NEW STRATEGIES FOR MANAGING DOLLAR SPOT AND SILVERY-THREAD MOSS IN CREEPING BENTGRASS PUTTING GREENS

by

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Abstract

Dollar spot, caused by *Sclerotinia homoeocarpa* F.T. Bennett, and silvery-thread moss (*Bryum argenteum* Hedw.) are pests affecting creeping bentgrass (*Agrostis stolonifera* L.) that typically require pesticide inputs. New strategies for pest management may reduce chemical inputs. The objectives of these 2009-2010 field studies were to evaluate: 1) creeping bentgrass cultivars for dollar spot susceptibility; 2) alternative chemical controls for silvery-thread moss; and 3) the response of silvery-thread moss to nitrogen (N) sources. During peak dollar spot development, 'Declaration', 'A-4', and 'Crenshaw' had 7.5, 139.4, and 288.9 infection centers m^{-2} under fairway and 2.1, 27.2, and 106.9 infection centers m^{-2} under putting green conditions, respectively. Two spring and two fall spot applications of sodium or potassium bicarbonate (45 g a.i. L^{-1}), premixed essential oil, and broadcast applications of carfentrazone-ethyl at 0.09 kg a.i. ha^{-1} suppressed moss 39% to 55% compared to untreated in 2009. Spot sprays of sodium or potassium bicarbonate, and essential oil, were phytotoxic to creeping bentgrass and required up to 8 or 18 days, respectively, to return to acceptable quality. Fertilization with liquid urea (N at 16.3 kg ha^{-1} biweekly, 210 kg ha^{-1} annually) resulted in 147%, 150%, and 155% more moss than fertilization with IBDU, organic N, and granular urea, respectively, and 156% more moss compared to untreated. Fertilization with urea (liquid or granular) resulted in the best creeping bentgrass color. Averaged across the entire season, plots treated with organic N had unacceptable color in 2009. Nitrogen concentrations in moss tissue ranged from 0.4% to 1.0% and were always significantly lower than N concentrations observed in creeping bentgrass (1.1% to 2.1%), regardless of treatment. In 2010, moss treated with liquid urea had higher tissue N concentrations (1.0%) than untreated moss (0.5%) or that fertilized with IBDU (0.4%). In summary, use of dollar spot-resistant creeping bentgrass cultivars could reduce fungicide requirements. Bicarbonate and essential oil products can reduce moss severity at a similar level to carfentrazone-ethyl, but rates and/or application methods need to be optimized to avoid injury to creeping bentgrass. Applications of liquid urea enhanced moss coverage in creeping bentgrass compared to other N sources.

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Chapter 1 - Review of Literature

Turfgrasses have been a common component of landscapes utilized by humans for more than 10 centuries (Walsh et al., 1999). Many species are available for use in lawns, landscapes, sports fields, and golf courses. Creeping bentgrass (*Agrostis stolonifera* L.) is one of the most common species utilized in closely mown turf in the Northern U.S. (Goodman and Burpee, 1991) and is the most common cool-season (C3 photosynthesizing) grass used for putting surfaces in the temperate regions of the world (Christians, 2007).

Dollar Spot

Dollar spot, caused by *Sclerotinia homoeocarpa* F.T. Bennett, is a chronic disease infecting many species of turfgrass and is a serious disease of closely mown creeping bentgrass fairways and greens (Bennett, 1937; Goodman and Burpee, 1991). Furthermore, dollar spot was considered one of the three most important turfgrass diseases as many as 45 years ago (Gould, 1965). The disease has several infection cycles every year and most readily develops at air temperatures of 15 to 30°C (Ellram et al., 2007; Smiley et al., 2005). Dollar spot causes straw-colored lesions with reddish-brown borders on individual leaf blades. In stands of closely mown turf, dollar spot appears as a few bleached blades of grass to straw-colored sunken patches around the size of a U.S. silver dollar (5.0 to 7.5 cm) (Monteith and Dahl, 1932; Smith, 1955; Walsh et al., 1999). Outbreaks of dollar spot, even when mild, disturb the uniformity of turf stands and, on golf courses, can impair playability (Latin, 2006). When dew is present, affected areas of turf can also be recognized by the tufts of white mycelium of the causal agent (Monteith and Dahl, 1932). When host species enter dormancy, *S. homoeocarpa* is thought to overwinter as darkly pigmented substomatal stroma remaining on margins of lesions from a previous infection (Walsh et al., 1999). Host species become infected when mycelial growth enters cut leaf blades and/or stomata, though it is suggested direct penetration into leaf blades does occur (Monteith and Dahl, 1932; Walsh et al., 1999).

Dollar Spot Management

Many strategies have been utilized to suppress dollar spot in creeping bentgrass. Cultural practices can limit the severity of infection, though fungicide applications are typically required to maintain creeping bentgrass quality at an acceptable level. Seventy-eight years ago, Monteith and Dahl (1932) recognized plant health was the first line of defense to pathogenic infections and suggested the judicious use of water and fertilizer would discourage the development of dollar spot. Williams et al. (1996) agreed that increasing plant health could decrease the host's susceptibility to dollar spot, and recommended adequate fertility, proper mowing height and frequency, and regular aerification. Specifically, Williams et al. (1996) attributed reductions in dollar spot severity to both increases in soil moisture and increased levels of nitrogen (N) fertility. Today, it is generally accepted that deficient N levels will predispose turf to dollar spot infection. Turf maintained without sufficient N fertility is more likely to develop weakened, senescent foliage which is more susceptible to *S. homoeocarpa* infection (Endo, 1966; Walsh et al., 1999). Furthermore, fertilizing with N can reduce dollar spot severity (Christians, 2007; Couch, 1995). Davis and Dernoeden (2002) observed that urea, sulfur-coated urea, Milorganite (activated sewage sludge), and organic fertilizers comprised of poultry waste materials effectively delayed dollar spot development when disease pressure was low. However, no treatments significantly reduced dollar spot when disease pressure was moderate, and organic fertilizers did not consistently reduce dollar spot severity more than synthetic N sources.

Lee et al. (2003) observed a reduction in dollar spot damage with the use of acibenzolar-s-methyl, a plant defense activator, and organic fertilizers, but did not observe acceptable dollar spot control without fungicide applications. Similarly, Zhang et al. (2006) found applications of calcium silicate did not reduce dollar spot severity in creeping bentgrass. Recent research from the Chicago District Golf Association indicates creeping bentgrass greens in the area are receiving deficient N fertilization of no more than 146.5 kg ha^{-1} in a season (Settle, 2009). Settle suggests many agronomic plans have excluded the practice of "spoon-feeding" greens in summer months, which involves frequent, low rates of N fertilization. The exclusion of this practice requires putting greens to perform at deficient N levels. Emphasis should be placed on ensuring adequate N fertility by returning to "spoon-feeding" with urea.

Reducing periods of leaf wetness by removing early morning dew can reduce disease severity (Monteith and Dahl, 1932; Walsh et al., 1999; Williams et al., 1996). Williams et al. (1996) found that mowing in the early morning displaced leaf surface moisture and reduced dollar spot severity by up to 81% at fairway height and 53% at putting green height. Reductions in dollar spot were also observed with early morning mowing, and the size of lesions on individual leaf blades was reduced when the duration of leaf wetness was decreased (Ellram et al., 2007). Pigati et al. (2010) not only observed lower disease severity with morning compared to afternoon mowing, but also found that the decreased disease severity from mowing in the morning improved the performance of fungicides.

Dollar spot has been found to be more severe when turfgrass experiences drought stress (Couch and Bloom, 1960; Williams et al., 1999). More recently, researchers in Maryland and Indiana found dollar spot incidence to be more severe when irrigation water was applied deeply and infrequently when compared to a light, frequent irrigation schedule (McDonald et al., 2006). On the other hand, daily irrigation of perennial ryegrass (*Lolium perenne* L.) in Kansas resulted in twice as many dollar spot infection centers compared to irrigating only three days each week to replace 80% evapotranspiration (ET) (Jiang et al., 1998). Furthermore, light, frequent watering is a known contributor to thatch accumulation (Christians, 2007; Fagerness, 2001) which can prevent water from penetrating the soil, resulting in low soil moisture and a subsequent increase in disease severity (Walsh et al., 1999).

Sand-topdressing is a common practice on golf course greens and fairways. Regular topdressing can help prevent thatch accumulation (Christians, 2007), and some topdressing strategies have been found to decrease dollar spot severity. Goodman and Burpee (1991) found that specific isolates of the fungus *Fusarium heterosporum* were toxic to *S. homoeocarpa* and topdressing with sand-cornmeal or chopped grain colonized by the *F. heterosporum* reduced the intensity of dollar spot symptoms. The researchers suggest that *F. heterosporum* produces compounds toxic to *S. homoeocarpa*, causing inhibition of growth and swelling of hyphae. It was also suggested that metabolites released by *F. heterosporum* inhibited the stromatization of *S. homoeocarpa*, making antibiosis the likely mode of antagonism. Nelson and Craft (1992) observed a reduction in dollar spot severity for up to one month following topdressing with a mixture of sand and organic fertilizers. Specifically, preventative applications of both composted and uncomposted blends of plant and animal meals consistently suppressed dollar spot, in some cases at a level similar to propiconazole. No synthetic fertilizer sources were tested.

Fungicides and Fungicide Resistance

Repeated fungicide applications have been the most successful method of controlling dollar spot in recent history. The first major effort to control turfgrass diseases with fungicides was attempted with Bordeaux mixture comprised of copper sulfate and hydrated lime around 1917. The mixture was routinely used for several years until repeated applications resulted in toxic accumulations of copper (Gould, 1965). Mercuric chlorides became popular around 1927 based on recommendation from the US Golf Association. Thiram (Tetramethylthiuram disulfide), one of the first synthetic fungicides, replaced mercurials during the World War II era, when they were in short supply, and was soon followed by many other synthetic products, both contact and systemic. Chlorothalonil (tetrachloroisophthalonitrile), a contact fungicide still in use today, was considered an effective means of dollar spot control even 46 years ago (Gould, 1965).

Typically, several fungicide applications are required throughout a season to adequately control dollar spot. As a result, fungicide resistance of *S. homoeocarpa* has become a markedly increasing problem in recent years. Detweiler et al. (1983) observed resistance of *S. homoeocarpa* to benzimidazole and dicarboximide fungicides almost 30 years ago. Resistance to demethylation inhibitor (DMI) fungicides was first anecdotally reported by golf course superintendents in 1990 (Golembiewski et al., 1995). Golembiewski et al. (1995) observed that DMI-resistant strains of dollar spot could not be controlled with triadimefon (Bayleton), fenarimol (Rubigan), or propiconazole (Banner). Only chlorothalonil (Daconil), a multi-site contact fungicide, provided acceptable dollar spot control, supporting the general consensus that resistance to one

DMI usually means cross-resistance to other DMI fungicides. Hsiang et al. (2007) found populations of *S. homoeocarpa* not previously exposed to DMI fungicides were still sensitive to propiconazole (Banner MAXX), whereas resistant isolates of the fungus more quickly overcame the inhibitory effects of fungicide application, reducing efficacy from three to two weeks.

Modeling by Hsiang et al. (2007) suggested that at least 42 applications of propiconazole would be necessary to select sensitive *S. homoeocarpa* isolates for resistance. Because populations of dollar spot quickly become resistant to some fungicides (Jo et al., 2008), applications of mixtures or rotations of fungicides with different modes of action are typically recommended.

Dollar Spot Resistance

Though fungicide applications have been an effective means of dollar spot control, fungicides are expensive and, with increase environmental regulations, becoming less popular. Researchers have experimented with both species and cultivar selection for dollar spot resistance. Colonial bentgrass (*Agrostis capillaris* L.) and velvet bentgrass (*Agrostis canina* L.) are less susceptible to dollar spot than creeping bentgrass (Chakraborty et al., 2006). Belanger et al. (2004) found that creeping and colonial bentgrass hybrids can have excellent dollar spot resistance. Similarly, Watkins et al. (2010) observed sheep fescue (*Festuca ovina* L.), Chewings fescue (*Festuca rubra* L. ssp. *fallax*), and colonial and velvet bentgrass maintained good quality with no pesticide applications at fairway height in St. Paul, MN. Though the use of alternative species is promising in the Northern U.S., fine fescues and colonial and velvet bentgrass are not appropriate for use throughout the U.S.

Improved creeping bentgrass cultivars less susceptible to *S. homoeocarpa* infection are of particular interest in reducing fungicide applications. The development of new cultivars less susceptible to dollar spot has heightened superintendents' interest in utilizing new cultivars to reduce inputs (Settle et al., 2001). Recently, improvement of dollar spot resistance has been a major objective in turfgrass breeding programs. Cultivars with improved dollar spot resistance have been found to have greater turf densities and larger trichomes compared to susceptible cultivars (Bonos et al, 2004).

However, Bonos et al. (2004) found no relationship between stomata densities and dollar spot resistance.

'L-93' creeping bentgrass was released in 1995 and has exhibited good dollar spot resistance. Kansas State researchers found 'L-93' was significantly less susceptible to dollar spot than 'Penncross' and 'Providence' (moderately resistant), and 'Crenshaw', the most susceptible, in a two-year putting green experiment (Settle et al., 2001). Abernathy et al. (2001) reported similar findings, with 'L-93' being the least susceptible and 'A-4', 'Mariner', and 'Penncross' exhibiting moderate susceptibility to dollar spot. More recently, new cultivars seem to be even less susceptible to infection. In a recent National Turfgrass Evaluation Program (NTEP) trial, 'Declaration', 'Memorial', and 'Kingpin' were the least susceptible to dollar spot at putting green height with '007', Penncross, 'Mackenzie', and 'LS-44' being moderately susceptible (NTEP, 2008 a). At fairway height, 'Declaration', 'Kingpin', 'L-93', 'Crystal Bluelinks', and 'LS-44' have demonstrated good dollar spot resistance (NTEP, 2008 b).

Using dollar spot-resistant cultivars allows greater flexibility in disease control strategies (Abernathy et al., 2001; Lee et al., 2003; Settle et al., 2001). Without resistant cultivars, strict adherence to preventative fungicide programs has been the only way to maintain acceptable quality of putting surfaces (Abernathy et al., 2001). Settle et al. (2001) demonstrated dollar spot could only be controlled in 'Crenshaw' (a susceptible cultivar) with a preventative fungicide application every 14 days. Conversely, curative fungicide applications were effective with 'L-93', and less total fungicide was applied in a season.

Integrated pest management (IPM) strategies allow fungicide applications after a predetermined threshold value has been reached, making curative applications very important in IPM (Settle et al., 2001). Using creeping bentgrass cultivars with greater dollar spot resistance may allow golf course superintendents to spend less money on fungicides, reduce the likelihood of adversely affecting water quality and wildlife, and delay the onset of fungicide resistance by reducing the number of fungicide applications each year.

Silvery-Thread Moss

Mosses used to be considered a minor problem on golf courses and were found primarily in moist, shady areas in roughs (Taylor and Danneberger, 1996). Today, mosses are considered common weeds in creeping bentgrass putting greens (Burnell et al., 2004; Cook et al., 2002; Happ, 1998; Kennelly et al., 2010), though they are found in a variety of urban environments, including concrete surfaces, tree roots, compacted soils, and cool and damp soils (Boesch and Mitkowski, 2005). Silvery-thread moss (*Bryum argenteum* Hedw.) is the most common species found on putting greens, though other species do occur (Hummel, 1994; Happ, 1998; Kennelly et al., 2010).

Silvery-thread moss is in the phylum Bryophyta. The bryophytes are a group of nonvascular plants consisting of mosses, liverworts, and hornworts (Glime, 2007). Nonvascular plants lack xylem and phloem, the primary conduction tissues in higher plants. Most mosses are ectohydric organisms that can absorb water and minerals over the entire plant surface. Mosses can move water in capillary spaces and apoplastically in intercellular spaces, but rely mainly on the external transport of water (Glime, 2007).

Mosses reproduce sexually and asexually. In sexual reproduction, a threadlike structure called the protonema is formed from a germinating spore. The protonema will grow rapidly in a moist environment (Glime, 2007) and it has been suggested that free water is required for mosses to establish (Nelson, 2007). As the protonema develops, it becomes a slimy black mat that is commonly mistaken for algal growth (Boesch and Mitkowski, 2005, Glime 2007). Tufts of moss (thallus) with rhizoids, the primary anchoring structures, arise from buds that form on the protonema (Boesch and Mitkowski, 2005; Glime, 2007). The green, leafy tissue of moss plants is known as the gametophyte (Glime, 2007). Silvery-thread moss is a short, diecious moss in which the haploid gametophyte contains both male and female sex organs (antheridium and archegonium, respectively). After sperm cells fertilize the zygote contained in the archegonium, a diploid sporophyte is formed that, in turn, releases haploid spores which give rise to protonemal growth and a new haploid gametophyte (Glime, 2007; Richardson, 1981). Daily mowing of putting greens may remove and/or destroys sporophyte capsules, restricting the dispersal of fertilized spores, limiting the likelihood of sexual reproduction, and making asexual reproduction (fragmentation) a more likely method of moss dispersal.

Mosses reproduce vegetatively with fragmentation of the gametophyte and possibly by specialized asexual propagules (Miles and Longton, 1990). On golf courses, moss fragments are thought to be moved mechanically by maintenance equipment and even by foot traffic (Cook et al., 2002; Happ, 1998). When fragments settle in a suitable location, a secondary protonema is formed (Dudones, 2002; Richardson, 1981). Vegetative propagation of silvery-thread moss allows the weed to spread quickly, especially when voids are present in the turf canopy. Silvery-thread moss most commonly occurs as a weed of disturbed ground (Longton, 1981).

The current state of mosses as invasive weeds on creeping bentgrass putting greens is a result of reduced turfgrass vigor likely due to lower mowing heights and reduced fertility (Burnell et al., 2004; Hummel, 1994; Radko, 1985). Kennelly et al. (2010) observed increases in moss severity at a mowing height of 3.2 mm compared to 4.0 mm. It is also suggested that over fertilization can lead to excessive organic matter development, which will in turn disrupt water infiltration, making a more conducive environment for *B. argenteum* development (Borst et al., 2010; Happ, 1998; Nelson, 2007). Hummel (1994) attributes increased moss invasion to the discontinued use of mercury-based fungicides. Once silvery-thread moss is established, it is difficult to control (Boesch and Mitkowski, 2005). Colonies of *B. argenteum* in creeping bentgrass putting greens reduce turfgrass quality by disrupting surface uniformity and ultimately interfere with ball roll on the playing surface (Burnell et al., 2004; Kennelly et al., 2010).

