IMPACT OF CULTURAL MANAGENMENT ON ANTHRACNOSE SEVERITY OF ANNUAL BLUEGRASS PUTTING GREEN TURF

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ABSTRACT OF THE THESIS

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Annual Bluegrass Putting Green Turf

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Anthracnose (*Colletotrichum cereale* Manns) has become an increasingly destructive disease of annual bluegrass (ABG) [*Poa annua* L. f. *reptans* (Hausskn) T. Koyama] putting green turf over the past two decades. Cultural management to enhance the playing surface characteristics of putting greens are thought to enhance abiotic stress and predispose turf to anthracnose. Three field trials conducted from 2006 to 2008 evaluated the effects of irrigation, equipment traffic and lightweight rolling, and sand topdressing on anthracnose severity of ABG turf mowed at 3.2 mm. Severe deficit irrigation [40% replacement of reference evapotranspiration (ET_o)] increased anthracnose severity during the study. Anthracnose was less severe under greater irrigation quantity. However, irrigating at 100% ET_o resulted in disease severity similar to irrigation at 40% ET_o by the end of 2006 and 2008. Irrigation to replace 80% ET_o typically resulted in the least amount of disease and the best turf quality. Plots receiving turning of mowers and lightweight rollers as well as clean-up mowing (representing the putting green perimeter) had lower disease severity compared to center plots on 6 of 13 dates in 2007 and 2008. Additionally, lightweight rolling reduced anthracnose 2 to 13% compared to non-rolled turf in 2007 and 2008; the heavier sidewinder roller treatment had less disease than the triplex mounted vibratory roller treatment on 4 of 13 rating dates. Initially, turf receiving

sand topdressing (0.3 L m^{-2} wk^{-1}) had a small increase in disease compared to non-topdressed turf during 2007; however, disease decreased as much as 9% by August 2007 and again in 2008 on topdressed plots. Surprisingly, turf receiving foot traffic (5 d wk^{-1}, ~200 rounds d^{-1}) had as much as 27% lower disease severity than non-trafficked turf. This effect was independent of the level of sand topdressing during 2007 and 2008. The treatment combination of weekly topdressing and frequent foot traffic resulted in the best turf quality by the end of both seasons. Overall, the results of these three studies indicate that best management practices should be an integral component of a disease control program intended to reduce anthracnose severity on ABG putting green turf.

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General Introduction: The Pathogen, Host, and Symptomology

Anthracnose is a destructive disease of weakened or senescent turf caused by the fungus *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman (Crouch et al., 2006). First reports of anthracnose on turfgrass in New Jersey designated *C. cereale* as the causal agent (Sprague and Evaul, 1930); however, later reports grouped most *Colletotrichum* species that attack grasses as *Colletotrichum graminicola* (Ces.) C. G. Wils., the fungus also responsible for anthracnose of corn (*Zea mays* L.) (Wilson, 1914). Recent research by Crouch et al. (2006) involving the phylogenetic analysis of three genetic-loci [ITS1/5,8S/ITS2; HMG (MAT1-2); SOD2] from 107 isolates obtained from the United States, Canada, and Brazil illustrated that *C. cereale* is in fact the correct designation and resurrected the former classification. Additionally, *C. cereale* may further diverge into two possibly four species, as Crouch et al. (2006) found evidence that *C. cereale* may be more of a species group rather than a homogenous species; however, additional research is needed to confirm this hypothesis. *C. cereale* is known to have a large host range causing infection on a wide variety of grasses including ornamentals and cereals. The sexual teleomorph of *C. cereale* still remains unknown as only the anamorphic stage has been observed.

