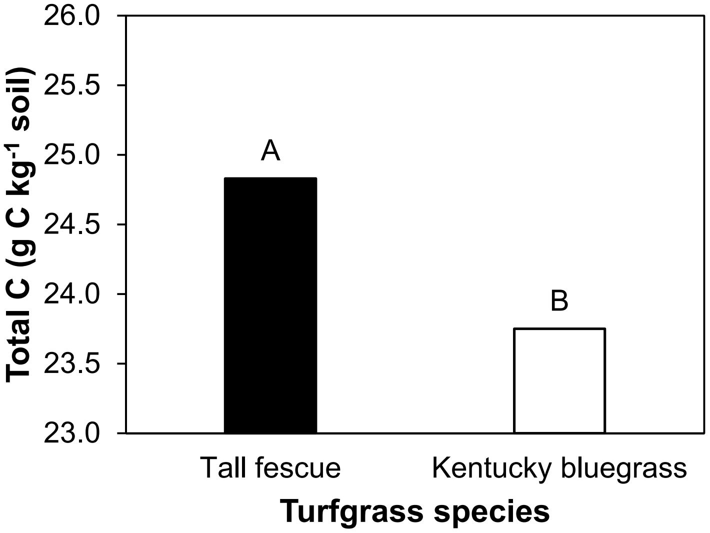

Fig. 3.3. Total soil carbon (C) values by turfgrass species for soil samples collected to a 5 cm depth on 19 Nov. 2013 from turfgrasses planted by seed in April 2011 in West Lafayette, IN. Each bar represents the average of four blocks for two mowing frequencies by two grass clippings management practices on the three cultivars of two species (n=48). Bars with the same letter are not significantly different according to Tukey's honest significant difference test (α=0.05).

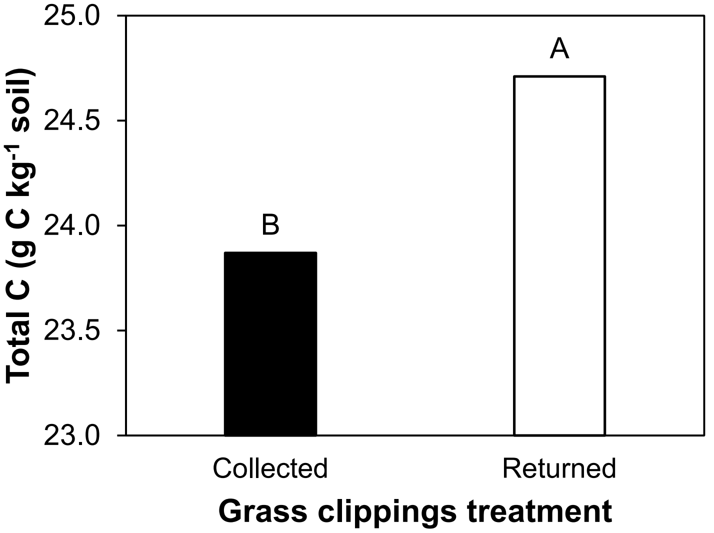

Fig. 3.4. Total soil carbon (C) values by grass clippings management treatment for soil samples collected to a 5 cm depth on 19 Nov. 2013 from turfgrasses planted by seed in April 2011 in West Lafayette, IN. Each bar represents the average of four blocks for two mowing frequencies on the three cultivars of two species (n=48). Bars with the same letter are not significantly different according to Tukey's honest significant difference test (α=0.05).

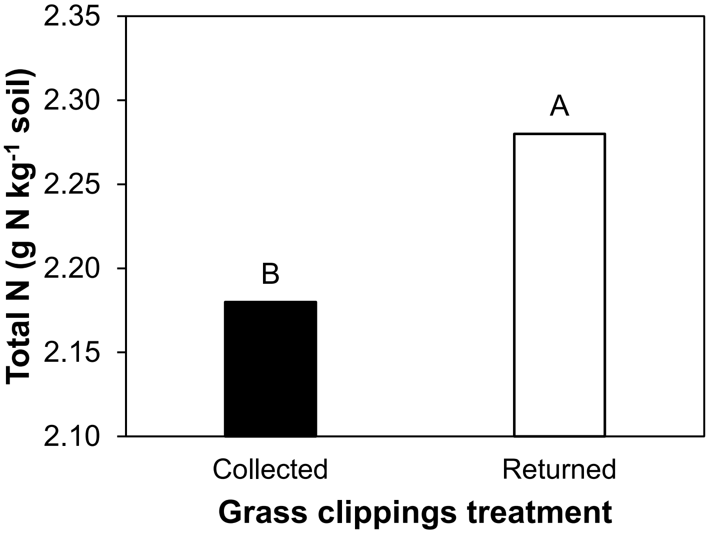

Fig. 3.5. Total soil nitrogen (N) values by grass clippings management treatment for soil samples collected to a 5 cm depth on 19 Nov. 2013 from turfgrasses planted by seed in April 2011 in West Lafayette, IN. Each bar represents the average of four blocks for two mowing frequencies on the three cultivars of two species (n=48). Bars with the same letter are not significantly different according to Tukey's honest significant difference test (α=0.05).

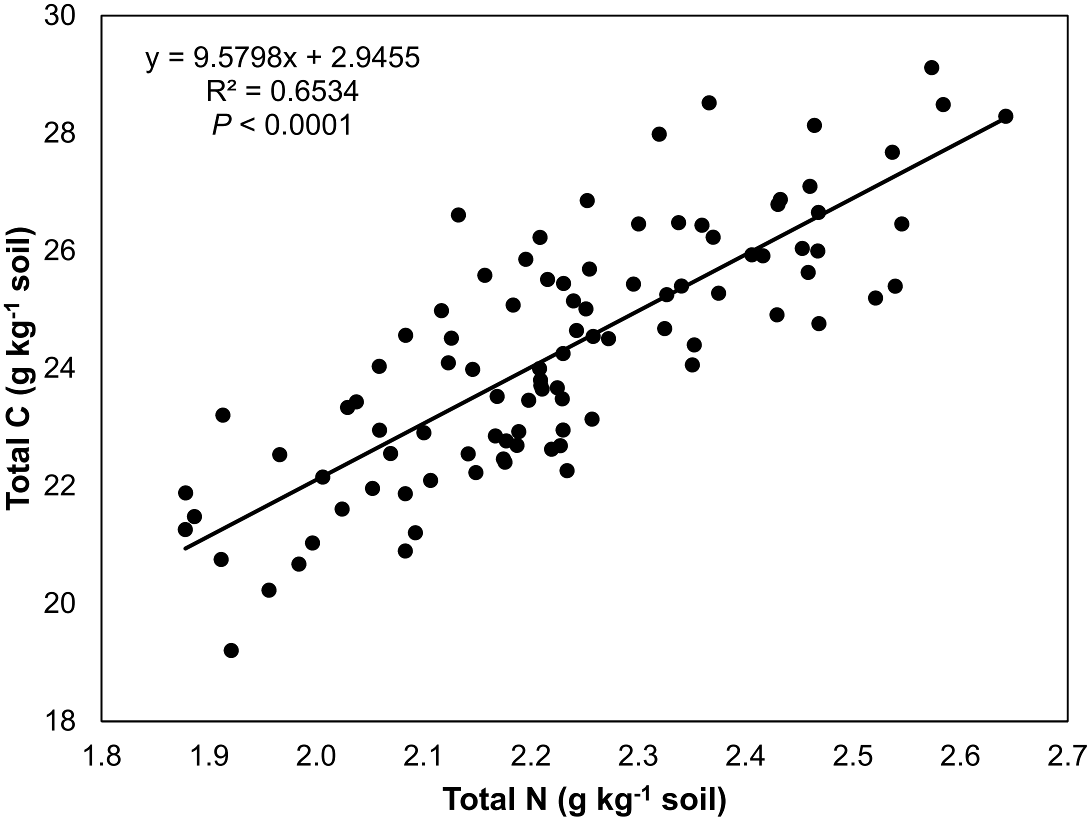

Fig. 3.6. Total soil nitrogen (N) vs. total soil carbon (C) values for soil samples collected to a 5 cm depth on 19 Nov. 2013 from turfgrasses planted by seed in April 2011 in West Lafayette, IN.