Chemical Control of Silvery-Thread Moss

Many silvery-thread moss reduction strategies and products have been evaluated with mixed results (Burnell et al., 2004; Cook et al., 2005; Kennelly et al., 2010; Taylor and Danneberger, 1996). Still, in recent history, repeated applications of synthetic fungicides and herbicides have been the most popular moss reduction strategies. Golf course superintendents are continually pressured to manage pests with fewer pesticide applications (Kennelly et al., 2010). More alternative moss control strategies should be examined.

It has been well documented that mercury is toxic to mosses, and the absence of mercury- and other heavy metal-based fungicides in the environment contributes to increased moss encroachment (Anonymous, 1985; Hummel, 1994; Nelson, 2007). Silvery-thread moss sampled from urban environments has been found to have higher concentrations of heavy metals (e.g., lead) compared to moss sampled from rural environments (Shaw et al., 1989). Furthermore, laboratory evaluation showed lower germination rates and less vigorous growth of urban- compared to rural-sampled moss (Shaw et al., 1989). Additionally, Shaw and Albright (1990) observed that treating silvery-thread moss with copper, zinc, nickel, or lead reduced protonemal growth in a laboratory experiment. Dudones (2002) found that copper hydroxide reduced silvery-thread moss populations up to 98%. More recently, Borst et al. (2010) observed 11% control three weeks after treatment with the fungicide Junction (mancozeb + copper hydroxide). Treatment with Junction did not suppress silvery-thread moss 16 weeks after treatment. Additionally, copper sulfate and copper soaps can control moss, but not without causing phytotoxicity to creeping bentgrass (Cook, 2002). While copper-based products may provide some moss control, repeated use of products containing copper may lead to copper toxicity, or possibly induce iron deficiency of creeping bentgrass (Boesch and Mitkowski, 2005; Borst et al., 2010; Dudones, 2002).

It has been suggested that fertilization with iron can reduce moss populations (Anonymous, 1985). Burnell et al. (2004) observed reduction in silvery-thread moss populations after application of a either a combined product including ferrous oxide, ferrous sulfate, and iron humates or a combined product containing iron disulfide and ferrous sulfate. In a similar study, Taylor and Danneberger (1996) found that both ferrous sulfate and ammonium sulfate initially reduced silvery-thread moss populations; however, moss resurgence was a problem.

Silver nitrate has also been found to effectively control moss. In a field study, Weber and McAvoy (2003) observed complete control of moss with only two applications of silver nitrate with no phytotoxicity to turf. Though silver nitrate shows great potential for moss reduction, it is not labeled for the control of silvery-thread moss and it has been suggested that it is likely too expensive for practical application (Nelson, 2007; Weber and McAvoy, 2003).

Carfentrazone-ethyl (CE, Quicksilver, Ethyl α,2-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1H-1,2,4-triazol-1-yl]-4-fluorobenzenepropanoate, FMC Corporation, Philadelphia, PA) is a broadleaf herbicide labeled for control of silvery-thread moss. Carfentrazone-ethyl has been found to reduce moss populations and has become a standard for comparison for alternative moss control strategies. Settle et al. (2007) observed suppression of moss on a creeping bentgrass putting green with spring and fall applications (four in total) of CE applied at 0.09 kg a.i. ha^{-1} with no phytotoxicity observed on creeping bentgrass. Similarly, Kennelly et al. (2010) found that CE was effective in reducing silvery-thread moss populations at the same rate, and was never phytotoxic to creeping bentgrass. The researchers also concluded that applications of CE may be more effective in the spring. Field studies in Tennessee demonstrated that applications of CE controlled silvery-thread moss up to 54% 16 weeks after initial treatment when applied alone, and between 68 and 78% when applied in conjunction with N fertilization, sand topdressing, or both (Borst et al., 2010). Borst et al. (2010) also observed that fertilization with N, sand topdressing, and a combination of the two cultural practices every other week suppressed moss populations 16 weeks after treatment at a similar level to CE applied alone. This supports previous reports that enhancing turfgrass health is one of the best ways to reduce moss (Cook et al., 2002; Taylor and Denneberger, 1996; Radko, 1985).

The contact fungicide chlorothalonil has been used in moss control studies with mixed results. Neither Cook et al. (2002) nor Taylor and Danneberger (1996) observed reduction of moss populations with application of chlorothalonil. However, treatment with chlorothalonil in North Carolina significantly reduced moss populations, with up to 90% control in some cases (Burnell et al., 2004). Settle et al. (2007) found that chlorothalonil could significantly reduce moss populations, though no fewer than three sequential applications every 14 days were required. In a more recent study, treatment with chlorothalonil in Illinois suppressed moss populations similarly to CE applied alone (Kennelly et al., 2010).

Numerous studies have evaluated alternative products for silvery-thread moss suppression. Dishwashing detergent (Dawn Ultra, Ajax, etc.) has been found to reduce moss populations; however, phytotoxicty of creeping bentgrass has been an issue

(Burnell et al., 2004; Happ, 1998). In contrast, Cook et al. (2002) did not observe moss suppression with dishwashing detergent. Hydrated lime has been reported to suppress moss, but only at levels that caused phytotoxicity to creeping bentgrass (Taylor and Danneberger, 1996). Several researchers have reported moss suppression with sodium bicarbonate (baking soda). Settle et al. (2007) found that spot application with baking soda dissolved in water (45 g a.i. L^{-1}) twice in the spring effectively reduced moss populations for the entire season, without causing phytotoxicity to creeping bentgrass. Kennelly et al. (2010) found that spot treatment with sodium bicarbonate (44.2 g a.i. L^{-1}) twice in the spring was as effective in moss suppression as CE. However, slight and variable gray-brown phytotoxicity to creeping bentgrass was observed for up to 14 days after treatment. Spot treatment of sodium bicarbonate can be effective for moss suppression, but is only practical when moss levels are low because of the labor-intensive nature of spot treatments, and sodium bicarbonate is not labeled for silvery-thread moss control (Kennelly et al., 2010)

More investigation is needed into alternative products for silvery-thread moss control. Sodium bicarbonate and similar products should be evaluated for moss control when compared to a standard moss control product (Quicksilver). Spot treatments of sodium bicarbonate and similar products should be evaluated at lower concentrations to minimize creeping bentgrass injury and determine if effective moss suppression can be achieved. It may also be possible to use sodium bicarbonate in broadcast, rather than spot-spray applications.

Response of Silvery-Thread Moss to Nitrogen

In their natural environment, mosses obtain water mainly from rainfall events, and take up little groundwater. Because of this, mosses have a limited nutrient supply, and usually obtain nutrients that are dissolved in rainwater or accumulate as dust (Glime, 2007). Most bryophytes require far lower nutrient concentrations than higher plants, and seem to grow best in low nutrient habitats (Glime, 2007), suggesting that increased fertilization of a putting green would favor creeping bentgrass, and allow turf to out-compete moss colonies. However, putting greens are irrigated daily, providing ample water to moss colonies and an artificial environment where the bryophyte may be able to utilize greater nutrient concentrations than it would require in a natural environment. While low N concentrations have been linked to increased moss severity (Hummel, 1994), the effect of differing N sources on moss has not been well studied and is relatively unknown. Recent research at Kansas State University and the Chicago District Golf Association (Kennelly et al., 2010) found conflicting trends in the influence of N sources on moss severity. Fertilization with liquid urea in Manhattan, KS increased silvery-thread moss coverage over 200% relative to initial amounts, whereas fertilization with a natural organic N source reduced moss coverage approximately 50%. In contrast, in Lemont, IL, moss coverage was higher in plots treated with organic fertilizer compared to urea, possibly due to the fact that *Bruym caespiticium* and *Bryum lisae* var. *cuspidatem* were the predominant species in Lemont, and *Bruym argenteum* was predominant in Manhattan (Kennelly et al., 2010). Bryophytes are thought to absorb NH_4^+-N more easily than NO_3^--N (Glime, 2007). Urea is quickly hydrolyzed after application, resulting in high and almost immediately available concentrations of NH_4^+ that could stimulate moss growth. Though natural organic N sources contain ammoniacal N, they are slowly available in the rootzone and are less likely to be absorbed by mosses.

The possibility that soluble N sources may enhance moss severity in creeping bentgrass had not been reported previously, and Kennelly et al. (2010) recommend further investigation to determine the effects of differing N sources on moss growth in putting greens.

Chapter 2 - Dollar Spot Susceptibility of Selected Creeping Bentgrass Cultivars

Abstract

Dollar spot, caused by *Sclerotinia homoeocarpa* F.T. Bennett, is a chronic pathogen that infects creeping bentgrass (*Agrostis stolonifera* L.) fairways and putting greens. New creeping bentgrass cultivars with increased resistance to dollar spot have heightened golf course superintendents' interest in using less susceptible cultivars to reduce fungicide inputs. Fifteen creeping bentgrass cultivars were established on a native soil fairway and a putting green constructed to USGA specification in Manhattan, KS in September 2008. Dollar spot development was studied in 2009 and 2010. Cultivar plots were split for fungicide application (treated or untreated). A preventive application of chlorothalonil + boscalid was applied each year to treated subplots at the first appearance of dollar spot infection centers in all replications of a highly susceptible cultivar ('Crenshaw'). Subsequent applications were to follow when predetermined threshold values (5% and 10% severity in putting green and fairway height stands, respectively) were reached in 'Declaration', a less-susceptible cultivar, but thresholds were not reached. Cultivars varied in dollar spot susceptibility and generally experienced less dollar spot injury in subplots that received fungicide application. According to area under the disease progress curve (AUDPC), a cumulative measure of disease severity, 'Kingpin', 'Memorial', 'Declaration', and 'L-93'were the most resistant to dollar spot infection under both fairway (AUDPC from 117 to 400) and putting green (AUDPC from 2 to 53) management. 'Crenshaw' and 'Independence' were highly susceptible to dollar spot infection under both fairway (AUDPC from 441 to 1406) and putting green (AUDPC from 244 to 1209) conditions. 'Bengal' was highly susceptible under fairway (AUDPC from 545 to 887) management. 'Declaration', 'Memorial', and 'Kingpin' consistently maintained higher quality (7.3 to 8.1, measured on a 1 to 9 scale, 9 = best) than other cultivars under both fairway and putting green management, particularly when disease pressure was highest. 'Crenshaw', 'T-1', 'Alpha', 'Penncross', 'A-4',

‘Independence’, and ‘Bengal’ were among the lowest in quality. Cultivars resistant to dollar spot can maintain high quality when disease pressure is elevated with fewer fungicide inputs.

Introduction

Dollar spot, caused by *Sclerotinia homoeocarpa* F.T. Bennett, is a chronic disease of many species of turfgrass, and is a serious disease of closely mown creeping bentgrass (Goodman and Burpee, 1991). Outbreaks of dollar spot, even when mild, disturb the uniformity of turf stands and, on golf courses, can impair playability (Latin, 2006).

Many strategies have been utilized to suppress dollar spot in creeping bentgrass. Cultural practices can limit the severity of infection, though fungicide applications are typically required to maintain creeping bentgrass quality at an acceptable level.

Improved creeping bentgrass cultivars less susceptible to *S. homoeocarpa* infection are of particular interest in reducing fungicide applications. The development of new cultivars less susceptible to dollar spot has heightened superintendents' interest in utilizing new cultivars to reduce inputs (Settle et al., 2001).

'L-93' creeping bentgrass was released in 1995 and has exhibited good dollar spot resistance. Kansas State University researchers found 'L-93' was less susceptible to dollar spot than 'Penncross' and 'Providence' (moderately resistant), and 'Crenshaw', the most susceptible in a two-year putting green experiment (Settle et al., 2001). Abernathy et al. (2001) reported similar findings, with 'L-93' being the least susceptible and 'A-4', 'Mariner', and 'Penncross' exhibiting moderate susceptibility to dollar spot. In a recent National Turfgrass Evaluation Program (NTEP) trial, 'Declaration', 'Memorial', and 'Kingpin' were the least susceptible to dollar spot at putting green height with '007', 'Penncross', 'Mackenzie', and 'LS-44' being moderately susceptible (NTEP, 2008 a). At fairway height, 'Declaration', 'Kingpin', 'L-93', 'Crystal Bluelinks', and 'LS-44' have demonstrated good dollar spot resistance (NTEP, 2008 b).

Using dollar spot-resistant cultivars allows greater flexibility in disease control strategies (Abernathy et al., 2001; Lee et al., 2003; Settle et al., 2001). Without resistant cultivars, strict adherence to preventative fungicide programs has been the only way to maintain acceptable quality of putting surfaces (Abernathy et al., 2001). Settle et al. (2001) demonstrated dollar spot could only be controlled in 'Crenshaw' (a susceptible cultivar) with a preventative fungicide application every 14 days. Conversely, curative fungicide applications, based on scouting, were effective with ‘L-93’, and less total fungicide was applied in a season.

In general, fungicides are required to adequately control dollar spot and maintain turf quality on golf course fairways and putting greens. However, populations of *S. homoeocarpa* have developed resistance to certain systemic fungicides. Detweiler et al. (1983) observed resistance of *S. homoeocarpa* to benzimidazole and dicarboximide fungicides nearly 30 years ago. Resistance to demethylation inhibitor (DMI) fungicides was first anecdotally reported by golf course superintendents in 1990 (Golembiewski et al., 1995). More recently, Hsiang et al. (2007) found populations of *S. homoeocarpa* not previously exposed to DMI fungicides were still sensitive to propiconazole (Banner MAXX), whereas resistant isolates of the fungus more quickly overcame the inhibitory effects of fungicide application, reducing efficacy from three to two weeks.

Integrated pest management (IPM) strategies allow fungicide applications after a predetermined threshold value has been reached, making curative applications very important in IPM (Settle et al., 2001). Using creeping bentgrass cultivars with greater dollar spot resistance may allow golf course superintendents to spend less money on fungicides, impact the environment less, and delay the onset of fungicide resistance by reducing the number of fungicide applications each year. My objective was to determine the susceptibility of creeping bentgrass cultivars when fungicide applications for all cultivars are scheduled based on threshold values in ‘Declaration’, a cultivar with reduced dollar spot susceptibility. This project is part of a North Central Extension and Research Association (NCERA-192) regional project in collaboration with Iowa State University, Michigan State University, North Dakota State University, Ohio State University, Purdue University, South Dakota State University, Southern Illinois University, the University of Illinois, the University of Minnesota, the University of Missouri, the University of Nebraska, and the University of Wisconsin.

Materials and Methods

Separate fairway and putting green studies were conducted at the Rocky Ford Turfgrass Research Center in Manhattan, KS. Fifteen creeping bentgrass cultivars were established on a native soil fairway and a putting green constructed to United States Golf

Association specifications. The cultivars evaluated were ‘L-93’, ‘T-1’, ‘Alpha’, ‘Kingpin’, ‘Crenshaw’, ‘Penncross’, ‘A-4’, ‘Crystal Bluelinks’, ‘007’, ‘Mackenzie’, ‘Memorial’, ‘Independence’, ‘Declaration’, ‘LS-44’, and ‘Bengal’. Each cultivar was seeded in September 2008 at 49 kg ha^{-1} in three 1.2 × 3.0 m plots. The experimental design was a randomized complete block. Plots were then split, making cultivar the main plot and fungicide regime (treated or untreated, described below) the subplot.

The fairway and the putting green were mowed with a triplex reel mower at 13 and 3 mm, respectively. The fairway was mowed three days per week and the putting green was mowed six days per week. Urea (46-0-0 N-P-K) was used to provide N at 25 kg ha^{-1} per month to the fairway and at 49 kg ha^{-1} per month to the putting green during establishment from September to November in the fall of 2008 and in May and June in the spring of 2009. When fungicide applications began in 2009, urea fertilization ceased and a polymer-coated methylene urea N source (Professional Fertilizer, 18-2-20 N-P-K, Spring Valley, Jackson, Wis.) was applied once monthly from July to November to provide N at 25 kg ha^{-1} to the fairway and at 49 kg N ha^{-1} to the putting green. In 2010, Professional Fertilizer was applied from May to November at 25 kg N ha^{-1} biweekly to the putting green and once monthly to the fairway. The fairway was irrigated at 75% of reference evapotranspiration (ET) three days/week and the putting green was irrigated daily at 100% ET. Evapotranspiration was estimated using an onsite weather station and the FAO-56 Penman-Monteith equation. Core aerification was performed on the putting green study leaving approximately 388 holes m^{-2} on 19 May 2009, and on putting green and fairway studies on 21 October in 2009. Aerification holes were 1.6 cm in diameter, and 3.8 cm deep. The putting green was sand-topdressed to fill aerification holes. The putting green study was vertically mown to a depth of 1 cm on 12 May 2009, and putting green and fairway studies were vertically mown to the same depth on 27 October 2010. The putting green was sand-topdressed to fill slits following vertical mowing. Additionally, the putting green was sand-topdressed to a depth of 2 mm biweekly from May to November in 2009 and 2010.

Dylox [trichlorfon, dimethyl (2,2,2-trichloro-1-hydroxy ethyl) phosphate, Bayer Environmental Science, Durham, NC] was applied at 6 kg a.i. ha^{-1} on six dates in 2009 (29 June, 6 and 15 July, 8 August, and 2 and 25 September) to control black cutworms

(*Agrotis ipsilon)*. In 2010, Dylox was applied once (25 May) and Acelepryn (chlorantraniliprole, 3-Bromo-N-[4-chloro-2-methyl-6-[(methyl amino)carbonyl]phenyl]-1-(3-chloro-2-pyridinyl)-1H-pyrazole-5-carboxamide, DuPont, Wilmington, DE) was applied at 0.06 kg a.i. ha^{-1} on 28 June and 25 August for black cutworm control.