C. cereale is known to infect numerous species from the Pooideae subfamily of grasses (Crouch et al., 2006). The first report of infection on the basal leaves and roots of annual bluegrass (ABG) [*Poa annua* L. f. *reptans* (Hausskn) T. Koyama] in New Jersey was made in 1928 by Sprague and Evaul. Since then, the disease has been observed throughout the United States, Canada, and Western Europe (Smiley et al., 2005; Smith et al., 1989) on almost all cool-season turfgrass species, but it has not been identified on warm-season grasses (Crouch et al., 2006). ABG is a widely distributed winter annual (also includes perennial biotypes) that occurs in both cool- and warm- season turfs, although it is rarely purposely planted due to its high susceptibility to both abiotic and biotic stresses (Turgeon, 2002; Vargas and Turgeon, 2004). While most would consider ABG an invasive weed (Vargas and Turgeon, 2004), its ability to tolerate low mowing heights while producing high quality turf with a high shoot density make it an acceptable species for putting green turf (Huff, 2003). In fact, many major golf tournaments in the cooler temperate climate regions are played on putting greens partially or predominately composed of ABG (Vargas and Turgeon, 2004).

Characterized as an allotetraploid, ABG was derived from both *Poa infirma* H.B.K. and *Poa supina* Schrad (Tutin, 1952). ABG possesses a folded vernation, pointed membranous ligule (0.8 to 3 mm long), broad collar, and characteristic boat-shaped leaf tip similar to other *Poa* species (Turgeon, 2004). Small, open panicle-shaped inflorescences are highly apparent in the spring and can be observed throughout the growing season (Turgeon, 2004). Two subspecies groups of ABG are recognized based on morphology and life cycle; *P. annua* var. *annua* L. is a “wild-type” winter annual with an upright growth habit while *P. annua* var. *reptans* (Hausskn.) T. Koyama is a “greens-type” perennial that produces a prostrate growth habit that can support low mowing heights (Huff, 2003; Turgeon, 2004). The “greens-type” subspecies is typically more desirable on golf course turf (Huff, 2003); however, its intolerance to both high temperatures and drought stress cause ABG to require intense management. Additionally, ABG is susceptible to numerous diseases such as dollar spot (*Sclerotinia* *homoeocarpa* F.T. Bennett), summer patch (*Magnaporthe poae* Landschoot & Jackson), brown patch (*Rhizoctonia solani* Kühn), and anthracnose (*C. cereale*) (Smiley et al., 2005).

Anthracnose infection on turfgrasses is thought to be initiated by soil-borne inoculum; fungal hyphae penetrate into the plant tissue through the epidermis and into the cortex and stele of the plant (Smith et al., 1989). According to Münch et al. (2008), during initial infection by *Collectotrichum* spp. the pathogen survives in vitro by preventing the production of plant chitinases; *Colletotrichum* spp. are able to convert chitin by a process called deactylation so that it is unrecognized by plant cells and the defense response is avoided. Infection continues in vascular tissues (Smith et al., 1989) as the dark hyphae of the fungus infests inner tissue of the plant clogging essential vessels such as mesophyll and phloem cells (Smith, 1954). This cuts off the nutrient supply to the acropetal region of the plant causing starvation and death. Once *C. cereale* enters the plant tissue, it behaves as a necrotroph, killing plant tissue by emitting enzymes or toxins such as pectinases as the mycelium continues to grow (Settle et al, 2006; Münch et al, 2008).

Anthracnose is observed as both basal rot and foliar blight (Smiley et al., 2005). According to Smith et al. (1989), anthracnose basal rot infection occurs under cool temperatures (15 to 25º C) and is characterized by a dark-brown discoloration at the base of the plant. This discoloration can extend from the base of the leaf sheath down to the adventitious roots. Disease progression develops slowly with older leaves and tillers becoming discolored first, followed by younger leaves. Continued infection results in poorly developed roots, with further discoloration giving the stem and adventitious roots a dark black appearance (Smith, 1954), which is the result of decay and the dark-colored hyphae of the fungus. Anthracnose foliar blight occurs during warmer temperatures (above 26º C) and greater humidity (Smith et al, 1989). Foliar symptoms on ABG appear as elongated, chlorotic lesions (Smith et al., 1989). Eventually, leaves turn brown, become covered with acervuli, and die (Settle et al., 2006) causing thinning of the turf canopy which can adversely influence the aesthetics and playability of putting green turf.