CHAPTER FOUR – THE INFLUENCE OF GROWTH RATE AND GRASS CLIPPINGS MANAGEMENT ON GREENHOUSE GAS FLUX IN TALL FESCUE AND KENTUCKY BLUEGRASS

Abstract

Carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) are greenhouse gases (GHGs) of concern to our environment because of their contribution to climate instability. The atmospheric concentrations of CO_2, N_2O, and CH_4 have all increased since 1750 due to human activity, which merits the monitoring of their release from various ecosystems. Species and/or cultivar selection may influence GHG flux in a turfgrass system, as may the practice of returning grass clippings. Thus, the objectives of this experiment were to 1) examine the GHG flux for tall fescue (*Lolium arundinaceum* (Schreb.) Darbysh. = *Schedonorus arundinaceus* (Schreb.) Durmort., formerly *Festuca arundinacea* Schreb. var. *arundinacea*) and Kentucky bluegrass (*Poa pratensis* L.) cultivars with varying leaf elongation rates and 2) evaluate the influence of collecting or returning clippings on GHG flux for tall fescue and Kentucky bluegrass. Carbon dioxide, N_2O, and CH_4 fluxes were measured following the GRACEnet protocol once monthly for a 6 mo period in 2013 in West Lafayette, IN. Tall fescue had a greater CO_2 flux than Kentucky bluegrass, and returning grass clippings had a greater CO_2 flux than collecting clippings, which occurred on five and one of the six collection dates, respectively.

Nitrous oxide flux differed for growth rate on one collection date, though it was likely due to a fertilizer response. There was not a measurable CH_4 flux.

Carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) are greenhouse gases (GHGs) of concern to our environment because of their contribution to climate instability (Follett et al., 2011). GHGs are named such due to their “greenhouse effect” in which they absorb thermal radiation from Earth’s surface and re-radiate it back to Earth, resulting in elevated temperatures (Follett et al., 2011). The atmospheric concentrations of CO_2, N_2O, and CH_4 have all increased since 1750 due to human activity (Stocker et al., 2013), which merits the monitoring of their release from various ecosystems. With an estimated 16 to 20 million hectares of urban grasslands in the United States (Milesi et al., 2005; Brown et al., 2005), measuring the release of GHGs in urban grasslands is warranted.

The current level (i.e. May 2014 average) of atmospheric CO_2, 402 ppm (Tans and Keeling, 2014), is 44 percent higher than estimated in 1750 (280 ppm)(Stocker et al., 2013). Plants release CO_2 through respiration, which provides the plant energy to produce and sustain biomass as well as acquire nutrients. The decomposition of organic matter by soil organisms also releases CO_2 into the atmosphere and nutrients into the soil, and this process is known as soil respiration. These two types of respiration, plant and soil, are responsible a portion of the CO_2 released from a turfgrass system. Together, they make up that system’s CO_2 flux. Turfgrass plant respiration rates differ both between (Watschke et al., 1973; Huylenbroeck and Bockstaele, 1999) and within species (Wilson, 1975; Huylenbroeck and Bockstaele, 1999), as well as amongst different plant tissues from the same plant (Moser et al., 1982). Furthermore, management practices such as mowing have been shown to influence turfgrass respiration rates (Liu and Huang, 2003). Soil respiration is also important, as an estimated 64 to 72 Pg C yr^{-1} is respired from terrestrial soil on a global scale (Raich and Schlesinger, 1992). The soil's physical environment (e.g. the temperature and moisture), quantity and quality of C substrate, and the microbial community are three factors that control the decomposition of organic matter and the subsequent release of CO_2 via soil respiration (Chapin et al., 2011).

Though the atmospheric concentration of N_2O is much less than that of CO_2 (Follett et al., 2011), the global warming potential of N_2O is over 300 times that of CO_2 (Stocker et al., 2013), and N_2O emissions are predicted to increase by 5% between 2005 and 2020 (U.S. Department of State, 2007). Nitrous oxide is produced through the natural processes of nitrification and denitrification, which are part of the N cycle (EPA, 2010). Soil bacteria utilize inorganic N as either an energy source or an electron acceptor in aerobic and anaerobic conditions, respectively (Sylvia et al., 2005). Ecological drivers of nitrification and denitrification, such as the availability of N and oxygen, influence N_2O production, and common turfgrass management practices (e.g. N fertilization and irrigation) directly influence the aforementioned ecological drivers (Bremer, 2006). The burning of fossil fuels to maintain turf is another anthropogenic source of N_2O emissions (EPA, 2010) in turfgrass systems. Additionally, N_2O flux is correlated with N mineralization (Matson and Vitousek, 1987), N fertilization (Mosier et al., 1991; Bremer, 2006), and the cultivation of grasslands (Mosier et al., 1991). Given that turfgrass species have the potential to influence N cycling via changes in N mineralization and nitrification (Wedin and Tilman, 1990), turfgrass selection may be an important factor in reducing N_2O losses from turf. Furthermore, Lewis (2010) reported lower N_2O emissions in zoysiagrass (*Zoysia japonica* Steud.) compared to bermudagrass (*Cynodon dactylon* L. Pers. × *C. transvaalensis* Burtt-Davy), though this may have been due to bermudagrass receiving twice the amount of N fertilization. Grass clipping management has also been shown to influence N_2O flux in a turfgrass system, but the influence appeared to be dependent on the aerobic status of the soil (Li et al., 2013).

Soils can both produce and consume CH_4, even simultaneously, under the correct soil conditions (Sylvia et al., 2005). Methane is produced by obligate anaerobic bacteria known as methanogens (Whitman et al., 1992). Conversely, a group of bacteria known as methanotrophs oxidize CH_4 in aerobic conditions and use it as a carbon and energy source (Sylvia et al., 2005), and this group of bacteria make up the largest natural biological sink of CH_4 (Dutaur and Verchot, 2007). However, high soil inorganic N concentrations (Steudler et al., 1989; Mosier et al., 1991), cultivation (Mosier et al., 1991), and overly high or low soil moisture (Smith et al., 2000) inhibit the microbial consumption of CH_4, which are all factors affected by common turfgrass management practices (i.e. fertilization, aerification, and irrigation). The uptake of CH_4 has also been shown to be inversely related to N_2O emissions (Mosier et al., 1991), which highlights the importance of management practices that influence the flux of these two gases. By causing a simultaneous increase in N_2O emissions and decrease in CH_4 consumption, management practices that affect this inverse relationship have an even greater potential to impact GHG concentrations.