A tank-mix of Emerald (boscalid, 3 pyridinecarboxamide,2-chloro-N-(4'-chloro(1,1'-biphenyl)-2-yl), BASF Corporation, Durham, NC) at 0.4 kg a.i. ha^{-1} and Daconil Ultrex (chlorothalonil, tetrachloroisophthalonitrile, Syngenta Group Company, Greensboro, NC) at 8 kg a.i. ha^{-1} was applied preventatively to the fungicide-treated subplot within each cultivar at the first appearance of dollar spot infection centers in three replicate plots of Crenshaw, a highly susceptible cultivar (Settle et al., 2001). Subsequent curative fungicide applications were to follow when two of three replicate subplots of fungicide-treated Declaration, a less susceptible cultivar (NTEP, 2008 a; NTEP, 2008 b), had > 10% dollar spot coverage in the fairway study. In the putting green study, curative fungicide applications were to be made when two of three replicate subplots of fungicide-treated Declaration plots had at least 5% dollar spot coverage. For treatment thresholds, plots were assessed weekly by visually estimating the percent of each plot blighted by dollar spot symptoms. Preventative fungicide applications were made on 7 July 2009 and 25 May 2010. Curative fungicide applications were not required in either 2009 or 2010 in either the putting green or the fairway study because thresholds were not reached.

Data Collection and Analysis

Study areas were rated biweekly for turfgrass quality in 2009 and 2010. Quality data were taken considering turfgrass color, texture, density, and uniformity and followed a 1 to 9 scale (1 = poorest quality, 6 = minimum acceptable quality, and 9 = optimum color, texture, density, and uniformity, including dollar spot damage).

Dollar spot severity was rated weekly, when disease was present, by counting the number of dollar spot infection centers (DSIC) in each research plot. A 1-meter square was arbitrarily placed three times in each plot and infection centers occurring within the square were counted and an average taken. Area under the disease progress curve (AUDPC) analysis was performed on dollar spot data to give a cumulative, season-long indication of disease pressure. Area under the disease progress curve was calculated as

AUDPC = $\sum^{ni-1}_{i=1}$ ([y_i + $y_{(i+1)}$] / 2) ($t_{(i+1)}$ - t_i); where i is the order index for the times, and n_i is the number of times (Madden et al., 2007).

There was an outbreak of foliar Pythium blight (*Pythium spp*) in the fairway study in 2009. Brown patch, caused by *Rhizoctonia solani*, infected the putting green in 2009 and 2010. Both diseases were rated, when present, as the percent of blighted turf in each plot.

Normality of raw data was tested with the *w* statistic of the Shapiro-Wilk test using the UNIVARIATE procedure of the Statistical Analysis System (Statistical Analysis System, Cary, NC) (Shapiro and Wilk, 1965). Dollar spot and brown patch data were not normally distributed in either 2009 or 2010 according to the Shapiro-Wilk test. For this reason, raw data were subjected to the $\log_{10}(y+1)$ transformation to normalize. Data were subject to analysis of variance using the GLM procedure of SAS. Means were separated using Fisher's Protected LSD, and transformed means were back-transformed for presentation.

Results and Discussion

Differences in dollar spot and brown patch susceptibility and creeping bentgrass quality were observed at the cultivar (main plot) and fungicide (subplot) levels in 2009 and 2010 in the green and fairway studies. Cultivars varied in dollar spot susceptibility and generally experienced less dollar spot injury and higher creeping bentgrass quality in subplots that received fungicide application (data not shown). There was never a significant cultivar × fungicide interaction; as such, cultivar means represent an average of fungicide-treated and nontreated plots.

Cultivar Performance at Fairway Height

Dollar Spot Susceptibility

Dollar spot data were collected throughout the 2009 growing season, but in 2010, dollar spot data were only collected from 24 May to 22 July because of low turf quality due to heat stress and scalping. Declaration had the least amount of dollar spot in both 2009 (AUPDC of 117) and 2010 (AUDPC of 149) (Table 2.1). With AUDPC values ranging from 262 to 400 in 2009 and from 227 to 333 in 2010, L-93, Kingpin, and

Memorial were not significantly different from Declaration in either year, indicating that Declaration, L-93, Kingpin, and Memorial were the least susceptible to dollar spot infection under fairway management. Crenshaw, Independence, and Bengal had the most dollar spot in both years (AUDPC values ranging from 545 to 1406 in 2009 and 441 to 1124 in 2010) and were the most susceptible to dollar spot. Crystal Bluelinks and 007 were not different from Declaration in 2009, but had more dollar spot than Declaration and less than Crenshaw in 2010 (AUDPC values of 409 and 365, respectively) and were moderately susceptible to dollar spot infection in this study. With AUDPC values ranging from 351 to 486, T-1, Alpha, Penncross, A-4, Mackenzie, and LS-44 were more resistant than Crenshaw in 2009, but similar in susceptibility in 2010 (AUDPC of 431 to 703), indicating that the cultivars are quite susceptible to dollar spot infection. These results partially agree with NTEP data taken from 2004 to 2007 where Declaration appeared to have been the most resistant to dollar spot infection at fairway height (NTEP, 2008 b). Kingpin, Crystal Bluelinks, Mackenzie, Alpha, T-1, LS-44, and Penncross experienced moderate dollar spot injury in the study, while L-93, Bengal, and Independence experienced the most injury. Crenshaw was not evaluated.

Creeping Bentgrass Quality

In 2009, mean quality of all cultivars was acceptable (Table 2.2). Crenshaw and Declaration were acceptable on 92% of rating dates, and all other cultivars were acceptable on 100% of rating dates. Memorial had the highest creeping bentgrass quality (8.1) and L-93, Kingpin, Penncross, 007, Mackenzie, LS-44, and Bengal were not significantly different from Memorial. Declaration had the lowest mean quality (7.3) and was not different from Crenshaw or Independence.

There were no significant differences in season-long creeping bentgrass quality in 2010. Quality ratings at fairway height were greatly affected by scalping of the research area. Crenshaw, Memorial, and LS-44 had acceptable creeping bentgrass quality on 58% of rating dates, A-4 and Declaration were acceptable on 50% of rating dates, and all other cultivars were acceptable on 42% of rating dates in 2010. Crenshaw, Penncross, Mackenzie, LS-44, and Bengal were the highest in quality in the fall of 2010 (data not shown) when plots were recovering from scalping during the summer, indicating that the cultivars were not as affected by scalping injury and recovered more quickly than other cultivars.

Cultivar Performance at Putting Green Height

Dollar Spot Susceptibility

Memorial, Declaration, L-93, Kingpin, Penncross, Crystal Bluelinks, and LS-44 had the least amount of dollar spot in 2009 (AUDPC values ranging from 2 to 22) and 2010 (AUDPC values ranging from 9 to 240) (Table 2.1). Crenshaw and Independence experienced the most dollar spot both years (AUDPC values of 707 and 244, respectively in 2009 and 1209 and 634, respectively in 2010). T-1, Alpha, A-4, 007, Mackenzie, and Bengal had less dollar spot than Crenshaw (2009 AUDPC values from 109 to 191 and 2010 AUDPC values from 156 to 456 in 2010).

Kingpin, Memorial, Declaration, L-93, Penncross, Crystal Bluelinks, and LS-44 were the least susceptible to dollar spot infection under putting green management. T-1, Alpha, A-4, 007, Mackenzie, and Bengal were moderately susceptible, and Crenshaw and Independence were highly susceptible to dollar spot infection. It is interesting that Bengal exhibited moderate susceptibility to dollar spot at putting green height, but was one of the most susceptible cultivars under fairway management. Weakened, senescent foliage is more susceptible to *S. homoeocarpa* infection (Endo, 1966; Walsh et al., 1999). The added stress from scalping may account for Bengal's increased susceptibility to dollar spot in the fairway study.

These results agree with data from the National Turfgrass Evaluation Program (NTEP) from 2004 to 2007 where Declaration and Memorial experienced the least amount of dollar spot (NTEP, 2008 a). Mackenzie, LS-44, and Kingpin experienced a moderate amount dollar spot. Furthermore, Independence, Bengal, Alpha, and T-1 experienced the most dollar spot according to NTEP data (NTEP, 2008 a). Settle et al. (2001) observed that, without fungicide application, L-93 was the least susceptible cultivar to dollar spot infection when compared to Penncross, Providence, and Crenshaw, though no cultivar maintained acceptable quality throughout the season without fungicide application. Furthermore, Penncross and Providence were intermediate regarding susceptibility, and Crenshaw was the most susceptible cultivar, only maintaining acceptable quality with preventative fungicide applications every 14 days. Similarly, Abernathy et al. (2001) found L-93 to be the least susceptible, when compared to A-4, Mariner, Penncross, and Crenshaw. A-4, Mariner, and Penncross were moderately susceptible, and Crenshaw was the most susceptible. The researchers also evaluated blends of the five creeping bentgrasses and found that L-93 reduced, and Crenshaw increased susceptibility when included in blends, whereas A-4, Mariner, and Penncross had no apparent effect.

Brown Patch Susceptibility

Cultivars differed in brown patch on three rating dates (28 Aug 2009 and 8 and 16 July 2010) (Table 2.3). L-93, Kingpin, A-4, Crystal Bluelinks, and Memorial, had the most blight from brown patch infection. 007, T-1, Alpha, Penncross, Independence, Declaration, and LS-44 experienced the least amount of brown patch. All other cultivars were more variable in response to the pathogen. Results are similar to those of Settle et al. (2001) who reported that Crenshaw and L-93 had higher brown patch susceptibility compared to Penncross and Providence.

Creeping Bentgrass Quality

In 2009, all cultivars had acceptable mean creeping bentgrass quality, and were acceptable on 92% of rating dates (Table 2.2). Declaration had the highest creeping bengrass quality (8.0) and only L-93, Crenshaw, 007, and Mackenzie (7.4 to 7.5) were significantly different. In 2010, mean quality of all cultivars was higher than minimally acceptable. T-1 and Penncross were acceptable on 92% of rating dates. Independence and Crenshaw were acceptable on 75% and 58% of rating dates, respectively. All other cultivars were acceptable on 100% of rating dates in 2010. Declaration had better quality (8.5) than any other cultivar. Memorial, Kingpin, Crystal Bluelinks, and LS-44 were slightly lower in quality. Crenshaw had significantly lower quality than any other cultivar.

Creeping bentgrass quality was consistently higher in blocks that received a fungicide application each year (data not shown). Regarding cultivars, Declaration, Memorial, Crystal Bluelinks, Kingpin, and LS-44 consistently maintained higher mean quality than others, particularly when disease pressure was highest. Crenshaw, T-1, Alpha, Penncross, A-4, Independence, and Bengal were among the lowest in quality. With the exception of Penncross, the lower quality of these cultivars can be attributed to excessive dollar spot injury.

Conclusions

Several cultivars performed well in this study. Declaration, Memorial, L-93, and Kingpin were the least susceptible to dollar spot infection under both fairway and putting green management. The four cultivars also maintained high quality at putting green height, and with the exception of Declaration, at fairway height. Cultivars resistant to dollar spot exhibited high quality when disease pressure was elevated even without fungicide application. These results indicate that establishing a resistant cultivar like Declaration, Memorial, or Kingpin would aid in the implementation of an IPM strategy for dollar spot management. Regular, preventive fungicide applications would not be required to maintain acceptable quality, and golf courses could save money and possibly delay or prevent the onset of fungicide resistance.

Additional dollar spot severity and turfgrass quality and density data were collected, and tables are available in Appendix A.

Table 2.1 Area under the disease progress curve (AUDPC) for dollar spot in cultivars maintained at fairway and putting green height in 2009 and 2010.

	AUDPC[†]			
	Fairway		Putting Green	
Cultivar	2009	2010	2009	2010
007	160 de[‡ §]	365 bcd	116 bcde	194 cde
A-4	480 bcd	683 abc	109 bcde	169 cde
Alpha	450 bcd	703 ab	114 bcd	156 cde
Bengal	545 abc	887 a	244 bcde	240 cde
Crenshaw	1406 a	1124 a	707 a	1209 a
Crystal Bluelinks	296 bcde	409 bcd	17 def	50 e
Declaration	117 e	149 e	9 ef	11 e
Independence	565 ab	441 abcd	244 ab	634 ab
Kingpin	234 cde	238 de	3 f	33 e
L-93	400 bcde	333 cde	22 def	53 e
LS-44	486 bcd	459 abcd	77 cdef	144 de
Mackenzie	351 bcde	431 abcd	117 bcde	379 bcd
Memorial	262 bcde	227 de	2 f	9 e
Penncross	388 bcde	510 abcd	16 def	80 de
T-1	456 bcd	602 abc	191 bc	456 bc

[†]Area under the disease progress curve (AUDPC) summarizes all rating dates in 2009 and 2010 (AUDPC = $\sum^{ni-1}_{i=1}$ ([y_i + $y_{(i+1)}$] / 2) ($t_{(i+1)}$ - t_i), where i is the order index for the times, and n_i is the number of times). Within a column, means with the same letter are not significantly different ($P \leq$

0.05) by Fisher's Protected LSD.

‡Cultivar means were determined from six observations; three fungicide-treated subplots, and three nontreated subplots.

§Data were subject to the $\log_{10}(y+1)$ transformation to normalize prior to analysis, and means were back-transformed for presentation.

Table 2.2 Quality of creeping bentgrass maintained at fairway and putting green height in 2009 and 2010.

	Fairway†				Putting Green			
	Mean‡		% Dates Acceptable§		Mean		% Dates Acceptable	
Cultivar	2009	2010	2009	2010	2009	2010	2009	2010
007	7.8 abc¶	5.3	100	42	7.4 c	7.6 cd	92	100
A-4	7.6 cde	5.4	100	50	7.8 ab	7.4 def	92	100
Alpha	7.6 cde	5.5	100	42	7.7 abc	7.3 ef	92	100
Bengal	7.9 abc	5.6	100	42	7.6 abc	7.3 ef	92	100
Crenshaw	7.5 def	5.0	92	58	7.5 bc	6.3 g	92	58
Crystal Bluelinks	7.7 bc	5.4	100	42	7.7 abc	7.8 bc	92	100
Declaration	7.3 f	5.2	92	50	8.0 a	8.5 a	92	100
Independence	7.4 ef	5.4	100	42	7.6 abc	7.1 f	92	75

Kingpin	7.9 abc	5.3	100	42	7.9 a	7.8 bc	92	100
L-93	7.9 abc	5.4	100	42	7.5 bc	7.4 de	92	100
LS-44	7.9 abc	5.0	100	58	7.9 a	7.9 bc	92	100
Mackenzie	7.8 abc	5.5	100	42	7.5 bc	7.4 de	92	100
Memorial	8.1 a	5.8	100	58	7.7 abc	7.9 b	92	100
Penncross	8.0 ab	5.7	100	42	7.7 abc	7.2 ef	92	92
T-1	7.7 bcd	5.7	100	42	7.9 a	7.2 ef	92	92

†Turf was rated on a 1 to 9 scale (1 = lowest possible quality, 6 = minimum acceptable quality, and 9 = optimum color, texture, density, and uniformity). Within a column, means with the same letter are not significantly different ($P \leq 0.05$) by Fisher's Protected LSD.

‡The season-long mean summarizes all rating dates in 2009 and 2010.

§Percent of rating dates at or above minimum acceptable quality in 2009 and 2010.

¶Cultivar means were determined from six observations; three fungicide-treated subplots, and three nontreated subplots.

Table 2.3 Brown patch in creeping bentgrass at putting green height in 2009 and 2010.

	Brown patch (%)[†]		
	2009	2010	
Cultivar	28 Aug.	8 July	16-July
007	1.2 e[‡§]	0.4 e	0.8 d
A-4	16.4 a	14.3 a	11.5 a
Alpha	4.8 bcde	0.5 de	1.5 cd
Bengal	5.2 bcd	4.3 abcd	1.0 d
Crenshaw	10.8 ab	3.6 abcde	1.1 cd
Crystal Bluelinks	12.6 ab	4.6 abc	6.1 abc
Declaration	7.5 abc	0.4 e	0.5 d
Independence	1.6 de	2.7 bcde	2.7 abcd
Kingpin	9.1 abc	4.8 abc	2.7 abcd
L-93	8.8 abc	10.0 ab	8.7 ab
LS-44	7.3 abc	1.7 cde	0.4 cd
Mackenzie	5.7 abcd	3.4 abcde	2.0 bcd
Memorial	9.4 abc	9.6 ab	10.6 a
Penncross	3.3 cde	1.0 cde	0.5 d
T-1	2.9 cde	2.3 bcde	3.0 abcd

[†]Rated visually as the percent of plot area with brown patch. Within a column, means with the same letter are not significantly different ($P \leq 0.05$) by Fisher's Protected LSD.

[‡]Cultivar means were determined from six observations; three fungicide-treated subplots, and three nontreated subplots.

[§]Data were subject to the $\log_{10}(y+1)$ transformation to normalize prior to analysis, and means were back-transformed for presentation.

Chapter 3 - Evaluation of Alternative Chemical Controls for Silvery-Thread Moss in Creeping Bentgrass Putting Greens

Abstract

Silvery-thread moss (*Bryum argenteum* Hedw.) is a common weed in creeping bentgrass (*Agrostis stolonifera* L.) putting greens, and alternative moss control strategies are needed. Spot- spray treatments of sodium bicarbonate (22.5 and 45 g a.i. L^{-1}), potassium bicarbonate (22.5 and 45 g a.i L^{-1}), and essential oil (Moss Buster, 1% essential oil of oregano, ready-to-use), as well as broadcast treatments of sodium bicarbonate (55 and 110 kg a.i. ha^{-1}), potassium bicarbonate (4.8, 11.4, and 93.5 kg a.i. ha^{-1}), and carfentrazone-ethyl (Quicksilver, 0.09 kg a.i. ha^{-1}) were applied twice in the spring and fall of 2009 and 2010 (4 applications each year). Moss severity and turf quality were assessed biweekly. Spot application of sodium or potassium bicarbonate (45 g a.i. L^{-1}), essential oil, and broadcast treatment with carfentrazone-ethyl suppressed moss 39 to 55% more than untreated in 2009. Broadcast applications of sodium or potassium bicarbonate were not effective in either year. Spot sprays of essential oil, sodium and potassium bicarbonate (45 g a.i. L^{-1}) were phytotoxic to creeping bentgrass. Creeping bentgrass treated with spot application of sodium and potassium bicarbonate (45 g a.i. L^{-1}) required up to 8 days to recover to acceptable quality. When treated with essential oil, creeping bentgrass required up to 18 days to recover. Carfentrazone-ethyl was not phytotoxic, and turf required no recovery period after treatment. Bicarbonate and essential oil products can reduce moss severity at a similar level to carfentrazone-ethyl, but rates and/or application methods may need to be optimized to avoid injury to creeping bentgrass putting greens.

