Advances in Creeping Bentgrass Late-Season Nitrogen Fertility and Fairway Establishment

A THESIS
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA
BY

Samuel James Bauer

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

May 2011

ACKNOWLEDGEMENTS

I would like to express gratitude to my advisors Dr. Brian Horgan, Dr. Eric Watkins, and Dr. Doug Soldat, for their continued support and guidance. I would also like to thank the U of M turf group, including: Andrew Hollman, Craig Krueger, Kari Hugie, Josh Friell, Cristal Cisneros, Eric Koeritz, and all of the undergraduate student workers. I am particularly indebted to Dr. Horgan and Andrew Hollman who have been influential mentors in both my work and life; Scott Kinkead and Turfco Manufacturing Co. for partial support and equipment use; Aaron Hathaway and the Michigan State Turfgrass Program for collaboration; Dr. Dave Gardner at Ohio State; Dan Lloyd at the University of Missouri; Roger Eliason and the U of M Research Analytical Lab for assistance with analytical techniques, sample processing, and the use of lab equipment; Joy Mathews at UC-Davis for advice and sample processing; Brent Belanger and Carl Mielke at Les Bolstad Golf Course; Paul Diegnau and Brett Wenzel at Keller Golf Course; and Christian Baldwin and Jacklin Seed by Simplot for seed donation.

I would also like to thank those who have provided guidance and encouragement in developing me as a turfgrass manager.

DEDICATION

This thesis is dedicated to my parents who always understood and applauded a young boy's passion for turfgrass.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SUMMARY OF RESEARCH PROJECTS

Creeping bentgrass (*Agrostis stolonifera* L.) has long been a desired cool-season turfgrass species for use in golf course settings. From greens to tees and fairways, it has withstood the test of time, becoming the most sought after turf by avid golfers and greenskeepers alike. After an in-depth look at creeping bentgrass management recommendations in the Midwest, two main areas are identified as lacking in supporting research: late-fall nitrogen fertility on putting greens and a cost-effective approach for fairway establishment in annual bluegrass (*Poa annua* L.) infested turf.

Late-fall nitrogen fertility has been regarded as an integral component in cool-season turfgrass nutrition programs for almost four decades. The benefits of this application from a turfgrass quality standpoint are fairly clear, though recent environmental concerns and rising nitrogen fertilizer costs have pressured turfgrass researchers to re-evaluate the benefit and efficiency of these applications. The late-fall nitrogen research herein focuses on creeping bentgrass in Upper Midwest putting green situations, with an attempt to quantify benefits and determine nitrogen uptake efficiency from various application strategies.

Annual bluegrass is a weedy species, which has long been problematic on golf courses throughout the world. More time and money is devoted to controlling this species than any other weed, and most attempts have achieved marginal success at best. Greenskeepers are constantly looking for a cost-effective approach to establish creeping bentgrass in annual bluegrass infested turf. This research looks at a quick and effective way to increase creeping bentgrass populations on annual bluegrass fairways.

CHAPTER 1. LITERATURE REVIEW

AGRONOMIC AND PHYSIOLOGICAL RESPONSES OF COOL-SEASON TURFGRASS TO FALL-APPLIED NITROGEN

(*a paper submitted to Crop Science Journal*)

Samuel J. Bauer, Brian P. Horgan, Douglas J. Soldat, Daniel T. Lloyd

OVERVIEW

Turfgrass is an integral component of the urban and suburban landscape and plays a key role in water quality and nutrient cycling. Nitrogen (N) is the mineral nutrient most important for turfgrass growth and development and is often applied as fertilizer because of temporally inconsistent availability of soil N or an inherent N deficiency in particular soils. Rising energy and subsequent N costs and environmental concerns have pressured turfgrass managers to schedule highly specific N applications in their fertilizer program to maximize N use efficiency. Late-fall N fertilization for cool-season turfgrass, targeted after shoot growth rate has declined, is a widely accepted practice among turf managers in temperate climates, with application rates ranging from 49-98 kg N ha^{-1} and accounting for 25-50% of annual N applied. Reported benefits from late fall N fertilization include improved color in fall and spring without stimulation of shoot growth, improved rooting in late fall and early spring, carbohydrate accumulation going into winter, and the ability to withhold undesirable spring applications of N fertilizer; however, research supporting these benefits in cool season turfgrass is limited and has yielded mixed results. Much of the late fall N research available has been conducted in relatively warm or temperate costal climates which may not relate to cooler temperature regimes of more northern climates. In addition, the N rates of older studies may not be relevant to current typical application rates. This literature review finds that the often cited physiological and agronomic benefits of applying N at high rates to cool-season turfgrass in the fall are poorly supported by peer-reviewed research, with the exception of fall and spring color responses. More climate-specific research on plant utilization and response to fall-applied N is necessary to determine appropriate N rates and optimal timings for this highly specific application.

INTRODUCTION

Turfgrass cover accounts for the vast majority of the pervious surface area in the urban and suburban landscape. Nationally, the U.S. turfgrass area is estimated to be larger than that of irrigated corn (Milesi et al., 2005). Turfgrass acreage in the U.S. will continue to grow as urbanization is expected to increase 79% in the next 25 years (Alig et al., 2004). Through its relationship with the urban landscape, turfgrass plays a prominent role in nutrient cycling and urban water quality.

Nitrogen (N) is the mineral nutrient required in greatest amounts in plants and is one of the most important nutrients for turfgrass growth and development (Liu et al., 2008). Nitrogen is essential in the structure and function of amino acids, amides, nucleotides, nucleic acids, pigments, and some hormones (Hull and Liu, 2005). In cool-season turfgrasses, N plays an important role in photosynthesis as a structural component of the carbon dioxide-binding enzyme Rubisco, which can account for more than 50% of total plant N (Hull, 1992). The nearly perpetual vegetative state of turfgrass and the physiological importance of N for new growth make turfgrass capable of assimilating much higher rates than are generally applied (Kussow, 1987; Bowman, 2003). Under ideal conditions, increased shoot growth responses are linearly correlated with N fertilization rates up to 11.1 kg ha^{-1} day^{-1} (Bowman, 2003) and 1000 kg ha^{-1} yr^{-1} (Kussow, 1987). The importance of N to turfgrass growth and development coupled with the seasonally inconsistent availability of mineral N in the soil make N the nutrient required and applied in the largest quantity. Still, fertility programs aim at moderating the supply of N to maintain submaximal levels of turfgrass growth and some level of N deficiency is most likely the normal state for turfgrass management (Bowman, 2003).

Traditional fertility programs that base nutrient application on historical needs or time of year often result in significant nutrient losses (Horgan and Rosen, 2010) and clearly fertilizer N that is not used by the plant is economically wasteful if lost from the agronomic system (Below, 2002). Efficient N use has been the goal of turfgrass researchers for many years (Hull and Liu, 2005). With recent increasing N fertilizer costs, turfgrass managers can no longer afford to make N applications that move off site and/or don't benefit their system. In the United States alone, N fertilizer prices have more than doubled since 1990 (ERS, 2010), reaching historic highs in mid-2008 due to high fertilizer demand and the inability of manufacturers to increase production levels (Huang et al., 2008). In the future, energy intensive products used in turfgrass management (such as nitrogen) will be less available, yet demands for new turfgrass areas will likely increase (Busey and Parker, 1992). For this reason, it is imperative that turfgrass managers understand how to maximize the efficiency of their N applications.

The fate of N in the turfgrass environment can be narrowed down to six basic processes: clipping disposition, N sequestration, nitrate leaching, nitrate runoff, denitrification, and ammonia volatilization (Hull and Liu, 2005). The latter four processes are off-target N losses that have environmental implications; particularly ground and surface water contamination and alteration of atmospheric composition. Research conducted on the environmental fate of fall-applied N in turfgrass systems has concluded that proper N management practices greatly reduce the risk of environmental losses (Starr and DeRoo, 1981; Miltner et al., 1996; Horgan et al., 2002; Frank et al., 2006; Paré et al., 2006); though late fall applications have a high risk potential for leaching losses due to restricted plant uptake, decreased microbial immobilization and denitrification, and the disparity between high precipitation and low evapotranspiration (Petrovic, 1990).

This review focuses on research surrounding the agronomic and physiological benefits of fall-applied N in cool season turfgrass management, which is a widely accepted practice among turfgrass managers and researchers in temperate climates, accounting for as much as 50% of the annual N applied. Knowing that price and environmental impacts are important components in the cost-benefit analysis of N fertilizer applications, it is critical that we gain an understanding of the agronomic and physiological benefits of this highly specific application.

CURRENT FALL NITROGEN FERTILIZER RECOMMENDATIONS

Annually, 50-250 kg N ha^{-1} is typically recommended for cool-season turfgrasses depending on a variety of factors (Liu et al., 2008). Nitrogen fertilizers are generally applied between one and 20 times with various rates, timings, and sources throughout the growing season. The recommended timings and intervals for N applications are often based on turfgrass function expectations and can be influenced by rate of a given N application, N carrier, seasonal growth patterns, carbon energy relations, and perceived N availability in the soil which is largely derived from temperature- and moisture-dependent mineralization of the organic N pool. Although soil organic N is often abundant in turfgrass systems and can mineralize at the rate of 40-160 kg ha^{-1} yr^{-1} as temperatures increase (Hull and Bushoven, 2001), the lower soil temperatures associated with spring and fall result in low rates of available mineral N, often creating a need for N fertilizer additions to maintain acceptable color and quality. Early spring N fertilization in cold climates is widely considered undesirable by turf managers concerned that the characteristically low soil temperatures will inhibit root development and hinder the plant's ability to survive the heat and drought stresses of summer (Koski, 1988; Kussow, 1991). Therefore, fall – specifically late fall – has become the preferred time for N fertilization of cool season turfgrass.

For the past thirty years, the ideal timing for late fall N fertilization of cool season turfgrasses across the northern climates has been said to be just after turfgrass shoot growth ceases (Duff, 1976; Snow, 1982; Kussow, 1988; Rieke, 1995; Reicher, 2005; Baird, 2007). The timing for late season application is thought to be extremely important as this is a time when the plant remains metabolically active but does not partition photosynthates to shoot growth. Kussow (1988) described this short window of time as a period with high recuperative potential for the turf; a time when net photosynthesis is high as a result of moderate temperatures, which decreases respiration and yields high photosynthate due to less demand for shoot growth. Instead of partitioning photosynthate and assimilated N for shoot growth as is observed in spring, it is suggested that photosynthates are partitioned for root, rhizome, and stolon development as well as the accumulation of reserve carbohydrates considered important for winter hardiness, root growth, and spring green-up (Snow, 1982; Kussow,1988; Rieke, 1997,1998; Reicher, 2005; Danneberger, 2006; Baird, 2007). Recommended application rates for the late-fall range from 25 to 98 kg N ha^{-1} (Snow, 1982; Koski 1988; Kussow,1992; Reike, 1998; Reicher, 2005; Danneberger, 2006; Baird, 2007), usually accounting for 25 to 50% of the total annual N fertilizer applied. Nitrogen sources used for the late-fall application should release independently of microbial activity due to low air and soil temperatures. The most efficient N sources are soluble and thus available for root uptake, such as urea or ammonium sulfate (Miltner et al., 2004; Koski and Street, 2010). It is important to note that fertilization of turfgrass after plant metabolic activity declines is termed as dormant fertilization and is not synonymous with the late fall N applications discussed here. Dormant fertilization is intended to be available for the plant in the spring while late fall fertilization is meant to be utilized by the turf during the autumn and to a lesser extent, the following spring.

HISTORICAL PERSPECTIVES OF FALL-APPLIED NITROGEN

Fall N fertilizer recommendations have changed substantially over the past century, influenced both by research and popular opinion. Table 1 summarizes late-fall N research performed on cool season turfgrass species in northern climates, dating back to 1930. In 1921, Piper and Oakley wrote that heavy fall N applications could be detrimental to the turf and at best have no advantage. While heavy application rates in 1921 likely exceeded 500 kg N ha^{-1} yr^{-1} as an organic source, the opinion remained that turf need not be fertilized in the fall. Carol and Welton (1939) performed a cold tolerance study on Kentucky bluegrass (*Poa pratensis* L.) and found that N fertilization at the rate of 245 kg N ha^{-1} in September or October increased susceptibility to winter injury, however, these rates are not relevant to today's turf managers. During a superintendent panel discussion on N fertility (Shields et al., 1953), a golf course superintendent in Maryland reported applying more than half of his annual 368 kg N ha^{-1} budget after October 1. In this same panel discussion, a superintendent from Ohio reportedly did not apply any N fertilizer after September 1 while another superintendent in California claimed to apply N year-round at six-week intervals totaling 800 kg N ha^{-1} yr^{-1} on putting greens.

Although regional and individual differences during the mid-1900s were apparent, many turf professionals considered N applications after September to be risky. Noer (1963) recommended that N fertilization of turfgrass in the northern U.S. should cease in September or early October to allow adequate time for the grass to harden-off and become dormant to avoid winter injury. Beard (1969) also suggested that late-fall fertilization of turfgrass stimulates growth and tissue hydration which may increase its susceptibility to cold injury. Recommendations in trade journals and industry opinions regarding fall N began to change in the early 1970s. Schmidt and Shoulders (1971) from Virginia recommended that both warm and cool season turfgrasses should be fertilized in the fall to improve vigor coming out of winter and into the summer. Griffin (1977) wrote in a popular trade journal that "the old theory that fertilizer applications just prior to cold weather are detrimental to both warm and cool-season turf is being replaced." Griffin (1977) also stated that numerous benefits can be derived from fertilization prior to and during cold weather, and that tissue N levels do not necessarily impact cold hardiness, which he thought was determined by a more complex internal balance of other plant nutrients including potassium. More recently, Webster and Ebdon (2005) evaluated late season N and K fertilization and concluded that late fall-applied N does not increase the potential for winter injury in perennial ryegrass, which is one of the cool season species most prone to winter injury (Rajashekar et al., 1980).

Late-fall N recommendations for cool season grasses in northern climates have remained relatively consistent from the 1980s until present and are in the range of 25-49 kg N ha^{-1} for golf course putting greens and 49-98 kg N ha^{-1} for turfgrass maintained at a higher height of cut (Kussow, 1988). It is also agreed that the timing for this application should be shortly after the turf has been mowed for the last time of the season (Snow, 1982; Koski, 1988; Kussow,1988; Rieke, 1997,1998; Reicher, 2005; Danneberger, 2006; Baird, 2007). Results from a 1989 survey of 25 Wisconsin golf course superintendents showed that the practice of fall N applications closely followed these recommendations

(Erdahl, 1989). In 1989, an average of 56 kg N ha^{-1} was applied to Wisconsin putting greens in October and November, accounting for 47% of the mean annual N budget. A follow up survey was administered in 2007: the 41 Wisconsin golf course superintendents returning the survey applied a mean of 40 kg N ha^{-1} in October and November accounting for 26% of the mean annual N budget (Lloyd, 2008), indicating a trend toward decreasing fall N application rates and an increase in annual application rates.

PREVIOUS RESEARCH ON FALL-APPLIED NITROGEN IN COOL-SEASON TURF

Color, Quality, and Growth Response

The literature states the primary benefits associated with late-fall fertilization of turfgrass includes improved color and quality later into the fall and earlier in the spring without a surge of shoot growth. These reports followed research performed in Virginia on creeping bentgrass (*Agrostis stolonifera* L.) and tall fescue (*Festuca arundinacea* Schreb.*)* (Powell et al., 1967a). These researchers concluded that late-fall and winter N fertilization of cool season grass in Virginia improved year-round color and quality without stimulating foliar growth in the winter. During a time period when fall N was considered detrimental to cold acclimation (Carroll and Welton, 1939; Noer, 1963; Beard, 1969), Powell also reported that fall and winter N applications did not decrease the cold hardiness of cool-season turfgrass. Powell's study examined cumulative fall and winter N rates of 49, 98, 147, 245, and 490 kg N ha^{-1} applied as ammonium nitrate using one to five applications of 49 or 98 kg N ha^{-1} between October and February. Water-insoluble N was also applied at the rate of 490 kg N ha^{-1}. All high N rates examined on bentgrass (147-490 kg N ha^{-1}) regardless of timing generally displayed greener visual color ratings and color by reflectance measurements throughout the winter and into the spring compared to lower N rates (49 and 98 kg N ha^{-1}). Growth was not greatly stimulated in the winter months; however, growth in the spring was significantly increased by the high N rates compared to the low rates. By May, high N treatments were producing roughly twice the clipping yield compared to the lower treatments.

Although Powell's research is often the primary justification cited for the benefits of late-fall fertilization across the country, research on the color, quality, and growth responses to fall N has been performed in different regions as well. Researchers in Rhode Island (Wilkinson and Duff, 1972; Ledborer and Skogely, 1973) evaluated fall-applied N with rates and timings more typical of fertility practices in northern climates. Wilkinson and Duff (1972) evaluated color, cold resistance, and growth of Kentucky bluegrass in Rhode Island under various fall N treatment timings. Six different application timings were evenly spaced at two-week intervals between October 1 and December 15 and were fertilized with ammonium nitrate at the rate of 98 kg N ha^{-1}. The researchers observed increased fall color for fertilizer applications made prior to Nov. 1, but concluded that any fertilizer applications after this date were too late to produce a fall color response. All fall fertilizer treatments provided good spring green up by mid-March and the treatments applied after Nov. 1 had greener color and greater clipping yield by mid-April. Fertilizer treatments applied before Nov. 1 produced growth responses in the fall while later applications increased clipping yields in the spring. Wilkinson and Duff (1972) also associated greater fall N fertilization rates with decreased cold resistance through laboratory freezing tests, although they concluded that data may not be relevant to field plots.

Ledborer and Skogely (1973) evaluated spring and fall application timings at rates ranging from 49-147 kg N ha^{-1} to various fescues (*Festuca* spp*.)*, bluegrasses (*Poa* spp.), and mixtures of these species. They concluded that early and/or late-fall N applications (Sept. and late-Nov.; before and after foliar growth ceased) maintained more uniform turf quality, sustained green color longer in the fall and earlier in the spring, and did not increase mowing requirements compared to spring N treatments. Winter injury was not observed through three years of field research in Rhode Island.

Although no evidence of increased winter injury on field plots from fall N was found in the mid-Atlantic region (Hanson and Juska, 1961; Powell et al., 1967a**)** or in coastal New England (Wilkinson and Duff, 1972; Ledborer and Skogely, 1973), limited field research is available from harsher northern climates (Carroll and Welton, 1939; Noer, 1963; Beard, 1973). Wehner et al. (1988) in central Illinois compared annual N fertility programs including either a spring N application (early May) or a late-fall N application (early Nov.) in Urbana, IL. Fall N treatments resulted in higher turf color ratings in early spring although spring treatments had greater color ratings in late spring. Nitrogen treatments including spring N had 48 weekly ratings of acceptable color compared to the fall treatments, which displayed 39 ratings of acceptable color. The authors' conclusion from this study was that a urea application in early Nov. improves color in the early spring but may necessitate a subsequent spring N application to maintain color and quality into the summer. No winter injury was reported in this study.

Wehner and Haley (1993) initiated a follow-up study to evaluate if the benefits from Nov. applications of N could be achieved through Oct., Dec., or Jan. N applications. Different N rates (49 and 98 kg N ha^{-1}) and sources (urea, sulfur coated urea, and a biosolids-based fertilizer) were evaluated as well as the Nov. plus light April combination treatment suggested in their previous study. The results indicated that higher rates applied later into the winter sustained color longer in the spring, as did the lower rate Nov./April combination treatment. In Wisconsin, Kussow (1992) also found improved spring color with dormant and late-fall N treatments using different sources, although a spring growth response was also attributed to these late-fall and winter treatments. None of the research performed in the Midwest United States reported winter injury as a result of late-season N fertilization. Researchers who have performed late-season N studies more recently in Washington (Miltner and Stahnke, 2004) and New England (Mangiafico and Guillard, 2006; Guillard and Morris, 2008) have suggested N applications should be applied earlier in the season to maximize fertilizer uptake while still achieving a spring color response. In contrast, Walker et.al (2007) found that a single application (73 kg N ha^{-1}) made in mid-Nov. was superior to an application (49 kg N ha^{-1}) in Sept. for growth of tall fescue, Kentucky bluegrass, and perennial ryegrass. Averaged across N programs, Kentucky bluegrass dry matter yield increased from 2004 to 2005, while turf-type tall fescue and perennial ryegrass showed a reduction in dry matter yield following these same years; this indicates a seasonal variation by species for N applications. As a species, turf-type tall fescue showed the least amount of variation among N programs evaluated in this study ranging from 0 to 196 kg N ha^{-1} annually. Researchers in Italy

(Grossi et al., 2005) evaluated seven different late-fall application timings of 100 kg N ha^{-1} of ammonium sulfate applied between Sept. 30th and Dec. 23rd to tall fescue. Conclusions from this study demonstrated that the greatest shoot and leaf density at the end of winter were obtained from N applied after Nov. 11th, though a single late-fall quick release N application was not sufficient in maintaining acceptable tall fescue color or quality for the entire fall-winter period.

Root Growth

Fall-applied N research evaluating late-season root development has yielded mixed results. Powell et al. (1967b) evaluated winter root growth of bentgrass putting greens in Virginia as affected by fall-applied N. Powell's results are difficult to interpret because not all treatments were sampled for roots at every sampling date. The samples that were collected during Feb. indicated that winter rooting increased in treatments that received no fertilizer or low rates (49 kg N ha^{-1} in Oct.) by approximately 30% compared to those samples that received N rates totaling 98 and 294 kg ha^{-1}. By April, no treatment differences were apparent and by June, the treatments receiving 98 and 147 kg N ha^{-1} between Oct. and Feb. had 40 and 50% greater root mass, respectively, compared to the control and treatments receiving the highest N rates (196 and 392 kg ha^{-1}). These data do not agree with several popular press articles that cite this study as evidence that late-season N applications improve low-temperature rooting.

Hanson and Juska (1961) evaluated root and rhizome growth in Kentucky bluegrass in the mid-Atlantic region and found no differences in rhizome development but found some interesting results for root mass. Late winter root mass was significantly greater in the treatments which received 147 kg N ha^{-1} in Sept. as well as those having the 147 kg N ha^{-1} application split between Sept. and Oct. compared to the unfertilized control. Differences in root production in May were not as apparent, with the highest amount of root mass observed in the treatment fertilized in March. Moore et al., (1996) performed research in Iowa which evaluated Kentucky bluegrass root growth comparing late-fall, heavy spring, and balanced N fertility programs. The late-fall program, which included a 49 kg N ha^{-1} application in Nov., produced 9% and 8% more root mass than the spring and balanced N program, respectively.

It was first explained by Stuckey (1941) that active root tip cell division takes place down to 0˚C in the soil. Soil temperatures cool more slowly than air temperatures and photosynthesis continues in low temperatures, suggesting that temperate climates are suitable for root production in the winter months. Consequently, the rooting studies performed by Powell et al. (1967b) and Hanson and Juska (1961) in the Mid-Atlantic region yielded results that may not be applicable to cooler climates where air temperatures decrease to near or below freezing for extended periods (e.g., months). Fall N rooting studies performed north of the mid-Atlantic region (Mangiafico and Guillard, 2006; Kussow, 1992) did not find root mass differences as a result of N applied in either Sept., Oct., Nov., or Dec. Possible explanations for the lack of rooting differences include; less net carbohydrate production than presumed in the late-fall, a rapid consumption of stored carbohydrates in early spring and/or a short duration of fall soil temperatures ideal for root growth. Research by Moon (1990) found a single chilling event substantially inhibits photosynthesis for the following 5-7 days. However, Moon's results are specific to perennial ryegrass (*Lolium perenne* L.), which is less tolerant of low temperatures than other cool-season grasses including Kentucky bluegrass and creeping bentgrass (Rajashekar, et al., 1980).

Reserve Carbohydrates

Reserve non-structural carbohydrates are beneficial for turfgrass to withstand and recover from periods of stress. Historically, this was one of the primary reasons to withhold N fertilizer in the fall as N application was thought to expend reserve carbohydrates through N assimilation necessary for cold tolerance (Beard, 1969). Currently, the accumulation of reserve carbohydrates is often listed among the benefits of late-fall N fertilization (Reike, 1998, Reicher, 2005; Danneberger, 2006; Baird, 2007). Limited research is available regarding the effect of reserve carbohydrate levels in cool temperatures as influenced by N fertilization. Research performed by Powell et al. (1967a) indicated that reserve carbohydrates were lower in high N compared to low N treatments. Powell noted this reduction but also states that late season N did not seriously deplete reserve carbohydrates, and may be considered a benefit if it reduces the need for a spring N application that would rapidly deplete reserve carbohydrates through a surge of shoot growth. Powell also hypothesized that high N fertilization will not always deplete reserve carbohydrates during winter because of a net gain in the carbon energy balance resulting from sustained photosynthetic activity and diminished growth; while possibly true for the mid-Atlantic region, this scenario is not as likely for cooler regions. Zanoni et al. (1969) in Massachusetts found an inverse relationship between soil temperatures and total soluble carbohydrates in turfgrass as well as consistently lower carbohydrates throughout the season with the treatments receiving N. A potential explanation for this could be related to energy required for N assimilation, which has been estimated to be 25% of the energy generated through photosynthesis (Solomonson and Barber, 1990). In Pennsylvania, Watschke and Waddington (1974) also observed lower carbohydrate levels in fall-fertilized treatments, which they attributed to a growth response in Oct. Welterlen and Watschke (1985) evaluated fall-applied N and found no significant differences in total non-structural carbohydrate levels between fertilized and unfertilized plants going into winter. However, in the laboratory, they observed a significant increase in freeze injury of crown tissue as a result of fall-applied N.

Photosynthesis

The plant net carbon energy balance mentioned by Powell et al. (1967a) describes the underlying assumption for many of the frequently proclaimed fall N benefits: as the plant is actively photosynthesizing and low temperatures are limiting top growth then the carbohydrate production must be used elsewhere in the plant, either for belowground root and rhizome development, tillering, or reserve carbohydrate storage. The accompanying notion is that if the plant is metabolically active, N uptake will continue as long as photosynthesis is still occurring. Net photosynthesis rates are believed to increase in cooler temperatures because of a decreased rate of respiration (Liu and Huang, 2001). However, actual photosynthesis measurements of turfgrass in cool temperatures are rare.