Infection results in the production of small, black, melanized acervuli (20-200µ) (Smith et al., 1989), with hair-like structures referred to as setae (32-120µ x 6-8µ) (Crouch et al., 2006). Mononucleate conidia produced in acervuli are 6.0-33.8µ long x 2.2-6.3µ wide, fusoid, guttulate and mostly haline but may appear salmon-orange in color in mass (Crouch et al., 2006; Smith, 1954). Appressoria, one-celled structures used for attachment to plant tissues, have thick, brown walls and are produced at the ends hyphae. They are rounded and smooth or irregular in shape and range from 8.5µ-11.6µ long x 6.5µ-10.2µ wide (Crouch et al., 2006). Appressoria are known to survive temperatures below 15-20ºC and may be incitants of latent infections (Smith et al, 1989). Conidia, appresoria, and mycelium on infected leaf debris function as survival structures for *Colletotrichum* spp. (Smiley et al., 2005).

ABG and creeping bentgrass (*Agrostis stolonifera* L.) foliage infested by *C. cereale* becomes orange or red; however, these symptoms are not observed on velvet bentgrass (*Agrostis canina* L.) (Smith et al., 1989). Not much is known about the survival of *C. cereale*. Survival of the *Colletotrichum* species is highly dependent upon the substrate and soil temperature. While fungal hyphae can grow efficiently on plant tissue and cause severe infection, absence of a substrate can be detrimental its survival.

Vizvary and Warren (1982) reported that *C. graminicola* cultures were killed within a few days when covered with field soil in absence of plant residue. However, it was also shown that conditions similar to winter that slow the microbial activity and decomposition of plant residue actually favored survival of *C. graminicola* conidia.

There are a number of suitable fungicides labeled for control of anthracnose on turfgrass including, but not limited to the nitriles, phosphonates, demethylation inhibitors, strobilurins (QoI's), benzimidazoles, phenylpyrroles, dicarboximides, and the antibiotic polyoxin-D (Murphy et al., 2008). In a recent fungicide trial, chlorothalonil (tetrachloroisophthalonitrile), fosetyl-Al [Aluminum tris (O-ethyl phosphonate)], and metconazole {5-[(4-chlorophenyl)methyl]-2,2-dimethyl-1-(1*H*-1,2,4-triazole-1-ylmethyl)cyclopentanol} were observed to provide adequate control of basal rot anthracnose on ABG greens (Clarke et al., 2007). While these chemicals can provide adequate disease suppression, continued applications are needed when conditions are conducive to infection to ensure that the disease does not reoccur. Fungicides can also be very costly to apply and thus can significantly impact a superintendent's budget. Mowover, in different regions of the United States, fungicide resistance has been documented to the benzimidazole and QoI chemistries {e.g., thiophanate-methyl [dimethyl 4,4'-(o-phenylene)bis(3-thioallophanate)] and azoxystrobin (Methyl(E)-2-{2-[6-(2-cyanophenoxy)pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate)} (Wong et al., 2007). Wong and Midland (2007) have also reported reduced sensitivity of *C. cereale* to DMI fungicides such as myclobutanil [(*RS*)-2-(4-chlorophenyl)-2-(1*H*-1,2,4-triazol-1-ylmethyl)hexanenitrile], tebuconazole [(*RS*)-1-*p*-chlorophenyl-4,4-dimethyl-3-(1*H*-1,2,4-triazol-1-ylmethyl)pentan-3-ol], and triadimefon [(*RS*)-1-(4-chlorophenoxy)-3,3-

dimethyl-1-(1*H*-1,2,4-triazol-1-yl)butan-2-one]. With increased resistance being observed, it is important to examine all methods for disease control including cultural management.

Influence of Management Practices on Anthracnose

The incidence and severity of anthracnose on ABG putting greens has increased within the past decade (Dernoeden, 2002; Inguagiato et al., 2009; Landschoot and Hoyland, 1995; Mann and Newell, 2005; Wong and Midland, 2004) and it has been suggested that management practices commonly employed on golf courses which enhance abiotic stress may predispose turf to this disease (Vermeulen, 2003; Zontek, 2004). It is probable that more than one or various combinations of management factors may be enhancing the severity of anthracnose on putting greens, making it more difficult to control since this disease is of greater intensity when turf is under stress (Smiley et al., 2005). Management to improve playability of golf course putting greens, such as greater ball roll distance (BRD) or 'green speed', is often achieved by lowering mowing heights, decreasing irrigation, lowering nitrogen, and using lightweight rolling. While golfers may enjoy faster greens, they often neglect the fact that increased speed often requires a more intensive management regime (Bigelow and Walker, 2007) that could be intensifying anthracnose. Thus, it is important to recognize how management impacts this devastating disease.