Introduction

Silvery-thread moss (*Bryum argenteum* Hedw.) is a common weed in creeping bentgrass (*Agrostis stolonifera* L.) putting greens (Burnell et al., 2004; Cook et al., 2002; Happ, 1998; Kennelly et al., 2010). Other moss species have been identified on putting greens, but silvery-thread moss is the most common (Hummel, 1994; Happ, 1998; Kennelly et al., 2010). Silvery-thread moss is in the phylum Bryophyta, a phylum of nonvascular plants consisting of mosses, liverworts, and hornworts (Glime, 2007). Nonvascular plants lack xylem and phloem, the primary conduction tissues in higher plants, and are "ectohydric organisms" which absorb water and minerals over the entirety of their plant surfaces (Glime, 2007).

Though mosses are able to reproduce both sexually and asexually, daily mowing of putting greens may remove and/or destroy sporophyte capsules, restricting the dispersal of fertilized spores, limiting the likelihood of sexual reproduction, and making asexual reproduction (fragmentation) a more likely method of moss dispersal. In laboratory and field studies, silvery-thread moss has been shown to arise from vegetative fragments and, to a lesser extent, from spores (Miles and Longton, 1990). In asexual reproduction, moss fragments are thought to be moved mechanically by maintenance equipment and even by foot traffic (Cook et al., 2002; Happ, 1998). Vegetative propagation of silvery-thread moss allows the weed to spread quickly, especially when voids are present in the turf canopy.

Carfentrazone-ethyl (CE, Quicksilver, Ethyl α,2-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1H-1,2,4-triazol-1-yl]-4-fluorobenzenepropanoate, FMC Corporation, Philadelphia, PA) is a broadleaf herbicide labeled for control of silvery-thread moss. Carfentrazone-ethyl has been found to reduce silvery-thread moss populations and has become a standard for comparison for alternative moss control strategies. Settle et al. (2007) observed suppression of moss with two spring and two fall applications (4 total) of CE applied at 0.09 kg a.i. ha^{-1} with no phytotoxicity observed on creeping bentgrass. Similarly, Kennelly et al. (2010) found that CE was effective in reducing silvery-thread moss populations at the same rate, and was never phytotoxic to creeping bentgrass. The researchers also concluded that applications of CE may be more effective in the spring. Borst et al. (2010) found that applications of CE controlled silvery-thread moss up to 54% 16 weeks after initial treatment when applied alone, and between 68 and 78% when applied in conjunction with nitrogen (N) fertilization, sand topdressing, or both. Borst et al. (2010) also observed that fertilization with N, sand topdressing, and a combination of the two cultural practices every other week suppressed moss populations sixteen weeks after treatment at a similar level to CE applied alone. This supports previous reports that enhancing turfgrass health is one of the best ways to reduce moss (Cook et al., 2002; Taylor and Danneberger, 1996; Radko, 1985).

Numerous studies have evaluated alternative products for silvery-thread moss suppression. In some studies dishwashing detergent (Dawn Ultra, Ajax, etc.) has been found to reduce moss populations; however, phytotoxicty of creeping bentgrass has been an issue (Burnell et al., 2004; Happ, 1998). In contrast, Cook et al. (2002) did not observe moss suppression with dishwashing detergent. Hydrated lime has been reported to suppress moss, but only at levels that caused phytotoxicity to creeping bentgrass (Taylor and Danneberger, 1996). Several researchers have reported moss suppression with sodium bicarbonate (baking soda). Settle et al. (2007) found that spot application with sodium bicarbonate dissolved in water (45 g a.i. L^{-1}) twice in the spring effectively reduced moss populations for the entire season, without causing phytotoxicity to creeping bentgrass. Kennelly et al. (2010) found that spot treatment with sodium bicarbonate (44.2 g a.i. L^{-1}) twice in the spring was as effective in moss suppression as CE. However, slight and variable gray-brown phytotoxicity to creeping bentgrass was observed for up to 14 days after treatment. Spot treatment of sodium bicarbonate can be effective for moss suppression, but is only practical when moss levels are low because of the labor-intensive nature of spot treatments, and sodium bicarbonate is not currently labeled for moss control in turf (Kennelly et al., 2010).

More investigation is needed into alternative products for silvery-thread moss control. Spot application with sodium bicarbonate can effectively control silvery-thread moss, but phytotoxicity to creeping bentgrass continues to be a concern. Lower concentration spot treatments of sodium bicarbonate and similar products may reduce moss populations, while minimizing creeping bentgrass injury. It may also be possible to use sodium bicarbonate in broadcast applications. Therefore, the objective of this study was to evaluate alternative chemical control methods for silvery-thread moss in creeping bentgrass putting greens and their effect on creeping bentgrass quality.

Materials and Methods

This study was conducted in 2009 and 2010 at the Rocky Ford Turfgrass Research Center in Manhattan, KS. In 2009, research plots were established on a 'Pennlinks' creeping bentgrass putting green constructed to United States Golf Association specifications. In 2010, the study was repeated on a native soil "push-up" 'Penncross' creeping bentgrass putting green that had been topdressed for years and a 30.5 cm sand cap was present on the surface. The moss at Rocky Ford was positively identified as *Bryum argenteum* before a prior study in 2008 (Kennelly et al., 2010). In this study, each site had a natural infestation of silvery-thread moss.

Treatments and Application

Treatments consisted of an untreated control and eleven spot or broadcast applications: Sodium bicarbonate (SB, Baking Soda, Arm and Hammer, Church and Dwight Co., Inc., Princeton, NJ) applied as a spot spray at 22.5 and 45 g a.i. L^{-1} or as a broadcast at 55 and 110 kg a.i. ha^{-1}; potassium bicarbonate (PB, Armicarb, Helena Chemical Company, Collierville, TN) applied as spot-sprays at 22.5 or 45 g a.i. L^{-1}, or broadcast treatments at 4.8, 11.4, and 93.5 kg a.i. ha^{-1}; essential oil (Moss Buster, 1% essential oil of oregano, Moss Buster LLC, Mason City, IA) was applied as a spot spray following label instructions; and CE (Quicksilver, FMC Corporation, Philadelphia, PA) broadcast at 0.09 kg a.i. ha^{-1}.

With spot spray treatments, solution was applied to individual colonies with a hand-held trigger-spray bottle until moss colonies were visibly wet. Broadcast sprays were applied using a hand-held CO_2 -powered sprayer equipped with a single TeeJet 8008EVS even flat spray nozzle at 207 kPa. All treatments were applied in the spring and fall of 2009 and 2010. In spring 2009, treatments were applied on 21 May on 4 June. Fall application dates were 11 September and 24 September 2009. In the second experiment in 2010, treatments were applied on 14 and 26 May in the spring, and on 8 and 23 September in the fall.

Experimental Design and Management

Plots were arranged in a randomized complete block design with four replications. The entire study area measured 5.5 × 7.3 m, with individual plots measuring 0.9 × 0.9 m. The putting green was mowed at 3.2 mm six days each week with a triplex reel mower and was irrigated at 100% ET replacement. Evapotranspiration was estimated using an onsite weather station and the FAO-56 Penman-Monteith equation. Urea (46-0-0 N-P-K) was applied at 49 kg N ha^{-1} per month in the spring and summer of 2009. In 2010, a polymer-coated methylene urea N source (Professional Fertilizer, 18-2-20 N-P-K, Spring Valley, Jackson, Wis.) was applied biweekly at 24 kg N ha^{-1}. Dylox (trichlorfon, dimethyl (2,2,2-trichloro-1-hydroxyethyl) phosphate, Bayer Environmental Science, Durham, NC) was applied at 6 kg a.i. ha^{-1} on six dates in 2009 (29 Jun, 6 and 15 Jul, 8 Aug, and 2 and 25 Sept) to control black cutworms (*Agrotis ipsilon)*. In 2010, Dylox was applied on once (25 May) and Acelepryn (chlorantraniliprole, 3-Bromo-N-[4-chloro-2-methyl-6-[(methylamino)carbonyl]phenyl]-1-(3-chloro-2-pyridinyl)-1H-pyrazole-5-carboxamide, DuPont, Wilmington, DE) was applied at 0.06 kg a.i. ha^{-1} on 2 dates (28 June and 25 Aug) for black cutworm control.

Data Collection and Analysis

Plots were rated every two weeks in 2009 and 2010 for moss severity and creeping bentgrass quality. Creeping bentgrass quality data were also collected 1 and 7 days after treatment. Moss severity was rated visually by estimating the percent of each plot infested by silvery-thread moss. Moss severity differed among plots at the beginning of the study in each year. For this reason, moss severity was considered to be 100% at the time of the initial rating and percent moss coverage for later rating dates was scaled accordingly (Moss severity in each plot = [% moss on rating date / % moss on 1st rating date] x 100) (Kennelly et al., 2010). Area under the curve (AUC) analysis was conducted on moss severity data to give a cumulative, season-long indication of moss severity (Kennelly et al., 2010). Area under the curve was calculated as AUC = $\sum^{ni-1}_{i=1}$ ([y_i + $y_{(i+1)}$] / 2) ($t_{(i+1)}$ - t_i); where i is the order index for the times, and n_i is the number of times (Madden et al., 2007).

Creeping bentgrass quality was rated using a 1 to 9 scale where 1 = poorest quality, 6 = minimum acceptable phytotoxicity from treatments, and 9 = optimum green color/no phytotoxicity.

Normality of raw data was tested with the *w* statistic of the Shapiro-Wilk test using the UNIVARIATE procedure of the Statistical Analysis System (Statistical Analysis System, Cary, NC) (Shapiro and Wilk, 1965). Moss severity data were not normally distributed in either 2009 or 2010 according to the Shapiro-Wilk test. For this reason, raw data were subjected to the $\log_{10}(y+1)$ transformation to normalize. Data were subject to analysis of variance using the GLM procedure of SAS. Means were separated using Fisher's Protected LSD, and transformed means were back-transformed for presentation.

Results and Discussion

Moss Severity

No treatment completely eliminated silvery-thread moss. According to AUC analysis in 2009, spot application with SB (45 g a.i. L^{-1}), PB (45 g a.i. L^{-1}), and essential oil, as well as broadcast applications of CE, reduced moss severity compared to untreated plots and were not different from each other (Fig. 3.1). All other treatments were not significantly different from untreated. Settle et al. (2007) and Kennelly et al. (2010) observed similar moss suppression with spot application of SB (45 and 44.2 g a.i. L^{-1}, respectively) and broadcast applications of CE (0.09 kg a.i. ha^{-1}). Borst et al. (2010) observed similar moss suppression with CE (0.12 kg ha^{-1}) and complemented the herbicide's use with a mix of cultural practices ultimately reducing moss up to 73% when CE application was followed by N fertilization and sand topdressing.

With the exception of PB (45 g a.i. L^{-1}), essential oil treated plots had significantly less moss than all other treatments on the final rating date in 2009 (20 Oct), and had reduced moss severity to 8.4, from the starting point of 100 (Table B.1). Sodium bicarbonate (45 g a.i. L^{-1}) had significantly more moss on this date than essential oil, with a moss severity rating of 25.3. All other treatments were not significantly different from untreated, which had a moss severity rating of 82.7, relative to the starting point of 100.

In 2010, no treatment reduced silvery-thread moss compared to untreated plots according to AUC analysis (data not shown). Moss levels in untreated plots at the beginning of the study in 2010 ranged from 10% to 40%, and colonies receded through the summer.

One of the major objectives of this study was to determine if reduced concentrations of previously tested spot treatments (SB at 45 g a.i. L^{-1}) would be less phytotoxic to creeping bentgrass and still suppress moss. In this study, spot treatments of SB or PB (22.5 g a.i. L^{-1}) were not effective in suppressing moss. Another goal of the study was to evaluate broadcast applications of alternative products in hopes of alleviating the labor-intensiveness of spot spray applications. However, broadcast applications of SB or PB were not effective at any rate tested.

Effect of Treatments on Creeping Bentgrass Quality

Of the treatments which were effective in suppressing moss in 2009, CE was the only one which caused no phytotoxicity in either 2009 on 'Pennlinks' or 2010 on 'Penncross' creeping bentgrass (Tables 3.1 and 3.2). Settle et al. (2007) and Kennelly et al. (2010) also observed no phytotoxicity associated with CE on either 'L-93' or 'L-93'/'G-2' (50:50) creeping bentgrass. Spot treatments of essential oil, SB, and PB were phytotoxic to creeping bentgrass, and affected turf bordering silvery-thread moss colonies. Spot treatments of essential oil were most phytotoxic to creeping bentgrass, resulting in quality ratings below 4 within one day after application and requiring up to 18 days to return to an acceptable level (data not shown). Average creeping bentgrass quality in essential oil treated plots was 6.7 in 2009 and 6.0 in 2010. In 2009, creeping bentgrass was acceptable on 71% of rating dates, and in 2010 on 41.2% of rating dates.

Creeping bentgrass quality after treating moss with spot applications of sodium bicarbonate (45 g a.i. L^{-1}) was variable (Tables 3.1 and 3.2). In 2009, the season-long average creeping bentgrass quality in SB-treated plots was 6.8, and acceptable on 76% of rating dates. Recovery time following creeping bentgrass injury with SB ranged from 1 to 7 days. In 2010, no adverse effects of applying SB were observed. Creeping bentgrass injury following treatment with SB has been variable in previous studies as well. Settle et al. (2007) observed no phytotoxicity following SB (45 g a.i. L^{-1}) application. Kennelly et al. (2010) occasionally observed slight phytotoxicity following SB (44.2 g a.i. L^{-1}) application with full recovery within 14 days.

Creeping bentgrass phytotoxicity was observed after treating moss with PB (45 g a.i. L^{-1}) in 2009 and 2010 (Tables 3.1 and 3.2). Average creeping bentgrass quality in plots spot treated with PB at this rate was 7.1 in 2009 and 7.3 in 2010. Creeping bentgrass was acceptable on 82.4% of rating dates in both years. Recovery time following creeping bentgrass injury associated with PB ranged from 1 to 8 days.

Spot treatment with SB or PB at reduced concentrations (22 g a.i. L^{-1}) was not phytotoxic to creeping bentgrass and neither were broadcast treatments with SB (55 kg a.i. ha^{-1}) or PB (4.8 or 11.4 kg a.i. ha^{-1}) (Tables 3.1 and 3.2). However, variable phytotoxicity to creeping bentgrass was observed after broadcast treatment with SB (110 kg a.i. ha^{-1}) or PB (93.5 kg a.i. ha^{-1}).

Conclusions

Spring and fall spot treatment with SB (45 g a.i. L^{-1}), PB (45 g a.i. L^{-1}), and essential oil reduced moss severity at a level similar to broadcast applications of CE, and significantly reduced moss severity compared to untreated. No other treatment effectively reduced moss severity. Moss suppression with SB and CE was similar to that reported in previous studies (Borst et al., 2008; Kennelly et al., 2010; Settle et al., 2007).

Essential oil was the most phytotoxic treatment to creeping bentgrass. Plots treated with essential oil were only acceptable on half the rating dates throughout 2009 and 2010, and sometimes required as many as 18 days after treatment to return to acceptable quality. Spot treatment with SB or PB (45 g a.i. L^{-1}) was phytotoxic to creeping bentgrass and recovery time ranged from 1 to 8 days. Broadcast treatment with CE was not phytotoxic to creeping bentgrass.

Two spring and 2 fall applications (4 total) with spot treatments of SB (45 g a.i. L^{-1}), PB (45 g a.i. L^{-1}), or essential oil, as well as broadcast applications of CE, can reduce moss severity. However, at least some phytotoxicity can be expected when using SB or PB, and abundant phytotoxicity should be expected when using essential oil. Carfentrazone-ethyl was not phytotoxic to 'Pennlinks' or 'Penncross' creeping bentgrass when applied at 0.09 kg a.i. ha^{-1}.

Spot treatments of bicarbonate and essential oil products can be used as alternatives for moss control and can suppress moss colonies at a level similar to CE. However, phytotoxicity can be a concern, and rates and/or application methods need to be optimized to avoid unnecessary injury to turfgrass.

Additional moss severity data were collected, and tables are available in Appendix B.

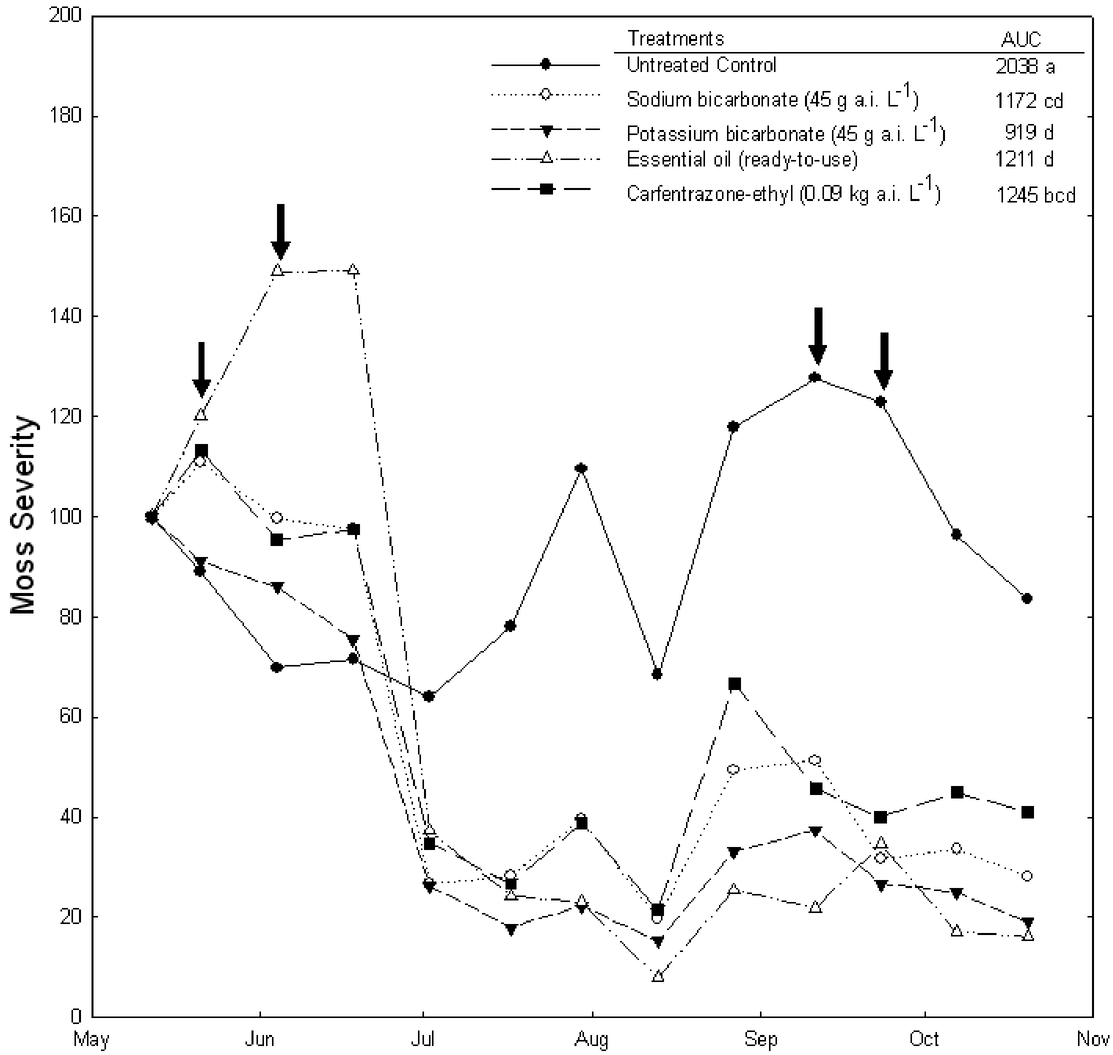


Figure 3.1 Effect of treatments on moss severity in 2009.