In Virginia, Powell et al. (1967a) measured photosynthesis of creeping bentgrass in Jan., Feb., Mar., and June on plots that had been treated with fall and winter nitrogen rates ranging from 49-490 kg N ha^{-1}. Powell observed that net photosynthetic rates in Jan. were the highest measured throughout the year on a day when night temperatures did not freeze and day temperature reached 16˚C. Two days later when the soil was frozen and air temperatures remained below freezing for much of the day, photosynthetic rates were extremely low. Measurements in Feb., Mar., and June showed that net photosynthetic rates were slightly lower than recorded in Jan. when the soil was not frozen. Dark respiration rates for these spring and summer measurements were greater than during the winter, explaining the lower net photosynthetic rates than observed in Jan. Powell et al. (1967a) also reported that the greener plots associated with the high N rates had higher levels of net photosynthesis as well as higher dark respiration. Other low temperature photosynthesis research that discusses N fertilization could not be found, although Moon et al. (1990) studied the impact that chilling temperatures can have on photosynthesis and found that just one chilling event (8˚C day and 5˚C night) inhibited perennial ryegrass photosynthetic capacity 85-90% and remained inhibited for 5-7 days after being returned to 22˚C day and 17˚C night temperatures. This research implies that low temperature swings in late-fall could diminish photosynthesis and thus the usefulness of the recuperative period when fall N is recommended. Considering the implications of Moon's (1990) research, temperatures that inhibit growth without greatly inhibiting photosynthesis may fall in a very short window in northern climates.

Plant Uptake of Fall-Applied N

Fertilizer application effectiveness can be assessed in many ways. However, we feel that the percent of applied N recovered by the plant represents the best way of evaluating and comparing N applications rates and timings from agronomic, economic, and environmental perspectives. Liu et al. (2008) concluded that N use efficiency (recovery by plant/N input x 100) of grasses is between 30 and 60%, with an average of below 50%. Miltner et al. (1996) evaluated N fertilizer uptake and fate in low temperatures with a mass balance study evaluating fall-applied N on Kentucky bluegrass in Michigan. Labeled ^{15}N fertilizer was applied on 8 Nov. 1991 at the rate of 39.2 kg N ha^{-1} and N fate was determined 18 days later. Two- thirds of the fertilizer N applied remained in the thatch and soil and one third was recovered in the verdure. The study was repeated on the same plots nine years later which evaluated high and low N regimes including a ^{15}N labeled urea application on 17 October 2000 applied at a low rate of 24.5 kg N ha^{-1} and a high rate of 49 kg N ha^{-1} (Frank et al., 2006). On December 1st, 45 days after treatment, 17 and 19% of labeled fertilizer N was recovered in the verdure and clippings from the low and high rates, respectively. Although tissue or root N concentrations were not collected during the fall, total fall N uptake appears to be substantially lower than recommended application rates. Walker et al. (2007) reported greater yield of tall fescue fertilized with urea at 73 kg N ha^{-1} in Nov. compared to 49 kg N ha^{-1} in Sept. While tissue N content was not measured (precluding calculation of uptake efficiency), greater yield indicates that the Nov. applications were likely more efficient than the Sept. application. Although not significant, the same trends existed for Kentucky bluegrass and perennial ryegrass.

Other research evaluating plant physiological responses in low temperatures suggest that turfgrass is less proficient at taking up N in the late-fall in northern climates than is often assumed. Researchers evaluating a range of plant species have found that temperatures below those for optimum growth reduce N uptake and adversely affect the process of N assimilation (Dubey and Pessarakli, 2002). In perennial ryegrass and annual ryegrass (*Lolium multiflorum* L.), even a short-term exposure to a low temperature treatment from 25˚C to 15˚C resulted in decreased N uptake (Clarkson et al., 1988). One reason N uptake may be down-regulated during periods of low growth is because N is not needed in the production of new amino acids, nucleic acids, and enzymes for new shoot growth, for which Bowman (2003) accounted for 88-119 % usage of N uptake. Evapotranspiration also decreases markedly in cold temperatures, diminishing the N contribution from mass flow, which is the dominant process by which N moves from soil solution to root surfaces. Xylem transport is also inhibited in cool temperatures, creating a buildup of N in the roots, which inhibits further uptake through diffusion (Laine et al., 1994).

Environmental Considerations

Late-fall is considered a susceptible time of year for nitrate leaching as precipitation rates greatly exceed evapotranspiration rates in the many regions of the world. While not the focus of this review, the environmental fate of fall-applied N to turfgrass has been more extensively studied. Petrovic (1990) compiled a comprehensive review of the leaching studies conducted for turfgrass systems. While some studies found substantial portions of N fertilizer in the leachate, Petrovic, along with other researchers, have concluded that proper management strategies can reduce the risk of groundwater nitrate contamination (Starr and DeRoo, 1981; Miltner et al., 1996; Horgan et al., 2002; Frank et al., 2006; Paré et al., 2006). Petrovic (1990) also concluded that there is a high risk for leaching losses from late-fall N fertilization due to restricted plant uptake, decreased microbial immobilization, denitrification, and the disparity between high precipitation and low evapotranspiration. Several researchers have evaluated this risk of late-fall N applications and have collected elevated nitrate levels in the leachate (Petrovic et al., 1986; Geron et al., 1993; Liu et al., 1997; Guillard and Kopp, 2004; Mangiafico and Guillard, 2006). Petrovic (1990) speculated that while late-fall N fertilization has potential agronomic benefits; the environmental consequences may overshadow the positive impact in areas susceptible to groundwater contamination. Mangiafico and Guillard (2006) concluded that late-fall fertilization in New England could be replaced by lower rates and earlier application timings to maintain both water and turf quality.

Another potential fate for excess soil N is gaseous loss through denitrification. Although not specific to late-fall N applications, Horgan et al. (2002) performed a mass balance of labeled fertilizer N applications and found 19% of applied N in N_2 or N_2O emissions in the spring and summer. A field study in Alberta (Malhi and Nyborg, 1983) that evaluated late-fall N applied to cleared cropland found total losses over winter averaging a total of 67% for potassium nitrate, 38% for urea, and 10% for ammonium sulfate applied to the soil at the rate of 49 kg N ha^{-1}. Based on minimal downward movement of labeled N in the soil, the researchers concluded that the majority of these losses were from denitrification during the following spring. While this research was not performed on turfgrass, it highlights the potential for denitrification losses of fall-applied N as the soils warm the following spring.

CONCLUSIONS

The benefits and recommendations for late-fall N fertilization are widely accepted across the cool-season region; however, after a thorough literature review, we suggest that recommendations be further evaluated through research and specified according to particular climatic regions, turfgrass species, and land use situations. The research regarding environmental losses of soluble N applied in the late-fall indicate a potential for significant N losses through leaching (Liu et al., 1997; Guillard and Kopp, 2004; Mangiafico and Guillard, 2006) and denitrification, bringing into question the actual costs-benefits of fall-applied N. With increasing N fertilizer costs and concern of losses from turfgrass systems, it is critical that turfgrass managers understand the agronomic and physiological benefits of their N fertilizer applications. The main reason that N fertilization in the late-fall is so highly regarded appears to be based on the assumption of increased photosynthesis and rooting. However, minimal research on photosynthesis rates exists and what has been reported does not unanimously support such benefits. Applying this notion of increased photosynthesis from late-fall N fertilization across all cool season turfgrass zones and species without supporting research is not sound judgment. Additionally, studies examining the influence of fall nitrogen rates and timings on root growth are highly mixed and indicate that responses are dependent on climatic zone, seasonal variability, and turfgrass species. Studies performed in more northern climates demonstrate that root growth may not be affected by fall-applied N (Kussow, 1992; Mangiafico and Guillard, 2006). Similarly, the perception that late-fall fertilization hastens spring green-up without a surge of top growth also appears to be highly dependent on species and seasonal weather conditions. For example, the work by Walker et al. (2007) in Indiana showed a Kentucky bluegrass yield increase averaged across late-fall N applications from 2004 to 2005, while turf-type tall fescue and perennial ryegrass had reduced yield between these same years and N treatments. Furthermore, very little research exists which describes the uptake potential of cool-season grasses in cool temperatures; the research that has calculated fertilizer uptake efficiency indicates uptake potential is low, suggesting that recommended late-fall N fertilizer rates are too high. Additional work is required to determine the appropriate late-fall N fertilizer rates, sources, and timings for cool-season turfgrass in northern climates, while understanding that recommendations should be based on seasonal variability. These studies should evaluate agronomic responses such as color, quality, rooting, and fertilizer uptake efficiency; and physiological responses such as photosynthetic rates and carbohydrate accumulation.

Table 1: Late-fall nitrogen research in northern turfgrass environments

Site information				Nitrogen application		Measurement								
Location	Date	Turf species†	Soil type‡	Source§	Application Time	Root growth	Clipping yield	Uptake	Color	TQ¶	CT#	PN††	CHO‡‡	Reference
Mid-Atlantic														
Maryland	1959-60	KBG	-	NH_4NO_3	Sept. - Mar	xxx	xxx							Hanson and Juska, 1961
Pennsylvania	1971-72	KBG	-	Urea, UF, MO, IBDU, Urex	May - Sept.		xxx						xxx	Watschke and Waddington, 1974
Pennsylvania	1982	PRYE	-	NH_4NO_3	Sept.						xxx		xxx	Welterlen and Watschke, 1985
Rhode Island	1965	KBG	ST loam	10-2.6-3.3	May - Nov.		xxx			xxx				Ledeboer and Skogley, 1973
Rhode Island	1965	CRF	ST loam	10-2.6-3.3	May - Nov.		xxx			xxx				Ledeboer and Skogley, 1973
Rhode Island	1965	COB	ST loam	10-2.6-3.3	May - Nov.		xxx			xxx				Ledeboer and Skogley, 1973
Rhode Island	1966	KBG	ST loam	UF, NH_4NO_3	April - Nov.		xxx			xxx				Ledeboer and Skogley, 1973
Rhode Island	1970	KBG	-	NH_4NO_3	Oct. - Dec.		xxx		xxx		xxx			Wilkinson and Duff, 1972
Rhode Island	1990-91	PRYE	ST loam	Urea, MU, NH_4NO_3	April, June, Nov.		xxx	xxx						Liu and Hull, 2006
Rhode Island	1990-91	TF	ST loam	Urea, MU, NH_4NO_3	April, June, Nov.		xxx	xxx						Liu and Hull, 2006
Rhode Island	1990-91	KBG	ST loam	Urea, MU, NH_4NO_3	April, June, Nov.		xxx	xxx						Liu and Hull, 2006
Virginia	1965	CBG	-	NH_4NO_3	Oct. - Feb.		xxx		xxx			xxx	xxx	Powell et al., 1967a
Virginia	1965	CBG	-	NH_4NO_3, UF	Oct. - Feb.		xxx		xxx				xxx	Powell et al., 1967a
Virginia	1965	TF	-	NH_4NO_3, UF	Oct. - Feb.		xxx		xxx				xxx	Powell et al., 1967a
Virginia	1966	CBG	TS/sand	NH_4NO_3	Oct. - June	xxx								Powell et al., 1967b
New England														
Connecticut	2000-03	KBG/CRF	Loam SD	NH_4/Urea	Sept. - Dec.	xxx	xxx		xxx					Mangiafico and Guillard, 2006
Connecticut	2006	KBG	-	Urea	Sept.			xxx	xxx					Guillard and Morris, 2008
Massachusetts	2000-03	PRYE	ST loam	Urea	April - Nov.		xxx				xxx			Webster and Ebdon, 2005
Pacific NW														
Washington	1998-2000	PRYE	SD loam	$(NH_4)_2SO_4$, PCU, PSCU, IBDU	Nov. - Feb.		xxx			xxx				Miltner et al., 2004
Washington	1998-2000	KBG	ST loam	$(NH_4)_2SO_4$, PCU, PSCU, IBDU	Nov. - Feb		xxx			xxx				Miltner et al., 2004
Washington	2000-02	PRYE	SD loam	10-0.9-5, 24-1.3-8.3	April - Nov.				xxx	xxx				Miltner et al., 2005

Table 1 (cont.)

Table 1 (cont.)

Site information				Nitrogen application		Measurement								
Location	Date	Turf species†	Soil type‡	Source§	Application Time	Root growth	Clipping yield	Uptake	Color	TQ¶	CT#	PN††	CHO‡‡	Reference
<u>Midwest</u>														
Illinois	1982-85	KBG	ST loam	Urea, IBDU, SCU	April - Nov.		xxx		xxx					Wehner et al., 1988
Illinois	1988-91	KBG	ST loam	Urea, MO, SCU	Oct. - Jan.		xxx		xxx					Wehner and Haley, 1993
Indiana	2003-05	TF	ST loam	Urea, SCU	Sept. - July		xxx	xxx	xxx	xxx				Walker et al., 2007
Indiana	2003-05	KBG	ST loam	Urea, SCU	Sept. - July		xxx	xxx	xxx	xxx				Walker et al., 2007
Indiana	2003-05	PRYE	ST loam	Urea, SCU	Sept. - July		xxx	xxx	xxx	xxx				Walker et al., 2007
Indiana	2003-06	KBG	ST loam	Urea, SCU, PCU	Sept., Oct., Nov.		xxx		xxx	xxx				Bigelow et al., 2007
Iowa	1986-88	KBG	Loam	Urea, UF, MU, MLU	April - Nov.	xxx	xxx			xxx				Moore et al., 1996
Michigan	1990-2002	KBG	SD loam	Urea	May - Oct.	xxx	xxx	xxx						Frank et al., 2006
Michigan	1991-93	KBG	SD loam	Urea	April - Nov.		xxx	xxx						Miltner et al., 1996
Michigan	1994-95	KBG	SD loam	$(NH_4)_2SO_4$	June - Nov.		xxx	xxx						Engelsjord et al., 2004
Michigan	1994-95	PRYE	SD loam	$(NH_4)_2SO_4$	June - Nov.		xxx	xxx						Engelsjord et al., 2004
Wisconsin	1988-90	FF/KBG	-	Urea, IBDU	May - Nov.	xxx	xxx	xxx	xxx					Kussow, 1992
Wisconsin	1988-90	CBG	-	Urea, IBDU	May - Nov.	xxx	xxx	xxx	xxx					Kussow, 1992
<u>International</u>														
Italy	2002-03	TF	Cl loam	$(NH_4)_2SO_4$	Sept. - Dec.		xxx		xxx	xxx	xxx			Grossi et al., 2005
Turkey	1994-96	PRYE/KBG/CRF/CF	SD loam	NH_4NO_3	April - Sept.		xxx		xxx	xxx	xxx			Oral and Acikgoz, 2001
Unknown	1930-36	KBG	-	NH_4SO_4	Apr. - Oct.			xxx			xxx		xxx	Caroll and Welton, 1939

† KBG, Kentucky bluegrass; PRYE, perennial ryegrass; CRF, creeping red fescue; COB, colonial bentgrass; TF, tall fescue; CBG, creeping bentgrass; FF, fine fescue; CF, chewings fescue
‡ ST loam, silt-loam; SD loam, sandy-loam; Loam SD, loamy-sand; CL loam, clay-loam; TS, topsoil
§ UF, urea-formaldehyde; MO, milorganite; IBDU, isobutylidene diurea; Urex, extruded urea-paraffin matrix; MU, methylene urea; SCU, sulfur coated urea; PCU, polymer coated urea; MLU, methylol urea; PSCU, polymer and sulfur coated urea
¶ Turfgrass quality
# Cold tolerance
†† Photosynthesis
‡‡ Carbohydrate

CHAPTER 2. LITERATURE REVIEW

CREEPING BENTGRASS ESTABLISHMENT IN ANNUAL BLUEGRASS FAIRWAYS

INTRODUCTION

Fairways make up the largest portion of intensively maintained and high quality turfgrass areas on a golf course (Lyman et al., 2007) and creeping bentgrass (*Agrostis stolonifera* L.) is desirable turf for use on fairways. Golf course fairways that are established with creeping bentgrass often experience invasion by annual bluegrass (*Poa annua* L.), which may easily become the dominant species over time (Christians, 2000). Annual bluegrass disrupts the desired creeping bentgrass monostand, affecting playability, aesthetic appearance, and turfgrass management programs. In an effort to combat annual bluegrass, golf course superintendents have utilized interseeding in combination with herbicide or plant growth regulator use as a means of establishing new creeping bentgrass into a predominantly annual bluegrass stand. Extensive research has been conducted on creeping bentgrass conversion and eradication of annual bluegrass in turfgrass systems, though the majority has been met with limited success. This literature review will set up the basis for controlling annual bluegrass and focus on previous researchers attempts to convert to creeping bentgrass in golf course settings.

ANNUAL BLUEGRASS INVASION AND ISSUES

In intensively maintained turfgrass situations, annual bluegrass is the most widespread weed species (Vargas and Turgeon, 2004). One of the earliest reports of controlling annual bluegrass on golf courses in the United States dates back to 1922 at the

Old Elm Club. The author, W.A. Alexander, discusses success in controlling annual bluegrass on fescue/bentgrass putting greens by painstakingly cutting it out by hand, while other golf courses in the area have "nothing but *Poa annua* on their putting greens, and of course have relatively poor greens for a month or two at least" (Alexander, 1922). Today, annual bluegrass continues to be a major problem plaguing golf courses (Christians, 2000).

Annual bluegrass is such an aggressive weed that it often becomes the dominant species on golf courses fairways (Branham, 1990; Christians, 2000), responding quickly to disturbance by producing new seedlings from its diverse seed bank (Rossi, 1999) and taking advantage of agronomic mismanagement and the weaknesses in other species (Beard, 1970). In addition, the genetic diversity of annual bluegrass has assured its survival (Christians, 1990). Annual bluegrass is a winter annual that germinates in the late summer, grows and sets seed throughout the fall, and then dies in the late spring. In a golf course environment, perennial grasses are required in order to produce a consistent playing surface. There are weak perennial biotypes of annual bluegrass (*Poa annua* L. spp. *reptans* (Hauskins)) that avoid the annual dying process, producing a playable surface under optimum growth conditions, though the disadvantages of annual bluegrass far out weigh any of its desirable attributes (Christians, 1990). Annual bluegrass is a poor performing turfgrass, having issues with light green color, seedhead production, drought and head stress, disease susceptibility, and lack of surface uniformity (Harivandi et al., 2008).

CREEPING BENTGRASS USE ON FAIRWAYS

Creeping bentgrass is an excellent grass for fairway use due to its tolerance of low mowing heights (< 12.5 mm), quick recovery potential, excellent playability, and improved texture and density (Christians, 2000). Creeping bentgrass is becoming increasingly popular for golf course fairways due to improved cultivars, more management tools and knowledge, and specialized maintenance equipment (Reicher and Hardebeck, 2002). Creeping bentgrass fairways are more tolerant to many of the abiotic and biotic stresses that plague annual bluegrass, and seed head production is not an issue (Murphy et al., 2005).

Seeding

Traditionally creeping bentgrass has been seeded during the optimum cool-season turfgrass growth period of late-summer or early-fall to avoid high temperature and drought pressures of the summer months, though this timing might not be optimum when seeding into an existing stand of annual bluegrass, due to competition from this germinating winter annual (Murphy et al., 2005). Annual bluegrass seed germination increases in the late summer when soil temperatures drop to 21°C and below (Engel, 1967), putting tremendous pressure on bentgrass seeded fairways, even if they were treated with a non-selective herbicide (Reicher and Hardebeck, 2002). Creeping bentgrass seed has the ability to germinate at higher temperatures than annual bluegrass (Kane, 1986) and annual bluegrass becomes physiologically stressed in the late spring after producing seed heads (Watschke, 1997). Based on this, Murphy et al. (2005) conducted a field experiment in New Jersey to determine the effect of seeding time while overseeding into a previously glyphosate-treated stand of annual bluegrass. These researchers concluded that competition from annual bluegrass is significantly reduced when seeding creeping bentgrass in June or August (80% establishment) versus September or October (50% establishment); these ratings were taken one year after seeding. Henry et al. (2005) attempted conversion of existing creeping bluegrass (*Poa annua* L. spp. *reptans* (Hauskins)) in a golf green situation through overseeding four cultivars of bentgrass on three dates over two years without the use of nonselective herbicides. Similar to other researchers, they found that successful conversion from creeping bluegrass to creeping bentgrass is increased when using summer seeding dates and improved creeping bentgrass cultivars, achieving a maximum of 72% creeping bentgrass coverage at 24 months after seeding from a July seeding date, although factors such as golfer or maintenance traffic did not exist in this study. Once a creeping bentgrass population is established, the objective is to utilize maintenance techniques that encourage the creeping bentgrass over the annual bluegrass. These techniques include sound fertility, irrigation, and mowing programs, in combination with herbicides or plant growth regulators (PGRs).

Seedling Competition and Bentgrass Varieties

The most important development associated with this type of overseeding has been the continual introduction of improved cultivars, and presently there are more creeping bentgrass choices than ever before. Beard et al. (2001) evaluated the competitive ability of thirteen creeping bentgrass cultivars against annual bluegrass, and concluded that cultural control of annual bluegrass is possible by selecting new creeping bentgrass cultivars with higher shoot densities. The cultivars having the highest shoot densities (> 2000 shoots dm^{-2}), and therefore the best competitiveness with annual bluegrass, included ‘Penn G2’, ‘Penn G6’, ‘Seaside II’, and ‘Penn A1’. This was confirmed by Murphy et al. (2005) in a New Jersey bentgrass overseeding study, which evaluated the bentgrass cultivars ‘Penn A-4’, ‘L-93’, ‘SR 7200’, ‘Providence’, and ‘Penncross’ for establishment competitiveness with annual bluegrass. They concluded that cultivars with higher shoot densities are more successful in establishing creeping bentgrass into stands of annual bluegrass.

CONTROLLING ANNUAL BLUEGRASS

Attempts to control annual bluegrass have been met with limited success (Christians, 1990) and there is no single annual bluegrass control strategy for creeping bentgrass fairways (Dernoeden, 2000). These attempts include cultural strategies, mechanical removal, pre- and post-emergent herbicides, PGRs, and even biological control (Christians, 1996).

Cultural management

Cultural strategies are an integral component of any turfgrass management program that aims to favor creeping bentgrass over annual bluegrass. The competitiveness of annual bluegrass on fairways can be reduced by clipping collection, alleviating soil compaction, improving drainage, using lightweight equipment, decreasing shade, and aerating at a time when annual bluegrass seed is not germinating (Dernoeden, 2000). In an attempt to determine the cultural management effects on species dominance in a mixed creeping bentgrass/annual bluegrass stand maintained as a golf course fairway, Gaussoin and Branham (1989) evaluated various levels of clipping management, irrigation, nitrogen fertility, overseeding, and PGR application. These researchers counted annual bluegrass seeds in soil where clippings had been returned or removed found between 50 and 420 viable annual bluegrass seeds kg^{-1} of soil, plots with clipping removal contained 60% fewer viable seeds, indicating the potential to reduce the annual bluegrass seed bank by removing clippings. Irrigation frequency was more important than amount, and maintaining constant surface moisture seemed to favor existing annual bluegrass plants and encourage annual bluegrass seed germination. Additionally, contrary to popular belief, higher nitrogen fertility did not consistently increase annual bluegrass over time. Creeping bentgrass overseeding was effective when used in combination with daily irrigation or application of the PGR flurprimidol. The PGR mefluidide increased annual bluegrass in certain cases. These researchers concluded that the reason for annual bluegrass persistence cannot be isolated to one cultural practice, but rather depends on the interactions of all factors in a management program.

Plant Growth Regulator Use

Successful establishment of overseeded bentgrass depends on the existing annual bluegrass being non-competitive. Plant growth regulators have been extensively tested for use in conversion, though these approaches have been inconsistent and rarely provide complete conversion from annual bluegrass (Gaussoin and Branham, 1989; Reicher and Hardebeck, 1997; Reicher and Hardebeck, 2002; Borger et al., 2008; McCalla et al., 2010). Researchers in Indiana studied the use of trinexapac-ethyl (TE) combined with seeding over 3 years in an attempt to gradually convert annual bluegrass fairways to creeping bentgrass. They obtained a maximum of 3% creeping bentgrass cover and concluded that it would be very difficult, if not impossible, to convert annual bluegrass to creeping bentgrass without using glyphosate and overseeding (Reicher and Hardebeck, 1997; Reicher and Hardebeck, 2002). In Pennsylvania, researchers studied the potential of paclobutrazol, trinexapac-ethyl, and melfluidide to selectively reduce annual bluegrass populations in a fairway comprised of 65% annual bluegrass and 35% bentgrass. These PGRs provided no reduction in annual bluegrass, although the non-treated plots increased in annual bluegrass by approximately 30% after 1 year (Borger et al., 2008). Still, other researchers have proven the effectiveness of selectively controlling annual bluegrass in creeping bentgrass with paclobutrazol (Bell et al, 2004; McCullough et al., 2005), flurprimidol (Bigelow et al., 2007), and ethofumesate (Woosley et al., 2003) in golf course settings over extended periods of time. However, to achieve any long term reduction in annual bluegrass, a PGR must be applied on a three to six week interval during periods of active growth (Dernoeden, 2000); this is a costly approach and only feasible on fairways with low populations of annual bluegrass.

Herbicide Use

Attempts to control annual bluegrass with herbicides date back to the 1930's, when control became associated with the use of lead arsenate (Christians 1996). However, most post-emergent herbicides that effectively control annual bluegrass also suppress creeping bentgrass, limiting these chemical control options in mixed annual bluegrass/creeping bentgrass fairways (McCarty, 1999). Pre-emergent herbicides have the ability to reduce annual bluegrass establishment, but they rarely provide acceptable levels of control once annual bluegrass has been established (Dernoeden, 2000).

The herbicide bispyribac-sodium has been tested extensively in recent years for selective control of annual bluegrass in creeping bentgrass fairways. Bispyribac-sodium is more rapidly metabolized by creeping bentgrass than annual bluegrass (McCullough et al., 2009), which explains some of the success with this chemical. However, applications of bispyribac-sodium can cause significant chlorosis for up to three weeks on creeping bentgrass maintained as fairway (McDonald et al., 2006). Effective protocols exist for annual bluegrass control with bispyribac-sodium and the most success has been achieved with weekly applications (McCullough et al., 2010), which may not be feasible for most golf courses. Additionally, courses with a high percentage of annual bluegrass will see virtually no benefit of using this selective herbicide.