Irrigation Management

Irrigation management is essential to the success of putting green turf as both plant health and playability are compromised if done improperly. The water lost by evaporation from the soil and through the transpiration of plants is referred to evapotranspiration (Beard, 1973) and comparative evapotranspiration rates are known to be influenced by morphological characteristics such as shoot density, leaf orientation and width (Kim and Beard, 1988). Variations in soil water content are also known to influence cuticle size and guard cell openings which are the first line of defense against disease (Couch, 1966). Smith et al. (1989) describe water as an essential element for both plant and pathogen illustrating that while plants may be dependent on water for growth and health, many pathogens are equally dependent on water as a growing medium. Many fungi disperse spores through water and outbreaks of foliar diseases are generally associated with wet weather and/or high humidity (Schoeneweiss, 1978).

In the case of putting greens, the need for firm, fast playing surfaces requires that putting greens be maintained at relatively low soil water availability, which requires daily hand watering or syringing to prevent severe drought stress. Long-term (i.e., weeks, months) deficit irrigation could weaken and potentially predispose plants to disease causing organisms. Conversely, over-watering increases the potential for mower scalp, algae and moss encroachment, susceptibility to traffic stresses, and may also influence disease susceptibility (Beard, 2002).

According to Marsh (1969), adequate soil water is needed to maintain satisfactory top growth and color in turf and this is especially important in ABG, which is fairly intolerant to even moderate soil water deficits. According to superintendents, loss of ABG in the summer months is primarily caused by high temperatures and drought conditions (Vargas and Turgeon, 2004). Under continued low soil water content, ABG will develop symptoms of wilt, described as the visible drooping, rolling, or folding of turfgrass leaves, which occurs when transpiration causes water loss that exceeds absorption by the roots (Beard, 1973). Initially, wilt appears as a purple to purple-grayish discoloration in the foliage, which can normally be corrected with irrigation; however, continued wilt stress can cause a necrotic appearance of the leaves which is a sign of damage to the turf (Beard, 1973). Some turf can recover from drought damage but long periods of drought will result in death of the plants (Marsh, 1969).

Severe deficit irrigation results in many reactions within a turfgrass that are not visible to the human eye. Stomates close or decrease in size in the presence of wilt stress to decrease the amount of water lost (Shimshi, 1963). While this may seem beneficial by inhibiting water loss, photosynthesis is decreased due to less CO_2 uptake. The decrease in transpiration also inhibits cooling of the plant allowing the temperatures within the plant to rise and impedes important metabolic processes needed to facilitate protein development and transport that aid in keeping the plant alive (Beard, 1973). Wilting of perennial ryegrass (*Lolium perenne* L.) has been shown to significantly reduce the amount of free amino acids, the building blocks of proteins, available to the plant (Kemble and Macpherson, 1954). If protein synthesis is reduced, a plant's response to pathogen ingress could be affected by reducing the production of compounds that impede pathogen growth (Schoeneweiss, 1978). Barnett and Taylor (1966) observed sustained amino acid production during water stress in bermudagrass [*Cynodon dactlyon* (L.) Pers.], but protein synthesis and protein levels decreased. Reduced protein synthesis has been reported in plants subjected to drought stress followed by hydrolysis and decomposition processes (Henckel, 1964; Vaadia et al., 1961). Also, when photosynthesis is decreased, plants must rely on carbohydrate reserves to sustain growth, which are only stored when the demand is below the rate of production. If the carbohydrate reserves are depleted before photosynthesis can recover, the turf may be more vulnerable to infection (Zanoni et al., 1969). Turf subjected to low soil water supply may also be more susceptible to traffic stress, as turgid cells are more supportive and are less likely to rupture compared to cells that are wilted (Ferguson, 1963). Increased susceptibility to traffic stresses could wound plants and provide entry points for fungi to infect (Agrios, 2005).