Treatments that reduced moss severity compared to untreated are displayed, and arrows signify application dates. Moss severity is a visual estimate of the percent of research plots infested with moss. Moss levels were significantly different on the first rating date. For this reason estimates for each plot were set to equal 100% on the first rating date, 12 May. Subsequent estimates were then scaled accordingly: (Moss severity in each plot = [% moss on rating date / % moss on 12 May] x 100). Data were subjected to the log $_{10}$ (y + 1) transformation to normalize data prior to analysis, and means were back-transformed for presentation. Area under the curve (AUC) values are also displayed AUC = $\sum^{n_i-1}_{i=1}$ ([y_i + $y_{(i+1)}$] / 2) ($t_{(i+1)}$ - t_i), where *i* is the order index for the times, and n_i is the number of times). Means

followed by the same letter are not significantly different (*P* < 0.05) according to Fisher's Protected LSD.

Figure 3.2 Research plot on 5 June 2009, one day after spot treatment with potassium bicarbonate (45 g a.i. L^{-1}) on 4 June. Sodium bicarbonate applications had similar effects on moss colonies. Moss colonies appear brown-orange, and bentgrass on the edges of colonies appears gray-green to straw-colored.

Figure 3.3 Research plot on 22 May 2009, one day after spot treatment with essential oil on 21 May. Moss colonies appear dark brown, and creeping bentgrass that received spray drift is straw-colored.

Figure 3.4 Silvery-thread moss on 22 May 2009, one day after treatment with carfentrazone-ethyl (0.09 kg a.i. ha^{-1}) on 21 May. Moss colonies appear brown-black, and creeping bentgrass is unaffected.

Table 3.1 Effect of treatments on creeping bentgrass quality in 2009.

Treatment	Quality†									
	22 May DAT-1‡	28 May DAT-7	5 June DAT-1	10 June DAT-6	12 Sept. DAT-1	23 Sept. DAT-12	25 Sept. DAT-1	2 Oct. DAT-8	**Mean§**	**% Dates acceptable¶**
Untreated Control (N/A)	7.9 a	8.8 a	8.0 a	8.3 a	8.8 a	8.0 a	7.8 a	7.8 ab	8.3 a	100
Sodium bicarbonate (45 g a.i. L^{-1})#	7.6 ab	7.3 b	3.8 f	5.8 d	5.8 c	6.2 cd	6.0 bc	6.5 bc	6.8 cd	76
Sodium bicarbonate (22.5 g a.i. L^{-1})#	7.8 ab	7.8 b	7.3 ab	8.3 a	6.5 bc	6.8 bcd	7.0 abc	7.3 ab	7.8 b	100
Potassium bicarbonate (45 g a.i. L^{-1})#	7.0 b	7.3 b	5.5 de	5.3 d	7.0 b	7.3 abc	6.3 bc	5.5 c	7.1 c	82
Potassium bicarbonate (22.5 g a.i. L^{-1})#	7.9 a	7.3 b	7.0 abc	7.8 ab	6.8 bc	7.8 ab	7.0 abc	7.3 ab	7.8 b	100
Essential oil (Ready-to-use)#	2.9 d	5.0 c	6.8 bc	5.3 d	3.3 e	5.8 d	7.0 abc	7.0 ab	6.7 d	71
Sodium bicarbonate (110 kg a.i. ha^{-1})	6.0 c	8.0 ab	3.8 f	7.0 bc	6.5 bc	7.5 abc	5.8 cd	6.5 bc	7.0 cd	82
Sodium bicarbonate (55 kg a.i. ha^{-1})	7.5 ab	7.3 b	6.0 cd	7.8 ab	8.5 a	8.3 a	6.8 abc	8.0 a	7.8 b	94

Potassium bicarbonate (4.8 kg a.i. ha^{-1})	7.8 ab	7.5 b	7.8 ab	8.3 a	8.8 a	8.0 a	7.3 ab	7.8 ab	8.1 ab	100
Potassium bicarbonate (11.4 kg a.i. ha^{-1})	7.6 ab	7.5 b	7.8 ab	8.5 a	8.5 a	8.0 a	7.8 a	7.8 ab	8.1 ab	100
Potassium bicarbonate (93.5 kg a.i. ha^{-1})	7.6 ab	7.8 b	4.5 ef	6.3 cd	4.5 d	7.3 abc	4.5 d	7.0 ab	7.0 cd	76
Carfentrazone-ethyl (0.09 kg a.i. ha^{-1})	7.6 ab	7.8 b	8.0 a	8.0 ab	8.8 a	7.8 ab	8.0 a	8.3 a	8.1 ab	100

†Creeping bentgrass quality ratings followed a 1 to 9 scale (1 = poorest quality, 6 = minimum acceptable greenness, and 9 = optimum green color/no phytotoxicity). Means with the same letter are not significantly different ($P \leq 0.05$) by Fisher's Protected LSD.

‡Days after treatment (DAT); application dates were 21 May, 4 June, 11 Sept, and 24 Sept.

§The season-long mean summarizes all 17 rating dates from 22 May to 20 Oct.

¶Quality was rated on 17 dates in 2009, % dates acceptable represents the % of rating dates above acceptable quality.

#Treatments were applied to plots with a hand-held trigger-bottle until moss colonies were visibly wet. Other treatments were applied using a hand-held CO_2-powered sprayer equipped with a single TeeJet 8008EVS even flat spray nozzle at 207 kPa.

Table 3.2 Effect of treatments on creeping bentgrass quality in 2010.

	Quality[†]									
Treatment	15 May DAT-1[‡]	21 May DAT-7	27 May DAT-1	2 June DAT-7	9 Sept. DAT-1	15 Sept. DAT-7	24 Sept. DAT-1	30 Sept. DAT-7	**Mean[§]**	**% Dates acceptable[¶]**
Untreated Control (N/A)	7.3 ab	8.0 a	8.0 a	8.8 a	8.3 a	7.8 bc	9.0 a	9.0 a	8.6 a	100
Sodium bicarbonate (45 g a.i. L^{-1})[#]	6.8 ab	7.8 ab	6.5 de	7.3 cd	8.3 a	7.8 bc	7.3 c	8.8 a	8.1 bc	100
Sodium bicarbonate (22.5 g a.i. L^{-1})[#]	7.3 ab	8.0 a	7.5 abc	8.5 ab	7.3 b	8.3 ab	9.0 a	9.0 a	8.5 ab	100
Potassium bicarbonate (45 g a.i. L^{-1})[#]	6.3 c	7.5 ab	6.0 e	6.5 d	4.8 cd	5.3 d	4.8 d	6.0 b	7.3 d	82
Potassium bicarbonate (22.5 g a.i. L^{-1})[#]	7.5 ab	7.5 ab	7.8 ab	8.8 a	5.0 c	8.5 ab	8.0 bc	9.0 a	8.3 abc	94
Essential oil (Ready-to-use)[#]	3.8 c	4.8 c	3.0 f	4.0 e	3.0 e	4.5 d	3.5 e	4.8 c	6.0 e	41
Sodium bicarbonate (110 kg a.i. ha^{-1})	7.5 ab	7.5 ab	7.5 abc	7.8 bc	8.5 a	9.0 a	9.0 a	9.0 a	8.5 ab	100
Sodium bicarbonate	7.8 a	8.0 a	8.0 a	8.8 a	8.0 ab	7.8 a	8.5 ab	9.0 a	8.6 a	100

(55 kg a.i. ha^{-1})										
Potassium bicarbonate	7.5 ab	7.8 ab	7.8 ab	8.8 a	8.5 a	9.0 a	9.0 a	9.0 a	8.6 a	100
(4.8 kg a.i. ha^{-1})										
Potassium bicarbonate	8.0 a	8.0 a	7.8 ab	8.8 a	8.3 a	8.8 a	8.8 ab	9.0 a	8.7 a	100
(11.4 kg a.i. ha^{-1})										
Potassium bicarbonate	7.0 ab	7.3 ab	6.8 cde	8.0 ab	4.0 d	7.3 c	8.5 ab	9.0 a	8.0 c	94
(93.5 kg a.i. ha^{-1})										
Carfentrazone-ethyl	7.5 ab	7.0 b	7.0 bcd	8.3 ab	7.8 ab	8.8 a	9.0 a	8.8 a	8.4 abc	100
(0.09 kg a.i. ha^{-1})										

†Creeping bentgrass quality ratings followed a 1 to 9 scale (1 = poorest quality, 6 = minimum acceptable greenness, and 9 = optimum green color/no phytotoxicity). Means with the same letter are not significantly different ($P \leq 0.05$) by Fisher's Protected LSD.

‡Days after treatment (DAT); application dates were 14 May, 26 May, 8 Sept, and 23 Sept.

§The season-long mean summarizes all 17 rating dates from 15 May to 13 Oct.

¶Quality was rated on 17 dates in 2010. Percent represents the % of rating dates above acceptable quality.

#Treatments were applied to plots with a hand-held trigger-bottle until moss colonies were visibly wet. Other treatments were applied using a hand-held CO_2-powered sprayer equipped with a single TeeJet 8008EVS even flat spray nozzle at 207 kPa.

Chapter 4 - Effect of N Sources on Silvery-Thread Moss on a Creeping Bentgrass Putting Green

Abstract

Silvery-thread moss (*Bryum argenteum* Hedw.) is a common weed in creeping bentgrass (*Agrostis stolonifera* L.) putting greens. Low nitrogen (N) fertility has been associated with increased moss severity, though the effect of N source on moss is unknown. Recent studies suggest that N source may be important in influencing moss encroachment. My objective was to evaluate the response of silvery-thread moss to differing N sources. In 2009 and 2010, liquid urea, granular urea, isobutylidene diurea (IBDU), and organic N were used to deliver N at 16.3 kg ha^{-1} biweekly for a total of 210 kg ha^{-1} annually. Moss coverage (0-100% of plot area) was assessed biweekly and creeping bentgrass color was assessed weekly on a scale of 1 to 9, with 6 = minimum acceptable. Tissue samples were taken from creeping bentgrass and from silvery-thread moss colonies for percent N analysis. In 2009, no treatment increased moss coverage. In 2010, relative to initial moss coverage in May, untreated plots and plots fertilized with IBDU had 17% and 8% less moss coverage, respectively, by October. In contrast, plots fertilized with organic N or granular or liquid urea had 23%, 67%, and 126% more moss coverage in October compared to May. According to area under the curve (AUC) analysis, plots fertilized with liquid urea had 147%, 150%, and 155% more moss in 2009 and 2010 compared to plots fertilized with IBDU, organic N, and granular urea, respectively, and 156% more moss compared to untreated plots. Fertilization with urea (liquid or granular) resulted in the best creeping bentgrass color among treatments. Averaged across the entire season, plots treated with organic N had unacceptable color in 2009, and untreated plots had unacceptable color in 2009 and 2010. Nitrogen concentrations in silvery-thread moss ranged from 0.4 to 1.0 % and were significantly lower than N concentrations observed in creeping bentgrass (1.1 to 2.1%), regardless of treatment. In 2010, moss treated with liquid urea had higher tissue N concentrations (1.0%) than untreated moss or moss treated with IBDU (0.5% and 0.4%, respectively). Application of liquid urea may increase moss encroachment.

Introduction

Mosses are common weeds in creeping bentgrass putting greens (Burnell et al., 2004; Cook et al., 2002; Happ, 1998; Kennelly et al., 2010). Silvery-thread moss is the most common species found on putting greens, though other species do occur (Hummel, 1994; Happ, 1998; Kennelly et al., 2010). Silvery-thread moss is a nonvascular plant that lacks the primary conduction tissues (xylem and phloem) of higher plants. Silvery-thread moss is an ectohydric organism which absorbs water and minerals over its entire plant surface (Glime, 2007).

Mosses can reproduce both sexually and asexually; however, daily mowing of putting greens may remove and/or destroy sporophyte capsules, restricting the dispersal of fertilized spores, limiting the likelihood of sexual reproduction, and making asexual reproduction (fragmentation) a more likely method of moss dispersal. In laboratory and field studies, silvery-thread moss has been shown to arise from vegetative fragments and, to a lesser extent, from spores (Miles and Longton, 1990). In asexual reproduction, moss fragments are thought to be moved mechanically by maintenance equipment and even by foot traffic (Cook et al., 2002; Happ, 1998). Vegetative propagation of silvery-thread moss allows the weed to spread quickly, especially when voids are present in the turf canopy.

Silvery-thread moss is very difficult to control in creeping bentgrass putting greens, and numerous studies have evaluated moss reduction strategies. See chapter 3 for additional information on silvery-thread moss control.

Response of Silvery-Thread Moss to Nitrogen

In their natural environment, mosses obtain water mainly from rainfall events, and take up little groundwater. Because of this, mosses have a limited nutrient supply, and usually obtain nutrients that are dissolved in rainwater or accumulate as dust (Glime, 2007). Most bryophytes require far lower nutrient concentrations than higher plants, and seem to grow best in low nutrient habitats (Glime, 2007), suggesting that increased fertilization of a putting green would favor creeping bentgrass, and allow turf to out-compete moss colonies. However, putting greens are irrigated daily, providing ample water to moss colonies and an artificial environment where the bryophyte may be able to utilize greater nutrient concentrations than it would require in a natural environment. While low N concentrations have been linked to increased moss severity (Hummel, 1994), the effect of differing N sources on moss has not been well studied and is relatively unknown. Recent research at Kansas State University and the Chicago District Golf Association (Kennelly et al., 2010) found conflicting trends in the influence of N sources on moss severity. Fertilization with liquid urea in Manhattan, KS increased moss coverage over 200% relative to initial amounts, whereas fertilization with a natural organic N source reduced moss coverage approximately 50%. In contrast, in Lemont, IL, moss coverage was higher in plots treated with organic fertilizer compared to urea (Kennelly et al., 2010). Bryophytes are thought to absorb NH_4^+-N more easily than NO_3^--N (Glime, 2007). Urea is quickly hydrolyzed after application, resulting in high and almost immediately available concentrations of NH_4^+ that could stimulate moss growth. Though natural organic N sources contain ammoniacal N, they are slowly available in the rootzone and are less likely to be absorbed by mosses.

With the conflicting result of recent work (Kennelly et al, 2010), and the general lack of knowledge of the effect of N source on moss development in putting greens, the objective of this study was to evaluate the response of silvery-thread moss to N sources.

Materials and Methods

This study was conducted in 2009 and 2010 at the Rocky Ford Turfgrass Research Center in Manhattan, KS. The study was conducted on a native soil "push-up" 'Penncross' creeping bentgrass putting green that had been topdressed for years and a 30.5 cm sand cap was present on the surface. The moss at Rocky Ford was positively identified as *Bryum argenteum* before a prior study in 2008 (Kennelly et al., 2010), and there was a natural infestation of *B. argenteum* in the study area.

Fertility Treatments

Treatments were applied biweekly from 14 May to 30 Oct. 2009, and from 21 May to 21 Oct. 2010. Four different N sources were used to deliver N at 16.3 kg ha^{-1} every other week, until 210 kg ha^{-1} had been applied each year, and a nonfertilized control was included for comparison. Urea (46-0-0) was applied to plots by dissolving granular urea in water and using a hand-held CO_2 -powered sprayer equipped with a single TeeJet 8008EVS even flat spray nozzle. The solution was applied at a water carrier rate equal to1,019 L water ha^{-1} at 207 kPa. Granular urea (46-0-0), isobutylidene diurea (IBDU 31-0-0), and a natural organic fertilizer (organic N, Sustane, 8-2-4, Sustane Natural Fertilizer Inc., Cannon Falls, MN) were mixed with 300 g of sand and applied in granular form using a shaker jar. The organic N source used is a complete fertilizer and application equal to N at 16.3 kg ha^{-1} resulted in 3.7 kg P_2O_5 ha^{-1} and 7.3 kg K_2O ha^{-1}. To ensure that any observed effects were due to an N response, super phosphate (0-18-0) and sulfate of potash (0-0-50) were applied granularly with liquid urea, granular urea, and IBDU to equal the amount of P_2O_5 and K_2O applied with organic N. Super phosphate and sulfate of potash were mixed with granular treatments and applied separately to liquid urea plots after mixing with 300 g of sand to aid in distribution.

Experimental Design and Management

Research plots were arranged in a completely randomized design within a 9 × 6 m area. Plots were laid out on 5 May 2009 by laying a 0.9 × 0.9 m template at fifteen locations on the putting green where moss was naturally present, and corners were marked. Each of the five treatments was randomly assigned to three plots.