Complete fairway turf conversion practices involve the use of nonselective herbicides, seedbed preparation, and seeding (Reicher and Hardebeck, 2002; Turgeon, 2002). It is important to choose a nonselective herbicide that has no soil activity, which will allow for adequate bentgrass germination (Watschke, 1997). One of the easiest and least disruptive methods would be application of the nonselective herbicide glyphosate followed by overseeding directly into the dead fairway with a slit or groove seeder. Glyphosate is a systemic, nonselective, post-emergent herbicide that is readily translocated through a plant system via phloem (Su et al., 2009) and is inactive in the soil due to adsorption, environmentally sound due to low application rates (Mosier et al., 1990), and has a low leaching and volatilization potential (Franz et al., 1997). Bingham et al. (1980) applied glyphosate at rates of 0, 0.14, 0.28, 0.56, 1.12, and 2.24 kg a.i. ha^{-1}

to two and four month old plants of perennial ryegrass (*Lolium perenne* L.), Kentucky bluegrass (*Poa pratensis* L.), creeping red fescue (*Festuca rubra* L.), orchardgrass (*Dactylis glomerata* L.), and highland bentgrass (*Agrostis tenuis* L.), and found that glyphosate applied at low dosages had variable effects on each species, with highland bentgrass being the most susceptible. These researchers suggest that there is potential for glyphosate to be used as a selective bentgrass control herbicide in a Kentucky bluegrass turf area. Su et al. (2009) evaluated sub-label glyphosate rates on nine different turfgrass species and found that 'Tiger II' creeping bentgrass was not affected by the lowest application rate, while 'Midnight' Kentucky bluegrass was highly susceptible. In a greenhouse experiment, Goss et al. (2005) demonstrated survival of multiple plant species after two glyphosate applications of 1.68 kg a.e. ha^{-1}. The number of plants surviving the initial glyphosate application ranged from 0 to 8% annual bluegrass, 12 to 42% creeping bentgrass, 17 to 33% large crabgrass (*Digitaria sanguinalis* L.), and 0 to 67% dandelion (*Taraxacum officinale* L). Other researchers have reported glyphosate tolerance variability in grass species (Lym and Kirby, 1991; Webster et al., 2004). The Razor Pro (41% glyphosate) label from Nufarm Americas Inc. recommends significantly lower rates for control of annual bluegrass (0.42 kg a.i. ha^{-1}) than for that of bentgrass (1.68 kg a.i. ha^{-1}), indicating the potential to selectively control annual bluegrass in a bentgrass system (Razor Pro Herbicide Label, Burr Ridge, IL).

Soil Fumigation

One major downfall of the glyphosate method is that it does not control the seed bank of annual bluegrass (Park and Landschoot, 2003; Branham et al., 2004). Soil fumigation is by far the most effective means of addressing the annual bluegrass seed bank. The two most common products that have been used in the golf course industry are methyl bromide and dazomet. Methyl bromide has been shown to deplete the stratospheric ozone layer and has therefore been phased out completely by the Environmental Protection Agency (EPA, 2011). Dazomet has been the soil fumigant of choice to replace methyl bromide. Park and Landschoot (2003) tested the effects of dazomet rate and plastic covering on annual bluegrass seedling emergence in a golf course fairway setting, concluding that dazomet is effective in providing up to a 98% reduction in annual bluegrass seedlings when covered with plastic. Non-covered dazomet treated plots had greater than 90% reduction in annual bluegrass seedlings when compared to the non-treated plots. In a similar research study, Branham et al. (2004) tested various dazomet rates and application timing of either spring or fall for controlling annual bluegrass seed. Overall they showed a 46 and 78% reduction of viable annual bluegrass seed in the spring and fall, respectively. Conclusions from this trial demonstrate that eradication of annual bluegrass is not likely and environmental conditions affect the success. In large-scale situations, dazomet cost, labor required, and environmental implications hinder its use. In a 2010 Midwest golf course renovation project the decision to use dazomet increased the cost by $280,000 (Dr. Brian Horgan, personal communication) and dazomet use warrants golf course closure, resulting in significant loss of revenue. The Environmental Protection Agency considers dazomet to be acutely toxic to mammals, birds, aquatic invertebrates, and fish (EPA, 2008). These statistics alone make dazomet use an undesirable choice for fairway conversion projects.

METHODS FOR SEEDING

In addition to improved cultivars of creeping bentgrass, the turfgrass industry has also witnessed an increase in the equipment available for the conversion process. Researchers have evaluated numerous methods for opening up the turfgrass canopy to allow for seed to soil contact, including vertical mowing and core aeration (Kendrick and Danneberger, 2002; Reicher and Hardebeck, 2002; Henry et al., 2005; Murphy et al., 2005), spiking (Bowman, 1998), scalping (Zuk and Fry, 2005) and slit-seeding (Keeley and Zhou, 2005). Dant and Christians (2005) evaluated five methods for introducing glyphosate-resistant creeping bentgrass seed into a stand of 'Penncross' creeping bentgrass. Results from this study showed that surface preparation method had little to no effect on the establishment of glyphosate-resistant creeping bentgrass, indicating that the method employed is of minor importance.

SUMMARY

Clearly, conversion from annual bluegrass to creeping bentgrass in a golf course fairway setting is a difficult task at best. For the conversion process to be most effective, a combination of the strategies proven by other researchers must be employed. These researchers have shown that creeping bentgrass establishment in an annual bleugrass system is best accomplished by choosing a summer seeding date when annual bluegrass germination and growth is suppressed. Glyphosate has been proven to be a safe, effective, and relatively inexpensive product. Additionally, the use of newer creeping bentgrass cultivars shows promise for competing with annual bluegrass over time.

CHAPTER 3. LATE-SEASON NITROGEN UPTAKE, PARTITIONING, AND UTILIZATION IN CREEPING BENTGRASS PUTTING GREENS

OVERVIEW

Late-fall nitrogen (N) fertilization is commonly recommended for turfgrass nutrition in the Upper Midwest, although research identifying its efficiency and subsequent benefit is lacking for creeping bentgrass (*Agrostis stolonifera* L.). Furthermore, rising N costs and concerns of off-target N loss have brought late-fall N applications into question from a cost-benefit perspective. The objectives of this research were to evaluate the efficiency and agronomic benefits of late-fall N applications on creeping bentgrass putting greens in order to determine the most effective timing and rate for N fertilization. Silt loam and sand based putting greens were established with 'L-93' creeping bentgrass (*Agrostis stolonifera* L.) seven years prior to this study in St. Paul, MN and Madison, WI. Labeled ^{15}N ammonium sulfate was applied to in-ground lysimeters at rates of either 25 kg N ha^{-1} or 50 kg N ha^{-1} in mid-Oct. or mid-Nov. 2009, and a spoon feeding approach of 10 kg N ha^{-1} was applied in five equally spaced applications (totaling 50 kg N ha^{-1}) between 25 Sept. and 15 Nov., 2009. The labeled ^{15}N was used to quantify uptake and partitioning to verdure, thatch, and roots in the late-fall and spring; root mass was also measured. The same treatments were applied to plots with unlabeled ammonium sulfate to determine utilization, as determined by turgrass quality, green color index, and clipping yield and N content. Nitrogen fertilizer applied up to mid-Oct. increased quality, green color, and yield prior to winter, while the benefit of mid-Nov. applications was not apparent until the following spring; higher N rates increased these effects. Greatest cumulative clipping yields were associated with all 50 kg N ha^{-1} rates, and application timing was not a significant factor. Clipping N content increased following spoon-feeding and Oct. applications in the fall, indicating good transport of N fertilizer to shoots prior to winter. Root growth was not affected by N application. Nitrogen applications were taken up efficiently by roots, thatch, and verdure from fall-harvested lysimeters; accounting for 50.8% (silt-loam) and 46.5% (sand based) labeled ^{15}N recovered. The efficiency of 25 and 50 kg N ha^{-1} applications was similar under optimum weather conditions, but this efficiency was reduced in environments conducive to N loss and reduced plant uptake. The most efficient use and consistent benefit from late-fall applied N occurred with the spoon-feeding approach.

INTRODUCTION

Defining human and environmental turfgrass benefits, while reducing resource inputs and costs, is a significant challenge for the turfgrass industry (Liu et al., 2008). From a cost-benefit perspective, golf course superintendents are being pressured to produce a healthy playing surface while maximizing efficiency in their fertilization programs. Nitrogen (N) is the fertilizer nutrient most important in maintaining turfgrass density and color, as well as providing resistance and recovery from stress (Bowman, 2003). Efficient fertilizer N use has been the goal of turfgrass researchers for many years (Hull and Liu, 2005). In northern climates, late-fall N fertilization of cool-season turfgrasses is a widely accepted practice (Miltner et al., 2004), with recommended rates ranging from 25 to 49 kg N ha^{-1} for bentgrass putting greens, depending on N source (Kussow, 1988). The recommended timing for this application is just after turfgrass shoot growth ceases due to low air temperatures (Wilkinson and Duff, 1972; Kussow, 1988), while the roots are still able to absorb nutrients (Snow, 1982; Landschoot, 2010). Soluble N sources, such as urea or ammonium sulfate, which are readily plant available, are commonly used for these applications (Miltner et al., 2004; Koski and Street, 2010). Reported benefits of late-fall N fertilization include improved fall and/or early spring color or quality (Powell et al., 1967a; Wilkinson and Duff, 1972; Ledeboer and Skogley, 1973, Wehner et al., 1988; Wehner and Haley, 1993; Miltner et al., 2004; Grossi et al., 2005; Mangiafico and Guillard, 2006; Bigelow et al., 2007), increased rooting (Hanson and Juska, 1961; Powell et al., 1967b; Moore et al., 1996), and an increase in carbohydrates (Schmidt and Shoulders, 1971).

Powell et al. (1967a) first reported the benefits of late-fall N cool-season turfgrass fertilization. These researchers investigated fall and winter N fertility on creeping bentgrass and tall fescue (*Festuca arundinacea* Shreb.) in Virginia, finding that late-fall and winter N fertilization of cool-season grass improved year-round color and quality without stimulating foliar growth in the winter. Reserve carbohydrates were also measured, and the results showed that liberal late-fall and winter N applications, totaling 500 kg N ha^{-1}, did not deplete soluble carbohydrates because low temperatures inhibited top growth; although this N rate is not relevant to turfgrass managers today. Powell et al. (1967b) also studied winter root growth of creeping bentgrass and found that root growth increased with ammonium nitrate applications of 50 to 150 kg N ha^{-1} applied between October and February. Root growth was low or negative in the absence of fall-applied N or heavy applications totaling 400 kg N ha^{-1} applied from Oct. to April. Based on this and similar research, Schmidt and Shoulders (1971) recommended N applications in the fall and winter to increase carbohydrates, improve color, and produce more roots.

However, inconsistencies in more recent late-fall N research studies have failed to support the notion of increased carbohydrates (Watschke and Waddington, 1974; Welterlen and Watschke, 1985) and root growth (Mangiafico and Guillard, 2006; Lloyd, 2009). Additionally, an increased potential for nitrate leaching losses associated with the late-fall fertilizer applications has been suggested (Petrovic, 1990; Geron et al., 1993; Miltner et al., 1996; Frank et al., 2006; Mangiafico and Guillard, 2006), bringing into question the overall efficiency of this application.

Mangiafico and Guillard (2006) evaluated four different late-fall N application timings on a mixed Kentucky bluegrass (*Poa pratensis* L.) and creeping red fescue (*Festuca rubra* L.) home lawn in Connecticut. A complete fertilizer, 10-7-17 (60% NH_4-N and 40% urea-N) was applied at 49 kg N ha^{-1} on dates of 15 Sept., 15 Oct., 15 Nov., and 15 Dec. While no shoot density or root mass differences were detected based on treatment, significant differences for chlorophyll concentration and clipping yield were reported. Treatments applied on 15 Oct. or later produced greater mean chlorophyll concentration and clipping yields than the unfertilized control or the 15 Sept. application. Nitrate leaching losses were greater for plots receiving N applications later into the fall, indicating reduced N uptake efficiency during cooler weather. Tissue N uptake was not reported.

Research on N uptake and recovery by turfgrass specific to late-fall applications is limited. Lloyd (2009) studied late-fall N uptake potential and physiological responses of creeping bentgrass, Kentucky bluegrass, and annual bluegrass (*Poa annua* var. *reptans* L.) in a controlled environment with two replications. Ammonium sulfate enriched with 10 atom-% ^{15}N was applied at rates of 0, 25, 49, and 98 kg N ha^{-1} to grasses acclimated to temperatures corresponding to 40-year averages of either 15 Sept., 15 Oct., or 15 Nov. in Madison, WI. Net canopy photosynthesis and root mass increased with decreasing temperatures (i.e. temperatures later into the fall) though this difference was not affected by N application rate. Fertilizer N uptake was reduced from Sept. to Oct., and again from Oct. to Nov. Averaged across N rates and species, 73% of ^{15}N-labeled fertilizer was taken up from the Sept. application, whereas 57 and 38% were taken up from Oct. and Nov. applications, respectively. These results demonstrate a decreased potential for N uptake later into the fall. Verdure and root accumulation of fertilizer N specific to creeping bentgrass showed no difference in efficiency of N uptake (N recovered / N applied x 100) between applications of 25 and 49 kg N ha^{-1} on any treatment month; however, if efficiency remained the same, then more fertilizer N was lost from the higher application.

Miltner et al. (1996) studied leaching and uptake of urea applied to Kentucky bluegrass in Michigan with either April through late-Sept. (spring) or early June through early-Nov. (fall) application regimes. April and Nov. applications were made with ^{15}N-labeled urea at a rate of 39.2 kg N ha^{-1} to determine uptake efficiency and leaching based on time of application. At eighteen days after treatment (DAT), 98% of the ^{15}N-labeled urea was recovered in the verdure and thatch from applications on 8 Nov.; whereas applications on 26 April recovered 67% in the verdure and thatch at eighteen DAT. This indicates a rapid uptake and transport of Nov. applied N, as compared to April applications. Root N recovery was not reported. Nitrate leaching was limited in this study (0.28% over 2 years), although late-fall N treatments had significantly more nitrate present in the leachate. On the same plots, Frank et al. (2006) studied N uptake and leaching at annual rates of 98 or 245 kg N ha^{-1} applied as urea. Applications in mid-Oct. were made with ^{15}N-labeled urea at rates of either 24.5 (low) or 49 (high) kg N ha^{-1}. Recovery of labeled fertilizer N in verdure and thatch at fifteen DAT accounted for 24 and 27% from low and high rates, respectively. This recovery is significantly lower than that presented by Miltner et al. (1996) ten years prior. Root recovery values were 15% (low) and 10% (high), from samples collected six months after application. The greatest amount of labeled N was recovered in the sandy-loam soil on all sampling dates, up to two years after application. Nitrate leaching values were ten times higher for the high N application; totaling 11% of 49 kg N ha^{-1} applied recovered in the leachate after two years of sampling. They suggested that single late-fall applications to mature turfgrass of 49 kg N ha^{-1} or greater soluble fertilizer sources should be avoided to minimize leaching losses.

Peer-reviewed putting green field research on late-fall N fertilization in the Midwest is not available. Therefore, the objectives of this research were to 1) evaluate timing and rate effects on N fertilizer uptake efficiency and 2) determine the effect of root zone composition on fall-applied N from an agronomic benefit and N utilization standpoint. We hypothesized that higher N rates applied later into the fall would result in lower uptake efficiency, and therefore a greater potential for N loss. Silt-loam root zones should retain more N fertilizer, resulting in an increased turfgrass response.

MATERIALS AND METHODS

Field experiments were conducted beginning in Sept. 2009 and continued through June 2010 at two locations: the Turfgrass Research, Outreach, and Education (TROE)

Center in St. Paul, MN and the O.J. Noer Turfgrass Research and Education Facility in Madison, WI. The Madison site is situated 250 miles southeast of the St. Paul site, allowing for seasonal weather variation in similar climatic settings. At both locations, 'L-93' creeping bentgrass putting greens were established seven years prior on both sand and silt-loam root zones. The sand root zones were initially constructed to conform to USGA specifications (USGA Green Section, 1993). The St. Paul sand root zone had a pH of 7.2 and organic matter content (OM) of 0.9%; Madison had a pH of 7.2 and OM of 1.0%. In St. Paul the silt-loam root zone was a Waukegan silt-loam (fine-silty over sandy or sandy-skeletal, mixed, mesic, Typic Hapludoll) with a pH of 6.7 and OM of 2.8%. Madison silt-loam was a Troxel silt-loam (fine-silty, mixed, superactive, mesic Pachic Argiudoll) with a pH of 6.9 and OM of 3.0%.

Nitrogen Treatments

Six fertilizer treatments replicated in triplicate were applied at both locations in the fall and late-fall in 2009 (Table 1). Ammonium sulfate in liquid solution was applied at a rate of 25 (low) or 50 (high) kg N ha^{-1} on either Oct. 15 (± 1 day) or Nov. 15 (± 4 days). A spoon-feeding approach was also applied, with plots receiving 10 kg N ha^{-1} application bi-weekly from Sept. 25 (± 1 day) to Nov. 15 (± 4 days), totaling 50 kg N ha^{-1}. The remaining treatment was a control, receiving no fall N application.

Tracking the movement of fall-applied N involved a combination of unlabeled and ^{15}N-labeled ammonium sulfate (10 atom-% ^{15}N). The ^{15}N-labeled fertilizer was used to quantify N uptake and partitioning in verdure, thatch, and roots prior to winter and in the following spring. In-ground lysimeters, maintained within each plot, were utilized for the ^{15}N-labeled treatment and sampling. Lysimeter construction involved removing two 10 cm wide by 30 cm deep soil cores from each plot in July of 2008 using a truck-mounted hydraulic soil probe (Giddings Machine Company, Fort Collins, CO). The intact soil cores were removed from the probe and trimmed vertically using a 2 cm long 10 cm diameter PVC ring with a beveled edge. Soil cores were inserted into 10 cm diameter by 30 cm long poly-vinyl chloride (PVC) lysimeters. Lysimeters were returned flush with the putting green surface and maintained with the rest of the plot area for one year prior to initiation of the study. Lysimeter ^{15}N-labeled treatments were applied in solution at a volume of 370 L 100 m^{-2} (3.7 mm) water after puncturing ten evenly spaced 5 mm diameter by 5 cm deep holes in the turf to avoid surface runoff. These treatments were not watered in.

Unlabeled ammonium sulfate treatments were applied to plots using a CO_2 pressurized sprayer calibrated to deliver water at a rate of 8.15 L 100 m^{-2}. Prior to application, lysimeters, which were installed within plots, were covered with 5 cm deep by 10 cm wide PVC caps to avoid contamination with the unlabeled ammonium sulfate. Plots were irrigated immediately after N application with 3-4 mm of water. Plots received the same N treatment as lysimeters.

Clipping N Content, Tissue Partitioning, and N Recovery

Clippings (unlabeled N) were collected during the study on four fall and four spring dates at both locations. A Toro Greensmaster 800 or 1000 walking reel mower (The Toro Co., Bloomington, MN) was used for clipping collection. Uniform plot size was established by mowing 45 cm (Toro 800) or 53 cm (Toro 1000) alleys between plots prior to collecting clippings. Clippings collected in the reel mower basket from individual plots were brushed into coin envelopes and dried at 60°C for 24 h. Sand was separated from dried clippings using a General Seed Blower (Seedburo Equipment Co., Des Plaines, IL) with the air-regulating gate dial set to 14 and operation for 20 seconds (Kreuser et al., 2011). Dial setting and run time were initially adjusted to the point at which clippings were no longer present in the seed cup. Clippings were then weighed to determine yield and ground to pass a 0.42 mm screen in a Wiley mill (Thomas Scientific, Swedesboro, NJ). Ground clipping samples were loaded into 150 mg gel capsules (LECO Corporation, St. Joseph, MI) and analyzed for total nitrogen by the Dumas combustion method (Simone et al., 1994; Matejovic, 1995) with a LECO FP-528 Nitrogen Analyzer (LECO Corporation, St. Joseph, MI). Duplicates and National Institute of Standards and Technology (NIST) Standard Reference Materials were analyzed every ten samples to verify equipment calibration. Values were reported as N concentration in clipping tissue. These values were averaged from four fall and four spring collections to obtain mean fall and spring N concentration values.

The distribution of ^{15}N-applied fertilizer in fall and spring verdure, thatch, and root tissue was determined through lysimeter harvests on November 23 and May 7 in Madison, WI and November 30 and May 6 in St. Paul, MN. Immediately following harvest, lysimeters were dried at 60°C for a minimum of 72 h. Verdure samples, including the plant portions above the crown left after mowing, were cut from each lysimeter with a scalpel. Lysimeters were then split vertically using a 30 cm bandsaw (sand root zone) or by first scoring with a table saw and carefully opening with a chisel (silt-loam root zone), to extract thatch and root portions. Thatch was removed from the core using a scalpel and included crown and thatch/mat plant portions. Roots were separated from sand and silt-loam root zones with running water and a series of 4, 2, and 1 mm sieves; sand based roots were first separated with sieves when dry. Forceps were used to remove individual roots from each sieve and sand or silt-loam soil was further flocculated from roots using a shaker jar. Verdure, thatch, and root samples were dried again at 60°C for 72 h, weighed, and ground to pass through a 0.42 mm screen in a Wiley mill. Samples were thoroughly mixed in a coin envelope, and a sub-sample was loaded into a 5 mm by 9 mm tin capsule (Costech Analytical Technologies Inc., Valencia, CA). Sub-samples were analyzed for isotopic ^{15}N using a PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20-20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK). Equipment calibration was verified with two NIST Standard Reference Materials and duplicates were run every ten samples. Natural abundance of 0.3663 % ^{15}N (Mariotti, 1983) was subtracted from sample values and fertilizer uptake in kg N ha^{-1} was determined. Three random samples from each plant part, root zone, and location were verified for N content using the previously described Dumas combustion method and all sample N concentrations were adjusted based on these results. These same samples were subject to loss on ignition (LOI) to determine ash content following procedures described by Karam (1993).

Clipping Yield and Root Mass

Clipping yields were determined using the previously described procedure including removal of sand. Creeping bentgrass growth rate d^{-1} was calculated for each harvest and values were multiplied between dates of subsequent clipping collection, beginning on 30 Sept. 2009 and concluding on 7 June 2010 at each location. For this calculation, four fall harvest dates were used in both locations and either four (Madison) or five (St. Paul) spring dates were used. Values were summed to determine cumulative yields in fall and spring.

Oven-dried root mass was determined from lysimeter harvests in Nov. and May in each location following the previously described root extraction procedure. All root mass values were corrected using the LOI method to account for only OM content.

Turfgrass Quality and Green Color Index

Turfgrass quality and green color index measurements were taken in the absence of snow cover throughout the duration of the study at both locations. Turfgrass quality ratings were assigned on a 1-9 scale (9 = best turf quality) based on color, density, uniformity, texture, and biotic or abiotic stresses following guidelines from the National Turfgrass Evaluation Program (NTEP). A rating of 6 or above was considered to be acceptable (Morris and Shearman, 2010). Green color index measurements were taken in full sun between 1100 and 1300 h using a handheld reflectance meter (CM-1000, Spectrum Technologies Inc., Plainfield, IL) positioned one meter above the canopy. The reflectance meter estimated the quantity of chlorophyll in the leaves by sensing light reflectance at wavelengths of 700 nm and 840 nm. For each plot, a serpentine grid pattern was used to get an average of 9 evenly spaced readings, which were reported on a scale of 0 to 999; higher values represent increased canopy greenness. Individual plot data for turfgrass quality and green color index was averaged from two ratings to determine monthly values. In the event that only one rating was taken for a particular month, that specific date is listed.

General Plot Maintenance

All plots received 5 kg N ha^{-1} application weekly (St. Paul) or 10 kg N ha^{-1} application biweekly (Madison) in the form of liquid ammonium sulfate throughout the 2009 growing-season up to the beginning of the study. The native soil and sand putting greens were mown at 3-4 mm at least five times weekly. In the absence of rainfall, irrigation was applied during the growing season to replace 80% of potential evapotranspiration, calculated by an onsite weather station for Madison and a satellite-derived data model for St. Paul.

Experimental Design and Statistical analysis

Treatments were arranged in a completely random design (CRD) at both locations and root zones on 1.5 by 1.8 m plots with three replications per treatment. All data was subject to analysis of variance (ANOVA) with software from JMP 8 (SAS Institute Inc., Cary, NC, 2008) using location and treatment as main effects for each root zone. When significant, means were separated using Fisher's protected LSD t-test ($\alpha = 0.05$).

RESULTS

Initial ANOVAs were determined for main plot and lysimeter data including all factors. The main plot ANOVA indicated the effects of location, treatment, and root zone were all significant; the interaction of location by treatment was significant for all variables and the interaction of location by root zone was significant for three of four variables (Table 2). Data was further separated by root zone and analyzed with sources of treatment, location, and the treatment by location interaction. Lysimeter ANOVA included factors of location, treatment, root zone, and season of harvest (Table 3). Significance of main factors was inconsistent depending on each variable. Season of harvest was always significant. Data was separated by season and root zone, and analyzed with sources of treatment, location, and the location by treatment interaction.

Weather Patterns

Rainfall, air temperature, and soil temperature (5 cm depth) levels were similar between St. Paul, MN and Madison, WI from 1 Sept. 2009 to 30 June 2010. Cumulative rainfall totals for this time period were 538 and 630 mm for St. Paul and Madison, respectively (Fig. 1). These rainfall levels are consistent with 30-yr average precipitation data for both Madison and St. Paul. Air and soil temperatures followed similar trends in both locations (Fig. 2 and 3). Prior to study initiation, air and soil temperatures were slightly above 20°C in St. Paul and slightly below 20°C in Madison. At the end of Sept. in both locations, air and soil temperatures started to decrease rapidly and by mid-Oct. fell to 0°C (air) and 5 to 10°C (soil). Temperatures remained in the range of 0 to 10°C (air) and 5 to 10°C (soil) until the mid-Nov. In both locations, winter air and soil temperatures remained stable from early-Dec. to mid-March; from 0 to -20°C (air) and 0°C (soil). In mid-March both air and soil temperatures increased rapidly, continuing to the end of the study in June 2010.