The objectives of this experiment were to 1) examine the GHG flux for tall fescue (*Lolium arundinaceum* (Schreb.) Darbysh. = *Schedonorus arundinaceus* (Schreb.) Durmort., formerly *Festuca arundinacea* Schreb. var. *arundinacea*) and Kentucky bluegrass (*Poa pratensis* L.) cultivars with varying leaf elongation rates and 2) evaluate the influence of collecting or returning clippings on GHG flux for tall fescue and Kentucky bluegrass.

Materials and Methods

Research was conducted at the W.H. Daniel Turfgrass Research and Diagnostic Center in West Lafayette, IN. Soil type was a Stark silt loam (fine-silty mixed mesic Aeric Ochraqualf) with a pH of 6.9, 154 kg P ha^{-1}, 398 kg K ha^{-1}, 36 g kg^{-1} organic matter, 597 mg kg^{-1} labile C, 17.45 g kg^{-1} total C, and 1.71 g kg^{-1} total N. The experimental area was fallow for 2 yr preceding this experiment. In April 2011, three cultivars of tall fescue (Table 4.1) were planted at 294 kg ha^{-1} and three cultivars of Kentucky bluegrass (Table 4.1) were planted at 98 kg ha^{-1}. Tall fescue and Kentucky bluegrass were used in this experiment due to their popularity as lawn grasses in temperate regions of the world. Cultivars were selected for this experiment based upon their growth in preliminary industry trials (Rose-Fricker et al., 2010) and their similar appearance and stress tolerance in previous National Turfgrass Evaluation Program field trials in West Lafayette, IN.

The experimental area was irrigated to prevent wilt, and pests (i.e. weeds, diseases, and insects) were controlled via pesticides and/or mechanical removal to maintain uniform plots across treatments. Plots were fertilized per Purdue Extension's recommendations for a moderate maintenance cool-season lawn with regular supplemental irrigation (Bigelow et al., 2013), receiving 142 kg of N, 20 kg of P_2O_5, and 54 kg of K_2O ha^{-1} yr^{-1}. Three fertilizer applications were made annually and occurred on 29 May, 18 September, and 19 November in 2013. The May/June applications were at a rate of 44 kg N ha^{-1} with 32% water insoluble N, and the September applications were at a rate of 49 kg N ha^{-1} with 40% water insoluble N. The November applications were made with urea (0% water insoluble N) at a rate of 49 kg N ha^{-1}.

Plots were mown at a height of 7 cm with a Troy-Bilt TriAction 53 cm wide deck walk-behind push mower (Modern Tool and Die Company, Cleveland, OH) weekly. Turf height was measured in three equally-spaced locations within each split plot using a TurfChek II grass height gauge (Turf-Tec International, Tallahassee, FL) weekly. If two of three measurements were at or above 8.3 cm, it was mown that day. However, if the turf had not reached a height of 8.3 cm, it was delayed until the next week. Mowing began on 4 April 2013 and had ceased by 8 Nov. 2013.

The experimental design was a randomized complete block with four blocks. A two by three factorial was utilized to evaluate the GHG flux for the two species (tall fescue and Kentucky bluegrass) and three growth rates (slow, intermediate, and fast) used in the experiment. Additionally, the grass clippings from the intermediate growth rate cultivars for both tall fescue and Kentucky bluegrass were either 1) removed with a rear bagging attachment, or 2) returned using a recycling mower deck; clippings from all other cultivars were returned. The unbalanced design was performed in an effort to reduce sampling costs while still investigating the influence of grass clipping management on GHG flux.

A vented-chamber method similar to the GRACEnet Sampling Protocol (Parkin et al., 2010) was used to collect GHG samples monthly. Anchors were established in plots for the duration of the study and measurements were obtained with a cylindrical vented gas flux chamber that had a 20.3 cm diameter and 15.2 cm height (Fig. 4.1). Collections occurred on 31 May, 29 June, 27 July, 22 August, 27 September, and 25 October in 2013. Samples were collected with a 30 mL syringe 0, 15, 30, and 45 min after chamber lid installation and injected into 20 mL vials with magnetic caps (Agilent, Santa Clara, CA catalog # 5188-2759) that were previously evacuated to 0.24 torr.

Gas analysis was performed on an Agilent 7890 Gas Chromatograph equipped with a FID detector, a TCD detector, and a micro ECD (Santa Clara, CA). A model 120 autosampler upgraded for headspace analysis (Quantum Analytics, Foster City, CA) was used to inject samples using the previously mentioned vials. The gas chromatograph was further customized (Custom Solutions Group, Katy, TX) by the installation of two pneumatically actuated 10 port gas sampling and backflush-to-vent valves, a 6 port series by-pass valve on Valco E rotors, and a switching solenoid valve for purge of valve loops between injection. Four columns were installed: a HayeSep N 80/10 mesh micropack stainless steel, a HayeSepQ 80/100 mesh micropack stainless steel, a HayeSep N 80/100 mesh silcosteel, and a HayeSepQ 80/100 mesh micropack silcosteel, all with the dimensions of 4’ by 1/16”. Helium was used as a carrier gas and make-up gas, except for the ECD, which used N as the make-up gas. Injector temperature was 100 C and flow rate was set at 40 mL min^{-1}. The modifications allowed for simultaneous analysis of CO_2, N_2O, and CH_4. Three standards were used to calibrate the gas chromatograph: the first standard contained 339 ppm CO_2, 0.5 ppm N_2O, and 1 ppm CH_4, the second standard contained 981 ppm CO_2, 2.5 ppm N_2O, and 5 ppm CH_4, and the third standard contained 10,200 ppm CO_2, 10 ppm N_2O, and 10 ppm CH_4.

All data were analyzed using PROC GLIMMIX (SAS Institute, Cary, NC). Means were separated using Tukey’s honest significant difference test ($\alpha=0.05$).

Results and Discussion

In this irrigated field experiment, tall fescue had a greater CO_2 flux than Kentucky bluegrass on five of the six collection dates (Fig. 4.2), and the CO_2 flux values were consistent with previously published research (Kaye et al., 2005). The greater CO_2 flux of tall fescue may be due to greater plant respiration, soil respiration, or both. The GRACEnet Sampling Protocol cannot differentiate if the greater amount of CO_2 released by the tall fescue was from plant or soil respiration. However, Watschke et al. (1973) and Huylenbroeck and Bockstaele (1999) noted differing plant respiration rates for different turfgrass species. Species was not significant on any collection date for N_2O flux (data not shown), but it ranged from 5 to 20 μg N m^2 hr^{-1} for tall fescue and from 6 to 15 μg N m^2 hr^{-1} for Kentucky bluegrass. By comparison, Kaye et al. (2004) reported N_2O fluxes of less than 4 μg N m^2 hr^{-1} for native grasslands during the growing season and greater than 10 μg N m^2 hr^{-1} for an urban ecosystem throughout the year.

Turfgrass growth rate did not affect CO_2 on any of the six collection dates. On 27 September, N_2O flux was significant for growth rate (P=0.0168). The fast-growing cultivars had a greater N_2O flux (13 μg N m^2 hr^{-1}) than the slow-growing cultivars (7 μg N m^2 hr^{-1}), and the moderate-growing cultivars (10 μg N m^2 hr^{-1}) were similar to the other growth rates. Nitrogen fertilization can increase N_2O production (Mosier et al., 1991), and the experimental area was fertilized with 49 kg N ha^{-1} only 9 d prior. Thus, the differences in growth rates for N_2O flux may be an artifact of how the growth rates responded to the recent N fertilization.