The putting green was mowed at 3.2 mm six days each week with a triplex reel mower and was irrigated at 100% ET replacement. Evapotranspiration was estimated using an onsite weather station and the FAO-56 Penman-Monteith equation. Besides study treatments, no additional fertilizer was applied to the area from spring 2009 until the study concluded in the fall of 2010. Emerald (boscalid, 3-pyridinecarboxamide,2-chloro-N-(4’-chloro(1,1’-biphenyl)-2-yl), BASF Corporation, Durham, NC) was applied at 0.5 kg a.i. ha^{-1} on 29 May 2009 for dollar spot control. Dylox (trichlorfon, dimethyl (2,2,2-trichloro-1-hydroxyethyl) phosphate, Bayer Environmental Science, Durham, NC) was applied at 6 kg a.i. ha^{-1} on six dates in 2009 (29 Jun, 6 and 15 Jul, 8 Aug, and 2 and 25 Sept) to control black cutworms (*Agrotis ipsilon).* In 2010, Dylox was applied on once (25 May) and Acelepryn (chlorantraniliprole, 3-Bromo-N-[4-chloro-2-methyl-6-[(methylamino)carbonyl]phenyl]-1-(3-chloro-2-pyridinyl)-1H-pyrazole-5-carboxamide, DuPont, Wilmington, DE) was applied at 0.06 kg a.i. ha^{-1} on 2 dates (28 June and 25 Aug) for black cutworm control.

Data Collection and Analysis

Plots were rated every two weeks for moss severity and every week for creeping bentgrass color in 2009 and 2010. Moss severity data were taken as a visual estimate of the percentage of each plot covered by moss colonies. Moss severity differed among plots at the beginning of the study. For this reason, moss severity was considered to be 100% at the time of the initial rating each year, and severity for later rating dates was scaled accordingly (Moss severity in each plot = [% moss on rating date / % moss on 1st rating date] x 100) (Kennelly et al, 2010). Area under the curve (AUC) analysis was conducted to give a cumulative, season-long indication of moss severity (Kennelly et al., 2010). Area under the curve was calculated as AUC = $\sum^{ni-1}_{i=1} ([y_i + y_{(i+1)}] / 2) (t_{(i+1)} - t_i)$; where i is the order index for the times, and n_i is the number of times (Madden et al., 2007). Area under the curve data were subjected to Levene's test to evaluate the homogeneity of variances between 2009 and 2010 (Levene, 1960). Variances were homogenous, and AUC data from 2009 and 2010 were pooled for analysis.

Creeping bentgrass color was rated using a 1 to 9 scale where 1 = completely brown, 6 = minimum acceptable green color, and 9 = optimum dark green color. Tissue samples of creeping bentgrass and from moss colonies were taken on 8 May 2009 before the study began, and after fertilization ceased each year (19 Nov 2009 and 5 Nov 2010). Creeping bentgrass tissue samples were collected from clippings after mowing. Three 2.5 cm moss plugs were removed from each plot and the top 2 – 3 mm of the plugs were then used for tissue analysis. Tissue samples were submitted to the K-State Research and Extension Soil Testing Laboratory where samples were dried and ground prior to analysis. Nitrogen in plant tissue was analyzed by the Sulfuric Peroxide digest (Thomas et al., 1967). Creeping bentgrass and silvery-thread moss tissue was analyzed for differences between plant species, and among fertility treatments.

Normality of raw data was tested with the *w* statistic of the Shapiro-Wilk test using the UNIVARIATE procedure of the Statistical Analysis System (Statistical Analysis System, Cary, NC) (Shapiro and Wilk, 1965). Moss severity data were not normally distributed in either 2009 or 2010 according to the Shapiro-Wilk test. For this reason, raw data were subjected to the $\log_{10}(y+1)$ transformation to normalize. Data were subject to analysis of variance using the GLM procedure of SAS. Means were separated using Fisher's Protected LSD, and transformed means were back-transformed for presentation.

Results and Discussion

Moss Severity

In October 2009, relative to initial moss coverage in May, plots fertilized with granular urea, organic N, liquid urea, and IBDU had 52%, 35%, 3%, and 1% less moss coverage, respectively, and untreated plots had 27% less moss coverage (Fig. 4.1). In 2010, relative to initial moss coverage in May, untreated plots and plots fertilized with IBDU had 17% and 8% less moss coverage, respectively, by October (Fig. 4.1). In contrast, plots fertilized with organic N or granular or liquid urea had 23%, 67%, and 126% more moss coverage in October compared to May.

Significant moss severity differences were observed among treatments on three dates in 2009, and on three dates in 2010 (Fig. 4.1). On two dates in 2009, plots fertilized with granular urea had significantly lower moss severity than untreated plots, and plots fertilized with IBDU. Additionally, plots fertilized with granular urea had lower moss severity than plots fertilized with liquid urea on three dates, and lower than plots fertilized with organic N on one date. Fertilization with IBDU resulted in significantly higher moss severity than the untreated and organic N on one date. Plots fertilized with liquid urea were not different from untreated on any date in 2009. In 2010, plots fertilized with liquid or granular urea were not different from one another on any significant rating date. Plots that were untreated or fertilized with IBDU or organic N averaged significantly less moss than plots fertilized with liquid urea on all three significant rating dates in 2010. Untreated plots and plots fertilized with IBDU averaged significantly less moss than plots fertilized with granular urea on two rating dates in 2010.

Variances from AUC data in 2009 and 2010 were homogenous, and pooled for analysis. There were significant nitrogen source, year, and, nitrogen source × year interactions (Table C.1). Greater silvery-thread moss populations were observed in 2010. According to AUC analysis, fertilization with liquid urea in 2010 resulted in significantly greater moss encroachment than any treatment in either year (Table C.1). However, fertilization with liquid urea in 2009 resulted in moss encroachment not different from untreated plots, or plots fertilized with IBDU or organic N in 2009, and not different from untreated plots, or plots fertilized with granular urea or organic N in 2010.

Recommendation based on nitrogen source × year interactions may not be practically applicable. Therefore, AUC data were examined regarding the main effect (nitrogen source), to evaluate average performance from 2009 and 2010 (Murray et al., 1999). Mean AUC values for plots fertilized with liquid urea were 147% higher compared to plots fertilized with IBDU, 150% higher compared to plots fertilized with organic N, 155% higher compared to plot fertilized with granular urea, and 156% higher compared to untreated plots (Fig. 4.1).

Kennelly et al. (2010) observed a similar response with liquid urea in Manhattan, KS (9 applications at 15 kg N ha^{-1}) increasing moss up to 200% compared to treatment with an organic N source. Similarly, Lyons et al. (2010) observed 35% to 46% more silvery-thread moss with “foliarly”-applied liquid urea compared to soil-applied liquid urea and granular urea. Kennelly et al. (2010) also reported greater moss encroachment in Lemont, IL with application of an organic fertilizer compared to liquid urea. In the study, moss in Lemont, IL was identified as either *Bryum caespiticium* or *Bryum lisae* var. *cuspidatem*, whereas *Bryum argenteum* was present in Manhattan, KS. The difference in moss species between sites could account for differences observed in moss response to N source.

Effect of Nitrogen Source on Creeping Bentgrass Color

In 2009, fertilization with liquid or granular urea led to creeping bentgrass season-long color averages of 7.7 and 7.5, respectively, and were acceptable on every rating date (Fig. 4.2). Fertilization with IBDU resulted in significantly lower average creeping bentgrass color of 6.8, and color was unacceptable on only one of 13 rating dates.

Averaged across the season, creeping bentgrass fertilized with organic N had unacceptable quality in 2009 (5.8) and was only acceptable on 50% of rating dates. Untreated plots averaged the lowest creeping bentgrass color (4.8) and were acceptable on 13% of rating dates.

Average creeping bentgrass color in plots treated with liquid or granular urea in 2010 was 8.0 and 8.2, respectively (Fig. 4.2). Fertilization with IBDU or organic N resulted in average creeping bentgrass color of 7.1. Untreated plots again had unacceptable creeping bentgrass color, with a season-long average of 4.8, and acceptable ratings on 52% of assessment dates. All other treatments were acceptable on every rating date in 2010.

Effect of Treatments on Plant N Concentrations

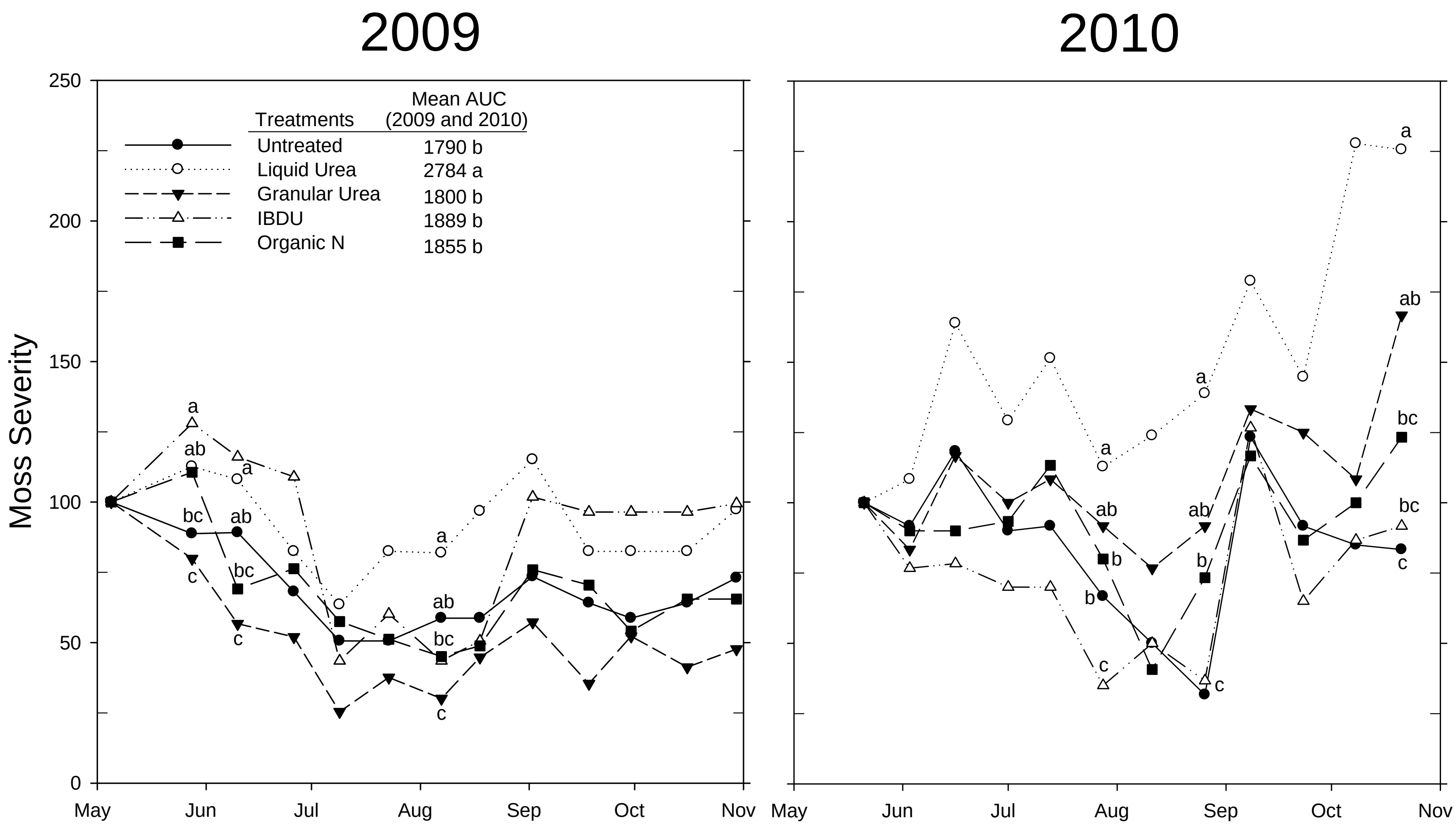
On 8 May 2009, before treatments, the baseline tissue N concentrations in creeping bentgrass and silvery-thread moss were 1.9% and 1.8%, respectively (Table 4.1). There was a plant species and plant species × fertility treatment interaction at the end of each season, on 19 Nov 2009 and 5 Nov 2010, and creeping bentgrass had significantly higher tissue N concentrations compared to silvery-thread moss. On 19 Nov 2009, creeping bentgrass fertilized with liquid urea, granular urea, or IBDU ranged in N concentrations from 1.8% to 2.1% and were significantly greater than untreated creeping bentgrass, creeping bentgrass treated with organic N, and silvery-thread moss paired with any fertility treatment. Considering silvery-thread moss, there were no differences among fertility treatments.

On 5 Nov 2010, there were no differences in N concentrations in creeping bentgrass among treatments. Silvery-thread moss had lower tissue N concentrations than creeping bentgrass for all fertility treatments. Silvery-thread moss fertilized with liquid urea had 1.0% foliar N, and was not different from moss fertilized with granular urea (0.9%) or organic N (0.8%). Untreated moss and moss treated with IBDU had the lowest tissue N concentrations (0.5 and 0.4%, respectively).

Conclusions

Silvery-thread moss response to N sources was variable in this study; however, liquid urea is capable of exacerbating moss encroachment. It may be possible to optimize fertility practices to give creeping bentgrass the competitive advantage. Mosses appear to most readily absorb nutrients “foliarly.” Further research is needed to determine how mosses absorb N.

Additional AUC analysis was performed and is available in Appendix C.



2009
2010
Moss Severity
Treatments
Mean AUC (2009 and 2010)
Untreated 1790 b
Liquid Urea 2784 a
Granular Urea 1800 b
IBDU 1889 b
Organic N 1855 b
0
50
100
150
200
250
May
Jun
Jul
Aug
Sep
Oct
Nov

Figure 4.1 Effect of treatments on moss severity in 2009 and 2010.

Moss severity is a visual estimate of the percent of research plots infested with moss. Moss levels were significantly different on the first rating date. For this reason estimates for each plot were set to equal 100% on the first rating date each year. Subsequent estimates were then scaled accordingly: (Moss severity in each plot = [% moss on rating date / % moss on initial rating date] x 100). Data were subjected to the log $_{10}$ (y + 1) transformation to normalize data prior to analysis, and means were back-transformed for presentation. Area under the curve (AUC) values are also displayed AUC = $\sum^{n_i-1}_{i=1}$ ($[y_i + y_{(i+1)}]$ / 2) ($t_{(i+1)}$ - t_i), where *i* is the order index for the times, and n_i is the number of times). Variances from AUC analysis in 2009 and 2010 were homogenous, and the mean AUC for 2009 and 2010 is displayed. Within a column on a given dates, and for mean AUC, means followed by the same letter are not significantly different ($P < 0.05$) according to Fisher's Protected LSD.

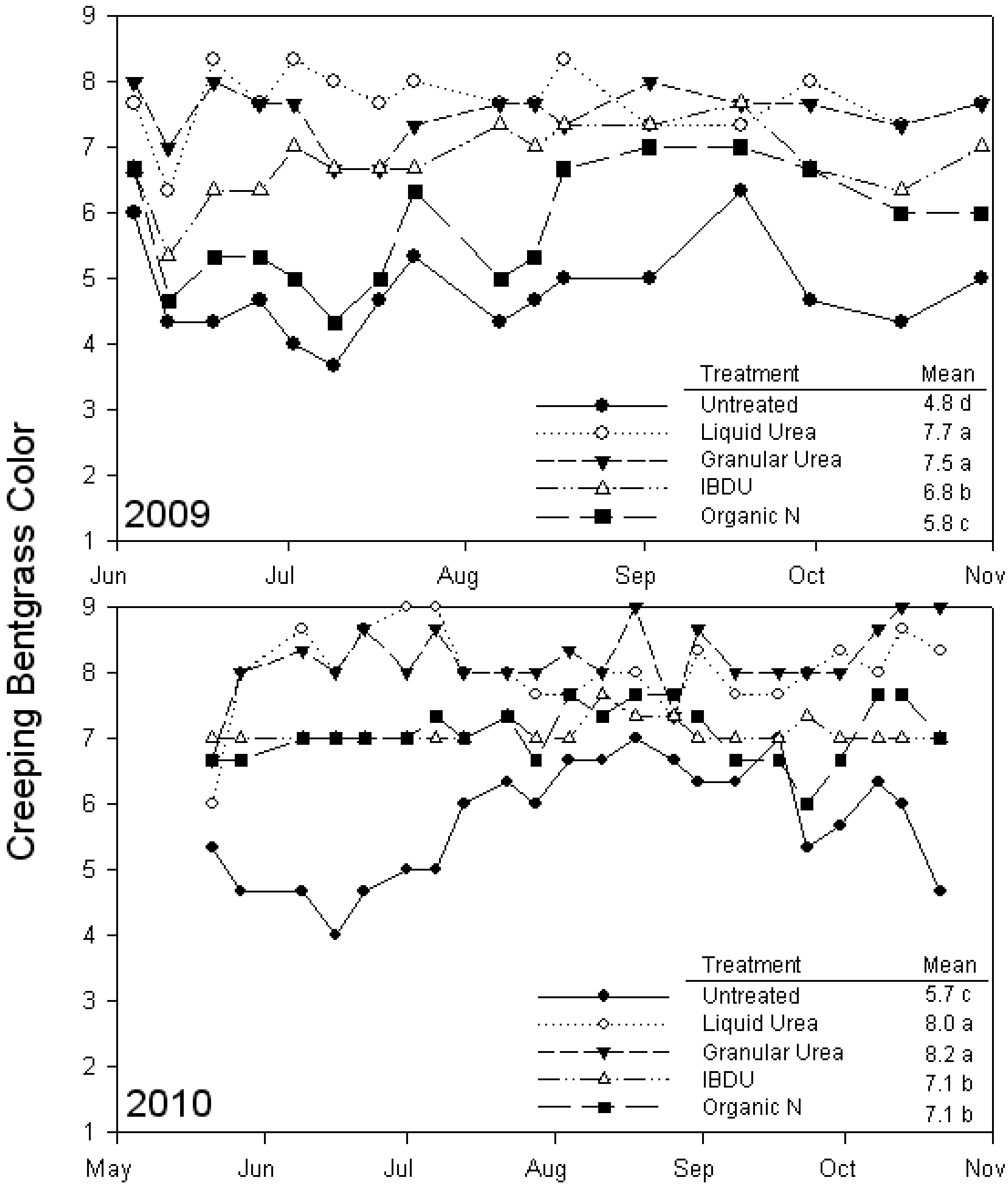


Figure 4.2 Effect of treatments on creeping bentgrass color in 2009 and 2010. Season-long average creeping bentgrass color in 2009 and 2010 are displayed in the legend. Means followed by the same letter are not significantly different (*P* < 0.05) according to Fisher's Protected LSD.