Specific weather conditions at the time of fall N treatments are important in understanding turfgrass response, as well as N uptake and partitioning. Spoon-feeding applications are less subject to sudden weather changes due to reduced N rates spaced over multiple fall timings. Plant responses to single dose N applications are less predictable, relying on stable weather following application. October applications in St. Paul and Madison were followed by 53.8 and 93.0 mm of rainfall, respectively, in the fifteen days after application. The increased precipitation in Madison is important to note because precipitation increases the potential for nitrate leaching (Petrovic, 2004; Mangiafico and Guillard, 2006) and late-fall has been identified as a primary time in which fertilizer leaching losses occur (Geron et al., 1993; Guillard and Kopp, 2004; Frank et al., 2006). Air and soil temperatures were consistent between locations at this time; at 3-5°C (air) and 6-8°C (soil). During Nov. applications, soil temperatures in St. Paul were 2-5°C, while Madison soil temperatures were 6-10°C.

Turfgrass Quality and Green Color Index

Turfgrass quality (Tables 4 and 5) and green color index (Tables 6 and 7) measurements were greatly affected by N treatment, and showed similar trends for both locations and root zones. Nitrogen treatment had a significant effect on turfgrass quality and green color during all rating months, except the initial fall rating; this rating was taken five (St. Paul) or seven (Madison) days after the first 10 kg N ha^{-1} spoon-feeding application. In both locations, the spoon-feeding regime produced the single greatest turf quality and green color index for the month of Oct. November turf quality and green color index ratings were greatest with the spoon-feeding and low or high N application in

Oct. All unfertilized control treatments and Nov. applications had the poorest fall turf quality and green color index ratings. Early spring response, determined by March ratings in both locations, statistically had the greatest values for the spoon-feeding and high N Oct. treatments. November low and high N applications were comparable to Oct. low N applications during the month of March. This same trend continued into April in Madison, although in St. Paul the Nov. high N application produced comparable ratings to the spoon-feeding and Oct. high N application. This lack of response in April from Madison Nov. applications may be attributed to nitrate leaching prior to plant uptake, as a result of a three-day rainfall event totaling 70 mm (5 to 7 April 2010). May and June turf quality and green color index ratings showed the highest values for all high N applications in both locations, no matter when they were applied. The unfertilized control plots received the lowest ratings on all spring dates.

Clipping Yield and Root Mass

Cumulative clipping yield varied by N treatment in St. Paul and Madison locations (Table 8). In St. Paul, greatest fall clipping yields were associated with spoon-feeding and Oct. applied N on the silt-loam root zone; sand root zone yields were not statistically different. In Madison, fall clipping yields did not indicate significance for either root zone based on N treatment. The greatest spring clipping yields in St. Paul were associated with high N treatments, whether applied in Oct., Nov., or on a spoon-feeding regime; this indicates similar utilization of fall-applied N across all application timings. Low N treatments applied in Oct. or Nov. produced intermediate clipping yields, while the control treatments had the lowest cumulative clipping yields in St. Paul.

In Madison, spring clipping yields were less significant (sand based) or not significant (silt-loam) based on N treatment. These results from Madison demonstrate diminished response from the single dose 50 kg N ha^{-1} applications applied in Oct. or Nov. as compared to 25 kg N ha^{-1} applications. In both locations, the native soil root zones produced the greatest fall and spring cumulative clipping yields, 42 and 60% greater than sand root zones for St. Paul and Madison, respectively.

Root mass measured from lysimeters harvested in Nov. and May was not affected by N application rate or timing in either location (Table 9). In St. Paul and Madison, the silt-loam root zones produced significantly greater root mass than the sand root zones; this could be attributed to the double (dry and wet) processing technique used for root extraction from sand based root zones.

Clipping N Content

In both locations, greatest clipping N content going into the winter was associated with spoon-feeding and Oct. high and low N applications (Table 10). November and control applications had the lowest clipping N values in the fall. In St. Paul, spring clipping N content was greatest with all 50 kg N ha^{-1} applications, while 25 kg N ha^{-1} applications had intermediate values, followed by control treatments having the lowest values. Spring clipping N content in Madison showed the greatest values for Nov. high N applications on the sand based root zone; silt-loam root zones did not indicate one application timing as being superior to another.

Silt-loam root zones consistently provided higher clipping N content than sand root zones in both St. Paul and Madison, relating to the higher CEC and OM for the silt-loam root zones aiding in storage of ammonium and having a lower potential for nitrate leaching losses.

Nitrogen Uptake and Partitioning in Fall and Spring

Labeled ^{15}N uptake and partitioning in fall and spring was determined from lysimeter harvests in the end of Nov. and early May. Fertilizer recovery (kg N ha^{-1}) was subject to ANOVA and found to be consistently significant (higher N rates = more N recovered) at the time of sampling for all plant parts in both locations, although this is not a good indicator of N uptake efficiency at various N rates and timings because higher N rates are expected to result in greater N recovery; therefore ANOVA and means separation data is presented as N uptake efficiency on a percentage basis (N recovered / N applied x 100). Labeled-^{15}N recovery values are reported as well. An initial comparison of lysimeter N recovery showed 13% (fall) and 9% (spring) more fertilizer N recovered in Madison lysimeters, and 6% greater recovery in silt-loam root zones versus sand root zones.

Fall-harvested N uptake and partitioning differed between silt-loam (Table 11) and sand based root zones (Table 12). In St. Paul, overall fall-harvested N partitioning of fertilizer applied to the silt-loam was 28.8% (verdure), 17.5% (thatch), and 2.0% (roots), accounting for a total of 47.6% fertilizer N present across all treatments going into winter. Partitioning in St. Paul silt-loam spring lysimeters was 22.2% (verdure), 11.5% (thatch), and 6.5% (roots), totaling 40.2%. While total N recovered was statistically significant by treatment for all turfgrass parts, uptake efficiency was only significant for root N in fall-harvested silt loam lysimeters in St. Paul; the Oct. high and Nov. low N applications had the highest efficiency of ^{15}N present in roots, whereas the spoon-feeding, Oct. low, and Nov. high N applications had the lowest efficiency of fertilizer N. However, the total amount of N recovered in the roots was relatively small. Madison fall-harvested N partitioning of fertilizer N applied to the silt loam was 22.0% (verdure), 29.9% (thatch), and 1.5% (roots), accounting for 53.9% recovery of fertilizer; verdure and thatch showed a significantly lower N uptake efficiency for Oct. high N applications from silt-loam lysimeters harvested in the fall. These data match up with lower fall N clipping concentrations going into winter and a reduced cumulative clipping yields between low and high N Oct. applications in Madison as compared to St. Paul. This reduced efficiency from Oct. application in Madison may be related to a two-day rainfall event, totaling 50 mm, on 22 and 23 Oct. (six days after treatment), as well as a slight reduction in soil temperatures (8°C) as compared to the Nov. application timing in which soil temperatures spiked to near 10°C for a short duration. Madison spring-harvested silt-loam lysimeters showed no statistical difference between N treatments, although the same trend of reduced efficiency with 50 kg N ha^{-1} applications in Oct. was observed. Partitioning of Madison fertilizer N in the spring was 24.8% (verdure), 11.8% (thatch), and 8.3% (root), accounting for a total of 45.3% N fertilizer recovered.

Nitrogen uptake efficiency in sand based lysimeters differed greatly between St. Paul and Madison (Table 11). The distribution across all N treatments in fall-harvested St. Paul lysimeters was 20.4% (verdure), 14.9% (thatch), and 1.7% (root), accounting for 37.0% of N fertilizer present. In the spring, total recovery dropped to 29.6%, partitioned as 15.4% (verdure), 11.5% (thatch), and 2.7% (root). There was no significant efficiency difference based on timing or rate of application in sand based root zones in St. Paul for fall or spring. In Madison, a reduced N efficiency was associated with Oct. high applications (same as silt-loam root zones), although this difference was not significant. Total efficiency of fertilizer N recovered in Madison fall-harvested sand based lysimeters accounted for 56.0% of fertilizer applied, distributed as 28.9% (verdure), 26.4% (thatch), and 0.7% (root). Spring-harvested lysimeters had a reduction in fertilizer N thatch content, dropping the total recovered to 41.8%.

Total tissue N content in creeping bentgrass plant portions, as averaged between treatments, locations, and harvest times, was 14.7, 12.7, and 11.5 mg g^{-1} for verdure, thatch, and roots, respectively. This small difference in N content of verdure/thatch samples to root samples fails to explain the drastic reduction in ^{15}N-labeled fertilizer recovered in the root portions, but rather indicates that little late-fall applied fertilizer N was stored in the roots. Unfertilized treatments had the same concentration of total N present in root tissue (Table 13).

Root Zone Comparison

Summarized data for fall (Table 14) and spring (Table 15) visual turf quality, green color index, growth response, clipping N content, and N fertilizer partitioning in St. Paul and Madison aids in identifying similarities and differences between root zones. In both locations and root zones, average fall visual turf quality and green color ratings were greatest for the spoon-feeding and Oct. N applications, higher N rates generally increased this effect. These results were similar to the response seen in fall clipping N content and cumulative fall clipping growth; although Madison clipping growth was less significant based on N treatment. This lack of consistency in Madison is further explained by the reduction in N fertilizer efficiency from the high N Oct. application, in which only 15 kg N ha^{-1} fertilizer N was recovered in verdure, thatch, and roots; 14.6 kg N ha^{-1} was recovered from the low application, indicating a lack of benefit and potential for significant loss from the high N Oct. application. St. Paul lysimeters had similar efficiency between all treatments. Turf quality, green color index, fall clipping yield, clipping N content, and lysimeter N recovery consistently showed greater fall values for silt-loam root zones in St. Paul, suggesting a greater retention of fall-applied N fertilizer. Madison data was similar between root zones.

Measurements taken in the spring continued to show high values for the spoon-feeding and Oct. applications, although the creeping bentgrass was now responding to Nov. applications as well. In all cases, highest turf quality and green color index data was associated with high N applications, no matter when they were applied. This data corresponds to cumulative spring clipping growth in St. Paul, but Madison clipping growth was less significant and indicated few differences between fertilizer rates or timing of application. Averaged spring clipping N concentration was greatest in both St. Paul and Madison for the high N Nov. application. While a greater amount of fertilizer N was present in lysimeters from 50 kg N ha^{-1} applications in both locations, efficiency of the single dose high N application was the generally the same as low N applications across all timings. Silt-loam root zones, again, showed the greatest values in St. Paul, while Madison silt-loam and sand based root zones performed similarly.

DISCUSSION

The delayed spring color and quality responses from Nov. applications, brings into question the benefit of applying N beyond mid-Oct. in Minnesota or Wisconsin. Additionally, there was little added response in late-spring from Nov.-applied N; overall spring color and quality from Nov.-applied N was essentially the same as Oct. or spoon-feeding. This is similar to a study by Magniafico and Guillard (2006) who observed no color differences from home lawn turf fertilized with 49 kg N ha^{-1} on 15 Oct., 15 Nov., or 15 Dec. in Connecticut. Wilkinson and Duff (1972) also reported comparable mid-April chlorophyll content in Kentucky bluegrass fertilized with ammonium nitrate (100 kg N ha^{-1}) on either Sept., Oct., or Nov. in Rhode Island.

Highest cumulative clipping yields in this study were associated with 50 kg N ha^{-1} rates, and time of application appeared to not be a factor. Walker et al. (2007), in a multi-species study evaluating eight N fertilizer programs over two years, attributed an increase in cumulative clipping yield to increasing N rates. Mangiafico and Guillard (2006) observed the same level of clipping growth from applications of 49 kg N ha^{-1} applied in Sept., Oct., Nov., or Dec.; different N rates were not included in this study. Lack of root growth response from fall-applied N in this study supports the results presented by Mangiafico and Guillard (2006) and Lloyd (2009), but differs from earlier work conducted by Hanson and Juska (1961) and Powell et al. (1967b) and Moore et al. (1996). Our research suggests that root mass response is most likely not a benefit of late-fall applied N on creeping bentgrass putting greens in Minnesota or Wisconsin.

Miltner et al. (2001) in Washington observed highest N clipping concentrations in Oct. and Nov. versus any other growing month, concluding that N uptake and transport was still occurring in the late-fall. Using ^{15}N-labeled urea on Kentucky bluegrass in Michigan, Miltner et al. (1996) reported that a majority of the labeled fertilizer recovered in turfgrass clippings from a Nov. 39.2 kg N ha^{-1} application was transported there within eighteen days of application. Our data supports this rapid transport of fall-applied N; however, the final clippings in the late-fall were collected either before or too soon after Nov.-applied N to confirm late-fall transport of N to clippings from Nov. applications. Transport of spoon-feed or Oct. N applications to clippings in the fall was rapid in both St. Paul and Madison, as observed by increased tissue in clipping N concentration soon after application.

Soluble N applications in the late-fall were taken up efficiently by roots, thatch, and verdure from fall-harvested lysimeters; accounting for 50.8% (silt-loam) and 46.5% (sand based) labeled N recovered at the end of Nov. This is an intermediate result between the values reported by Miltner et al. (1996) and Frank et al. (2006). Thatch appeared to be immobilizing a good portion of this fertilizer N in the fall; this was also observed by Miltner et al. (1996). Spring lysimeter harvests showed reduced fertilizer N in thatch, likely resulting from N mineralization and subsequent N transport to shoots as spring soil temperatures increased; this corresponded to elevated clipping N concentrations from samples taken in April (data not shown). Mineralization to inorganic N is associated with rising microbial activity in the spring (Miltner et al. 2001), increasing the potential for nitrate leaching brought on by spring precipitation. This is possibly a factor delaying April turf quality and green color index response in Madison from 50 kg N ha^{-1} applied in Nov., although leachate was not collected in our study. Mangiafico and Guillard (2006) in Connecticut observed greater spring nitrate leaching from N applications made later into the fall, attributing this to precipitation and reduced plant N uptake in cooler temperatures. Fall nitrate leaching from increased precipitation and cooler temperatures appears to be responsible for a reduced thatch and verdure N uptake efficiency from 50 kg N ha^{-1} Oct. applications in Madison; this is most likely due to the soluble form of N used. Petrovic et al. (1986) in New York observed up to 47% leaching of urea (97 kg N ha^{-1}) applied in Nov., whereas less than 2% N was leached from activated sewage sludge, ureaformaldehyde, or resin-coated urea. Guillard and Kopp (2004) reported 16.8% annual leaching of ammonium nitrate, as compared to 1.7% and 0.6% from resin-sulfur-coated urea and organic fertilizer, respectively.

With the high N Oct. application in Madison being an exception, we observed no efficiency difference based on rate of application; albeit if efficiency is the same, then more fertilizer N is lost from the higher application. Lloyd's (2009) data showed no difference in efficiency of N uptake from ammonium sulfate applications of 25 and 49 kg N ha^{-1} in verdure and roots of creeping bentgrass; although reduced uptake was associated with applications made later into the fall. Our data suggests that weather, specifically rainfall and temperature, is more important than timing. Air and soil temperatures were fairly similar between Oct. and Nov. applications in both locations; therefore the uptake efficiency was comparable between rates and timings.

While fall-applied N was taken up rapidly by the creeping bentgrass in this study, it appears that very little fertilizer N is actually stored in the roots in the fall; in this case, recovery of applied N in roots was 1.7% (silt-loam) and 1.2% (sand based) in the fall. Total root N concentration was not dependent on fertilizer application. Lloyd (2009) reported 12% N fertilizer recovery in creeping bentgrass roots at 10 DAT; this is an average of 25 and 49 kg N ha-1 applications in Sept., Oct., and Nov. However, this work was conducted in a controlled environment, on young plants, and a new sand root zone, and would therefore be less prone to leaching and immobilization losses of N. Similarly, Frank et al. (2006) observed 13% root recovery at 45 DAT from a mid-October application of 24.5 or 49 kg N ha^{-1}. The greater root N recovery in Michigan is most likely attributed to the higher root and rhizome mass of Kentucky bluegrass, averaging 13,451 kg ha^{-1} at the 0-5 cm depth.

CONCLUSION

Numerous researchers have shown cool-season turfgrass agronomic benefits related to quality and color from fall-applied N fertilizer. This research on creeping bentgrass putting greens supports the benefits, and increasing nitrogen rates generally provided a greater response. Nitrogen fertilizer applied earlier in the fall produced a color and yield response prior to winter, and the benefit of mid-Nov. N applications in Minnesota and Wisconsin was delayed in the following spring. The efficiency of 25 and 50 kg N ha^{-1} soluble N applications appears to be similar under optimum weather conditions, but this efficiency is reduced in environments conducive to N loss and reduced plant uptake; although the creeping bentgrass in this study exhibited an increased response, which consequently brings into consideration the cost-benefit analysis of late-fall N fertilizer applications. There also appeared to be an increased retention of N fertilizer on silt-loam root zones, although this could not be replicated at both locations. The most efficient use and consistent benefits from late-fall applied N were seen with lower N rates (10 kg N ha^{-1}) spaced over multiple applications. If the single dose 50 kg

N ha^{-1} application is desired, this data suggests that a good portion be of a slow release N source, thus minimizing the potential for off-target loss.

Table 1. Nitrogen treatments applied to 'L-93' creeping bentgrass silt-loam and sand based putting greens and lysimeters in St. Paul, MN and Madison, WI in the fall of 2009.

Application timing	N rate (kg N ha^{-1})†
Spoon-feeding‡	50
October§ low	25
October high	50
November¶ low	25
November high	50
Control	0

†Nitrogen was applied as ammonium sulfate in liquid solution.
‡Spoon-feeding consisted of 10 kg N ha-1 applications spaced over five dates. St. Paul dates were 25-Sept., 2-Oct., 15-Oct., 3-Nov., 17-Nov. Madison dates were 24-Sept., 8-Oct., 16-Oct., 28-Oct., 11-Nov.
§October applications were applied on 15 Oct. (St. Paul) and 16 Oct. (Madison).
¶November applications were applied on 17 Nov. (St. Paul) and 11 Nov. (Madison).

Table 2. Analysis of variance for 'L-93' creeping bentgrass putting green plot data taken from 30 Sept. 2009 to 7 June 2010, including cumulative clipping yield, %N, turfgrass quality, and green color index data. Numbers presented are p-values.

Source	df†	Cumulative Clipping Yield	% N (Average)	Turfgrass Quality (Average)	Green Color Index (Average)
Location (L)‡	1	0.0308 *	0.487	<.0001 ***	<.0001 ***
Treatment (T)§	5	<.0001 ***	<.0001 ***	<.0001 ***	<.0001 ***
L*T	5	0.0006 ***	<.0001 ***	<.0001 ***	<.0001 ***
Rootzone (RZ)¶	1	<.0001 ***	<.0001 ***	0.0004 ***	0.0002 ***
L*RZ	1	0.0315 *	0.0001 ***	0.484 NS	<.0001 ***
T*RZ	5	0.6208 NS	0.4612 NS	0.0105 *	0.3626 NS
L*T*RZ	5	0.2656 NS	0.1172 NS	0.1726 NS	0.6784 NS

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, and 0.001, respectively.
†degrees of freedom.
‡Locations in St. Paul, MN and Madison, WI.
§Six N treatments: 25 and 50 kg N ha^{-1} in mid-Oct. and mid-Nov., spoon-feed (5 x 10 kg N ha^{-1} applications from end-Sept. to mid-Nov.), and unfertilized control. Nitrogen was in the form of ammonium sulfate (21% N).
¶Silt-loam and sand based root zones.

Table 3. Analysis of variance for 'L-93' creeping bentgrass putting green lysimeter data. All N data was analyzed as N fertilizer uptake efficiency (N recovered / N applied * 100). Numbers presented are p-values.

Source	df[†]	Root mass	df	Verdure N	Thatch N	Root N	Total N
Treatment (T)[‡]	5	0.3223 NS	4	0.0182 *	0.0031 **	0.491 NS	0.0002 ***
Location (L)[§]	1	<.0001 ***	1	0.0002 ***	<.0001 ***	0.5263 NS	<.0001 ***
T*L	5	0.3468 NS	4	0.0135 *	0.0165 *	0.1797 NS	0.0002 ***
Rootzone (RZ)[¶]	1	<.0001 ***	1	0.1743 NS	0.378 NS	<.0001 ***	0.0061 **
T*RZ	5	0.6437 NS	4	0.1306 NS	0.2253 NS	0.3677 NS	0.3289 NS
L*RZ	1	0.0015 **	1	<.0001 ***	0.9961 NS	0.0353 *	0.0152 *
T*L*RZ	5	0.6922 NS	4	0.0657 NS	0.2058 NS	0.6284 NS	0.1597 NS
Season (S)[#]	1	<.0001 ***	1	0.0269 *	<.0001 ***	<.0001 ***	<.0001 ***
T*S	5	0.366 NS	4	0.1985 NS	0.2699 NS	0.4086 NS	0.6313 NS
L*S	1	0.0076 **	1	0.0071 **	0.0003 ***	0.1648 NS	0.3213 NS
T*L*S	5	0.2686 NS	4	0.3053 NS	0.0728 NS	0.3232 NS	0.0885 NS
RZ*S	1	<.0001 ***	1	0.3279 NS	0.1865 NS	<.0001 ***	0.4785 NS
T*RZ*S	5	0.4537 NS	4	0.8098 NS	0.2708 NS	0.7106 NS	0.429 NS
L*RZ*S	1	0.1242 NS	1	0.1679 NS	0.6534 NS	0.1163 NS	0.4819 NS
T*RZ*L*S	5	0.4837 NS	4	0.4518 NS	0.3949 NS	0.6724 NS	0.9135 NS

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, and 0.001, respectively.

[†]degrees of freedom.

[‡]Six N treatments: 25 and 50 kg N ha^{-1} in mid-Oct. and mid-Nov., spoon-feed (5 x 10 kg N ha^{-1} applications from end-Sept. to mid-Nov.), and unfertilized control. Nitrogen was in the form of ammonium sulfate (21% N).

[§]Locations in St. Paul, MN and Madison, WI.

[¶]Silt-loam and sand based root zones.

[#]Season indicates harvest dates of 30 Nov. 2009 or 6 May 2010 (St. Paul) and 23 Nov. 2009 or 7 May 2010 (Madison).

Table 4. Silt-loam root zone 'L-93' creeping bentgrass visual turf quality measurements in St. Paul, MN and Madison, WI from Sept. 2009 to June 2010. Months of Oct., Mar., April, and May represent the average of two ratings.

		Monthly rating†						
Location	Treatment	Sept.	Oct.	Nov.	Mar.	April	May	June
		1-9						
St. Paul, MN	Spoon-feeding	7.0	7.5 a‡	6.7 ab	4.2 b	5.5 b	5.3 b	4.0 a
	October low	7.0	6.3 b	6.3 b	3.8 bc	4.5 c	4.0 c	2.7 bc
	October high	7.0	6.3 b	7.0 a	4.8 a	6.5 a	5.7 ab	3.7 ab
	November low	7.0	6.0 c	3.0 c	3.3 c	4.3 c	3.7 c	2.7 bc
	November high	7.0	6.2 bc	3.0 c	4.2 b	7.0 a	6.5 a	4.7 a
	Control	7.0	6.0 c	3.0 c	2.0 d	2.7 d	2.8 d	2.2 c
Madison, WI	Spoon-feeding	7.2	6.9 a	6.5 b	6.0 a	7.6 a	7.6 ab	7.2 ab
	October low	7.2	6.3 b	6.5 b	4.3 bc	6.3 bc	7.0 ab	7.2 ab
	October high	7.2	6.3 b	7.0 a	5.7 a	7.5 a	7.7 a	7.8 a
	November low	7.0	6.3 b	6.0 c	3.9 c	5.8 c	6.8 b	6.7 bc
	November high	7.2	6.4 b	6.0 c	4.8 b	6.8 b	7.6 ab	7.7 a
	Control	7.1	6.5 b	6.0 c	2.7 d	4.6 d	5.8 c	6.2 c
	Source				Anova			
	Treatment (T)	NS	***	***	***	***	***	***
	Location (L)	*	NS	***	***	***	***	***
	T*L	NS	***	***	*	***	**	NS

NS, *, **, ***Nonsignificant or significant at P ≤ 0.05, 0.01, and 0.001, respectively.
†St. Paul ratings were taken on 30-Sept., 9 and 19-Oct., 9-Nov., 22 and 29-Mar., 12 and 27-Apr., 3 and 25-May, and 7-June. Madison ratings were taken on 15-Sept., 9 and 16-Oct. 13-Nov., 24 and 31-Mar., 13 and 27-Apr., 14 and 26-May, and 7-June.
‡Means followed by the same letter within each location and month are not significantly different based on Fisher's protected LSD t-test at α = 0.05.

Table 5. Sand based root zone 'L-93' creeping bentgrass visual turf quality measurements in St. Paul, MN and Madison, WI from Sept. 2009 to June 2010. Months of Oct., Mar., April, and May represent the average of two ratings.

		Monthly rating†						
Location	Treatment	Sept.	Oct.	Nov.	Mar.	April	May	June
		1-9						
St. Paul, MN	Spoon-feeding	6.0	6.0 a‡	7.0 a	5.2 a	6.0 a	5.3 a	4.0 a
	October low	6.0	5.2 b	5.7 c	3.5 b	4.8 b	4.0 c	3.7 a
	October high	6.0	5.0 bc	6.3 b	5.5 a	6.5 a	5.7 a	4.3 a
	November low	6.0	4.8 bc	3.0 d	3.8 b	5.2 b	4.5 b	4.3 a
	November high	6.0	4.7 c	3.0 d	4.0 b	6.2 a	5.5 a	4.0 a
	Control	6.0	4.7 c	3.0 d	2.0 c	2.3 c	2.8 d	2.3 b
Madison, WI	Spoon-feeding	7.0	7.3 a	6.7 a	5.2 a	7.3 a	7.5 a	7.5 a
	October low	7.0	6.8 ab	6.7 a	4.5 a	6.2 b	6.5 c	6.7 ab
	October high	7.0	6.8 ab	7.0 a	4.9 a	7.2 a	7.4 ab	7.7 a
	November low	7.0	6.8 ab	6.0 b	4.4 a	6.2 b	6.7 bc	7.2 a
	November high	7.0	6.6 b	6.0 b	4.4 a	6.1 b	7.0 abc	7.0 a
	Control	7.1	6.8 ab	6.0 b	2.9 b	5.2 c	5.6 d	5.8 b
	Source	Anova						
	Treatment (T)	NS	***	***	***	***	***	***
	Location (L)	***	***	***	**	***	***	***
	T*L	NS	*	***	**	***	*	NS

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, and 0.001, respectively.
†St. Paul ratings were taken on 30-Sept., 9 and 19-Oct., 9-Nov., 22 and 29-Mar., 12 and 27-Apr., 3 and 25-May, and 7-June. Madison ratings were taken on 15-Sept., 9 and 16-Oct. 13-Nov., 24 and 31-Mar., 13 and 27-Apr., 14 and 26-May, and 7-June.
‡Means followed by the same letter within each location and month are not significantly different based on Fisher's protected LSD t-test at $\alpha = 0.05$.