Though growth rate did not influence CO_2 flux and was only significant on one date, planting slower growing cultivars has been shown to reduce annual mowing requirements (Law, 2014), which therefore reduces CO_2 and N_2O emissions from fossil fuel powered mowers. Fast-growing plant species have higher rates of shoot and root respiration, but the increase in plant respiration due to a faster growth rate is not proportional to the increase in relative growth rate (Lambers and Poorter, 1992). Despite their faster growth rates, fast-growing cultivars have a more efficient respiration process that results in a greater net amount of CO_2 fixed (i.e. CO_2 consumed less CO_2 respired)(Lambers and Poorter, 1992). As such, growth rate is an important factor in the amount of GHGs released from a turfgrass system. However, we were unable to detect differences between growth rates for CO_2 flux. This may have been due a dilution effect from our sampling method, as it cannot separate plant and soil respiration.

Returning grass clippings resulted in a greater CO_2 flux ($P = 0.0344$) compared to when clippings were collected on one of the six sampling dates (31 May)(data not shown). This increase may have been due to soil respiration, which is the result of the decomposition of organic matter by soil organisms. By returning grass clippings, more organic matter was available for soil organisms to decompose, which may have increased the soil respiration and subsequently CO_2 flux. The stimulated growth as a result of returning grass clippings may have also increased plant respiration enough to make up part or possibly even all of the difference in CO_2 flux. Again, the GRACEnet Sampling Protocol cannot discern if the CO_2 measured was from plant or soil respiration. Soil management practices, such as tillage, have also been shown to influence CO_2 flux (Reicosky and Lindstrom, 1993). Despite an increased CO_2 flux when clippings are returned, the practice has been shown to actually increase the net soil organic matter accumulation (Qian et al., 2003; Law, 2014).

Nitrous oxide flux is influenced by N availability and mineralization (Bremer, 2006; Matson and Vitousek, 1987). Despite increased soil N concentrations and leaf tissue N concentrations (Law, 2014) due to the practice of returning grass clippings in this experiment, there were no recorded differences in N_2O flux between the grass clippings management treatments (data not shown). Li et al. (2013) saw an influence of grass clipping management on N_2O flux, but it appeared to be dependent on the aerobic status of the soil. The soils were aerobic (i.e. not under saturated conditions) when samples were collected for our experiment. More research is needed to understand the influence of grass clipping management on N_2O flux.

There was no CH_4 flux measured during the course of the study (data not shown). When comparing CH_4 concentrations at time=0 min and time=45 min for all treatments on all six collection dates, there was no net flux in either direction (i.e. CH_4 was neither emitted nor consumed). Though our results were showed no net flux, aerobic soils are a globally important sink for atmospheric CH_4 (Follett et al., 2013). Furthermore, both native grasslands and urban soils have been documented to consume CH_4 (Kaye et al., 2004).

With tall fescue having a greater CO_2 flux than Kentucky bluegrass, this research highlights the importance of turfgrass species on C cycling in urban grasslands. This research also emphasizes the significance of management practices on the GHG dynamics of urban grasslands, as returning grass clippings had a greater CO_2 flux compared to when clippings were collected. It should be noted, though, that this report only addresses the CO_2 flux portion of the C cycle. Neither the C fixed via photosynthesis nor the C sequestered in the soil were discussed, which are two other important processes in the C cycle. As a whole, perennial urban grasslands have been shown to be a C sink (Milesi et al., 2005; Zirkle et al., 2011).

References

Bigelow, C.A., J.J. Camberato, and A.J. Patton. 2013. Fertilizing established cool-season lawns: Maximizing turf health with environmentally responsible programs. Purdue University, Cooperative Extension Service. AY-22-W.

Bremer, D.J. 2006. Nitrous oxide fluxes in turfgrass. Journal of Environmental Quality 35:1678-1685.

Brown, D.G., K.M. Johnson, T.R. Loveland, and D.M. Theobald. 2005. Rural land-use trends in the conterminous United States, 1950-2000. Ecological Applications 15:1851-1863.

Chapin III, F.S., M.C. Chapin, P.A. Matson, and P. Vitousek. 2011. Principles of terrestrial ecosystem ecology. Springer, New York.

Dutaur, L., and L.V. Verchot. 2007. A global inventory of the soil CH_4 sink. Global Biogeochemical Cycles 21:GB4013.

EPA. 2010. Methane and nitrous oxide emissions from natural sources. U.S. Environmental Protection Agency, Washington, DC, USA.

Follett, R., S. Mooney, J. Morgan, K. Paustian, L.H. Allen Jr, S. Archibeque, J.M. Baker, S.J. Del Grosso, J. Derner, and F. Dijkstra. 2011. Carbon sequestration and greenhouse gas fluxes in agriculture: Challenges and opportunities. Council for Agricultural Science and Technology (CAST), Ames.

Huylenbroeck, V., and V. Bockstaele. 1999. Photosynthetic characteristics of perennial ryegrass and red fescue turf-grass cultivars. Grass and Forage Science 54:267-274.

Kaye, J.P., R.L. McCulley, and I.C. Burke. 2005. Carbon fluxes, nitrogen cycling, and soil microbial communities in adjacent urban, native and agricultural ecosystems. Global Change Biology 11:575-587.

Lambers, H., and H. Poorter. 1992. Inherent variation in growth rate between higher plants: A search for physiological causes and ecological consequences. In: M. Begon and A.H. Fitter, editors, Advances in ecological research. Academic Press, San Diego. p. 187-261.

Law, Q.D. 2014. Defining management strategies to maximize soil carbon retention in turfgrass systems. M.S. thesis, Purdue University, West Lafayette, IN.

Lewis, J.D. 2010. Carbon, nitrogen, and water fluxes from turfgrass ecosystems. Ph.D. dissertation, Kansas State University, Manhattan, KS.

Li, X., F. Hu, D. Bowman, and W. Shi. 2013. Nitrous oxide production in turfgrass systems: Effects of soil properties and grass clipping recycling. Applied Soil Ecology 67:61-69.

Liu, X., and B. Huang. 2003. Mowing height effects on summer turf growth and physiological activities for two creeping bentgrass cultivars. HortScience 38:444-448.

Matson, P.A., and P.M. Vitousek. 1987. Cross-system comparisons of soil nitrogen transformations and nitrous oxide flux in tropical forest ecosystems. Global Biogeochemical Cycles 1:163-170.

Milesi, C., S.W. Running, C.D. Elvidge, J.B. Dietz, B.T. Tuttle, and R.R. Nemani. 2005. Mapping and modeling the biogeochemical cycling of turf grasses in the United States. Environmental Management 36:426-438.

Moser, L.E., J.J. Volenec, and C.J. Nelson. 1982. Respiration, carbohydrate content, and leaf growth of tall fescue. Crop Science 22:781-786.

Mosier, A., D. Schimel, D. Valentine, K. Bronson, and W. Parton. 1991. Methane and nitrous oxide fluxes in native, fertilized and cultivated grasslands. Nature 350:330-332.

Parkin, T.B., and R.T. Venterea. 2010. Chamber-Based Trace Gas Flux Measurements. In: R.F. Follett, editor, GRACEnet sampling protocols. p. 3.1-3.9. Available at www.ars.usda.gov/research/GRACEnet (verified 1 April 2014).