Table 4.1 Effect of treatments on N concentrations in creeping bentgrass and silvery-thread moss.

Treatments§	N concentration (%)‡		
	8 May 2009¶	19 Nov. 2009	5 Nov. 2010
Creeping Bentgrass			
Untreated	1.9	1.1 c	1.6 a
Liquid Urea#		1.8 ab	1.5 a
Granular Urea		2.1 a	1.6 a
IBDU		2.0 a	1.7 a
Organic N		1.2 bc	1.7 a
Silvery-Thread Moss			
Untreated	1.8	0.7 cd	0.5 cd
Liquid Urea#		1.0 cd	1.0 b
Granular Urea		0.8 cd	0.9 bc
IBDU		0.5 d	0.4 d
Organic N		0.8 cd	0.8 bc
	ANOVA		
Source of variation			
Nitrogen source		ns†	ns
Plant species (creeping bentgrass or moss)		***	***

Nitrogen source × Plant species	*	*

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

†ns, not significant at the 0.05 probability level.

‡Plots were sampled at the end of the season in 2009 and 2010 and analyzed for N concentration using the sulfuric acid / hydrogen peroxide digest method. Within columns, means followed by the same letter are not significantly according to Fisher's protected LSD ($P < 0.05$).

§Treatments were applied at 16.3 kg N ha^{-1} biweekly from 14 May to 30 Oct. 2009, and from 21 May to 21 Oct. 2010.

¶Creeping bentgrass and silvery-thread moss were sampled on 8 May 2009, before the study began.

#Granular urea was dissolved in water and applied with a hand held CO_2-powered sprayer.

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Appendix A - Additional Tables for Chapter 2

Table A.1 Dollar spot in creeping bentgrass cultivars maintained at fairway height in 2009.

	Dollar Spot (no. infection centers m^{-2})[†]							
Cultivar	9 Sept.	18 Sept.	25 Sept.	30 Sept.	9 Oct.	16 Oct.	21 Oct.	**AUDPC**[‡]
007	6.0 cde[§¶]	16.8 bc	16.8 bc	10.1 fg	9.8 ef	8.2 ef	6.5 e	160 de
A-4	13.5 b	33.7 b	35.2 b	32.8 bcd	27.8 bcd	24.0 bcd	19.4 bcd	480 bcd
Alpha	7.3 bcde	29.6 b	30.9 b	30.3 bcde	29.3 bcd	27.2 bc	21.1 bcd	449 bcd
Bengal	11.9 bc	34.7 b	34.5 b	39.0 abc	37.7 ab	32.1 b	25.5 bc	545 abc
Crenshaw	26.9 a	74.1 a	77.8 a	72.9 a	69.5 a	63.7 a	55.7 a	1406 a
Crystal Bluelinks	4.3 def	24.8 bc	23.6 bc	18.4 defg	17.0 cdef	13.7 cdef	11.5 cde	296 bcde
Declaration	1.3 f	12.2 c	11.9 c	7.6 g	8.0 f	6.6 f	4.9 e	117 e
Independence	9.8 bcd	34.2 b	35.0 b	40.0 ab	39.2 ab	35.5 ab	30.3 ab	565 ab
Kingpin	4.0 ef	18.5 bc	19.6 bc	13.1 fg	12.6 def	11.5 def	9.7 de	234 cde
L-93	5.3 def	20.1 bc	20.9 bc	18.7 cdefg	18.3 bcdef	16.7 bcdef	15.7 bcde	400 bcde
LS-44	8.8 bcde	31.6 b	33.2 b	32.6 bcd	31.7 bc	26.2 bcd	22.1 bcd	486 bcd
Mackenzie	4.4 def	24.0 bc	23.4 bc	21.2 bcdef	21.4 bcdef	17.4 bcdef	14.8 bcde	351 bcde
Memorial	4.8 def	19.1 bc	19.0 bc	13.9 efg	14.6 cdef	12.5 cdef	11.2 cde	262 bcde
Penncross	5.9 cde	27.3 bc	26.6 bc	22.5 bcdef	21.8 bcde	18.7 bcde	16.5 bcde	388 bcde

T-1	9.9 bcd	25.0 bc	26.5 bc	32.9 bcd	28.9 bcd	25.0 bcd	21.4 bcd	456 bcd

†Data were collected on 8 dates, and the 7 significant dates are shown. Within a column, means with the same letter are not significantly different ($P \leq 0.05$) by Fisher's Protected LSD.

‡Area under the disease progress curve (AUDPC) summarizes all 8 rating dates in 2010 (AUDPC = $\sum^{ni-1}_{i=1}$ ([y_i + $y_{(i+1)}$] / 2) ($t_{(i+1)}$ - t_i), where i is the order index for the times, and n_i is the number of times).

§Cultivar means were determined from six observations; three fungicide-treated subplots, and three nontreated subplots.

¶Data were subject to the $\log_{10}(y+1)$ transformation to normalize prior to analysis, and means were back-transformed for presentation.

Table A.2 Dollar spot in creeping bentgrass cultivars maintained at fairway height in 2010.

	Dollar Spot (no. infection centers m^{-2})[†]						
Cultivar	24 May	3 June	9 June	7 July	16 July	22 July	**AUDPC**[‡]
007	77.3 bcd[§¶]	50.1 cd	25.5 abc	49.7 cde	83.7 cdef	38.4 ef	365 bcd
A-4	128.2 abc	139.4 abc	24.6 abc	79.3 abcd	95.1 bcdef	53.5 bcde	683 abc
Alpha	87.0 bcd	106.0 abcd	34.1 a	140.7 a	146.5 ab	95.3 ab	703 ab
Bengal	141.4 ab	230.8 ab	31.1 ab	130.8 a	139.7 abc	70.0 abcde	887 a
Crenshaw	349.5 a	288.9 a	38.1 a	73.0 abcd	169.6 a	101.8 a	1124 a
Crystal Bluelinks	33.7 def	29.3 de	17.6 abc	108.9 abc	106.3 abcde	49.5 cdef	409 bcd
Declaration	15.8 ef	7.5 e	3.8 d	25.9 e	41.3 g	25.3 f	149 e
Independence	39.3 def	52.9 cd	24.0 abc	122.6 ab	119.6 abcd	77.0 abcd	441 abcd
Kingpin	10.8 f	9.3 e	11.5 cd	42.6 de	77.3 def	42.4 def	238 de
L-93	31.5 def	40.2 cde	15.6 bc	46.0 de	63.4 efg	46.9 cdef	333 cde
LS-44	47.5 bcdef	70.8 bcd	17.3 abc	113.4 ab	86.1 bcdef	58.6 abcde	460 abcd
Mackenzie	44.7 cdef	59.2 cd	21.7 abc	117.0 ab	75.9 def	70.9 abcde	431 abcd
Memorial	12.3 f	7.0 e	10.7 cd	56.2 bcde	58.5 fg	25.1 f	227 de
Penncross	61.2 bcde	28.3 de	26.2 abc	105.0 abc	102.2 abcdef	71.1 abcde	510 abcd
T-1	95.7 bcd	130.1 abc	26.1 abc	120.1 ab	113.7 abcd	83.3 abc	602 abc

[†]Data were collected on 9 dates; the 6 significant dates are shown. Within a column, means with the same letter are not

significantly different ($P \leq 0.05$) by Fisher's Protected LSD.

‡Area under the disease progress curve (AUDPC) summarizes all 9 rating dates in 2010 (AUDPC = $\sum^{ni-1}_{i=1}$ ([y_i + $y_{(i+1)}$] / 2) ($t_{(i+1)}$ - t_i), where i is the order index for the times, and n_i is the number of times).

§Cultivar means were determined from six observations; three fungicide-treated subplots, and three nontreated subplots.

¶Data were subject to the $\log_{10}(y+1)$ transformation to normalize prior to analysis, and means were back-transformed for presentation.

Table A.3 Dollar spot in creeping bentgrass cultivars maintained at putting green height in 2009.

	Dollar Spot (no. infection centers m^{-2})†								
Cultivar	28 Aug.	9 Sept.	18 Sept.	25 Sept.	30 Sept.	9 Oct.	16 Oct.	21 Oct.	**AUDPC**‡
007	5.6 abc§¶	9.5 bcde	10.8 bc	10.7 bc	7.2 bc	6.6 bcd	5.2 bcde	3.3 bcd	116 bcde
A-4	3.4 bcde	10.3 bcd	10.9 bc	10.9 bc	6.7 bcd	5.8 bcdef	4.5 bcdef	3.5 bcd	109 bcde
Alpha	5.5 abcd	11.3 bc	11.3 bc	11.6 bc	7.8 bc	6.6 bcd	4.9 bcdef	3.9 bcd	114 bcd
Bengal	4.0 bcde	8.8 bcdef	11.0 bc	10.8 bc	7.4 bc	6.5 bcde	4.8 bcdef	3.8 bcd	124 bcde
Crenshaw	11.3 a	27.3 a	29.0 a	29.4 a	27.9 a	25.8 a	22.8 a	18.3 a	707 a
Crystal Bluelinks	0.4 e	2.2 fg	1.9 de	1.8 de	1.2 de	0.8 fg	0.6 def	0.6 d	17 def
Declaration	0.5 e	1.6 g	1.5 de	1.9 de	0.8 e	0.9 efg	0.2 ef	0.1 d	9 ef
Independence	9.0 ab	17.2 ab	16.4 b	15.2 b	13.7 b	13.2 b	10.8 b	8.2 b	244 ab
Kingpin	0.0 e	0.9 g	0.8 e	0.7 e	0.0 e	0.1 g	0.0 f	0.0 d	3 f
L-93	1.8 cde	3.1 efg	2.6 de	2.3 de	1.4 de	1.5 defg	0.7 def	0.6 d	22 def
LS-44	2.8 cde	6.1 cdefg	6.4 cd	6.5 cd	3.8 cde	3.2 cdefg	2.5 cdef	2.1 cd	77 cdef
Mackenzie	4.1 bcde	10.4 bcd	9.8 bc	9.3 bc	7.6 bc	6.6 bcd	5.4 bcd	3.7 bcd	117 bcde
Memorial	0.0 e	0.6 g	0.4 e	0.4 e	0.2 ef	0.0 g	0.0 f	0.0 d	2 f
Penncross	0.8 de	3.4 defg	2.7 de	2.9 de	1.2 de	1.1 defg	0.5 def	0.3 d	16 def
T-1	8.9 ab	16.4 ab	17.2 ab	18.1 ab	10.1 bc	9.7 bc	8.2 bc	6.5 bc	191 bc

†Means in a column with the same letter are not significantly different ($P \leq 0.05$) by Fisher's Protected LSD.

‡Area under the disease progress curve (AUDPC) summarizes all 8 rating dates in 2010 (AUDPC = $\sum^{ni-1}_{i=1}$ ([y_i + $y_{(i+1)}$] / 2) ($t_{(i+1)}$ - t_i), where i is the order index for the times, and n_i is the number of times).

§Cultivar means were determined from six observations; three fungicide-treated subplots, and three nontreated subplots.

¶Data were subject to the log $_{10}$ (y +1) transformation to normalize prior to analysis, and means were back-transformed for presentation.

Table A.4 Dollar spot in creeping bentgrass cultivars maintained at putting green height in 2010.

	Dollar Spot (no. infection centers m^{-2})[†]										
Cultivar	24 May	9 June	16 June	16 July	22 July	18 Aug.	26 Aug.	17 Sept.	23 Sept.	8 Oct.	13 Oct.	**AUDPC**[‡]
007	3.5 b[§¶]	3.4 cd	2.5 d	2.7 cd	1.0 c	1.3 b	4.7 cd	26.6 bc	34.5 bcd	24.5 cd	28.0 cd	194 cde
A-4	3.7 b	10.1 bc	3.5 cd	1.3 d	0.5 c	1.3 b	2.8 cd	16.9 cd	27.2 cd	18.8 cde	12.4 def	169 cde
Alpha	1.2 b	7.8 bcd	9.1 cd	3.5 cd	3.5 bc	0.5 b	4.5 cd	13.2 cdef	26.2 cd	10.7 def	14.6 de	156 cde
Bengal	3.1 b	10.1 bc	7.5 cd	1.3 d	1.9 c	0.0 b	2.5 cd	31.4 bc	36.1 bcd	31.3 bcd	23.6 cd	240 cde
Crenshaw	25.7 a	39.4 a	31.6 a	16.2 a	25.4 a	14.8 a	28.3 a	113.6 a	106.9 a	111.7 a	130.4 a	1209 a
Crystal Bluelinks	2.0 b	9.5 bcd	5.8 cd	0.0 d	0.0 c	0.0 b	0.0 d	3.6 efg	6.1 ef	4.8 efg	2.4 fg	50 e
Declaration	1.8 b	0.5 d	2.8 d	0.0 d	0.0 c	0.0 b	0.0 d	0.0 g	2.1 f	1.0 fg	0.0 g	11 e
Independence	3.1 b	10.7 bc	13.1 bc	7.4 bc	18.9 a	8.9 a	26.5 a	56.3 ab	73.4 ab	78.9 a	65.0 ab	634 ab
Kingpin	1.0 b	2.6 cd	10.8 bcd	0.0 d	0.0 c	0.0 b	0.0 d	1.9 fg	4.0 f	2.4 fg	1.0 g	33 e
L-93	0.8 b	3.7 cd	5.4 cd	0.0 d	0.0 c	0.0 b	0.0 d	4.1 defg	5.7 ef	4.6 efg	4.5 efg	53 e
LS-44	0.5 b	2.2 cd	1.9 d	2.2 cd	0.0 c	1.0 b	0.5 d	13.8 cde	20.3 de	18.9 cde	19.7 d	144 de
Mackenzie	4.7 b	10.4 bc	3.9 cd	3.8 cd	8.3 b	5.8 ab	6.6 bc	30.9 bc	57.5 abc	32.1 bc	29.8 bcd	379 bcd
Memorial	0.2 b	0.5 d	3.5 cd	0.0 d	0.0 c	0.0 b	0.0 d	0.0 g	1.5 f	0.0 g	0.0 g	9 e
Penncross	1.2 b	19.9 ab	26.6 ab	0.5 d	1.3 c	0.0 b	0.0 d	4.0 defg	4.4 f	0.0 g	1.6 fg	80 de
T-1	1.7 b	4.7 cd	0.6 cd	9.9 ab	8.4 b	6.2 ab	15.4 ab	46.0 b	53.1 abc	63.3 ab	50.7 bc	456 bc

[†]Data were collected on 21 dates, and 11 of 19 significant dates are shown. Means in a column with the same letter are not significantly different ($P \leq 0.05$) by Fisher's Protected LSD.

[‡]Area under the disease progress curve (AUDPC) summarizes all 21 rating dates in 2010 (AUDPC = $\sum_{i=1}^{ni-1} ([y_i + y_{(i+1)}] / 2) (t_{(i+1)} - t_i)$, where i is the order index for the times, and n_i is the number of times).

[§]Cultivar means were determined from six observations; three fungicide-treated subplots, and three nontreated subplots.

[¶]Data were subject to the $\log_{10}(y+1)$ transformation to normalize prior to analysis, and means were back-transformed for presentation.

Table A.5 Quality of creeping bentgrass cultivars maintained at fairway height in 2009.

	Turfgrass quality[†]								
	14 May	28 May	26 June	23 July	7 Aug.	18 Aug.	30 Sept.	16 Oct.	**Mean**[‡]
007	8.0 a[§]	8.7 ab	7.0 abc	7.0 bcd	8.0 c	7.5 bcd	8.0 a	8.0 abcd	7.8 abc
A-4	7.3 bc	8.7 ab	6.7 bc	6.3 de	8.3 bc	8.2 abc	6.7 c	7.8 bcd	7.6 cde
Alpha	7.3 bc	8.0 c	7.3 ab	6.7 cd	8.7 ab	8.0 abcd	7.2 abc	7.8 bcd	7.6 cde
Bengal	8.0 a	8.7 ab	7.7 a	7.7 ab	9.0 a	7.8 abcd	6.7 c	7.3 de	7.9 abc
Crenshaw	6.7 d	8.7 ab	7.0 abc	7.3 abc	8.7 ab	8.2 abc	5.7 d	6.7 e	7.5 def
Crystal Bluelinks	7.3 bc	8.7 ab	7.3 ab	7.3 abc	8.0 c	7.5 bcd	7.5 abc	8.3 ab	7.7 bc
Declaration	7.7 ab	9.0 a	6.7 bc	5.7 e	7.3 d	6.3 e	7.8 ab	8.0 abcd	7.3 f
Independence	7.3 bc	8.0 c	6.3 c	6.7 cd	8.3 bc	7.3 cd	6.7 c	7.5 cd	7.4 ef
Kingpin	7.7 ab	9.0 a	7.0 abc	7.7 ab	8.3 bc	8.2 abc	7.7 ab	8.3 ab	7.9 abc
L-93	7.0 cd	8.3 bc	7.3 ab	7.0 bcd	9.0 a	8.0 abcd	7.5 abc	8.2 abc	7.9 abc
LS-44	7.7 ab	8.7 ab	7.3 ab	7.3 abc	9.0 a	8.5 a	7.3 abc	8.0 abcd	7.9 abc
Mackenzie	7.7 ab	8.7 ab	6.7 abc	7.3 abc	8.7 ab	7.2 de	7.3 abc	8.2 abc	7.8 abc
Memorial	8.0 a	8.7 ab	7.3 ab	7.3 abc	9.0 a	8.7 a	8.7 ab	8.2 abc	8.1 a
Penncross	7.0 cd	8.3 bc	7.7 a	8.0 a	9.0 a	8.3 ab	7.3 abc	8.7 a	8.0 ab
T-1	7.7 ab	8.7 ab	7.7 a	6.3 de	8.7 ab	7.5 bcd	7.0 bc	8.2 abc	7.7 bcd

[†]Turf was rated on a 1 to 9 scale (1 = lowest possible quality, 6 = minimum acceptable quality, and 9 = optimum color,

texture, density, and uniformity). Data were collected on 12 dates, and the 8 significant dates are shown. Means in a column with the same letter are not significantly different ($P \leq 0.05$) by Fisher's Protected LSD.