Table 6. Silt-loam root zone 'L-93' creeping bentgrass green color index measurements in St. Paul, MN and Madison, WI from Sept. 2009 to June 2010. Months of Oct., Mar., April, and May represent the average of two ratings.

		Monthly rating[†]						
Location	Treatment	Sept.	Oct.	Nov.	Mar.	April	May	June
		0-999						
St. Paul, MN	Spoon-feeding	276	257 a[‡]	193 b	158 ab	277 b	250 b	224 a
	October low	272	235 b	191 b	147 bc	236 c	223 c	208 b
	October high	278	236 b	202 a	167 a	288 b	264 b	227 a
	November low	271	221 b	146 c	134 d	229 c	224 c	206 b
	November high	261	229 b	150 c	145 cd	327 a	286 a	237 a
	Control	267	223 b	147 c	115 e	174 d	181 d	188 c
Madison, WI	Spoon-feeding	294	255 a	208 a	210 a	259 a	215 a	237 a
	October low	303	243 a	214 a	178 bc	209 c	210 a	231 ab
	October high	288	239 a	177 ab	191 b	254 a	233 a	242 a
	November low	297	250 a	167 b	166 c	229 b	217 a	245 a
	November high	303	236 a	178 ab	169 c	236 b	219 a	238 a
	Control	302	243 a	171 b	135 d	164 d	181 b	215 b
	Source	Anova						
	Treatment (T)	NS	**	***	***	***	***	***
	Location (L)	***	**	*	***	***	***	***
	T*L	NS	NS	NS	*	***	**	NS

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, and 0.001, respectively.
[†]St. Paul ratings were taken on 30-Sept., 9 and 19-Oct., 9-Nov., 22 and 29-Mar., 12 and 27-Apr., 3 and 25-May, and 7-June. Madison ratings were taken on 15-Sept., 9 and 16-Oct. 13-Nov., 24 and 31-Mar., 13 and 27-Apr., 14 and 26-May, and 7-June.
[‡]Means followed by the same letter within each location and month are not significantly different based on Fisher's protected LSD t-test at $\alpha = 0.05$.

Table 7. Sand based root zone ‘L-93’ creeping bentgrass green color index measurements in St. Paul, MN and Madison, WI from Sept. 2009 to June 2010. Months of Oct., Mar., April, and May represent the average of two ratings.

		Monthly rating[†]						
Location	Treatment	Sept.	Oct.	Nov.	Mar.	April	May	June
		0-999						
St. Paul, MN	Spoon-feeding	240	227 a[‡]	187 a	166 a	249 a	214 b	188 ab
	October low	223	179 b	167 b	139 b	199 b	189 c	171 c
	October high	231	193 b	188 a	175 a	276 a	236 a	195 ab
	November low	228	185 b	132 c	137 b	220 b	200 bc	182 bc
	November high	219	181 b	130 c	138 b	270 a	233 a	200 a
	Control	222	180 b	131 c	109 c	151 c	154 d	158 d
Madison, WI	Spoon-feeding	300	272 a	209 a	208 a	286 a	255 a	257 a
	October low	294	243 b	188 b	179 b	240 b	218 b	237 a
	October high	306	259 ab	205 a	211 a	290 a	252 a	254 a
	November low	294	257 ab	160 c	175 b	241 b	214 b	236 a
	November high	281	244 b	151 c	170 b	242 b	238 a	250 a
	Control	306	249 b	157 c	150 c	181 c	181 c	212 b
	Source	Anova						
	Treatment (T)	NS	***	***	***	***	***	***
	Location (L)	***	***	***	***	**	***	***
	T*L	NS	NS	NS	NS	*	NS	NS

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, and 0.001, respectively.
[†]St. Paul ratings were taken on 30-Sept., 9 and 19-Oct., 9-Nov., 22 and 29-Mar., 12 and 27-Apr., 3 and 25-May, and 7-June. Madison ratings were taken on 15-Sept., 9 and 16-Oct. 13-Nov., 24 and 31-Mar., 13 and 27-Apr., 14 and 26-May, and 7-June.
[‡]Means followed by the same letter within each location and month are not significantly different based on Fisher’s protected LSD t-test at $\alpha = 0.05$.

Table 8. Cumulative clipping yields in fall and spring for 'L-93' creeping bentgrass grown on silt-loam and sand root zones in St. Paul, MN and Madison, WI based on N treatment.

		Silt-loam		Sand	
Location	Treatment	Fall[†]	Spring[‡]	Fall	Spring
		kg ha^{-1}			
St. Paul, MN	Spoon-feeding	559 a[§]	1735 b	326	1267 abc
	October low	480 ab	1417 c	298	1002 cd
	October high	578 a	2005 ab	356	1553 a
	November low	390 b	1365 c	294	1102 bc
	November high	412 b	2109 a	354	1413 ab
	Control	420 b	1037 d	251	678 d
Madison, WI	Spoon-feeding	583 a	2103	423	1371 a
	October low	483 abc	1895	378	1034 bc
	October high	493 abc	1542	393	1269 ab
	November low	547 ab	1986	401	950 bc
	November high	463 bc	2029	344	1125 abc
	Control	436 c	1564	359	850 c
	Source	Anova			
	Treatment (T)	***	***	NS	***
	Location (L)	NS	**	***	NS
	T*L	NS	**	NS	NS

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, and 0.001, respectively.

[†]Fall clippings were collected on four dates: 30-Sept., 19-Oct., 2-Nov., and 9-Nov. (St. Paul) or 1-Oct., 20-Oct., 29-Oct., and 13-Nov. (Madison). Bentgrass shoot growth d^{-1} was determined and this value was multiplied by dates between clipping collections from 30-Sept. to 13-Nov., 2009.

[‡]Spring clippings were collected on four dates: 12-Apr., 3-May, 25-May, and 7-June (St. Paul) or 13-Apr., 14-May, 26-May, and 7-June (Madison). Bentgrass shoot growth d^{-1} was determined and this value was multiplied by dates between clipping collections from 12-Apr. to 7-June, 2010.

[§]Means followed by the same letter are not significantly different based on Fisher's protected LSD t-test at $\alpha = 0.05$.

Table 9. Creeping bentgrass root mass grown on silt-loam and sand based root zones in St. Paul, MN and Madison, WI for fall and spring harvested lysimeters.

	Silt-loam		Sand	
Treatment	Fall†	Spring‡	Fall	Spring
	kg ha^{-1}			
Spoon-feeding	4675	7448	1382	1569
October low	4441	8601	1503	1066
October high	6298	9979	1796	1748
November low	5624	9233	1096	1635
November high	3330	10020	1146	1455
Control	6050	8205	1220	1188
St. Paul, MN	7002 a§	9463	1730 a	1437
Madison, WI	3138 b	8366	984 b	1450
Source	Anova			
Treatment (T)	NS	NS	NS	NS
Location (L)	***	NS	***	NS
T*L	NS	NS	NS	NS

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, and 0.001, respectively.
†Fall lysimeter harvest dates were 30-Nov. (St. Paul) and 23-Nov. (Madison) 2009.
‡Spring lysimeter harvest dates were 6-May (St. Paul) and 7-May (Madison) 2010.
§Means followed by the same letter are not significantly different based on Fisher's protected LSD t-test at $\alpha = 0.05$.

Table 10. Creeping bentgrass average clipping nitrogen concentration in fall and spring grown on silt-loam and sand root zones in St. Paul, MN and Madison, WI from Sept. 2009 to June 2010.

		Silt-loam		Sand	
Location	Treatment	Fall†	Spring‡	Fall	Spring
		mg g^{-1}			
St. Paul, MN	Spoon-feeding	37.6 b§	31.5 bc	35.2 b	29.7 bc
	October low	36.5 b	29.0 d	33.1 c	27.9 d
	October high	39.7 a	32.6 b	37.0 a	30.5 b
	November low	30.6 d	30.0 cd	27.6 d	28.4 cd
	November high	33.2 c	36.5 a	27.9 d	32.3 a
	Control	31.4 d	27.5 e	27.7 d	25.9 e
Madison, WI	Spoon-feeding	34.7 a	32.1 abc	33.6 a	31.7 bc
	October low	32.8 ab	31.1 bc	31.2 b	30.7 c
	October high	33.8 a	32.5 abc	32.2 b	32.2 b
	November low	31.0 bc	32.5 ab	29.1 c	30.8 c
	November high	30.2 c	33.8 a	29.2 c	33.6 a
	Control	30.7 c	30.7 c	28.9 c	29.4 d
	Source	**Anova**			
	Treatment (T)	***	***	***	***
	Location (L)	***	*	**	***
	T*L	***	***	***	*

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, and 0.001, respectively.

†Fall clippings were averaged between four dates: 30-Sept., 19-Oct., 2-Nov., and 9-Nov. (St. Paul) or 1-Oct., 20-Oct., 29-Oct., and 13-Nov. (Madison).

‡Spring clippings were averaged between four dates: 12-Apr., 3-May, 25-May, and 7-June (St. Paul) or 13-Apr., 14-May, 26-May, and 7-June (Madison).

§Means followed by the same letter are not significantly different based on Fisher's protected LSD t-test at $\alpha = 0.05$.

Table 11. Silt-loam root zone 'L-93' creeping bentgrass N fertilizer recovery from lysimeters. Values presented are N fertilizer uptake efficiency (N recovered / N applied * 100). Values in parenthesis represent recovery in kg N ha^{-1}.

		Fall†				Spring‡			
Location	Treatment	Verdure	Thatch	Root	Total	Verdure	Thatch	Root	Total
		% Fertilizer Recovery							
St. Paul, MN	Spoon-feeding	26.7 (13.4)	16.4 (8.2)	1.5 b§ (0.8)	44.6 (22.3)	27.4 (13.7)	12.9 (6.5)	5.4 (2.7)	45.7 (22.9)
	October low	23.1 (5.8)	15.6 (3.9)	1.7 b (0.4)	40.4 (10.1)	21.7 (5.4)	9.4 (2.4)	6.5 (1.6)	37.6 (9.4)
	October high	32.4 (16.2)	18.5 (9.3)	2.8 a (1.4)	53.7 (26.9)	18.1 (9.1)	10.3 (5.2)	8.1 (4.1)	36.6 (18.3)
	November low	32.2 (8.1)	22.6 (5.7)	2.8 a (0.7)	57.6 (14.4)	24.1 (6.0)	14.0 (3.5)	6.7 (1.7)	44.8 (11.2)
	November high	26.0 (13.0)	14.5 (7.3)	1.3 b (0.7)	41.8 (20.9)	19.6 (9.8)	11.0 (5.5)	5.9 (3.0)	36.5 (18.3)
Madison, WI	Spoon-feeding	22.7 a (11.3)	36.3 ab (18.1)	2.0 ab (1.0)	61.0 a (30.5)	31.1 (15.6)	14.8 (7.4)	5.7 (2.8)	51.6 (25.8)
	October low	29.0 a (7.3)	23.5 bc (5.9)	2.2 a (0.6)	54.8 a (13.7)	21.9 (5.5)	10.4 (2.6)	8.9 (2.2)	41.2 (10.3)
	October high	10.4 b (5.2)	10.3 c (5.2)	0.9 b (0.4)	21.6 b (10.8)	15.1 (7.5)	10.5 (5.2)	5.6 (2.8)	31.2 (15.6)
	November low	25.7 a (6.4)	36.7 ab (9.2)	1.3 ab (0.3)	63.7 a (15.9)	29.7 (7.4)	11.5 (2.9)	11.8 (3.0)	53.0 (13.3)
	November high	22.5 a (11.3)	44.7 a (22.3)	1.1 b (0.5)	68.3 a (34.1)	28.2 (14.1)	12.7 (6.4)	8.7 (4.3)	49.6 (24.8)
	Source				Anova				
	Treatment (T)	NS	NS	NS	**	NS	NS	NS	NS
	Location (L)	*	**	*	NS	NS	NS	NS	NS
	T*L	*	*	**	***	NS	NS	NS	NS

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, and 0.001, respectively.
†Fall lysimeter harvest dates were 30-Nov. (St. Paul) and 23-Nov (Madison) 2009.
‡Spring lysimeter harvests dates were 6-May (St. Paul) and 7-May (Madison) 2010.
§Means followed by the same letter are not significantly different based on Fisher's protected LSD t-test at $\alpha = 0.05$.

Table 12. Sand based root zone ‘L-93’ creeping bentgrass N fertilizer recovery from lysimeters. Values presented are N fertilizer uptake efficiency (N recovered / N applied * 100). Values in parenthesis represent recovery in kg N ha^{-1}.

		Fall†				Spring‡			
Location	Treatment	Verdure	Thatch	Root	Total	Verdure	Thatch	Root	Total
		% Fertilizer Recovery							
St. Paul, MN	Spoon-feeding	21.7 ab§ (10.8)	18.3 (9.2)	1.6 ab (0.8)	41.5 (20.8)	16.4 (8.2)	14.6 (7.3)	3.0 (1.5)	33.9 (17.0)
	October low	23.3 a (5.8)	14.3 (3.6)	1.8 ab (0.5)	39.4 (9.9)	14.2 (3.5)	10.3 (2.6)	1.7 (0.4)	26.2 (6.55)
	October high	23.0 a (11.5)	16.0 (8.0)	2.1 a (1.1)	41.1 (20.6)	15.1 (7.5)	11.1 (5.5)	3.4 (1.7)	29.6 (14.8)
	November low	15.6 b (3.9)	13.2 (3.3)	1.3 b (0.32)	30.1 (7.5)	13.6 (3.4)	12.1 (3.0)	2.8 (0.7)	28.5 (7.12)
	November high	18.4 ab (9.2)	12.9 (6.5)	1.5 ab (0.7)	32.8 (16.4)	17.6 (8.8)	9.5 (4.7)	2.6 (1.3)	29.7 (14.8)
Madison, WI	Spoon-feeding	30.1 (15.1)	34.4 (17.2)	1.1 (0.6)	65.6 (32.8)	31.0 a (15.5)	14.9 ab (7.5)	1.9 ab (0.9)	47.7 ab (23.9)
	October low	25.8 (6.5)	35.2 (8.8)	0.6 (0.16)	61.6 (15.4)	19.0 b (4.8)	10.5 b (2.6)	1.1 b (0.3)	30.6 c (7.6)
	October high	26.0 (13.0)	11.6 (5.8)	0.9 (0.5)	38.5 (19.2)	25.4 ab (12.7)	8.9 b (4.4)	1.3 b (0.6)	35.5 bc (17.8)
	November low	33.5 (8.4)	28.8 (7.2)	0.5 (0.1)	62.9 (15.7)	28.6 ab (7.2)	23.9 a (6.0)	2.5 a (0.6)	55.0 a (13.8)
	November high	29.1 (14.6)	22.0 (11.0)	0.5 (0.3)	51.6 (25.8)	30.5 a (15.2)	8.2 b (4.1)	1.4 b (0.7)	40.1 abc (20.0)
	Source	Anova							
	Treatment	NS	NS	NS	NS	NS	**	NS	*
	Location	***	**	***	**	***	NS	**	***
	T*L	NS	NS	NS	NS	NS	NS	NS	NS

NS, *, **, ***Nonsignificant or significant at P ≤ 0.05, 0.01, and 0.001, respectively.
†Fall lysimeter harvest dates were 30-Nov. (St. Paul) and 23-Nov (Madison) 2009.
‡Spring lysimeter harvests dates were 6-May (St. Paul) and 7-May (Madison) 2010.
§Means followed by the same letter are not significantly different based on Fisher’s protected LSD t-test at α = 0.05.

Table 13. Creeping bentgrass root nitrogen concentrations in St. Paul, MN and Madison, WI from silt-loam and sand lysimeter harvests.

		Silt-loam		Sand	
Location	Treatment	Fall[†]	Spring[‡]	Fall	Spring
		mg g^{-1}			
St. Paul, MN	Spoon-feeding	11.7	10.8	12.2	10.2
	October low	10.8	10.3	10.8	9.3
	October high	11.2	8.0	12.1	10.4
	November low	9.8	9.5	11.7	11.3
	November high	11.9	9.1	12.4	11.5
	Control	10.0	12.1	12.6	11.1
Madison, WI	Spoon-feeding	14.7	13.8	12.6	7.4
	October low	16.2	11.8	14.2	7.4
	October high	11.7	10.2	13.9	7.7
	November low	11.2	12.2	16.1	9.5
	November high	16.4	13.3	15.3	8.5
	Control	13.4	12.6	11.9	9.9
	Source	Anova			
	Treatment (T)	NS	NS	NS	NS
	Location (L)	**	***	**	***
	T*L	NS	NS	NS	NS

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, and 0.001, respectively.
[†]Fall lysimeter harvest dates were 30 Nov. (St. Paul) and 23 Nov. (Madison) 2009.
[‡]Spring lysimeter harvest dates were 6 May (St. Paul) and 7 May (Madison) 2010.
[§]Means followed by the same letter within each location and month are not significantly different based on Fisher's protected LSD t-test at $\alpha = 0.05$.

Table 14. Summary of ‘L-93’ creeping bentgrass fall turfgrass quality, green color index, clipping growth, clipping nitrogen, and total lysimeter N fertilizer uptake efficiency (N recovered / N applied * 100) data between locations in St. Paul, MN and Madison, WI, collected from Sept. to Nov., 2009.

		Fall									
Location	Treatment	Turfgrass Quality (Average)		Color Index (Average)		Fall Growth (Cumulative)		Clipping Nitrogen (Average)		Lysimeter Fertilizer Efficiency	
		Silt-loam	Sand	Silt-loam	Sand	Silt-loam	Sand	Silt-loam	Sand	Silt-loam	Sand
		1-9		0-999		kg ha^{-1}		mg g^{-1}		%	
St. Paul, MN	Spoon-feeding	7.1 a†	6.4 a	246 a	221 a	559 a	326	37.6 b	35.2 b	44.6 (22.3)	41.5 (20.8)
	October low	6.6 b	5.6 b	234 a	189 c	480 ab	298	36.5 b	33.1 c	40.4 (10.1)	39.4 (9.9)
	October high	6.9 a	5.8 b	241 a	204 b	578 a	356	39.7 a	37.0 a	53.7 (26.9)	41.1 (20.6)
	November low	5.2 c	4.3 c	209 b	178 cd	390 b	294	30.6 d	27.6 d	57.6 (14.4)	30.1 (7.5)
	November high	5.3 c	4.3 c	212 b	173 d	412 b	354	33.2 c	27.9 d	41.8 (20.9)	32.8 (16.4)
	Control	5.2 c	4.3 c	210 b	174 d	420 b	251	31.4 d	27.7 d	N/A	N/A
Madison, WI	Spoon-feeding	7.0 a	7.0 a	255 a	266 a	583 a	423	34.7 a	33.6 a	61.0 a (30.5)	65.6 (32.8)
	October low	6.7 b	6.7 abc	246 ab	239 bc	483 abc	378	32.8 ab	31.2 b	54.8 a (13.7)	61.6 (15.4)
	October high	6.8 b	6.9 ab	238 abc	254 ab	493 abc	393	33.8 a	32.2 b	21.6 b (10.8)	38.5 (19.2)
	November low	6.4 c	6.5 bc	237 abc	241 bc	547 ab	401	31.0 bc	29.1 c	63.7 a (15.9)	62.9 (15.7)
	November high	6.4 c	6.4 c	228 c	228 c	463 bc	344	30.2 c	29.2 c	68.3 a (34.1)	51.6 (25.8)
	Control	6.5 c	6.5 bc	234 bc	233 c	436 c	359	30.7 c	28.9 c	N/A	N/A
	Source	Anova									
	Treatment (T)	***	***	***	***	***	NS	***	***	**	NS
	Location (L)	***	***	***	***	NS	***	***	**	NS	**
	T*L	***	***	*	NS	NS	NS	***	***	***	NS

NS, *, **, ***Nonsignificant or significant at P ≤ 0.05, 0.01, and 0.001, respectively.
†Means followed by the same letter are not significantly different based on Fisher’s protected LSD t-test at α = 0.05.

Table 15. Summary of 'L-93' creeping bentgrass spring turfgrass quality, green color index, clipping growth, clipping nitrogen, and total lysimeter N fertilizer uptake efficiency (N recovered / N applied *100) data between locations in St. Paul, MN and Madison, WI, collected from Mar. to June, 2010.

		Spring									
		Turfgrass Quality (Average)		Color Index (Average)		Spring Growth (Cumulative)		Clipping Nitrogen (Average)		Lysimeter Fertilizer Efficiency	
		Silt-loam	Sand	Silt-loam	Sand	Silt-loam	Sand	Silt-loam	Sand	Silt-loam	Sand
		———1-9———		———0-999———		———kg ha^{-1}———		——— mg g^{-1}———		———%———	
St. Paul, MN	Spoon-feeding	5.0 b	5.6 a	238 b	221 b	1735 b	1267 abc	31.5 bc	29.7 bc	45.7 (22.9)	33.9 (17.0)
	October low	4.0 c	4.1 c	209 c	183 c	1417 c	1002 cd	29.0 d	27.9 d	37.6 (9.4)	26.2 (6.55)
	October high	5.6 ab	5.9 a	250 ab	243 a	2005 ab	1553 a	32.6 b	30.5 b	36.6 (18.3)	29.6 (14.8)
	November low	3.8 c	4.7 b	204 c	196 c	1365 c	1102 bc	30.0 cd	28.4 cd	44.8 (11.2)	28.5 (7.12)
	November high	6.0 a	5.5 a	266 a	232 ab	2109 a	1413 ab	36.5 a	32.3 a	36.5 (18.3)	29.7 (14.8)
	Control	2.6 d	2.4 d	162 d	143 d	1037 d	678 d	27.5 e	25.9 e	N/A	N/A
Madison, WI	Spoon-feeding	7.1 a	6.7 a	229 a	251 a	2103	1371 a	32.1 abc	31.7 bc	51.6 (25.8)	47.7 ab (23.9)
	October low	6.0 c	5.9 c	203 b	216 b	1895	1034 bc	31.1 bc	30.7 c	41.2 (10.3)	30.6 c (7.6)
	October high	7.1 a	6.7 ab	228 a	251 a	1542	1269 ab	32.5 abc	32.2 b	31.2 (15.6)	35.5 bc (17.8)
	November low	5.7 c	6.0 bc	210 b	214 b	1986	950 bc	32.5 ab	30.8 c	53.0 (13.3)	55.0 a (13.8)
	November high	6.6 b	6.0 abc	212 ab	221 b	2029	1125 abc	33.8 a	33.6 a	49.6 (24.8)	40.1 abc (20.0)
	Control	4.6 d	4.7 d	168 c	177 c	1564	850 c	30.7 c	29.4 d	N/A	N/A
	Source	Anova									
	Treatment (T)	***	***	***	***	***	***	***	***	NS	*
	Location (L)	***	***	***	***	**	NS	*	***	NS	***
	T*L	**	***	***	*	**	NS	***	*	NS	NS

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, and 0.001, respectively.

†Means followed by the same letter are not significantly different based on Fisher's protected LSD t-test at $\alpha = 0.05$.

Figure 1. Precipitation (mm) in Madison, WI and St. Paul, MN from 1 Sept. 2009 to 30 June 2010.

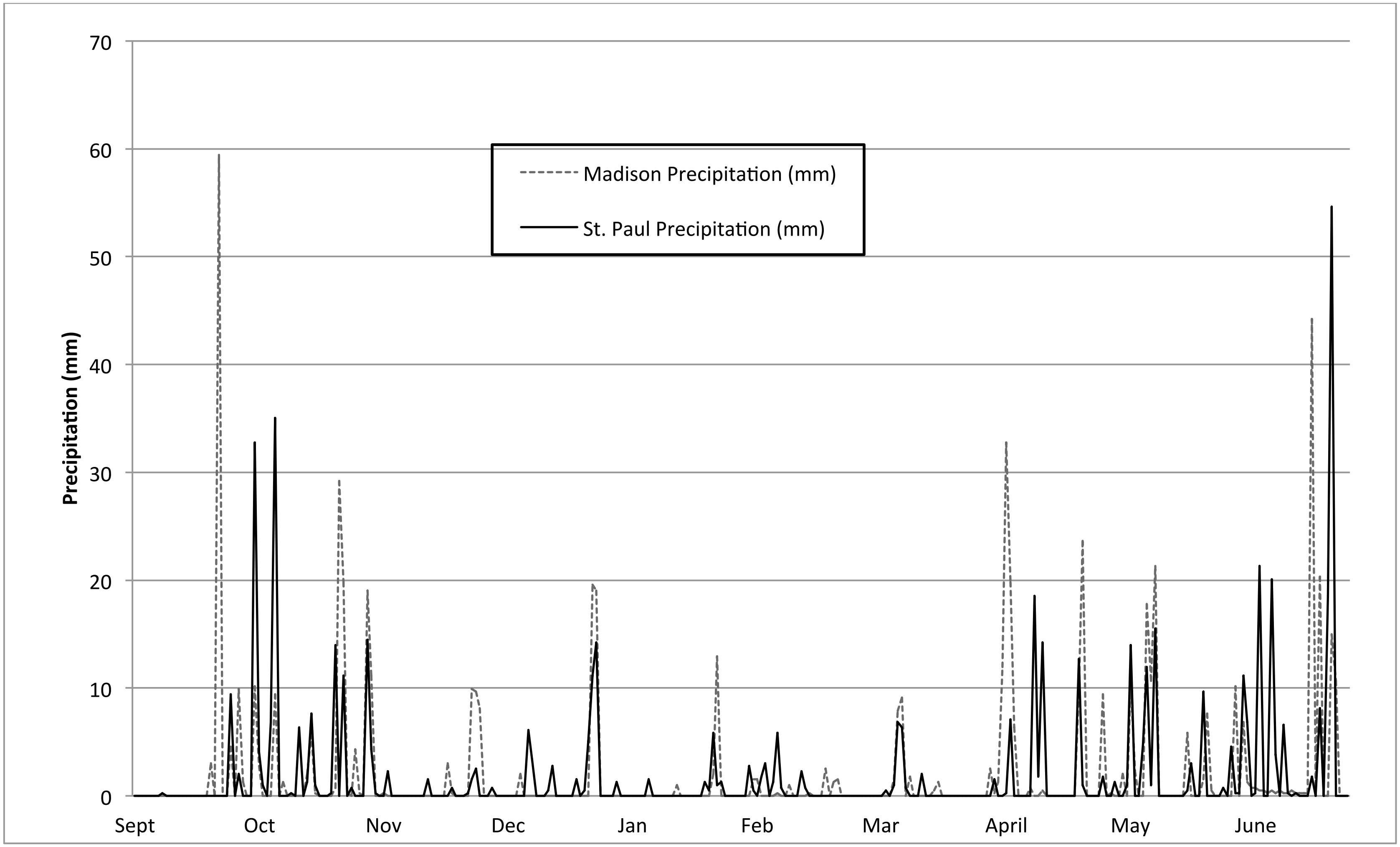


Figure 2. Mean daily air temperature (°C) in Madison, WI and St. Paul, MN from 1 Sept. 2009 to 30 June 2010.