Qian, Y.L., W. Bandaranayake, W.J. Parton, B. Mecham, M.A. Harivandi, and A.R. Mosier. 2003. Long-term effects of clipping and nitrogen management in turfgrass on soil organic carbon and nitrogen dynamics. Journal of Environmental Quality 32:1694-1700.

Raich, J.W., and W.H. Schlesinger. 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus B 44:81-99.

Reicosky, D.C., and M.J. Lindstrom. 1993. Fall tillage method: Effect on short-term carbon dioxide flux from soil. Agronomy Journal 85:1237-1243.

Rose-Fricker, C.A., C.P. Scott, M.L. Fraser, L.P. Sharp Jr., J. Frelich, and S. Staples. 2010. Improving tall fescue (*Festuca arundinacea*) and Kentucky bluegrass (*Poa pratensis*) cultivars for summer performance. In: A. Zuin, editor, Proceedings of the 2nd European Turfgrass Society Conference, Loire Valley, France. 11-14 Apr. 2010. p. 186-187.

Smith, K.A., K.E. Dobbie, B.C. Ball, L.R. Bakken, B.K. Sitaula, S. Hansen, R. Brumme, W. Borken, S. Christensen, and A. Priemé. 2000. Oxidation of atmospheric methane in Northern European soils, comparison with other ecosystems, and uncertainties in the global terrestrial sink. Global Change Biology 6:791-803.

Steudler, P.A., R.D. Bowden, J.M. Melillo, and J.D. Aber. 1989. Influence of nitrogen fertilization on methane uptake in temperate forest soils. Nature 341:314-316.

Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley. 2013. Climate change 2013: The physical science basis. Intergovernmental Panel on Climate Change, Working Group I Contribution to the IPCC Fifth Assessment Report. Cambridge University Press, New York.

Sylvia, D.M., J.J. Fuhrmann, P.G. Hartel, and D.A. Zuberer. Principles and applications of soil microbiology. 2nd ed. Pearson Education Inc., Upper Saddle River.

Tans, P. and R. Keeling. 2014. Trends in Atmospheric Carbon Dioxide. http://www.esrl.noaa.gov/gmd/ccgg/trends/ (verified 30 June 2014).

U.S. Department of State. 2007. Projected Greenhouse Gas Emissions. In: Fourth Climate Action Report to the UN Framework Convention on Climate Change. U.S. Department of State, Washington, DC, USA.

Watschke, T.L., R.E. Schmidt, E.W. Carson, and R.E. Blaser. 1973. Temperature influence on the physiology of selected cool season turfgrasses and bermudagrass. Agronomy Journal 65:591-594.

Wedin, D.A., and D. Tilman. 1990. Species effects on nitrogen cycling: A test with perennial grasses. Oecologia 84:433-441.

Whitman, W.B., T.L. Bowen, and D.R. Boone. 2006. The methanogenic bacteria. In: M. Dworkin, S. Falkow, E. Rosenberg, K. Schleifer, and E Stackebrandt, editors, Prokaryotes. Springer, New York. p. 165-207.

Wilson, D. 1975. Variation in leaf respiration in relation to growth and photosynthesis of *Lolium*. Annals of Applied Biology 80:323-338.

Zirkle, G., R. Lal, and B. Augustin. 2011. Modeling carbon sequestration in home lawns. HortScience 46:808-814.

Table 4.1. Tall fescue (*Schedonorus arundinaceus*) and Kentucky bluegrass (*Poa pratensis*) cultivars, growth rates, experimental names, and providers.

Species	Cultivar	Growth rate†	Experimental	Provider
Tall fescue	Gazelle II	Slow	PST-5HP	Pure Seed Testing
Tall fescue	Tar Heel II	Moderate	PST-5TR1	Pure Seed Testing
Tall fescue	Endeavor	Fast	PST-5R94E	Pure Seed Testing
Kentucky bluegrass	Prosperity‡	Slow	PST-Y2K-59	Pure Seed Testing
Kentucky bluegrass	Moonshine§	Moderate	PST-1804	Pure Seed Testing
Kentucky bluegrass	Thermal blue¶	Fast	HB-129	O.M. Scotts Company

† Cultivars were selected from information on leaf elongation rate provided by Pure Seed Testing (Canby, OR).

‡ Compact-type Kentucky bluegrass classification.

§ Shamrock-type Kentucky bluegrass classification.

¶ Texas (*Poa arachnifera*) × Kentucky bluegrass hybrid.

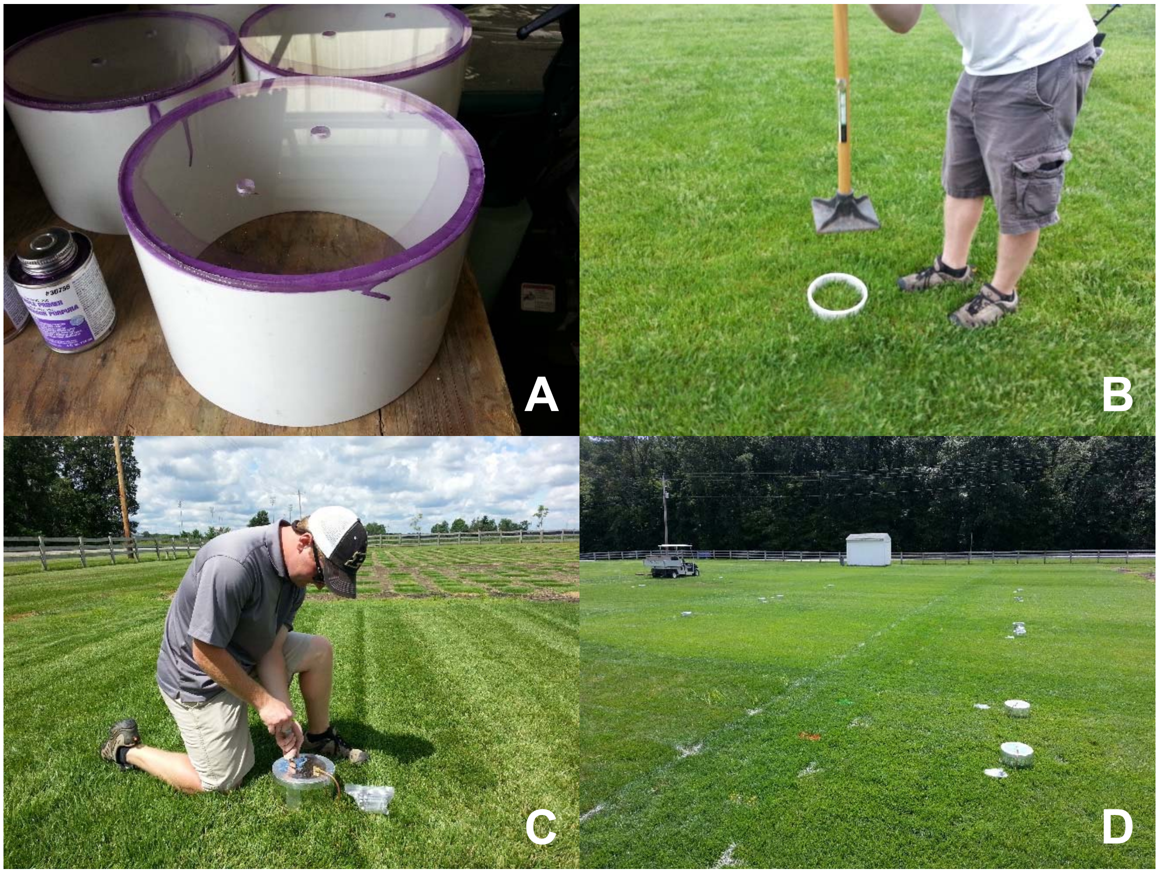

Fig. 4.1. Photos of the vented chamber construction (A), anchor installation (B), greenhouse gas sampling (C), and the experimental area with chambers installed (D).