While a severe soil water deficit can be detrimental to plants, a slight deficit in irrigation can actually be beneficial by providing aeration and increasing rooting depth; Weaver and Himmel (1930) observed increased rooting depth with decreased soil water content until soil became too dry for growth. Additionally, Doss et al. (1960) observed decreased rooting depth when irrigating to field capacity when available soil water was depleted to 85% compared to 65 and 30% on five warm season forage species and Bennett and Doss (1960) observed a similar response on eight cool-season forage species. If the soil is constantly moist, roots can extract water needed to support growth without the need to extend deeper into the soil, thus making them more susceptible to other environmental (e.g, heat) stresses. Slight deficit irrigation can also result in increased water use efficiency, which is essential for water-saving management practices. DeCosta and Huang (2006) observed the same level of turf quality and gas-exchange water-use efficiency in creeping bentgrass, colonial bentgrass (*A. capillaris* L.), and velvet bentgrass that were irrigated three times per week at 60, 80, and 100% ET_o during the summer and fall months; however, irrigating these same species at 40% ET_o resulted in decreased water use efficiency and reduced turf quality during the summer months.

Long intervals between consecutive irrigation events are believed to favor plant growth by maximizing air exchange between the soil and atmosphere (Vargas and Turgeon, 2004). Increasing the interval between irrigation events from one to two days and two days to four days has been shown by Jordan et al. (2003) to increase turf quality, shoot density, root length and root density of creeping bentgrass when all of the water lost through ET_o was replaced. However, replacing the full amount of water lost daily resulted in decreased root length and mean shoot density compared to irrigating with the same amount of water every two and four days (Jordan et al., 2003). Deep-infrequent irrigation (irrigation only when observing wilt) of creeping bentgrass increased water soluble and total non-structural carbohydrates in plants compared to daily irrigation (Fu and Dernoeden, 2008), which could possibly explain the increase in shoot and root density observed by Jordan et al. (2003). However, a deep infrequent approach may not be possible when maintaining ABG as a putting green during the summer months, since shallow roots can readily deplete the accessible soil water. Additionally, low mowing heights to maintain putting greens also reduce root growth (Liu and Huang, 2002) thus requiring a more frequent irrigation schedule (Vargas and Turgeon, 2004). However, it is important not to exceed the infiltration capacity of the turf to avoid excessive soil moisture (Vargas and Turgeon, 2004). Thus, daily irrigation at a slight deficit to support plant growth while providing adequate soil aeration on putting greens should provide acceptable turf quality and encourage increased shoot density and root growth. Increased shoot density and root growth could significantly reduce plant stress during summer heat, thereby potentially reducing the plants susceptibility to anthracnose, a disease believed to be enhanced when plants are stressed (Smiley et al., 2005).

Over-watering can have detrimental effects on putting green turf as well. Although ABG is particularly favored by moist to wet soil conditions (Beard et al., 1978), it does not persist well in waterlogged conditions (Sprague and Evaul, 1930). Large amounts of water can encourage succulent plant growth and increase the humidity in the turf canopy, which can increase the potential for fungal spore germination (Smiley et al., 2005). Muse and Couch (1965) showed that continuously watering creeping red fescue (*Festuca rubra* L.) to field capacity increased red thread [*Laetisaria fuciformis* (McAlpine) Burdsall reported as *Corticium fuciforme* (Berk.) Wakef.] disease on 'Rainier' red fescue plants; watering at half of field capacity reduced disease by 10% while maintaining plants at permanent wilting percentage reduced disease by 11%. Vargas and Turgeon (2004) observed that basal rot anthracnose was often present in saturated soils. Similarly, one of the first observations of anthracnose in New Jersey occurred in turf that had been well saturated from previous rain events (Sprague and Evaul, 1930). Excessive water content causes a lack of oxygen that hinders respiration rates and reduces root system function (Smith et al., 1989). A reduction in root function and mass will have a negative effect on plant health and may inhibit tolerance to potential pathogens. Water is also a dispersal medium for Oomycetes such as *Pythium* spp. that have motile zoospores enabling them to move freely in water and infect plants (Smith et al., 1989). Additionally, excessive water can cause important plant nutrients to leach (Smith et al., 1989). Leaching of plant nutrients can be detrimental to plant vigor and can increase the need for fertilization to maintain adequate turf quality.