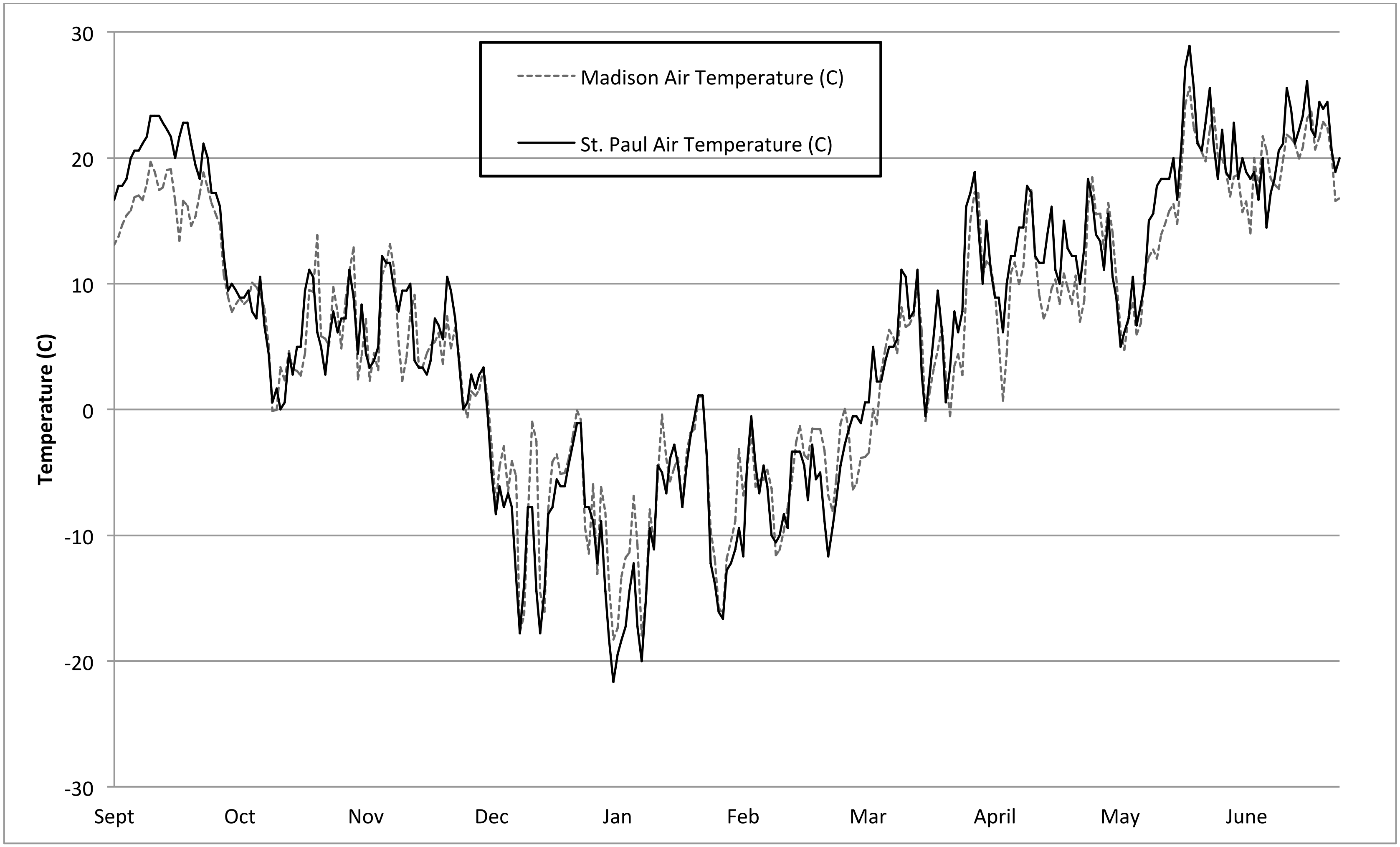
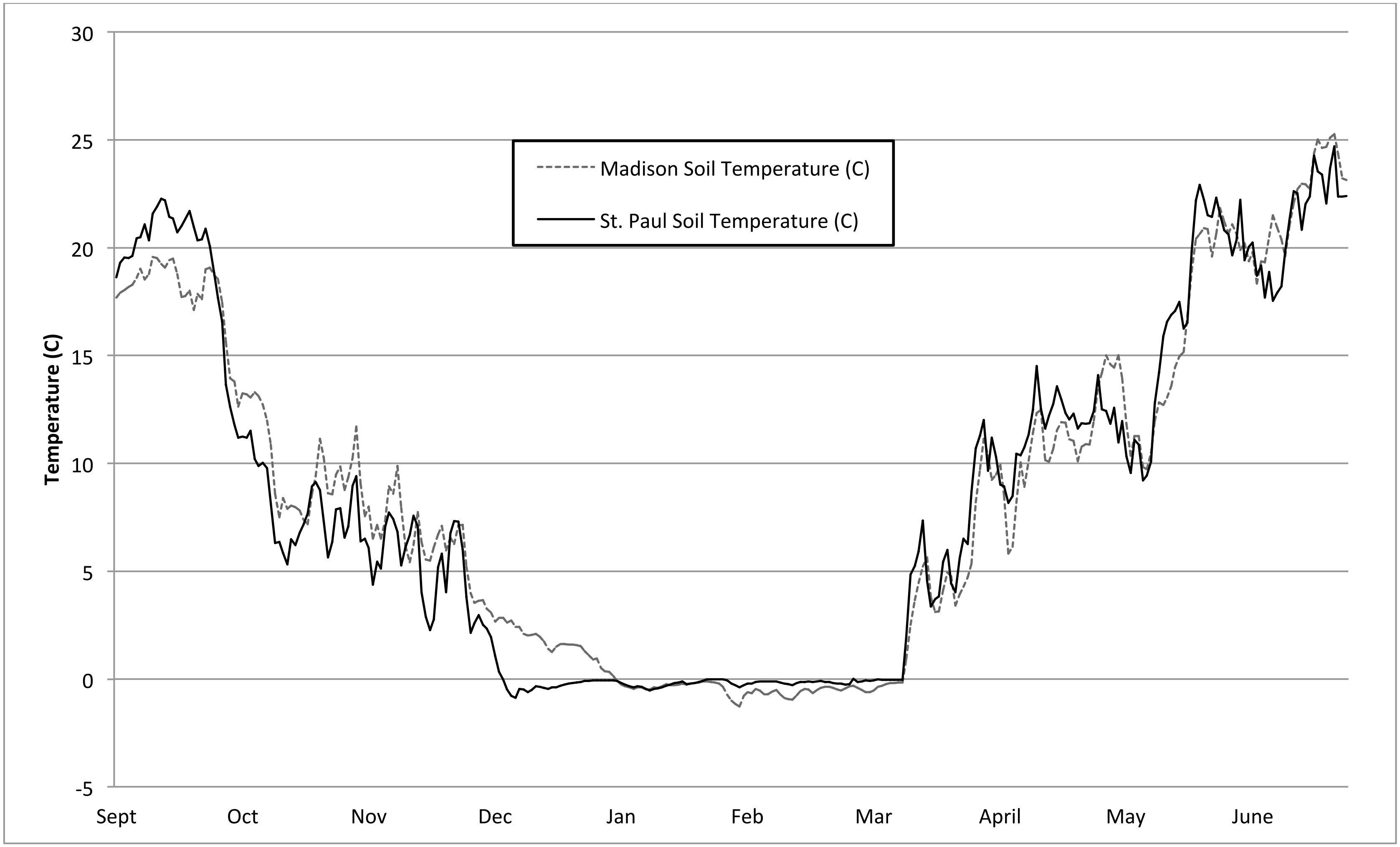


Figure 3. Mean daily soil temperature (°C) at 5 cm depth in St. Paul, MN and Madison, WI from 1 Sept. 2009 to 30 June 2010.



CHAPTER 4. ESTABLISHMENT OF CREEPING BENTGRASS IN ANNUAL BLUEGRASS FAIRWAYS USING GLYPHOSATE AND INTERSEEDING

(*a paper formatted for submission to Applied Turfgrass Science*)

Sam Bauer, Brian Horgan, Eric Watkins, Aaron Hathaway, Ronald Calhoun

OVERVIEW

Creeping bentgrass (*Agrostis stolonifera* L.) is a highly desirable cool-season turfgrass that produces a quality golf playing surface. Golf courses that are established with creeping bentgrass are often invaded by annual bluegrass (*Poa annua* L.) and other turfgrass species over a relatively short period of time. Interseeding and non-selective herbicides, like glyphosate, have often been used to increase creeping bentgrass on golf course fairways. The objective of this research was to determine the most effective glyphosate rate and application timing necessary to quickly increase creeping bentgrass populations through interseeding into predominantly annual bluegrass fairways, while keeping the golf course open for play. This study was conducted from July to October, 2010 at the University of Minnesota Les Bolstad Golf Course (St. Paul, MN) and Michigan State University Turfgrass Research Facility (East Lansing, MI). The experimental design was a randomized complete block with four replicates. Glyphosate was applied to plots at 14, 7, or 0 days before seeding (DBS) at rates of 0, 0.28, 0.42, 0.84, 1.68, or 5.62 kg a.i. ha^{-1}. 'T-1' creeping bentgrass was slit-seeded into the entire plot area in two directions at a total rate of 73.2 kg ha^{-1}. Results demonstrate that higher glyphosate rates provided for the greatest increase in bentgrass abundance at both locations. The highest bentgrass abundance (54%) was observed in Michigan for the

5.62 kg a.i. ha^{-1} treated plots at 8 weeks after seeding (WAS). The glyphosate applications at 7 and 0 DBS had the longest duration of acceptable turf quality and the greatest increase in creeping bentgrass abundance. The recommendation from this study would be glyphosate application of 1.68 kg a.i. ha^{-1} or greater, applied at 0-7 DBS, while interseeding bentgrass at a rate of 73 kg ha^{-1} during mid-summer high stress periods.

INTRODUCTION

Fairways make up the largest portion of intensively maintained turfgrass areas on a golf course (Lyman et al., 2007) and creeping bentgrass is a desirable species for use on fairways in the Midwest. Golf course fairways that are established with creeping bentgrass are often invaded by annual bluegrass, which may easily become the dominant species over time (Branham, 1990; Christians, 2000). Undesirable traits associated with annual bluegrass are a light green color, prodigious seed-head production, poor environmental stress tolerance, high disease susceptibility, and lack of uniformity (Harivandi et al., 2008). Golf course superintendents have utilized interseeding in combination with herbicides or plant growth regulators as a means of establishing creeping bentgrass into a predominantly annual bluegrass stand. Researchers have demonstrated success with plant growth regulators for selective suppression of annual bluegrass in creeping bentgrass turf, including paclobutrazol (Woosley et al., 2003; McCullough et al., 2005), flurprimidol (Bigelow et al, 2007), ethofumesate (Woosley et al., 2003), amicarbazone (McCullough et al., 2010), and chlorsulfuron (Gaul and Christians, 1988). Additionally, the herbicide bispyribac-sodium has been shown to selectively control annual bluegrass in creeping bentgrass, although multiple applications are required (Lycan and Hart, 2006; McCullough and Hart, 2010). However, a gradual conversion to creeping bentgrass is only possible if creeping bentgrass populations are relatively abundant to begin with (Reicher and Hardebeck, 2002). If bentgrass populations are low, the use of interseeding and a non-selective herbicide with low soil residual may be necessary.

To avoid high temperature and drought pressures of the summer months, creeping bentgrass seed is typically sown in late summer or early fall; however, this timing might not be best when seeding into an existing stand of annual bluegrass due to competition from this germinating winter annual (Murphy et al., 2005). Annual bluegrass seed germination increases in the late summer when soil temperatures fall below 21°C, putting tremendous pressure on newly-seeded bentgrass fairways. Bentgrass seed is able to germinate at higher temperatures than annual bluegrass (Engel, 1967) and annual bluegrass becomes physiologically stressed at these high temperatures after producing seed-heads in the late spring (Vargas and Turgeon, 2004). Murphy et al. (2005) conducted a field experiment in New Jersey to determine the effect of seeding time while overseeding into a mixed annual bluegrass and creeping bentgrass putting green previously treated with glyphosate. They determined that competition from annual bluegrass is significantly reduced when seeding creeping bentgrass in June or August (80% establishment) versus September or October (50% establishment); these ratings were taken one year after seeding. Similarly, Henry et al. (2005) attempted conversion of existing creeping bluegrass [*Poa annua* L. spp. *reptans* (Hauskins) Timm.] in a golf green situation through overseeding four varieties of bentgrass (*Agrostis* spp.) on three dates over two years without the use of non-selective herbicides. They found that conversion from creeping bluegrass to creeping bentgrass is increased when using summer seeding dates and higher density creeping bentgrass cultivars. A maximum of 72% creeping bentgrass coverage was achieved 24 months after seeding from a July seeding date, though factors such as a large bluegrass seed-bank and golfer or maintenance traffic were not present in this study.

Perhaps the most important improvement in the turfgrass industry has been the continual introduction of improved cultivars. 'T-1' creeping bentgrass was released by Jacklin in October 2004. 'T-1' has shown improved competitiveness with annual bluegrass (Morris, 2005, 2006) and the potential to establish more readily by seed into established annual bluegrass than 'Southshore' creeping bentgrass (Brede, 2007).

Researchers have evaluated numerous methods for opening up the turfgrass canopy to allow for seed to soil contact, including vertical mowing and core aeration (Kendrick and Danneberger, 2002; Reicher and Hardebeck, 2002; Henry et al., 2005; Murphy et al., 2005), spiking (Bowman, 1998), scalping (Zuk and Fry, 2005) and slit-seeding (Keeley and Zhou, 2005). Dant and Christians (2005) evaluated five methods for introducing glyphosate-resistant creeping bentgrass seed into a stand of 'Penncross' creeping bentgrass. Results from this study showed that surface preparation method had little to no effect on the establishment of glyphosate-resistant creeping bentgrass, indicating that the method employed is of minor importance. However, a successful establishment of bentgrass depends on the existing annual bluegrass being non-competitive, and glyphosate has been the product of choice for annual bluegrass suppression and control (Park and Landschoot, 2003). Glyphosate is a systemic, non-selective, post-emergent herbicide that is readily phloem translocated (Su et al., 2009). It is inactivated by soil adsorption, environmentally sound due to low application rates (Mosier et al., 1990), and has a low leaching and volatilization potential (Franz et al., 1997).

The objective of this study was to determine the most effective glyphosate application rate and timing necessary to increase creeping bentgrass populations while keeping the fairway in play. We accomplished this objective by evaluating the effectiveness of summer creeping bentgrass seeding using an improved cultivar, as affected by various rates and timings of glyphosate on two predominantly annual bluegrass fairways in Michigan and Minnesota.

MATERIALS AND METHODS

Research was conducted from July to October, 2010 at the University of Minnesota Les Bolstad Golf Course (St. Paul, MN) and Michigan State University Hancock Turfgrass Research Facility (East Lansing, MI). The Minnesota location was established in 1929 and has since transitioned to annual bluegrass. The plots in Michigan were established in 2006 from annual bluegrass seed-heads collected during mowing of an annual bluegrass stand. Minnesota was subjected to normal golf traffic and received routine fairway maintenance (12.5 mm height of cut, mowing three times $week^{-1}$) throughout the duration of the study, while the Michigan site was not subject to golf traffic, but did receive routine fairway maintenance. Soil type in Minnesota and Michigan were a Cathro Muck (organic material over loamy sediment) and Colwood-Brookston loam, respectively.

Initial turfgrass species composition was evaluated prior to initiation of the study using the grid intersect method described by Tinney et al. (1937) and modified by Gaussoin and Branham (1989). A 1.2 by 1.8 m PVC frame with an internal monofilament grid of 240 intersections was placed over individual plots. The turf species present under each intersection was recorded and converted to a percentage by dividing individual species counts by 240. Species compositions as averaged over the study areas at each location were: Minnesota, 99% annual bluegrass and 1% perennial ryegrass (*Lolium perenne* L.); Michigan, 96% annual bluegrass and 4% creeping bentgrass. Kentucky bluegrass abundance was less than 1% at both locations.

Treatment factors included glyphosate rate and application timing relative to date of seeding. The glyphosate product used was Razor® Pro (Nufarm Americas Inc., Burr Ridge, IL), containing 41% glyphosate in the form of isopropylamine salt. Glyphosate applications were applied with a CO_2 pressurized sprayer calibrated to deliver 7.5 L 100 m^{-2}. Application rates were 0, 0.28, 0.42, 0.84, 1.68, and 5.62 kg a.i. ha^{-1}, applied either 14, 7, or 0 days before seeding (DBS). Seeding dates were July 15 and 20, 2010 for Minnesota and Michigan, respectively. Seeding was done using a Turfco Triwave™ (Turfo Manufacturing Co., Minneapolis, MN) slit-seeder calibrated to deliver a total of 73 kg ha^{-1} 'T-1' creeping bentgrass seed to the study area by seeding in two directions on 45° angles from a fixed line. Seeder depth was set to penetrate the surface to the thatch-soil interface, not exceeding 12.5 mm. Subdue® GR (Syngenta Crop Protection Inc, Greensboro, NC), 1% mefanoxam, was applied and watered in with 4 mm of water on the day of seeding and 2 weeks after seeding (WAS) for the prevention of *Pythium*. A starter fertilizer was applied at a rate of 24.5 kg N ha^{-1}, 49 kg P_2O_5 ha^{-1}, and 24.5 kg K_2O ha^{-1} on the day of seeding and 3 WAS. Subsequent fertilizer applications of 24.5 kg N ha^{-1} and 24.5 kg K_2O ha^{-1} were applied at 6 WAS and 9 WAS; additional phosphorus was not required based on a soil test. Irrigation during grow-in was applied daily at 600 h, 1200 h, and 1800 h and delivered uniform applications of no more than 12.5 mm water day^{-1}. Following establishment, irrigation schedules were adjusted to apply water at 80-100% of evapotranspiration as dictated by onsite or local weather station data.

Dollar spot (*Sclerotinia homoecarpa*, F.T. Bennett) occurred at both locations throughout the study and was controlled with clorothalonil (Daconil Weather Stik®;Syngenta Crop Protection Inc, Greensboro, NC). An infection of *Pythium* occurred in Minnesota on August 12th, 2010 and was controlled with propamocarb hydrochloride (Banol®;Bayer Environmental Science, Research Triangle Park, NC); this was beyond the 14 day mefenoxam re-application interval and attributed to excessively wet, hot, and humid weather. Additional fungicide applications were not required for the remainder of the study.

Data Collection and Experimental Design

Increase in bentgrass abundance was evaluated using the previously-described grid intersect method at 3 WAS and again when all plots received 100% cover ratings.

Visual turfgrass quality was evaluated weekly following the initial glyphosate application and continued until all plots gained 100% cover. Following guidelines from the National Turfgrass Evaluation Program (NTEP), visual turfgrass quality was assessed on a 1-9 scale (9 = best turf quality) based on color, density, uniformity, texture, and biotic or abiotic stresses. A 6 or above was considered to be acceptable (Morris and Shearman, 2010).

The experimental design was a 5 by 3 factorial with a control (no glyphosate) in a randomized complete block with four replicates. Plot size was 1.2 by 1.8 m with a 0.3 m border around each plot. Data were subjected to analysis of variance (ANOVA) using software from The R Project For Statistical Computing (R Development Core Team, 2009). Means were separated using Fisher's least significant difference at a 95% confidence level.

RESULTS AND DISCUSSION

Bentgrass Abundance

Bentgrass abundance had a significant location by treatment interaction, and therefore locations were analyzed separately (Table 1).

In Michigan bentgrass abundance was significantly affected by glyphosate rate at 3 and on the final rating date (8 WAS, when all plots reached 100% cover) and a significant effect of application timing on the bentgrass abundance on the final rating date. Neither the rate by time interaction or the effect of blocking was significant on either rating date. On both rating dates, bentgrass abundance was greatest with increasing glyphosate rates. The 5.62 kg a.i. ha^{-1} rate provided the greatest increase in bentgrass abundance, with 83% and 53% bentgrass at 3 WAS and 8 WAS, respectively; although this rate was not statistically different from the 1.68 kg a.i. ha^{-1} rate (Fig. 1). Glyphosate treatments at 7 DBS provided the highest bentgrass abundance (41%) at 8 WAS, versus 14 DBS (26%) and 0 DBS (34%) (Fig. 2).

Glyposate rates also resulted in significant differences in bentgrass abundance in Minnesota. Again, higher rates provided for the greatest increase in bentgrass abundance at 3 WAS as well as on the final rating date (12 WAS, when all plots reached 100% cover). Maximum bentgrass abundance was 30% at 3 WAS and 24% on the final rating date (Fig. 3). This is approximately half of the increase as reported in Michigan, which is likely a result of additional golfing traffic and a large annual bluegrass seed-bank at the Minnesota site. Timing of application was not statistically significant in Minnesota on either rating date.

Overall, highest bentgrass abundance was associated with increasing glyphosate rates, with the assumption that higher glyphosate rates suppressed the existing turf enough to allow adequate germination of new bentgrass seedlings. Annual bluegrass regrowth and competition was likely the main factor inhibiting bentgrass germination and spread in the lower rate glyphosate treated plots. Due to this competition, both locations showed a reduction in creeping bentgrass populations from 3 WAS to the final rating date.

Although not consistently significant, glyphosate application timing at 7 DBS produced greater bentgrass abundance on the final rating date at both locations. This was expected, as the 14 DBS application allowed for annual bluegrass regrowth before seeding was conducted. Additionally, the 0 DBS application took approximately 5-7 days to suppress the existing annual bluegrass, while creeping bentgrass germination occurred as soon as 3 days after seeding and was therefore competing with the annual bluegrass.

Turfgrass Quality

Turfgrass quality showed a significant effect of the location by treatment interaction on multiple rating dates, and therefore locations were analyzed separately. Turfgrass quality was preserved with lower glyphosate rates more so in Michigan (Fig. 4) than Minnesota (Fig. 5); the Minnesota applications were made earlier in the morning to avoid golfer traffic and it is hypothesized that more glyphosate was taken up by the plant during this time period; foliar uptake of glyphosate is enhanced in more humid environments (Franz et al., 1997) and weather data for St. Paul, MN demonstrates that the relative humidity is historically 27% higher in the morning than in the afternoon during the month of July (National Climatic Data Center, 2002). At the beginning of the study, all glyphosate-treated plots showed a reduction in turfgrass quality compared to the control plots. At approximately 3 WAS in both locations the control plots, comprised primarily of annual bluegrass due to no glyphosate application, showed a significant reduction in turfgrass quality. This is consistent with observations in New Jersey by Henry et al. (2005) showing summer decline of annual bluegrass putting surfaces. In terms of resistance to heat stress, annual bluegrass is inferior to creeping bentgrass

(Beard, 1970). In Minnesota, this annual bluegrass quality reduction continued beyond 5 WAS, at which time the control plots received lower turfgrass quality ratings than all of the glyphosate treated plots. Michigan control plots received lower turfgrass quality ratings than the treatment plots beyond 4 WAS. Dollar spot disease played a role in the decline of the annual bluegrass control plots at both locations. Trends in turfgrass quality ratings beyond 5 WAS reflected the amount of bentgrass present; plots that had more bentgrass received higher turfgrass quality ratings. This turfgrass quality difference based on glyphosate rate was statistically significant in Michigan, but not in Minnesota.

Turfgrass quality as affected by glyphosate application time showed similar trends for both locations, with the 14 DBS application having the longest duration of unacceptable turfgrass quality (data not shown). In Michigan, turfgrass quality levels based on the timing of glyphosate application were not significantly different by 5 WAS. Although on the final rating date, both 0 and 7 DBS applications had significantly higher turfgrass quality values than the 14 DBS application, which is reflected in the higher level of bentgrass in these plots. In Minnesota the timing of glyphosate application did not have a significant effect on turfgrass quality beyond 4 WAS.

CONCLUSIONS AND RECOMMENDATIONS

Results from this study demonstrate that this summer glyphosate and slit-seeding approach has a high potential increase bentgrass populations in annual bluegrass fairways, while keeping the golf course open for play. The control plots receiving no application of glyphosate showed a bentgrass increase of less than 5%, which indicates that interseeding without suppressing the existing turf is an ineffective technique. This result is similar to a fairway study performed by Reicher and Hardebeck (2002) in which a 3% bentgrass increase was obtained after three years of interseeding into a stand of annual bluegrass without the use of non-selective herbicides. Other researchers have shown that creeping bentgrass populations will increase over time after the initial seeding (Henry et al., 2005; Murphy et al., 2005), although our results showed a reduction over time. Aggressive bentgrass varieties, such as 'T-1', have been shown in other research to outcompete annual bluegrass (Morris, 2005, 2006; Beard et al., 2001); although this is probably dependent on altering management practices to favor creeping bentgrass over annual bluegrass, including clipping collection, reducing irrigation frequency (Gaussoin and Branham, 1989), alleviating soil compaction, improving drainage, using lightweight equipment, decreasing shade, and minimizing soil disturbance (Dernoeden, 2000).