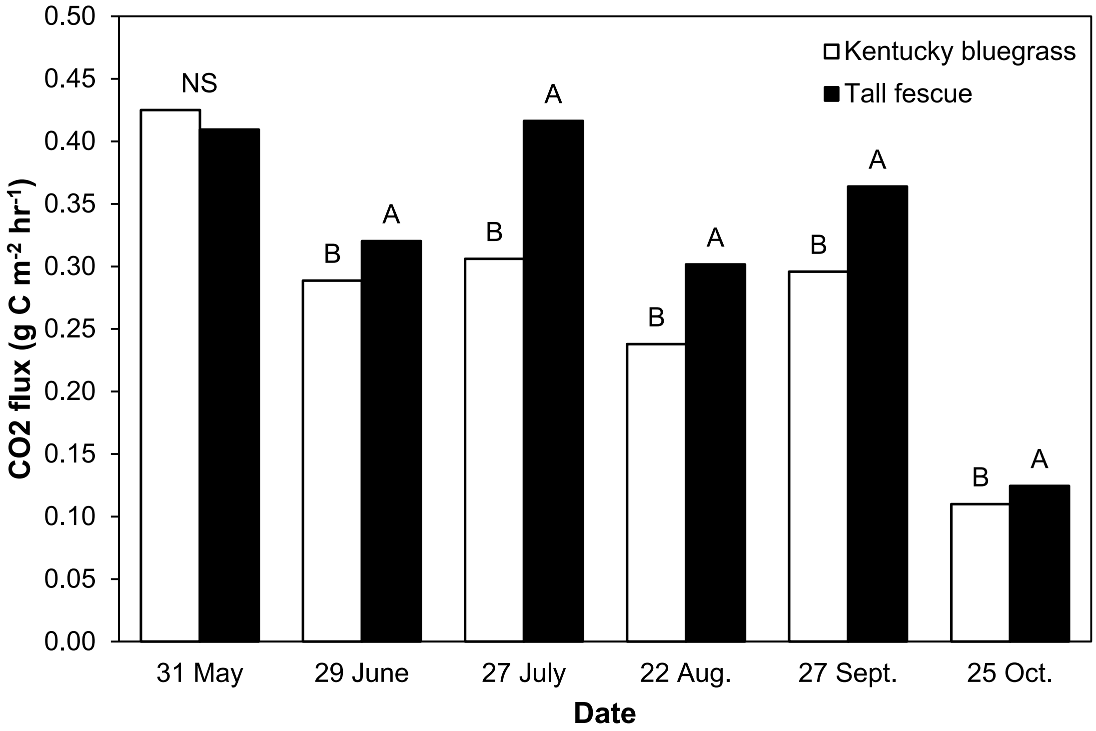

Fig. 4.2. CO_2 flux by turfgrass species over six sampling dates in West Lafayette, IN in 2013. Each bar represents the average of four blocks for the three cultivars of the respective species with grass clippings returned plus grass clippings collected for the moderate-growing cultivars (n=16). Within date, bars with the same letter are not significantly different according to Tukey's honest significant difference test (α=0.05).

CHAPTER FIVE – SUMMARY AND CONCLUSIONS

Soil carbon (C) sequestration has been proposed as a method to reduce atmospheric carbon dioxide (CO_2)(Powlson et al., 2011). Managed turf areas are both a source and a sink for greenhouse gases (GHGs) including CO_2, methane (CH_4), and nitrous oxide (N_2O), among others (Stier et al., 2013). Management practices, including turfgrass selection and mowing, influence the amount of C and N stored in the soil, as well as the resulting GHG emissions. This thesis evaluated how turfgrass selection (both species and cultivar) and mowing practices (i.e. mowing frequency and grass clipping management) influence the annual mowing requirements and dry matter yield, soil C and N accumulation, and GHG flux (CO_2, N_2O, and CH_4) in a turfgrass system.

Given that most residential lawn mowers are gasoline powered (Davis and Truett, 2004), and the CO_2 emitted from the fuel consumption in the maintenance of turfgrass is estimated to be about 24% of the organic C stored in ornamental lawns (Townsend-Small and Czimczik, 2010). By planting slower-growing cultivars and implementing alternate mowing regimes, annual mowing requirements and thus mower emissions can be reduced. When averaged across all species and cultivars for both years of the experiment, mowing on a weekly basis resulted in an average of 26 mowing events in West Lafayette, IN. By comparison, 18 mowing events were required if the one-third rule was followed at a 7 cm mowing height. The specific lawn mower used in this experiment emitted 2.3 kg C equivalent ha^{-1} $mowing^{-1}$.

Therefore, 59.8 kg C equivalent ha^{-1} yr^{-1} was emitted when mowing weekly, and 41.4 kg C equivalent ha^{-1} yr^{-1} was released when turf was mown by the one-third rule (Table 5.1). The C emitted for mowing tall fescue (25 mowing events yr^{-1}) and Kentucky bluegrass (19 mowing events yr^{-1}) was 57.5 and 43.7 kg C equivalent ha^{-1} yr^{-1}, respectively (Table 5.1). Emissions from mowing the slow- (18 mowing events yr^{-1}), moderate- (23 mowing events yr^{-1}), and the fast-growing cultivars (25 mowing events yr^{-1}) were 41.1, 52.9, and 57.5 kg C equivalent ha^{-1} yr^{-1}, respectively (Table 5.1). Even when mowing on a weekly basis, less than 4% of the C that accumulated in the soil was emitted while mowing over the course of a year. This figure is significantly lower than the 24% reported by Townsend-Small and Czimczik (2010), who included the fuel required for leaf blowing and transportation to the turfgrass areas being maintained. Furthermore, the lawn mower used in our experiment was more efficient than previously reported values (Priest et al., 2000; Zirkle et al., 2011).

Dry matter yields ranged from 1.56 (slow-growing Kentucky bluegrass) to 4.62 Mg ha^{-1} yr^{-1} (fast-growing tall fescue), and returning grass clippings increased dry matter yields by approximately 33% compared to when clippings were collected. All main effects that had significant increases in labile and total soil C and total soil N also had a greater cumulative dry matter yield, which agrees with the notion that improving biomass production increases C sequestration (Lal et al., 1999). Though growth rate influenced dry matter yield, it did not influence soil C accumulation. More time may be needed for differences in soil C to occur between growth rates. However, this means that, at least shortly after establishment, slow-growing cultivars can reduce mowing requirements without reducing the soil C accumulation rate (Table 5.1).

Using a bare area immediately adjacent to the experimental area as a baseline and an average bulk density of 1.33 g cm^{-3} (data not shown), Kentucky bluegrass and tall fescue had gross total soil C accumulations of 1.408 and 1.629 Mg C ha^{-1} yr^{-1}, respectively, in the top 5 cm of soil (Table 5.1). These values are consistent with previous research that has reported soil organic C sequestration rates of 0.38-1.5 Mg C ha^{-1} yr^{-1} (Qian et al., 2010; Townsend-Small and Czimczik, 2010; Zirkle et al., 2011). Soil carbon accumulation rates are generally highest shortly after turfgrass establishment, and they tend to level off 30 to 40 yr after establishment (Bandaranayake et al., 2003). Given that the soil C accumulation rates in this experiment were calculated for grasses that had been established less than 3 yr prior, stand age may partially explain why the soil C accumulation rates were on the high end of the previously published range in our experiment.