Soil water content has been shown to have a significant effect on many diseases of cool-season turfgrasses. Dollar spot has been observed to be more severe in years of little rainfall (Couch, 1966). Moreover, a study by Couch and Bloom (1960) showed that Kentucky bluegrass (*Poa Pratensis* L.) was more susceptible to dollar spot in soil maintained at or below ¾ field capacity compared to soil irrigated at field capacity. Plants grown in soil dried to ¼ field capacity and the permanent wilting percentage had nearly two times the dollar spot severity compared to plants irrigated to field capacity. Since dollar spot is a stress related disease (Smiley et al., 2005), avoiding soil moisture extremes can significantly reduce plant stress thus potentially reducing the susceptibility to this disease. Similarly, *Pythium* blight [*Pythium ultimum* Trow and *P. aphanidermatum* (Edson) Fitzpatrick (Syn. *P. butleri* Subrm)] of highland bentgrass (*A. tenuis* Sibth.) was much more severe in plants allowed to reach permanent wilting percentage before watering back to field capacity, while plants maintained under conditions of constant and ½ field capacity had less disease (Moore et al., 1963). In Kentucky bluegrass, drought stress was the most important factor affecting *Fusarium* foliar blight [*Fusarium graminearum* Schwabe, *F. equiseti* (Corda) Sacc., *F. sambucinum sensu stricto, F. culmorum* (W.G. Sm.) Sacc., *F. heterosporum* Nees. Ex Fr., *and F. poae* (Peck) Wollenw.]; disease severity was increased when drought stressed areas were then flooded or incubated at high humidity after being exposed to drought stress (Smiley, 1985). Increased disease observed in drought areas that were flooded was due to drought conditions weakening plants making them more susceptible to infection and flooding then creating an adequate environment for fungal germination. Leaf spot, caused by *Bipolaris sorokiniana* (Sacc.) Shoemaker [reported as *Helminthosporium sativum* Pammel, C.M. King & G. Paxton], of Kentucky bluegrass was also increased under drought conditions and disease incidence tended to decrease with increased distance from localized dry areas (Endo and Colbaugh, 1975). Additionally, Danneberger et al. (1995) observed greater anthracnose disease on ABG plants in a growth chamber subjected to drought stress before inoculation. However, the effect of irrigation quantity on anthracnose in the field has not been reported.

Pathogen growth can also be influenced by the amount of water present in the soil. Blair (1943) stated that *R. solani* grows best in soil at 33% volumetric water content saturation compared to soil at 50 and 80% saturation. Greater soil water content is thought to reduce fungal growth because of the decline in soil aeration associated with increased soil water content (Papavizas and Davey, 1961). This possibly explains why Blair (1943) observed the growth of *R. solani* to be least affected by increased soil water when sand was used as the soil medium. *Rhizoctonia* spp. have also been shown to cause the most disease under dry soil conditions (40% volumetric water content saturation); low soil water content allows for the fungus to spread prolifically while weakening the plant and restricting its growth making ideal conditions for disease (Das and Western, 1959). *Colletotrichum acutatum* J.H. Simmonds survival increased in soil residues with 26.8% volumetric water content compared to 35.3% (Feil et al, 2003). When dried soil debris was re-wetted, *H. sativum* germinated at a greater rate compared to constantly moist soil debris (Endo and Colbaugh, 1975) suggesting that rewetting the soil after a period of drought stress releases nutrients thus enhancing fungal growth and giving soil microorganisms (e.g., *H. sativum*) a competitive advantage compared to the weakened plant.