Annual bluegrass reduction programs have proven successful for selective control of annual bluegrass in creeping bentgrass fairways (Gaul and Christians, 1988; Gaussoin and Branham, 1989; Woosley et al., 2003; McCullough et al., 2005; Bigelow et al., 2007; McCullough and Hart, 2010); however, implementation of a reduction program requires a moderate population of creeping bentgrass in order to maintain turfgrass quality and encourage bentgrass growth and development. This glyphosate and interseeding approach appears to be a good strategy to quickly increase bentgrass populations when initial populations are low (i.e. 1%). A specific recommendation based on this study would be glyphosate application of 1.68 kg a.i. ha^{-1} or greater, applied at 0-7 DBS, while interseeding bentgrass at a rate of 73 kg ha^{-1} mid-summer high stress periods. Lower rates of glyphosate will benefit turfgrass quality, though the difference appears to be proportional to the increase in bentgrass. Annual bluegrass fairways typically decline during the summer months in the Midwest, making this an optimum time to increase bentgrass populations. Timing glyphosate application from 0 to 7 DBS will maximize the duration of acceptable turfgrass quality and provide for a greater increase in bentgrass populations.

ACKNOWLEDGEMENTS

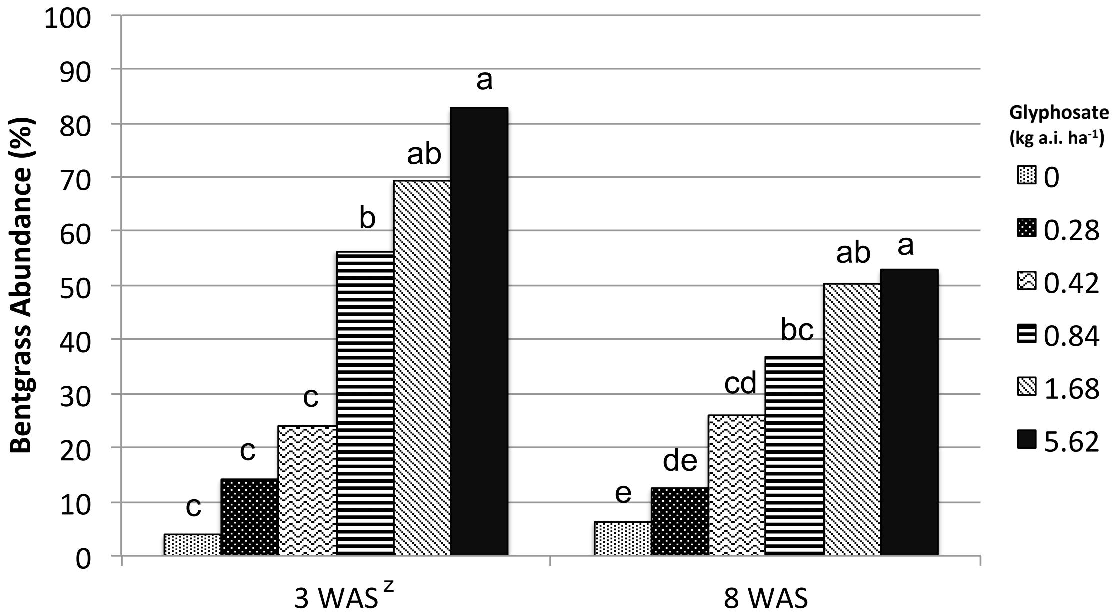
The authors would like to thank Turfco Manufacturing for financial support and the use of the Triwave. We also thank Brent Belanger and Carl Mielke from Les Bolstad Golf Course, and Paul Diegnau and Brett Wenzel from Keller Golf Course.

Table 1. Analysis of variance for bentgrass abundance in Michigan and Minnesota.

		Michigan		Minnesota	
Source of variation	df	3 WAS[v]	8 WAS	3 WAS	12 WAS
Glyphosate Rate (Rate)	5	***[w]	***	**[x]	**
Application Time (Time)	2	NS[z]	***	NS	NS
Block	3	NS	NS	*[y]	NS
Rate*Time	8	NS	NS	NS	NS
Error	45				

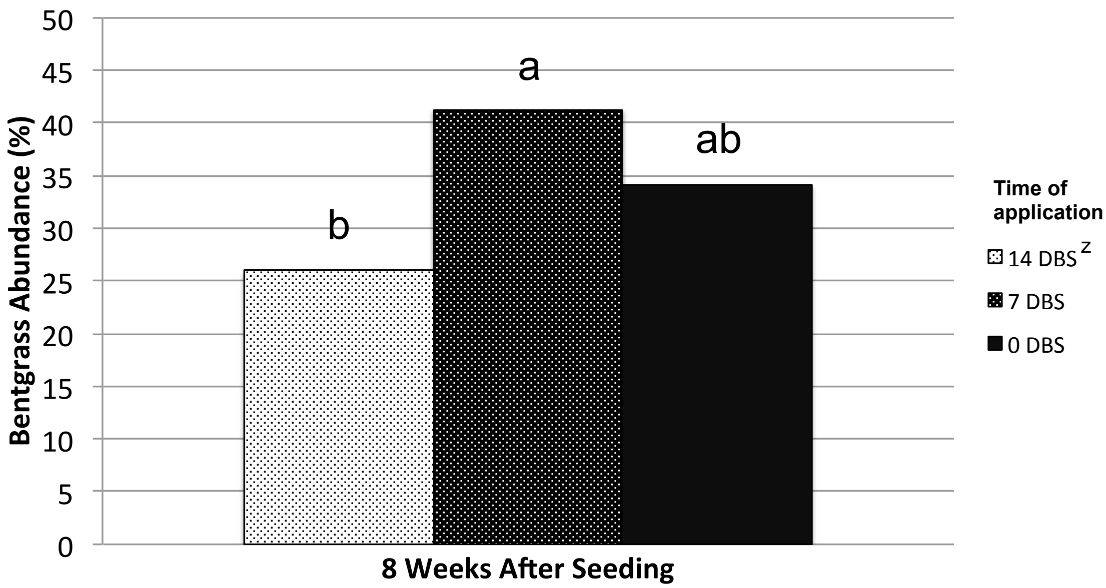
[v] weeks after seeding
[w] *** indicates significance at $P \leq 0.001$
[x] ** indicates significance at $P \leq 0.01$
[y] * indicates significance at $P \leq 0.05$
[z] NS indicates non significance

Figure 1. Percent bentgrass abundance in Michigan as affected by glyphosate application rate. Bars sharing the same letter are not significantly different based on Fisher's protected LSD t-test (α = 0.05).



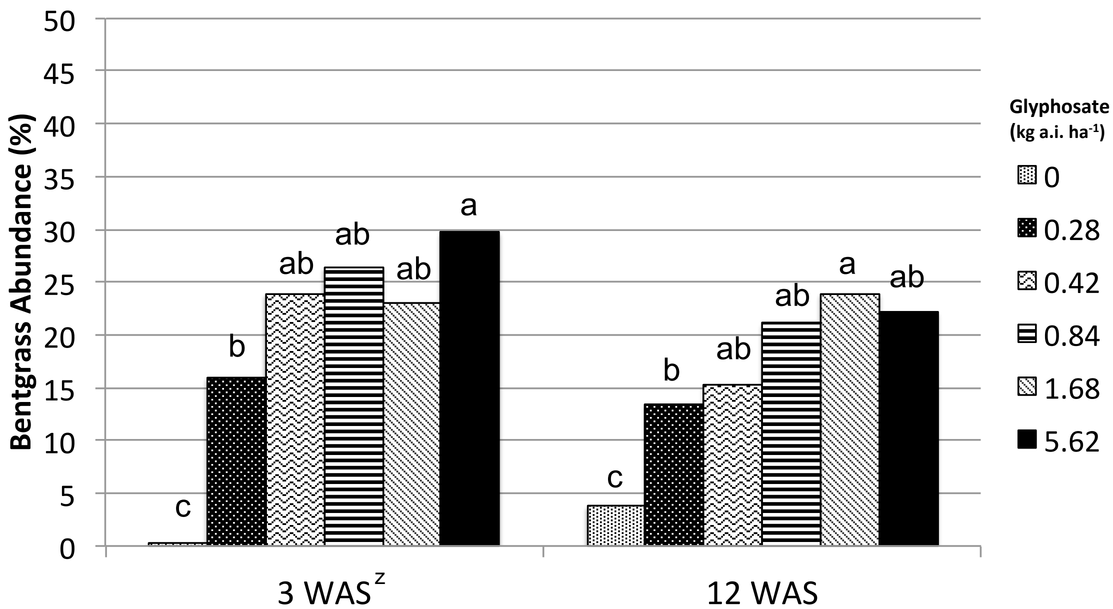
[z] weeks after seeding

Figure 2. Percent bentgrass abundance in Michigan as affected by glyphosate application time. Bars sharing the same letter are not significantly different based on Fisher's protected LSD t-test (α = 0.05).



[z] days before seeding

Figure 3. Percent bentgrass abundance in Minnesota as affected by glyphosate application rate. Bars sharing the same letter are not significantly different based on Fisher's protected LSD t-test (α = 0.05)



[z] weeks after seeding

Figure 4. Turfgrass quality ratings in Michigan as affected by glyphosate application rate. Error bar values were obtained from Fisher's protected t-test LSD (α = 0.05).

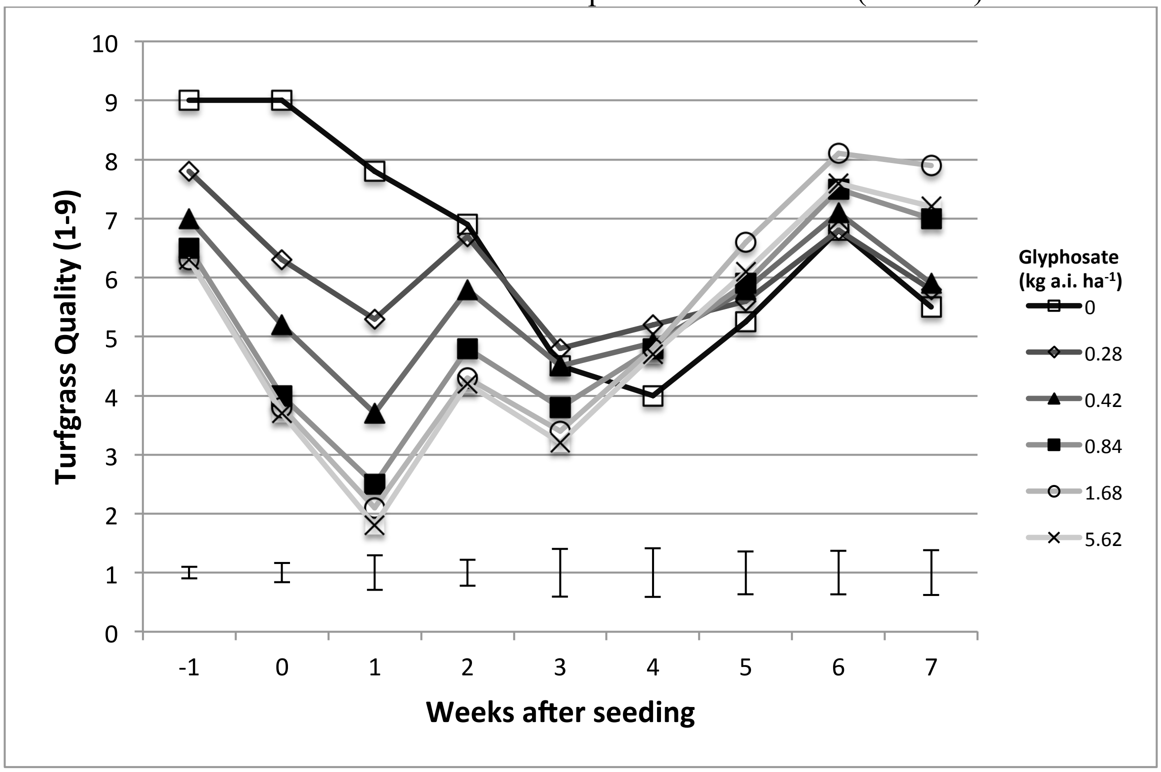
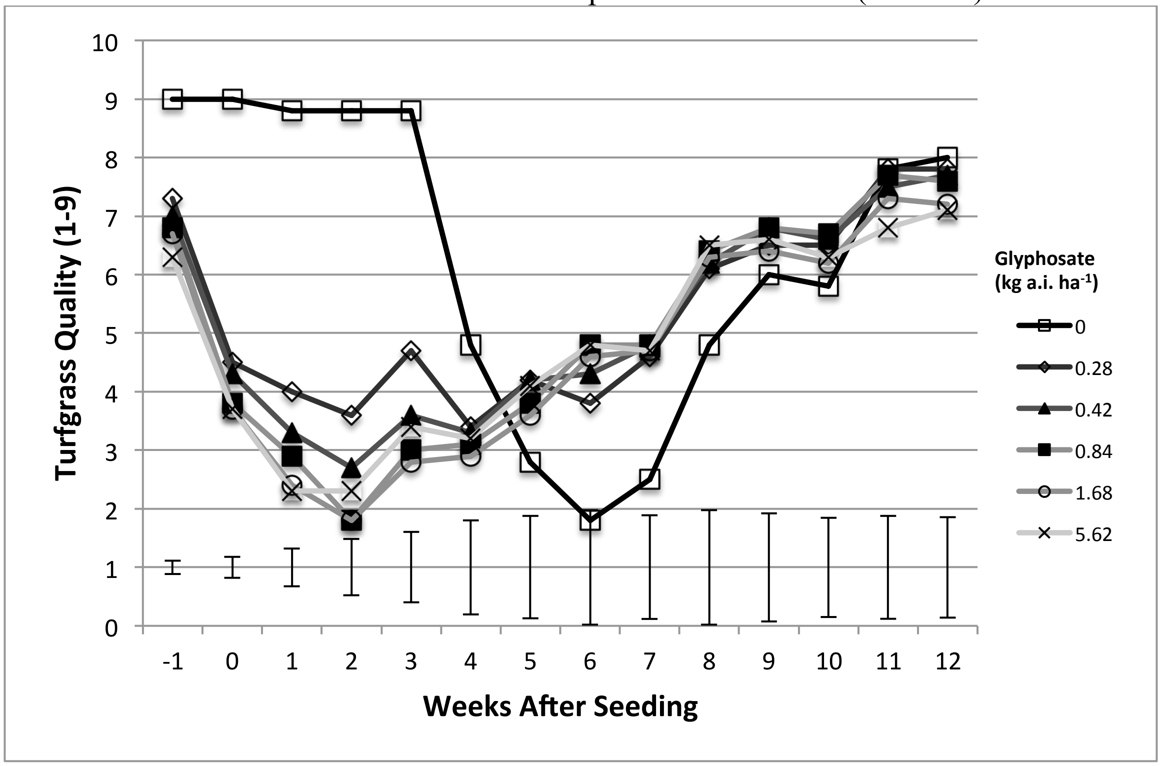


Figure 5. Turfgrass quality ratings in Minnesota based on glyphosate application rate. Error bar values were obtained from Fisher's protected LSD t-test (α = 0.05).



REFERENCES

CHAPTER 1

Alig R.J., Kline J.D., and M. Lichtenstein. 2004. Urbanization on the U.S. landscape: looking ahead in the 21st century. Landscape and Urban Planning 69:219–234.

Baird, J. H. 2007. Soil fertility and turfgrass nutrition 101: Some important concepts you might have missed in or outside of the classroom. USGA Green Sec. Rec. 45:1-8.

Beard, J. B. 1969. Winter injury of turfgrasses. Proc. Int. Turfgrass Res. Conf. 1:226-234.

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

Below, F. E. 2002. Nitrogen metabolism and crop productivity. p. 385-406. *In* M. Pessarakli (ed.). Handbook of plant and crop physiology 2nd ed. Marcel Dekker, Inc., New York, NY.

Bigelow, C. A., K. S. Walker, and G. A. Hardebeck. 2007. Single fall applications of coated urea fertilizers produce a high quality Kentucky bluegrass turf. Applied Turf. Sci. Online. doi:10.1094/ATS-2007-0702-01-RS.

Bowman, D.C. 2003. Daily vs. periodic nitrogen addition affects growth and tissue nitrogen in perennial ryegrass turf. Crop Sci. 43:247-257.

Busey, P. and J.H. Parker. 1992. Energy conservation and efficient turfgrass maintenance. p. 473-498. *In* D.V. Waddington, R.N. Carrow, and R.C. Shearman (eds.) Turfgrass, Agronomy Monograph No. 32. Amer. Soc of Agron., Madison, WI.

Carroll, J.C., and F.A. Welton. 1939. Effect of heavy and late applications of nitrogenous fertilizer on the cold resistance of Kentucky bluegrass. Plant Physiol. 14:297-308.

Clarkson, D.T. 1988. Regulation of the absorption and release of nitrate by plant cells: a review of current ideas and methodology. p 3. *In* H. Lambers, J.J. Neeteson, I. Stulen, (eds) Fundamental, Ecological and Agricultural Aspects of Nitrogen Metabolism In Higher Plants. Marinus Nijhoff., Dordrecht, The Netherlands.

Danneberger, Karl. 2006. Fall fertilization is fundamental. Golfdom. Online http://www.golfdom.com/golfdom/article/articleDetail.jsp?id=35316. Checked August 2009.

Dubey, R.S. and M. Pessarakli. 2002. Physiological mechanisms of nitrogen absorption and assimilation in plants under stressful conditions. p. 637-655. *In* M. Pessarakli (ed.). Handbook of plant and crop physiology 2nd ed. Marcel Dekker, Inc., New York, NY.

Duff, D.T. 1976. Some effects of fall fertilization. GreenMaster. 12:6.

Economic Research Service. 2010. Fertilizer use and price. United States Department of Agriculture. http://www.ers.usda.gov/data/fertilizeruse. Checked January 2011.

Engelsjord, M.E., B.E. Branham, and B.P. Horgan. 2004. The fate of nitrogen-15 ammonium sulfate applied to Kentucky bluegrass and perennial ryegrass turfs. Crop Sci. 44:1341-1347.

Erdahl, R. J. 1989. Putting green management (Part 1). Grass Roots. 16:1, 19-23, 25.

Frank, K. W., J. R. Crum, R. N. Calhoun, and K. M. O'Reilly. 2006. The fate of nitrogen applied to a mature Kentucky bluegrass turf. Crop Sci. 46:209-215.

Geron, C.A., T.K. Danneberger, S.J. Traina, T.J. Logan, and J.R. Street. 1993. The effects of establishment methods and fertilization practices on a nitrate leaching from turfgrass. J. Environ. Qual. 33:1822-1827.

Griffin, H. M. 1977. It's-no time till spring. Golf Superintendent. 45:34-37, 39-40.

Grossi, N., F. Lulli, M. Volterrani, and S. Miele. 2005. Timing of fall nitrogen application on tall fescue turf. Int. Turfgrass Soc. Res. J. 10:465-465.

Guillard, K., and K.L. Kopp. 2004. Nitrogen fertilizer form and associated nitrate leaching from cool-season lawn turf. J. Enivon. Qual. 33:1822-1827.

Guillard, K., and T. F. Morris. 2008. Relationship between autumn verdure nitrate concentrations and spring color quality in Kentucky bluegrass. 2007 Connecticut Turfgrass Res. Rep. 84-89.

Hanson, A.A., and F.V. Juska. 1961. Winter root activity in Kentucky bluegrass (*Poa pratensis* L.). Agron. J. 53:372-374.

Horgan, B. P., B. E. Branham, and R. L. Mulvaney. 2002. Mass balance of ^{15}N Applied to Kentucky bluegrass including direct measurement of denitrification. Crop Sci. 42:1595-1601.

Horgan, B., and C. Rosen. 2010. Restricting phosphorus fertilizer use: Minnesota superintendents have reinforced their reputations as environmental stewards by working with state and local lawmakers and acting as partners in solving water-quality problems. Golf Course Manage. 78:92-96.

Huang, W. Y., W. McBride, and U. Vasavada. 2008. Recent volatility in U.S. fertilizer prices. Amber Waves. 7:28-31.

Hull and Liu, 2005. Turfgrass nitrogen: physiology and environmental impacts. Int. Turfgrass Soc. Res. J. 10:962-975.

Hull, R. J. 1992. Energy Relations and Carbohydrate Partitioning in Turfgrasses. p. 175-205. In D.V. Waddington, R. N. Carrow and R. C. Shearman (eds.) Turfgrass, Agronomy Monograph No. 32. Amer. Soc of Agron., Madison, WI.

Hull, R. J., and J. T. Bushoven. 2001. A metabolic approach: Improving nitrogen use efficiency in turfgrass. USGA Green Sec. Rec. 39:16-17.

Koski, A. J. 1988. Late-season nitrogen fertilization: What we do and do not know. USGA Green Sec. Rec. 26:8-11.

Koski, A. J., and J. R. Street. 1988. Late-Season nitrogen fertilization of perennial ryegrass and tall fescue. Annu. Meet. Abstr. 80:153.

Koski, A. J.; Street, John R. 2010. Benefits of late fall fertilization. The Ohio State University: Turfgrass Pathology Program. October 22. p. 1-2.

Kussow, W. R. 1987. Fall fertilization of turfgrass: Part II. The practice. Grass Roots. 14:25-27.

Kussow, W. R. 1988. Fall fertilization of cool-season turfgrasses: When the leaves begin to drop, cool-season grasses can use a nutritional boost to speed their recovery from the stress of summer. Golf Course Manage. 56:20-30.

Kussow, Wayne R. 1992. Late fall nitrogen fertilization. Proceedings of the 62nd Annual Michigan Turfgrass Conference. 21:135-156.

Laine, P., Bigot, J., Ourry, and A., Boucaud, J. 1994. Effects of low temperature on nitrate uptake, and xylem and phloem flows of nitrogen, in *Secale cerale* L. and *Brassica napus* L. New Phytol. 127:675-683.

Ledeboer, F.B., and C.R. Skogley. 1973. Effects of various nitrogen sources, timing, and rates on quality and growth rate of cool-season turfgrasses. Agron. J. 65:243-246.

Liu, H., R. J. Hull, and D. T. Duff. 1997. Comparing cultivars of three cool-season turfgrasses for soil water NO_3^- concentration and leaching potential. Crop Sci. 37:526-534.

Liu, X., and B. Huang. 2001. Seasonal changes and cultivar difference in turf quality, photosynthesis, and respiration of creeping bentgrass. HortScience. 36:1131-1135.

Liu, H., and R.J. Hull. 2006. Comparing cultivars of three cool-season turfgrasses for nitrogen recovery in clippings. HortScience. 41:827-831.

Liu H., C.M. Baldwin, H. Luo, and M. Pessarakli. 2008. Enhancing turfgrass nitrogen use under stresses. p. 557-581. *In* M. Pessarakli (ed.) Handbook of turfgrass management and physiology. Taylor and Francis group, LLC Boca Raton, Fl.

Lloyd, D. 2008. Late season nitrogen fertility on putting greens: The Wisconsin survey. Grass Roots. 37:15-17.

Malhi, S. S., and M. Nyborg. 1983. Field study of the fate of fall-applied 15N-labelled fertilizers in three Alberta soils. Agron J. 75:71-74.

Mangiafico, S.S., and K. Guillard. 2006. Fall fertilization timing effects on nitrate leaching and turfgrass color and growth. J. Environ. Qual. 35:163-171.

Milesi, C., and 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. 36:472-476.

Miltner, E.D., B.E. Branham, E.A Paul, and P.E. Rieke. 1996. Leaching and mass balance of ^{15}N-labeled urea applied to a Kentucky bluegrass turf. Crop Sci. 36:1427-1433.

Miltner, E. D., G. K. Stahnke, W. J. Johnston, and C. T. Golob. 2004. Late fall and winter nitrogen fertilization and turfgrass in two pacific northwest climates. HortScience. 39:1745-1749.

Miltner, E.D., G.K. Stahnke, and G.J. Rinehart. 2005. Mowing height, nitrogen rate, and organic and synthetic fertilizer effects on perennial ryegrass quality and pest occurrence. Int. Turfgrass Soc. Res. J. 10:982-988.

Moon, J. W. Jr., D. M. Kopec, E. Fallahi, C. F. Mancino, D. C. Slack, and K. Jordan. 1990. Limitations of photosynthesis in *Lolium perenne* after chilling. J. Am. Soc. Hort. Sci. 115:478-481.

Moore, R. W., N. E. Christians, and M. L. Agnew. 1996. Response of three Kentucky bluegrass cultivars to sprayable nitrogen fertilizer programs. Crop Sci. 36:1296-1301.

Noer, O. J. 1963. Winter injury to cool season turf. Golf Course Reporter. 31:38-40.

Oral, N., and E. Acikgoz. 2001. Effects of nitrogen application timing on growth and quality of a turfgrass mixture. Journal of Plant Nutrition. 24:101-109.

Paré, K., M. H. Chantigny, K. Carey, W. J. Johnston, and J. Dionne. 2006. Nitrogen uptake and leaching under annual bluegrass ecotypes and bentgrass species: A lysimeter experiment. Crop Sci. 46:847-853.

Petrovic, A.M., N.W. Hummel, and M.J. Carrol. 1986. Nitrogen source effects on nitrate leaching from late fall nitrogen applied to turfgrass. p. 137. *In* Agronomy abstracts. ASA, Madison, WI.

Petrovic, A.M. 1990. The fate of nitrogenous fertilizers applied to turfgrass. J. Environ. Qual. 19:1-14.

Piper, C. V., and R. A. Oakley. 1921. Some suggestions for fall treatment of putting greens. Bull. U.S. Golf Assoc. Green Sec. 1:159-161.

Powell, A. J., R. E. Blaser, and R. E. Schmidt. 1967a. Physiological and Color Aspects of Turfgrasses with Fall and Winter Nitrogen. Agron. J. 59:303-307.

Powell, A.J., R.E. Blaser, and R.E. Schmidt. 1967b. Effect of nitrogen on winter root growth of bentgrass. Agron. J. 59:529-530.