The practice of returning grass clippings over a 2 yr period increased total soil C to a 5 cm depth by 0.532 Mg C ha^{-1} (Table 5.1), which was an increase of about 3% compared to when clippings were collected. Qian et al. (2003) reported a 10 to 25% increase in soil organic C when grass clippings were returned for a 10 to 50 yr period and fertilized at a similar N rate to what was used in this experiment. Thus, the magnitude of influence that grass clipping management has on soil C accumulation may increase with time. The relative increase in total soil N was similar to that of soil C in this experiment, which agrees with Qian et al. (2003). Returning grass clippings for 2 yr resulted in an increase of 0.066 Mg N ha^{-1} compared to when clippings were collected (1.516 vs. 1.450

Mg N ha^{-1}). This increase in soil C and N from returning grass clippings justifies the additional mowing events resulting from the practice.

Plant and soil respiration are natural processes that release CO_2 into the atmosphere, which detract from the net C fixation and subsequent sequestration of an ecosystem. In this study, managed Kentucky bluegrass and tall fescue had a combined plant and soil respiration (i.e. CO_2 flux) of 12 and 14 Mg C ha^{-1}, respectively, between May and October 2013. By reducing plant respiration or increasing photosynthesis and slowing the decomposition of organic matter, C sequestration can be increased. Total N_2O flux for the period between May and October 2013 was 550 g N_2O-N ha^{-1} when averaged between species. Converted to C equivalents and scaling up to an annual basis, N_2O flux contributed approximately 140 kg C ha^{-1} yr^{-1} in emissions (Table 5.1). However, extrapolating a single 45 min sampling period to represent CO_2 and N_2O flux for an entire month and summed for the year potentially results in inherent error, and these values should be considered broad estimations.

Emissions also arise from other turfgrass management practices, including fertilization, irrigation, and pesticide applications, and these emissions need to be considered as part of the net C balance of a turfgrass system. Based on the C equivalent conversions for fertilizers outlined by Lal (2004), fertilizer-related emissions in this experiment totaled between 135 and 272 kg C equivalent ha^{-1} yr^{-1} (Table 5.1), which was largely attributed to N. Irrigation and pesticides were also used in this experiment, but their use was not directly measured. Thus, values reported by Zirkle et al. (2011) were used to estimate emissions as a result of irrigation (16 kg C equivalent ha^{-1}) and pesticide use (8-56 kg kg C equivalent ha^{-1}) to determine the net C balance. Carbon and N are also held within unmown turfgrass tissue (i.e. verdure, thatch, and roots). Thus, it is important to note the concentrations of C and N in these tissues (Table 5.2).

All of the turfgrasses and management practices in this experiment resulted in a system-wide net C sink, though the magnitude of the sink was variable by management strategy (Table 5.1). The results of this experiment support the assertion that managed turfgrass areas can act as a net C sink to help curb the increasing atmospheric GHG concentrations. The C sequestration potential of managed turfgrass is another of the numerous functional benefits of urban grasslands.

Based on this research, the following practices are recommended for increasing net soil C accumulation: planting tall fescue, mowing by the one-third rule, and returning grass clippings. Additionally, the following practices are recommended for decreasing emissions: planting slow-growing Kentucky bluegrass cultivars and mowing by the one-third rule. Finally, returning grass clippings is recommended to increase soil N accumulation.

References

Bandaranayake, W., Y.L. Qian, W.J. Parton, D.S. Ojima, and R.F. Follett. 2003. Estimation of soil organic carbon changes in turfgrass systems using the CENTURY model. Agronomy Journal 95:558-563.

Davis, S.C., and L.F. Truett. 2004. Off-highway transportation-related fuel use. ORNL/TM-2004/92. Oak Ridge National Laboratory, Oak Ridge, TN.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304:1623-1627.

Lal, R., R.F. Follett, J. Kimble, and C.V. Cole. 1999. Managing US cropland to sequester carbon in soil. Journal of Soil and Water Conservation 54:374-381.

Powlson, D.S., A.P. Whitmore, and K.W.T. Goulding. 2011. Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false. European Journal of Soil Science 62:42-55.

Priest, M.W., D.J. Williams, and H.A. Bridgman. 2000. Emissions from in-use lawn-mowers in Australia. Atmospheric Environment 34:657-664.

Qian, Y.L., W. Bandaranayake, W.J. Parton, B. Mecham, M.A. Harivandi, and A.R. Mosier. 2003. Long-term effects of clipping and nitrogen management in turfgrass on soil organic carbon and nitrogen dynamics. Journal of Environmental Quality 32:1694-1700.

Qian, Y., R.F. Follett, and J.M. Kimble. 2010. Soil organic carbon input from urban turfgrasses. Soil Science Society of America Journal 74:366-371.

Stier, J.C., K. Steinke, E.H. Ervin, F.R. Higginson, and P.E. McMaugh. 2013. Turfgrass benefits and issues. In: J.C. Stier, B.P. Horgan, and S.A. Bonos, editors, Turfgrass: Biology, Use, and Management. Agronomy Monograph 56. ASA, CSSA, and SSSA, Madison, WI. p. 105-145.

Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley. 2013. Climate change 2013: The physical science basis. Intergovernmental Panel on Climate Change, Working Group I Contribution to the IPCC Fifth Assessment Report. Cambridge University Press, New York.

Townsend-Small, A., and C.I. Czimczik. 2010. Carbon sequestration and greenhouse gas emissions in urban turf. Geophysical Research Letters 37:L02707. doi: 10.1029/2009GL041675 [erratum:37:L06707. doi: 10.1029/2010GL042735].

Zirkle, G., R. Lal, and B. Augustin. 2011. Modeling carbon sequestration in home lawns. HortScience 46:808-814.

Table 5.1. The carbon accumulated and emitted on an annual basis by species, growth rate, mowing frequency, and grass clipping management during the experiment in West Lafayette in 2012 and 2013.

	Species		Growth rate			Mowing frequency		Grass clippings	
	KBG	TF	Slow	Moderate	Fast	Weekly	One-third	Collected	Returned
	kg C equivalent ha^{-1} yr^{-1}								
Soil carbon accumulation	1408	1629	1408-1629	1408-1629	1408-1629	1408-1629	1408-1629	1433	1600
Mowing emissions†	44	58	41	53	58	60	41	48	53
Nitrous oxide emissions‡	140	140	140	140	140	140	140	140	140
Fertilizer emissions§	135-272	135-272	135-272	135-272	135-272	135-272	135-272	135-272	135-272
Irrigation emissions¶	16	16	16	16	16	16	16	16	16
Pesticide emissions¶	8-56	8-56	8-56	8-56	8-56	8-56	8-56	8-56	8-56
Net carbon accumulation	880-1065	1087-1272	883-1289	871-1277	866-1272	864-1270	883-1289	901-1086	1063-1248

† Mower emissions were calculated as follows: 12.5 mL gasoline consumed min^{-1}, 465 m^2 mown in 15 min, density of gasoline = 0.7197 g mL^{-1}, and 0.8 g carbon equivalent g^{-1} gasoline (Lal, 2004).