‡The season long mean summarizes all 12 rating dates.

§Cultivar means were determined from six observations; three fungicide-treated subplots, and three nontreated subplots.

Table A.6 Quality of creeping bentgrass cultivars maintained at fairway height in 2010.

	Turfgrass quality†						
Cultivar	21 May	3 June	1 July	16 July	8 Sept.	8 Oct.	**Mean**‡
007	6.8 bcd§	7.5 abc	8.3 a	6.8 abc	2.3 de	4.7 cd	5.3
A-4	6.3 d	6.5 de	7.3 cde	6.8 abc	2.8 bcde	5.2 bc	5.4
Alpha	6.7 cd	7.2 abcd	7.3 cde	6.7 abc	3.2 abcd	5.3 abc	5.5
Bengal	6.8 bcd	6.7 cde	8.2 ab	6.2 cd	3.5 abc	5.5 abc	5.6
Crenshaw	6.3 d	6.2 e	7.7 bcd	6.5 abc	4.0 a	6.8 a	6.0
Crystal Bluelinks	7.3 abc	7.7 ab	7.7 bcd	6.2 cd	2.7 cde	5.0 bcd	5.4
Declaration	7.5 ab	7.5 abc	7.1 de	7.0 ab	1.8 e	3.5 d	5.2
Independence	7.0 bcd	7.7 ab	7.7 bcd	6.3 bc	2.8 bcde	4.7 cd	5.4
Kingpin	6.8 bcd	7.7 ab	6.8 e	7.2 a	2.8 bcde	4.8 bcd	5.3
L-93	6.5 d	7.2 abcd	7.7 bcd	6.7 abc	2.8 bcde	5.2 bc	5.4
LS-44	7.0 bcd	7.3 abcd	7.8 abc	7.0 ab	3.8 ab	6.3 ab	6.0
Mackenzie	6.7 cd	7.5 abc	7.3 cde	6.2 cd	3.0 abcd	5.5 abc	5.5
Memorial	7.8 a	8.0 a	7.3 cde	6.7 abc	3.2 abcd	5.2 bc	5.8
Penncross	7.5 ab	7.2 abcd	7.7 bcd	6.7 abc	3.5 abc	5.3 abc	5.7
T-1	7.0 bcd	6.8 bcde	7.5 cd	5.5 d	3.7 abc	5.8 abc	5.7

†Data were collected on a 1 to 9 scale (1 = lowest possible quality, 6 = minimum acceptable quality, and 9 =

optimum color, texture, density, and uniformity). Data were taken on 12 dates and the 6 significant dates are shown. Means in a column with the same letter are not significantly different ($P \leq 0.05$) by Fisher's Protected LSD.

‡The season long mean summarizes all 12 rating dates and was not significant.

§Cultivar means were determined from six observations; three fungicide-treated subplots, and three nontreated subplots.

Table A.7 Quality of creeping bentgrass cultivars maintained at putting green height in 2009.

	Turfgrass quality†						
Cultivar	28 May	10 June	23 July	7 Aug.	18 Sept.	16 Oct.	**Mean‡**
007	7.7 ab§	8.3 abc	6.7	7.8 d	7.5 bcde	8.5	7.4 c
A-4	7.0 cd	8.7 ab	7.0	8.7 abc	7.7 abcd	8.3	7.8 ab
Alpha	8.0 a	8.3 abc	7.0	8.5 abc	7.5 bcde	8.5	7.7 abc
Bengal	7.0 cd	8.0 bc	7.0	9.0 a	7.2 de	8.7	7.6 abc
Crenshaw	7.0 cd	8.0 bc	7.3	8.7 abc	6.8 e	7.7	7.5 bc
Crystal Bluelinks	7.3 bc	8.0 bc	7.3	8.5 abc	8.0 abc	8.3	7.7 abc
Declaration	7.3 bc	8.7 ab	6.3	8.7 abc	8.2 ab	8.7	8.0 a
Independence	7.7 ab	8.7 ab	6.7	8.5 abc	7.3 cde	8.2	7.6 abc
Kingpin	7.3 bc	8.0 bc	7.3	9.0 a	8.3 a	8.7	7.9 a
L-93	6.7 d	8.0 bc	7.0	8.3 bcd	7.3 cde	8.0	7.5 bc
LS-44	7.7 ab	8.3 abc	7.0	9.0 a	7.5 bcde	8.5	7.9 a
Mackenzie	6.7 d	8.3 abc	6.3	8.3 bcd	7.5 bcde	8.2	7.5 bc
Memorial	7.3 bc	8.3 abc	6.7	8.3 bcd	7.8 abcd	8.2	7.7 abc
Penncross	7.3 bc	7.7 c	7.0	8.2 cd	7.8 abcd	8.0	7.7 abc
T-1	7.7 ab	9.0 a	7.7	8.8 ab	7.2 de	8.3	7.9 a

†Data were taken on a 1 to 9 scale (1 = lowest possible quality, 6 = minimum acceptable quality, and 9 =

optimum color, texture, density, and uniformity). Data were taken on 12 dates. Of the 6 dates shown, 4 are significant. Means in a column with the same letter are not significantly different ($P \leq 0.05$) by Fisher's Protected LSD.

‡The season long mean summarizes all 12 rating dates.

§Cultivar means were determined from six observations; three fungicide-treated subplots, and three nontreated subplots.

Table A.8 Quality of creeping bentgrass cultivars maintained at putting green height in 2010.

	Turfgrass quality[†]									
Cultivars	21 May	3 June	16 June	16 July	28 July	8 Sept.	23 Sept.	8 Oct.	21 Oct.	**Mean**[‡]
007	7.2 abcd[§]	7.7 abc	8.0 abc	8.5 a	8.0 bc	8.2 abc	6.5 cd	6.8 def	7.3 bcde	7.6 cd
A-4	7.2 abcd	7.2 bc	7.8 abc	7.0 d	7.3 de	8.2 abc	6.7 c	7.0 cde	7.5 bcd	7.4 def
Alpha	7.0 abcd	7.3 abc	7.3 bcd	8.2 ab	7.7 bcde	7.5 cd	7.0 bc	6.8 efg	7.2 cde	7.3 ef
Bengal	6.5 de	6.8 c	7.8 abc	8.0 abc	7.8 bcd	8.0 bc	6.2 cde	6.7 ef	7.0 de	7.3 ef
Crenshaw	5.7 f	5.5 d	7.2 cd	7.3 cd	7.3 de	6.2 e	4.7 f	5.2 g	5.3 g	6.3 g
Crystal Bluelinks	7.0 abcd	7.2 bc	8.2 ab	8.0 abc	7.8 bcd	8.3 ab	8.0 ab	7.7 bcd	8.0 abc	7.8 bc
Declaration	7.5 ab	8.3 a	8.3 a	8.7 a	8.8 a	8.8 a	8.7 a	8.8 a	8.8 a	8.5 a
Independence	7.3 abc	7.8 abc	8.5 a	7.7 bcd	7.7 bcde	7.0 d	5.3 ef	5.5 g	5.7 fg	7.1 f
Kingpin	7.3 abc	7.5 abc	7.7 abcd	8.2 ab	8.0 bc	7.8 bc	8.2 a	8.0 ab	8.2 ab	7.8 bc
L-93	6.8 bcde	7.0 c	7.2 cd	7.0 d	7.3 de	8.2 abc	7.8 ab	7.8 bc	8.2 ab	7.4 de
LS-44	7.3 abc	7.8 abc	8.2 ab	8.7 a	8.2 b	8.2 abc	7.0 bc	7.7 bcd	8.0 abc	7.9 bc
Mackenzie	6.7 cde	7.8 abc	7.8 abc	7.7 bcd	7.5 cde	8.0 bc	6.5 cd	6.7 ef	7.2 cde	7.4 de
Memorial	7.2 abcd	7.5 abc	8.0 abc	7.7 bcd	7.7 bcde	8.5 ab	8.7 a	8.0 ab	8.0 abc	7.9 b
Penncross	6.2 ef	5.5 d	6.8 d	7.7 bcd	7.2 e	7.8 bc	8.3 a	7.5 bcde	8.0 abc	7.2 ef
T-1	7.7 a	8.2 ab	7.8 abc	7.7 bcd	7.7 bcde	6.8 de	5.5 def	6.0 fg	6.5 ef	7.2 ef

[†]Data were taken on a 1 to 9 scale scale (1 = lowest possible quality, 6 = minimum acceptable quality, and 9 = optimum

color, texture, density, and uniformity). Data were taken on 12 dates and the 9 significant dates are shown. Means in a column with the same letter are not significantly different ($P \leq 0.05$) by Fisher's Protected LSD.

[‡]The season long mean summarizes all 12 rating dates.

[§]Cultivar means were determined from six observations; three fungicide-treated subplots, and three nontreated subplots.

Table A.9 Density of creeping bentgrass at fairway height in 2010.

	Turfgrass density[†]			
Cultivar	16 June	1 July	28 July	**Mean**[‡]
007	8.3[§]	8.8	8.3 ab	8.5 a
A-4	8.0	7.7	8.7 ab	8.1 ab
Alpha	7.5	8.5	7.5 c	7.8 b
Bengal	7.8	8.5	8.7 ab	8.3 ab
Crenshaw	7.8	8.2	7.5 c	7.8 b
Crystal Bluelinks	8.3	8.5	8.7 ab	8.5 a
Declaration	8.2	8.3	9.0 a	8.5 a
Independence	8.5	8.3	8.7 ab	8.5 a
Kingpin	8.2	8.0	8.3 ab	8.2 ab
L-93	8.0	8.3	8.5 ab	8.3 ab
LS-44	8.2	8.2	9.0 a	8.4 a
Mackenzie	8.5	7.7	8.3 ab	8.2 ab
Memorial	8.3	8.5	8.2 bc	8.3 ab
Penncross	7.5	8.0	6.3 d	7.3 c
T-1	8.0	8.0	8.5 ab	8.2 ab

[†]Creeping bentgrass density was taken following a 1 to 9 scale (1 = very thin turf, 6 = minimum acceptable density, and 9 = very dense turf). Data were taken on 3 dates and data were significant on 1 date. Means in a column with the same letter are not significantly different ($P \leq 0.05$) by Fisher's Protected LSD.

[‡]The season long mean summarizes all 3 rating dates.

[§]Cultivar means were determined from six observations; three fungicide-treated subplots, and three nontreated subplots.

Table A.10 Density of creeping bentgrass at putting green height in 2010.

	Turfgrass density[†]						
Cultivar	16 June	1 July	28 July	26 Aug.	23 Sept.	21 Oct.	**Mean**[‡]
007	8.3 a[§]	8.0 abc	8.2 bc	8.0 a	8.3 abc	8.5 ab	8.22 cdef
A-4	8.5 a	8.2 abc	8.7 ab	8.3 a	8.0 bc	8.2 abc	8.31 abcde
Alpha	7.2 bc	7.8 abc	6.7 d	6.7 b	6.7 d	7.3 d	7.05 g
Bengal	7.8 ab	7.7 bc	8.7 ab	8.2 a	8.2 abc	8.5 ab	8.17 def
Crenshaw	7.2 bc	7.3 cd	7.0 d	7.0 b	7.2 d	7.7 cd	7.22 g
Crystal Bluelinks	7.8 ab	8.2 abc	8.0 c	8.0 a	7.8 c	7.8 bcd	7.94 f
Declaration	8.7 a	8.7 a	9.0 a	8.2 a	8.5 ab	8.5 ab	8.58 ab
Independence	8.3 a	8.7 a	8.7 ab	8.5 a	8.5 ab	8.5 ab	8.53 abc
Kingpin	8.0 ab	8.2 abc	8.0 c	8.0 a	8.0 bc	8.5 ab	8.11 def
L-93	7.8 ab	7.3 cd	9.0 a	8.3 a	8.7 a	8.7 a	8.31 abcde
LS-44	8.3 a	8.7 a	9.0 a	8.5 a	8.5 ab	8.7 a	8.61 a
Mackenzie	8.0 ab	8.2 abc	8.3 bc	8.2 a	8.2 abc	8.8 a	8.28 bcde
Memorial	7.7 ab	7.8 abc	8.2 bc	8.2 a	8.0 bc	8.3 abc	8.03 ef
Penncross	6.5 c	6.7 d	6.0 e	6.0 c	6.0 e	6.5 e	6.28 h
T-1	8.3 a	8.3 ab	8.3 bc	8.3 a	8.5 ab	8.5 ab	8.38 abcd

[†]Creeping bentgrass density was taken following a 1 to 9 scale (1 = very thin turf, 6 = minimum acceptable density, and 9 = very dense turf). Data were taken on 6 dates and data were

significant on every date. Means in a column with the same letter are not significantly different ($P \leq 0.05$) by Fisher's Protected LSD.

‡The season long mean summarizes all 6 rating dates.

§Cultivar means were determined from six observations; three fungicide-treated subplots, and three nontreated subplots.

Appendix B - Additional Tables for Chapter 3

Table B.1 Effect of treatments on moss severity in 2009.

	Moss severity†								
Treatment	17 July DAT-43‡	30 July DAT-56	13 Aug. DAT-70	27 Aug. DAT-84	11 Sept. DAT-0	23 Sept. DAT-12	7 Oct. DAT-13	20 Oct. DAT-26	**AUC§**
Untreated Control (N/A)	76.9 a¶	102.7 a	62.2 a	115.5 a	120.4 a	118.9 a	94.6 a	82.7 a	2038 a
Sodium bicarbonate (45 g a.i. L^{-1})#	25.3 cde	34.4 bc	18.7 bcd	42.9 bcd	46.7 bc	30.1 bcd	28.8 cd	25.3 bc	1172 cd
Sodium bicarbonate (22.5 g a.i. L^{-1})#	34.4 bcd	55.7 ab	26.6 abcd	93.1 a	79.0 ab	62.2 abc	41.2 bcd	46.1 ab	1471 abc
Potassium bicarbonate (45 g a.i. L^{-1})#	16.1 e	21.1 c	12.0 de	30.3 cd	35.4 c	25.1 cd	21.1 de	17.0 cd	919d
Potassium bicarbonate (22.5 g a.i. L^{-1})#	50.9 ab	50.9 ab	40.7 abc	71.9 ab	81.8 ab	61.4 abc	51.6 abc	64.3 a	1422 abc
Essential oil (Ready-to-use)#	21.4 de	18.8 c	5.4 e	21.4 d	18.5 d	16.1 d	13.5 e	8.4 d	1211 d
Sodium bicarbonate (110 kg a.i. ha^{-1})	47.9 abc	59.9 ab	44.6 abc	64.5 ab	72.5 ab	59.0 abc	61.5 ab	47.2 ab	1421 abc

Sodium bicarbonate (55 kg a.i. ha^{-1})	82.7 a	67.6 ab	45.2 abc	103.9 a	106.2 a	66.9 abc	81.3 ab	78.3 a	2926 a
Potassium bicarbonate (4.8 kg a.i. ha^{-1})	56.0 ab	67.3 ab	49.8 ab	85.7 ab	88.2 a	64.8 abc	63.7 ab	64.5 a	1642 abc
Potassium bicarbonate (11.4 kg a.i. ha^{-1})	71.1 a	73.9 ab	54.5 a	97.0 a	97.8 a	79.3 ab	82.4 ab	71.8 a	1856 ab
Potassium bicarbonate (93.5 kg a.i. ha^{-1})	45.2 abc	59.5 ab	40.4 abc	61.1 abc	76.0 ab	64.5 abc	46.5 bc	59.5 ab	1494 abc
Carfentrazone-ethyl (0.09 kg a.i. ha^{-1})	25.4 cde	35.9 bc	18.3 cd	63.9 ab	45.4 bc	32.5 bcd	42.3 bcd	40.8 ab	1245 bcd

[†]Moss severity is a visual estimate of the percent of research plots infested with moss. Moss levels were significantly different on the first rating date. For this reason estimates for each plot were set to equal 100% on the first rating date, 12 May. Subsequent estimates were then scaled accordingly:
(Moss severity in each plot = [% moss on rating date / % moss on 12 May] x 100). Within a column, means with the same letter are not significantly different ($P \leq 0.05$) according to Fisher's Protected LSD.

[‡]Days after treatment (DAT); application dates were 21 May, 4 June, 11 Sept, and 24 Sept.

[§]Area under the curve (AUC) value summarizes all 13 rating dates from 12 May to 20 Oct. (AUC = $\sum^{ni-1}_{i=1} ([y_i + y_{(i+1)}] / 2) (t_{(i+1)} - t_i)$, where i is the order index for the times, and n_i is the number of times).

[¶]Data were subject the $\log_{10}(y + 1)$ transformation to normalize prior to analysis, and means were back-transformed for presentation.

[#]Treatments were applied to plots with a hand-held trigger-bottle until moss colonies were visibly wet. Other treatments were applied using a hand-held CO_2-powered sprayer equipped with a single TeeJet 8008EVS even flat spray nozzle at 207 kPa.

Appendix C - Additional Tables for Chapter 4

Table C.1 Effect of treatments on silvery-thread moss populations in 2009 and 2010.

Treatments†	AUC‡
2009	
Untreated	1717 bcd§
Liquid Urea¶	2283 bc
Granular Urea	1263 d
IBDU	2197 bc
Organic N	1719 bcd
2010	
Untreated	1863 bcd
Liquid Urea¶	3285 a
Granular Urea	2337 b
IBDU	1582 cd
Organic N	1991 bcd
	ANOVA
Source of variation	
Nitrogen source	**
Year (2009 or 2010)	**
Nitrogen source × Year	**

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

†Treatments were applied at 16.3 kg N ha^{-1} biweekly from 14 May to 30 Oct. in 2009, and from 21 May to 21 Oct in 2010.

‡Area under the curve (AUC) summarizes all 13 rating dates from 5 May to 30 Oct. 2009, and all 12 rating dates from 21 May to 21 Oct. 2010 (AUC = $\sum^{ni-1}_{i=1}$ ([$y_i + y_{(i+1)}$]

/ 2) ($t_{(i+1)}$ - t_i), where i is the order index for the times, and ni is the number of times). Within a column, means followed by the same letter are not significantly different (P < 0.05) according to Fisher's Protected LSD.

[§]Data were subject the log $_{10}$ (y +1) transformation to normalize prior to analysis, and means were back-transformed for presentation.

[¶]Granular urea was dissolved in water and applied with a hand held CO_2-powered sprayer.