Rajashekar, C., Tao, D., and P. Li. 1983. Freezing resistance and cold acclimation in turfgrasses. HortScience, 18:1-93.

Reicher, Z. 2005. November fertilization is money in the bank. [Online] Available at http://www.agry.purdue.edu/turf/tips/2005/novn1024.htm (verified 10/22/2007). Purdue University, Agronomy Department, Turfgrass Science Program.

Reilly, T.E., Dennehy, K.F., Alley, W.M., and W.L. Cunningham. 2008. Ground-Water Availability in the United States: U.S. Geological Survey Circular 1323, 70 p., also available online at http://pubs.usgs.gov/circ/1323/.

Rieke, P. E. 1981. Late fall fertilization of turf. p. 63-64. In Proceedings of the 51st Annual Michigan Turfgrass Conference. East Lansing, MI: January 13-14, 1981. East Lansing : Michigan State University.

Rieke, P.E. 1995. Fall fertilization: Breakfast for champions. Sportsturf. 11:8-9.

Rieke, P. E. 1997. The view from M.S.U.: Late fall fertilization philosophies. On Course. 51:20-34.

Rieke, P. E. 1998. Cool-season turf benefits from fall fertilization. Grounds Maint. 33:22-24.

Schmidt, R. E., and J. E. Shoulders. 1971. Fertilization practices and quality turf. USGA Green Sec. Rec. 9:12-13.

Shields, L. R., W. Beresford, and N. Monical. 1953. Fertilizing turf grasses: How much - when - for what reason. Golf Course Reporter. 21:33-40.

Snow, J. T. 1982. Early spring greenup - don't push it. USGA Green Sec. Rec. 20:6-8.

Solomonson, M. P., and M.J. Barber. 1990. Assimilitory nitrate reductase: Functional properties and regulation. Annual Review of Plant Physiology and Plant Molecular Biology. 41:225-253.

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

Stuckey, I. H. 1941. Seasonal growth of grass roots. Amer. J. Bot. 28:486-491.

Vitousek, P.M., J.A. Aber, R.W. Howarth, G.E. Likens, P.A. Matson, D.W. Shindler, W.H. Schlesinger, and G.D. Tilma. 1997. Human alterations of the global nitrogen cycle: Causes and consequences. Ecological Applications. 7:737-750.

Wisconsin Agricultural Statistics Service, University of Wisconsin. 2001. 1999 Wisconsin Turfgrass Industry Survey. (2), 16pp. (Madison, WI) University of Wisconsin, Madison, UW Extension, and Wisconsin Agricultural Statistics Service.

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

Watschke, T. L., and D. V. Waddington. 1974. Effect of nitrogen source, rate, and timing on growth and carbohydrates of Merion bluegrass. Agron. J. 66:691-696.

Webster, D. E., and J. S. Ebdon. 2005. Effects of nitrogen and potassium fertilization on perennial ryegrass cold tolerance during deacclimation in late winter and early spring. HortScience. 40:842-849.

Wehner, D.J., J.E. Haley, and D.L. Martin. 1988. Late fall fertilization of Kentucky bluegrass. Agron. J. 80:466-471.

Wehner, D.J., and J.E. Haley. 1993. Effects of late fertilization on turfgrass as influenced by application timing and N source. Int. Turfgrass Soc. Res. J. 7:580-586.

Welterlen, M. S., and T. L. Watschke. 1985. Influence of drought stress and fall nitrogen fertilization on cold deacclimation and tissue components of perennial ryegrass turf. Int. Turfgrass Soc. Res. J. 831-840.

Wilkinson, J.F., and D.T. Duff. 1972. Effects of fall fertilization on cold resistance, color, and growth of Kentucky bluegrass. Agron. J. 64:345-348.

Zanoni, L. J., L. F. Michelson, W. G. Golby, and M. Drake. 1969. Factors affecting carbohydrate reserves of cool season turfgrasses. Agron. J. 61:195-198.

CHAPTER 2

Alexander, W. A. 1922. How we controlled *poa annua* at Old Elm. Bulletin of the Green Section of the U.S. Golf Association. 2:213-214.

Beard, J. B. 1970. An ecological study of annual bluegrass. USGA Green Section Record. March. 8:13-18.

Beard, J. B., Croce, P., Mocioni, M., De Luca, A., Volterrani, M. 2001. The comparative ability of thirteen Agrostis stolonifera cultivars to Poa annua. International Turfgrass Society Research Journal. 9:828-831.

Bell, Greg, Stiegler, Chris, Koh, Kyungjoon. 2004. Poa control: perhaps there’s hope: applications of paclobutrazol reduce annual bluegrass cover in putting greens. Golf Course Management. March. 72:23-126.

Bigelow, Cale A., Hardebeck, Glenn A., and B. Todd Bunnell. 2007. Monthly flurprimidol application reduce annual bluegrass populations in a creeping bentgrass fairway. Applied Turfgrass Science. Online at doi:10.1094/ATS-2007-0508-02-RS.

Bingham, S.W., J. Segura, and C.L. Foy. 1980. Susceptibility of several grasses to glyphosate. Weed Science. September. 28:579-58.

Borger, J. A., Naedel, M. B., Elmore, M. T. 2008. Annual bluegrass control in fairway height creeping bentgrass. 2008 Annual Research Report [Penn State]. p. 1-3.

Bowman, Daniel. 1998. Determining best management practices to convert a putting green from Penncross to a new variety. 1998 Turfgrass and Environmental

Research Summary [USGA]. p. 20-21.

Branham, B. E. 1990. A selective annual bluegrass control- finally! USGA Green Section Record. January/February. 28:6-8.

Branham, Bruce E., Hardebeck, Glenn A., Meyer, Joseph W., Reicher, Zachary J. 2004. Turfgrass renovation using dazomet to control the *poa annua* L. soil seed bank. HortScience. December. 39:1763-1767.

Christians, Nick. 1990. Fairway conversion: the annual bluegrass to rye to bent approach. Golf Course Management. August. 58:36-38.

Christians, Nick. 1996. A historical perspective of annual bluegrass control: fighting Poa annua has kept researchers and superintendents gainfully employed through more than eight decades. Golf Course Management. November. 64:49-57.

Christians, Nick. 2000. Fairway grasses for Midwest golf courses. Golf Course Management. April. 68:49-56.

Dant, L. A., and Christians, N. E. 2005. p. 23-44. In: Dant, Lukas Aryn. Rapid Conversion of Golf Course Turf to Glyphosate-Resistant Creeping Bentgrass. M.S. Thesis: Iowa State University.

Dernoeden, Peter H. 2000. Creeping Bentgrass Management: Summer Stresses, Weeds, and Selected Maladies. Sleeping Bear Press. Chelsea, MI.

Engel, Ralph E. 1967. Temperatures required for germination of annual bluegrass and colonial bentgrass. The Golf Superintendent. September/October. 35:20, 23.

Environmental Protection Agency. 2008. Red fact sheet: dazomet. Office of Pesticide Programs. Washington, D.C.

Environmental Protection Agency Web Resource: http://www.epa.gov/ozone/mbr. Checked January 2011.

Franz, John E., Mao, Michael K., Sikorski, James A. 1997. Glyphosate: a unique global herbicide. American Chemical Society. Washington, D.C.

Gaussoin, R. E., Branham, B. E. 1989. Influence of cultural factors on species dominance in a mixed stand of annual bluegrass/creeping bentgrass. Crop Science. March/April. 29:480-484.

Goss, R. M., Gaussoin, R. E., Martin, A. R. 2005. Survival of common turfgrass weed populations following glyphosate application. International Turfgrass Society

Research Journal. 10:1189-1192.

Harivandi, M. A., Hagan, W. B., Morris, K. N. 2008. Evaluating bentgrasses for quality, ball-roll distance, thatch/mat development and annual bluegrass invasion. Acta Horticulturae. February. 783:309-316.

Henry, Gerald M., Hart, Stephen E., Murphy, James A. 2005. Overseeding bentgrass species into existing stands of annual bluegrass. HortScience. April. 40:468-470.

Kane, R. T. 1986. Renovation techniques and management strategies for bentgrass fairways. The Bull Sheet. April. 39:4, 7, 11.

Keeley, S. J., and Zhou, Han-E. 2005. Preemergence herbicide and seeding method effects on seedling growth of Kentucky bluegrass. Weed Technology. 19:43-46.

Kendrick, D.L. and T.K. Danneberger. 2002. Lack of competitive success of an intraseeded creeping bentgrass cultivar into an established putting green. Crop Sci. 42:1615-1620.

Lym, R.G., and D.R. Kirby. 1991. Effect of glyphosate on introduced and native grasses. Weed Technology. 5:421-425.

Lyman, G. T., Throssell, C. S., Johnson, M. E., Stacey, G. A., and Brown, C. D. 2007. Golf course profile describes turfgrass, landscape, and environmental stewardship features. Applied Turf. Sci. 7:1-25.

McCalla, John, Richardson, Mike, Boyd, John, Patton, Aaron. 2010. Annual bluegrass control in creeping bentgrass putting greens. Arkansas Turfgrass Report 2009. p. 133-138.

McCarty, Bert. 1999. Controlling poa annua in bentgrass greens. Grounds Maintenance. January. 34:17-18, 20.

McCullough, Patrick E., Hart, Stephen E., and Darren E. Lycan. 2005. Plant growth regulator regimes reduce Poa annua populations in creeping bentgrass. Applied Turfgrass Science. Online at doi: 1094/ATS-2005-0304-01-RS.

McCullough, Patrick E., Hart, Stephen E., Gianfagna, Thomas J., Chaves, Fabio C. 2009. Bispyribac-sodium metabolism in annual bluegrass, creeping bentgrass, and perennial ryegrass. Weed Science. September/October. 57:470-473.

McCullough, Patrick E., Hart, Stephen E. 2010. Bispyribac-sodium application regimes for annual bluegrass (poa annua) control on creeping bentgrass (agrostis stolonifera) putting greens. *Weed Technology*. July. 24:332-335.

McDonald, Steven J., Dernoeden, Peter H., Kaminski, John E. 2006. Creeping bentgrass tolerance and annual bluegrass control with bispyribac-sodium tank-mixed with iron and nitrogen. Applied Turfgrass Science. August 11:1-7.

Mosier, Dwight G., Peterson, Dallas E., Regehr, David L. 1990. Herbicide mode of action. Cooperative Extension Service, Manhattan, Kansas. p. 1-12.

Murphy, J. A., Samaranayake, H., Lawson, T. J., Honig, J. A., Hart, S. 2005. Seeding date and cultivar impact on establishment of bentgrass in soil containing annual bluegrass seed. International Turfgrass Society Research Journal. 10:410-415.

Park, Bradley S., Landschoot, Peter J. 2003. Effect of dazomet on annual bluegrass emergence and creeping bentgrass establishment in turf maintained as a golf course fairway. Crop Science. 43:1387-1394.

Razor Pro Herbicide Label. Nufarm America Inc. Burr Ridge, IL (EPA Reg. No. 228-366).

Reicher, Z., Hardebeck, Glenn. 1997. Conversion of golf course fairways without using nonselective herbicides. 1997 Annual Report [Purdue University Turfgrass Science Program].

Reicher, Zachary J., Hardebeck, Glenn A. 2002. Overseeding strategies for converting golf course fairways to creeping bentgrass. HortScience. June. 37:508-510.

Rossi, Frank S. 1999. Interseeding bentgrasses into established turf. Golf Course Management. August. 67:53-56.

Su, Y. Senem, Ozturk, L., Cakmak, I., and Budak, H. 2009. Turfgrass species response exposed to increasing rates of glyphosate application. European Journal of Agronomy. October. 31:120-125.

Turgeon, A.J. 2002. Turfgrass Management. Prentice-Hall, Upper Saddle River, N.J.

Vargas, J.M., Turgeon, A.J. 2004. Poa Annua: Physiology, Culture, and Control of Annual Bluegrass. John Wiley and Sons Inc., Hoboken, N.J.

Watschke, Thomas L. 1997. Convert your fairways to bentgrass. Grounds Maintenance. July. 32:G38, G42-G43.

Webster, T.M., Hanna, W.W., Mullinix Jr., B.G. 2004. Bermudagrass (*Cynodon* spp.) dose-response relationships with clethodim, glufosinate and glyphosate. Pest Management Science. 60:1237-1244.

Woosley, Paul B., David W. Williams, and A.J Powell Jr. 2003. Postemergence control of annual bluegrass (Poa annua spp. reptans) in creeping bentgrass (Agrostis stolonifera) turf. Weed Technology. 17:770-776.

Zuk, A. J., and Fry, J. D. 2005. Seeded zoysiagrass establishment in a perennial ryegrass sward. Crop Sci. 45:1521-1528.

CHAPTER 3

Bigelow, C. A., K. S. Walker, and G. A. Hardebeck. 2007. Single fall applications of coated urea fertilizers produce a high quality Kentucky bluegrass turf. Appl. Turfgrass Sci. July p. 1-10.

Bowman, D.C. 2003. Daily vs. periodic nitrogen addition affects growth and tissue nitrogen in perennial ryegrass turf. Crop Sci. 43:247-257.

Frank, K. W., J. R. Crum, R. N. Calhoun, and K. M. O'Reilly. 2006. The fate of nitrogen applied to a mature Kentucky bluegrass turf. Crop Sci. 46:209-215.

Geron, C.A., T.K. Danneberger, S.J. Traina, T.J. Logan, and J.R. Street. 1993. The effects of establishment methods and fertilization practices on nitrate leaching from turfgrass. J. Environ. Qual. 22:119-125.

Guillard, K., and K. L. Kopp. 2004. Nitrogen fertilizer form and associated nitrate leaching from cool-season lawn turf. J. Environ. Qual. 33:1822-1827.

Grossi, N., F. Lulli, M. Volterrani, and S. Miele. 2005. Timing of fall nitrogen application on tall fescue turf. Int. Turfgrass Soc. Res. J. 10:465-465.

Hanson, A.A., and F.V. Juska. 1961. Winter root activity in Kentucky bluegrass (*Poa pratensis* L.). Agron. J. 53:372-374.

Hull and Liu. 2005. Turfgrass nitrogen: physiology and environmental impacts. Int. Turfgrass Soc. Res. J. 10:962-975.

Karam, A. 1993. Chemical Properties of Organic Soils. p. 459-472. *In* Carter, M. R. (ed.) Soil Sampling and Methods of Analysis. Lewis Publishers. Boca Raton, FL.

Koski, A. J. and J. R. Street. 2010. Benefits of late fall fertilization. The Ohio State University: Turfgrass Pathology Program. October 22. p1-2.

Kreuser, W.C., M.P. Fish, D.J. Soldat, S.J. Bauer. 2011. Removing sand from putting green clippings substantially reduces clipping weight measurement error. Crop Sci. 51:1268-1273.

Kussow, W. R. 1988. Fall fertilization of cool-season turfgrasses: When the leaves begin to drop, cool-season grasses can use a nutritional boost to speed their recovery from the stress of summer. Golf Course Manage. 56:20-30.

Landschoot, Peter. 2010. Late fall fertilization. SportsTurf. 26:18-19.

Ledeboer, F.B., and C.R. Skogley. 1973. Effects of various nitrogen sources, timing, and rates on quality and growth rate of cool-season turfgrasses. Agron. J. 65:243–246.

Lloyd, D.T. 2009. Low temperature nitrogen uptake and utilization of turfgrass. M.S. Thesis. University of Wisconsin-Madison. Madison, WI.

Liu H., C.M. Baldwin, H. Luo, and M. Pessarakli, 2008. Enhancing turfgrass nitrogen use under stresses. p. 557-581. *In* M. Pessarakli (ed.) Handbook of turfgrass management and physiology. Taylor and Francis group, LLC Boca Raton, Fl.

Mangiafico, S.S., and K. Guillard. 2006. Fall fertilization timing effects on nitrate leaching and turfgrass color and growth. J. Environ. Qual. 35:163-171.

Mariotti, A. 1983. Atmospheric nitrogen is a reliable standard for natural ^{15}N abundance measurements. Nature 303:685-687.

Matejovic, I. 1995. Total nitrogen in plant material determined by means of dry combustion: A possible alternative to determination by Kjedahl digestion. Commun. Soil. Sci. Plant Anal. 26:2217-2229.

Miltner, E.D., B.E. Branham, E.A Paul, and P.E. Rieke. 1996. Leaching and mass balance of ^{15}N-labeled urea applied to a Kentucky bluegrass turf. Crop Sci. 36:1427-1433.

Miltner, E.D., G.K. Stahnke, and P.A. Backman. 2001. Leaf tissue N content and soil N status following monthly applications of nitrogen fertilizer to fairway turf. Int. Turfgrass Soc. Res. J. 9:409-415.

Miltner, E. D., G. K. Stahnke, W. J. Johnston, and C. T. Golob. 2004. Late fall and winter nitrogen fertilization and turfgrass in two pacific northwest climates. HortScience. 39:1745-1749.

Moore, R. W., N. E. Christians, and M. L. Agnew. 1996. Response of three Kentucky bluegrass cultivars to sprayable nitrogen fertilizer programs. Crop Sci. 36:1296-1301.

Morris, K.N., and Shearman, R.C. 2010. NTEP turfgrass evaluation guidelines. Online. National Turfgrass Evaluation Program (NTEP). Beltsville, MD. www.ntep.org/pdf/ratings.pdf. Checked March 2010.

Petrovic, A.M., N.W. Hummel, and M.J. Carroll. 1986. Nitrogen source effects on nitrate leaching from late fall nitrogen applied to turfgrass. Agronomy abstracts. ASA. Madison, WI. p 137.

Petrovic, A.M. 1990. The fate of nitrogenous fertilizers applied to turfgrass. J. Environ. Qual. 19:1-14.

Petrovic, A.M. 2004. Nitrogen source and timing impact on nitrate leaching from turf. Acta Hort. 66:427-432.

Powell, A. J., R. E. Blaser, and R. E. Schmidt. 1967a. Physiological and Color Aspects of Turfgrasses with Fall and Winter Nitrogen. Agron. J. 59:303-307.

Powell, A.J., R.E. Blaser, and R.E. Schmidt. 1967b. Effect of nitrogen on winter root growth of bentgrass. Agron. J. 59:529–530.

Schmidt, R. E., and J. E. Shoulders. 1971. Fertilization practices and quality turf. USGA Green Sec. Rec. 9:12-13.

Simone, H.A., J.B. Jones, Jr., D.A. Smitties, and C.G. Hussey. 1994. A comparison of analytical methods for nitrogen analysis in plant tissues. Commun. Soil Sci. Plant Anal. 25:943-954.

Snow, J. T. 1982. Early spring greenup - don't push it. USGA Green Sec. Rec. 20:6-8.

USGA Green Section. 1993. USGA recommendations for a method of putting green construction. USGA Green Sec. Rec. 31:1-3.

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

Watschke, T. L., and D. V. Waddington. 1974. Effect of nitrogen source, rate, and timing on growth and carbohydrates of Merion bluegrass. Agron. J. 66:691-696.

Wehner, D.J., J.E. Haley, and D.L. Martin. 1988. Late fall fertilization of Kentucky bluegrass. Agron. J. 80:466-471.

Wehner, D.J., and J.E. Haley. 1993. Effects of late fertilization on turfgrass as influenced by application timing and N source. Int. Turfgrass Soc. Res. J. 7:580-586.

Welterlen, M. S., and T. L. Watschke. 1985. Influence of drought stress and fall nitrogen fertilization on cold deacclimation and tissue components of perennial ryegrass turf. Proceedings of the Fifth International Turfgrass Research Conference. p. 831-840.

Wilkinson, J.F., and D.T. Duff. 1972. Effects of fall fertilization on cold resistance, color, and growth of Kentucky bluegrass. Agron. J. 64:345-348.

CHAPTER 4

Beard, J. B. 1970. An ecological study of annual bluegrass. USGA Green Sec. Rec. 8:13-18.

Beard, J. B., Croce, P., Mocioni, M., De Luca, A., and Volterrani, M. 2001. The comparative competitive ability of thirteen *Agrostis stolonifera* cultivars to *Poa annua*. Int. Turfgrass Soc. Res. J. 9:828-831.

Bigelow, C. A., Hardebeck, G. A., and Bunnell, B. T. 2007. Monthly flurprimidol applications reduce annual bluegrass populations in a creeping bentgrass fairway. Applied Turf. Sci. 8:1-7.

Bowman, D. 1998. Determining best management practices to convert a putting green from Penncross to a new variety. 1998 Turfgrass and Environmental Research Summary [USGA]. 20-21.

Branham, B. E. 1990. A selective annual bluegrass control- finally! USGA Green Sec. Rec. 28:6-8.

Brede, A. D. 2007. 'Alpha' and 'T-1' creeping bentgrass, new cultivars for golf. HortSci. 42:1301-1302.

Christians, N. 2000. Fairway grasses for Midwest golf courses. Golf Course Management. 68:49-56.

Dant, L. A., and Christians, N. E. 2005. p. 23-44. *In*: Dant, Lukas Aryn. Rapid Conversion of Golf Course Turf to Glyphosate-Resistant Creeping Bentgrass.

M.S. Thesis: Iowa State University.

Dernoeden, P. H. 2000. Creeping Bentgrass Management: Summer Stresses, Weeds, and Selected Maladies. Sleeping Bear Press. Chelsea, MI.

Engel, R. E. 1967. Temperatures required for germination of annual bluegrass and colonial bentgrass. The Golf Superintendent. 35:20, 23.

Franz, J. E., Mao, M. K., and Sikorski, James A. 1997. Glyphosate: A Unique Global Herbicide. American Chemical Society. Washington, D.C.

Gaul, M. C., and Christians, N. E. 1988. Selective control of annual bluegrass in cool-season turfs with fenarimol and chlorsulfuron. Agronomy Journal. 80(1):120-125.

Gaussoin, R. E.; Branham, B. E. 1989. Influence of cultural factors on species dominance in a mixed stand of annual bluegrass/creeping bentgrass. Crop Sci. 29:480-484.

Harivandi, M. A., Hagan, W. B., and Morris, K. N. 2008. Evaluating bentgrasses for quality, ball-roll distance, thatch/mat development and annual bluegrass invasion. Acta Hort. 783:309-316.

Henry, G. M., Hart, S. E., and Murphy, J. A. 2005. Overseeding bentgrass species into existing stands of annual bluegrass. HortSci. 40:468-470.

Keeley, S. J., and Zhou, Han-E. 2005. Preemergence herbicide and seeding method effects on seedling growth of Kentucky bluegrass. Weed Technology. 19:43-46.

Lycan, D. W. and Hart, S. E. 2006. Seasonal effects on annual bluegrass (*Poa annua*) control in creeping bentgrass with bispyribac-sodium. Weed Technology. 20:722-727.

Lyman, G. T., Throssell, C. S., Johnson, M. E., Stacey, G. A., and Brown, C. D. 2007. Golf course profile describes turfgrass, landscape, and environmental stewardship features. Applied Turf. Sci. 7:1-25.

McCullough, P. E., Hart, S. E., and Lycan, D. W. 2005. Plant growth regulator regimens reduce *Poa annua* populations in creeping bentgrass. Applied Turf. Sci. 4:1-6.

McCullough, P. E., and Hart, S. E. 2010. Bispyribac-sodium application regimes for annual bluegrass (*Poa annua*) control in creeping bentgrass (*Agrostis stolonifera*) putting greens. Weed Technology. 24:332-335.

McCullough, P. E., Hart, S. E., Weisenberger, D., and Reicher, Z. J. 2010. Amicarbazone efficacy on annual bluegrass and safety on cool-season turfgrasses. Weed Technology. 24:461-470.

Morris, K.N. 2005. Fairway/tee bentgrass test 2003. Progress Report NTEP No. 05-1, National Turfgrass Evaluation Program, USDA ARS, Beltsville, MD.

Morris, K.N. 2006. Fairway/tee bentgrass test 2003. Progress Report NTEP No. 06-2, National Turfgrass Evaluation Program, USDA ARS, Beltsville, MD.

Morris, K.N., and Shearman, R.C. 2010. NTEP turfgrass evaluation guidelines. Online. National Turfgrass Evaluation Program (NTEP). Beltsville, MD. www.ntep.org/pdf/ratings.pdf. Checked March 2010.

Mosier, D. G., Peterson, D. E., and Regehr, D. L. 1990. Herbicide mode of action. Cooperative Extension Service, Manhattan, Kansas. p. 1-12.

Murphy, J. A., Samaranayake, H., Lawson, T. J., Honig, and J. A., Hart, S. 2005. Seeding date and cultivar impact on establishment of bentgrass in soil containing annual bluegrass seed. Int. Turfgrass Soc. Res. J. 10:410-415.

National Climatic Data Center. 2002. Average relative humidity. Online. URL http://lwf.ncdc.noaa.gov/oa/climate/online/ccd/avgrh.html. Checked March 2010.

Park, B. S., and Landschoot, P. J. 2003. Effect of dazomet on annual bluegrass emergence and creeping bentgrass establishment in turf maintained as a golf course fairway. Crop Sci. 43:1387-1394.

R Development Core Team. 2009. A language and environment for statistical computing. R Foundation for Staistical Computing. Vienna, Austria. ISBN3-900051-07-0, URL http://www.R-project.org. Checked March 2010.

Reicher, Z. J., and Hardebeck, G. A. 2002. Overseeding strategies for converting golf course fairways to creeping bentgrass. HortSci. 37:508-510.

Su, Y. S., Ozturk, L., Cakmak, I., and Budak, H. 2009. Turfgrass species response exposed to increasing rates of glyphosate application. Euro. J. Agron. 31:120-125.

Tinney, F.W., O.S. Aamodt, and H.L. Ahlgren. 1937. Preliminary report of a study on methods used in botanical analysis of pasture swards. J. Am. Soc. Agron. 29:835-840.

Vargas, J.M. and A.J. Turgeon. 2005. Poa Annua: Physiology, Culture, and Control of Annual Bluegrass. John Wiley and Sons, Inc. Hoboken, New Jersey.

Woosley, P. B., Williams, D. W., and Powell, A. J. Jr. 2003. Postemergence control of annual bluegrass (*Poa annua* spp. *reptans*) in creeping bentgrass (*Agrostis stolonifera*) turf. Weed Technology. 17:770-776.

Zuk, A. J., and Fry, J. D. 2005. Seeded zoysiagrass establishment in a perennial ryegrass sward. Crop Sci. 45:1521-1528.