‡ Nitrous oxide emissions were converted from kg N_2O ha^{-1} yr^{-1} to kg CO_2 ha^{-1} yr^{-1} by multiplying by 298 (Stocker et al., 2013).

§ Fertilizer emissions were calculated according to Lal (2004).

¶ Irrigation and pesticide emissions values were based on Zirkle et al. (2011).

Table 5.2. Representative carbon (C) and nitrogen (N) concentrations in a turfgrass system based on the management of Kentucky bluegrass and tall fescue receiving 142 kg N ha^{-1} yr^{-1} in West, Lafayette, IN.

System component	Carbon	Nitrogen
Greenhouse gas flux	0.322 g CO_2-C m^2 hr^{-1}	5-20 µg N_2O-N m^2 hr^{-1}
Removed clippings	0.439 g C g^{-1} clippings tissue	0.030 g N g^{-1} clippings tissue
Verdure and thatch	0.278 g C g^{-1} verdure and thatch tissue	0.011 g N g^{-1} verdure and thatch tissue
Roots	0.327 g C g^{-1} root tissue	0.009 g N g^{-1} root tissue
Soil	24.7 g total C kg^{-1} soil 82.6 mg labile C kg^{-1} soil	2.28 g total N kg^{-1} soil

APPENDICES

Appendix A – Selected ANOVA Tables

Table A.1. Analysis of variance for the number of mowing events by species, growth rate, mowing frequency, grass clippings management, and all interactions in 2013.

Effect	Num DF	Den DF	F Value	Pr > F
Species (S)	1	15	466.89	<.0001
Growth rate (G)	2	15	495.22	<.0001
S × G	2	15	80.70	<.0001
Mowing Frequency (M)	1	54	7072.93	<.0001
S × M	1	54	6.26	0.0154
G × M	2	54	138.81	<.0001
S × G × M	2	54	38.37	<.0001
Clippings (C)	1	54	293.37	<.0001
S × C	1	54	0.33	0.5661
G × C	2	54	2.37	0.1031
S × G × C	2	54	16.44	<.0001
M × C	1	54	45.37	<.0001
S × M × C	1	54	19.59	<.0001
G × M × C	2	54	23.26	<.0001
S × G × M × C	2	54	4.15	0.0211

Table A.2. Analysis of variance for the two year (i.e. 2012 and 2013) cumulative dry matter yield by species, growth rate, and the interaction.

Effect	Num DF	Den DF	F Value	Pr > F
Species (S)	1	15	230.36	<.0001
Growth rate (G)	2	15	51.55	<.0001
S × G	2	15	19.78	<.0001

Table A.3. Analysis of variance for the number of mowing events by species, growth rate, grass clippings management, season, and all interactions in 2013 when mown by the one-third rule.

Effect	Num DF	Den DF	F Value	Pr > F
Species (S)	1	15	49.78	<.0001
Growth rate (G)	2	15	103.15	<.0001
S × G	2	15	6.84	0.0078
Clippings (C)	1	90	40.91	<.0001
S × C	1	90	0.03	0.8609
G × C	2	90	0.94	0.3943
S × G × C	2	90	0.43	0.6544
Season (Se)	2	90	122.96	<.0001
S × Se	2	90	1.93	0.1512
G × Se	4	90	4.84	0.0014
S × G × Se	4	90	6.29	0.0002
C × Se	2	90	0.59	0.5559
S × C × Se	2	90	1.47	0.2362
G × C × Se	4	90	0.65	0.6291
S × G × C × Se	4	90	2.47	0.0499

Table A.4. Analysis of variance for the dry matter yield by species, growth rate, season, and all interactions in 2013.

Effect	Num DF	Den DF	F Value	Pr > F
Species (S)	1	15	23.19	0.0002
Growth rate (G)	2	15	25.02	<.0001
S × G	2	15	8.72	0.0031
Season (Se)	2	36	394.37	<.0001
S × Se	2	36	36.67	<.0001
G × Se	4	36	2.51	0.0586
S × G × Se	4	36	2.69	0.0463

Table A.5. Analysis of variance for labile soil carbon (C), total soil C, and total soil nitrogen (N) by species, growth rate, grass clippings management, and all interactions for soil samples collected to a 5 cm depth on 19 Nov. 2013.

			Labile C		Total C		Total N	
Effect	Num DF	Den DF	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F
Species (S)	1	15	15.94	0.0012	4.84	0.0439	1.39	0.2574
Growth rate (G)	2	15	0.21	0.8167	1.86	0.1899	1.52	0.2512
S × G	2	15	0.25	0.7854	0.07	0.9323	0.20	0.8223
Clippings (C)	1	66	10.26	0.0021	6.61	0.0124	13.08	0.0006
S × C	1	66	0.60	0.4421	0.66	0.4195	1.13	0.2909
G × C	2	66	0.27	0.7640	0.73	0.4848	0.26	0.7693
S × G × C	2	66	2.79	0.0684	0.30	0.7386	0.57	0.5688

Table A.6. Analysis of variance for carbon dioxide by species, growth rate, and grass clippings management for the six collection dates in 2013. The interactions were not analyzed due to an unbalanced design.

			31 May		29 June		27 July		22 August		27 September		25 October	
Effect	Num DF	Den DF	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F
Species	1	24	0.66	0.4243	5.44	0.0284	24.15	<.0001	19.94	0.0002	8.53	0.0075	6.25	0.0197
Growth rate	2	24	0.34	0.7165	3.96	0.0325	1.22	0.3142	1.35	0.2789	1.83	0.1825	0.57	0.5722
Clippings	1	24	5.03	0.0344	1.24	0.2761	1.78	0.1945	0.82	0.3738	2.14	0.1569	0.33	0.5686

Table A.7. Analysis of variance for nitrous oxide flux by species, growth rate, and grass clippings management on 27 Sept. 2013. The interactions were not analyzed due to an unbalanced design.

Effect	Num DF	Den DF	F Value	Pr > F
Species	1	24	3.86	0.0610
Growth rate	2	24	4.86	0.0168
Clippings	1	24	0.75	0.3958

Appendix B – Turfgrass Dark Green Color Index

Table B.1. Monthly dark green color index (DGCI) values by grass clippings management averaged across species and cultivar for the weekly-mown plots in 2012.

Grass clippings management	May	June	July	August	September	October	November
	--			DGCI			--
Collected	0.4727	0.4717	0.5076	0.5325	0.5513	0.5470	0.4801
Returned	0.4728	0.4769	0.5110	0.5363	0.5528	0.5460	0.4861
P-value	NS	NS	NS	NS	NS	NS	NS

Table B.2. Monthly dark green color index (DGCI) values by grass clippings management averaged across species and cultivar for the weekly-mown plots in 2013.

Grass clippings management	April	May	June	July	August	September	October	November
	----------------------	----------------------	----------------------	DGCI	----------------------	----------------------	----------------------	----------------------
Collected	0.6344	0.5633	0.5137 B†	0.5197 B	0.5300 B	0.5456 B	0.4999 B	0.4993
Returned	0.6303	0.5620	0.5224 A	0.5331 A	0.5423 A	0.5528 A	0.5101 A	0.5086
P-value	NS	NS	0.0001	<.0001	0.0003	0.0102	0.0134	NS

† Within column, means followed by the same letter are not significantly different according to Tukey's honest significant difference test (α=0.05).