The amount of irrigation that can be termed adequate for plant growth is directly related to the growing medium and type of turfgrass maintained. Reasons for varying water capacities of different soil types is directly related to soil particle size or texture (the amount of sand, silt, and clay). Sand is the largest soil particle. Soils dominated by large amounts of sand have large pore spaces. Larger pore sizes allow greater water infiltration rates, and drainage rates (Beard, 1973). Silt and clay particles are much smaller, allowing closer packing and consequently smaller pore sizes, but they typically have a greater pore volume. Greater pore volume of clayey and silty soils allow for a greater holding capacity, but the smaller pore size inhibit water infiltration and drainage (Beard, 1973). Thus, irrigation management should account for such soil conditions. Irrigation should be applied to fulfill plant requirements while avoiding accumulation of thatch (organic matter) or black layer (Nikolai, 2005), which are common in excessively irrigated areas. Irrigation applied to support plant growth and minimize wilt stress will decrease plant stress, which could greatly influence anthracnose development since this disease appears to be intensified by stress (Smiley et al., 2005).

Lightweight Rolling

Rolling is often recommended after seeding to increase soil contact with seeds and also in the spring to recover from frost heaving, the upward lifting of plants that exposes root and crown tissues encouraging desiccation (Beard, 1973). Rolling is also useful in smoothing surface irregularities from ball marks and foot traffic and can be beneficial in increasing putting BRD. These beneficial aspects of rolling encouraged the use of this cultural practice during the early 20^{th} century, but research regarding negative aspects of compaction, the pressing together of soil particles into a more dense soil mass (soil bulk density), caused many mangers to reduce or discontinue this practice during the mid-1900’s (Beard, 1973; DiPoala and Hartwiger, 1994). The introduction of lightweight rollers and increased use of sand-based putting green rootzones has enabled superintendents to once again implement rolling practices to increase putting BRD and smooth irregularities on the putting surface (DiPaola and Hartwiger, 1994). Many superintendents are increasingly pressured by their members to have firm, fast putting greens which are often obtained by initiating lower mowing, lightweight rolling, decreased irrigation, and low N fertility practices. These management practices can impact disease severity, since plant health and vigor are affected by many of these practices.

Previous studies examining rolling practices have generally focused on putting BRD. Rolled plots tend to have a BRD around 0.3 m greater than non-rolled plots on the day of rolling application (Nikolai, 2004). Increased BRD can be sustained for up to 48 hours after rolling (Nikolai, 2001; 2002a; 2002b; 2004). Rolling 3 times a week can significantly increase BRD and provide a superintendent the option of raising the mowing height to reduce plant stress during hot weather, a practice that can significantly reduce anthracnose severity (Inguagiato et al., 2009). While regular rolling can improve BRD and putting green uniformity, it is important to recognize negative aspects that can arise from excessive rolling.

Compaction of soil can occur with lightweight rolling on native soil greens (Hartwiger et al., 2001). Severe compaction of the soil can inhibit oxygen flow to roots and decrease water infiltration and drainage. These conditions can decrease root system function thereby decreasing water uptake and nutrient transport, which reduce plant health and the ability to avoid pathogen infection (Beard, 1973). Anaerobic conditions can also favor the development of pathogens that can infect stressed plants (Drew and

Lynch, 1980). Increases in soil bulk density are related to both the amount of rolling and soil composition of the putting green. Root zone mixtures vary in their susceptibility to compaction from rolling. However, when maintained under a regular topdressing schedule, Nikolai (2001; 2002a; 2002b; 2004) states that sand-based putting greens can be rolled as much as every other day without negative effects. Similarly, soil-based greens can be rolled three times per week without observing negative effects on turf quality as long as a regular topdressing schedule is maintained. Sand-based greens are less affected by rolling because of the large particle size; the larger particle size inhibits the tight packing of soil particles that can decrease macropore (non-capillary) space and inhibit root growth (Beard, 1973). Smaller particles such as silt and clay can pack tightly together into a dense soil (Lull, 1959) which can inhibit root growth, water percolation and diffusion of oxygen. Negative aspects of rolling can be exacerbated when the root zone is wet; therefore, avoiding the use of rollers when the ground is wet is recommended (Piper and Oakley, 1921). Negative effects of rolling can include shallow and thick roots, decreased shoot growth, discoloration, and thinning which allows for weed encroachment (Harivandi, 2002). However, a soil that is extremely loose can also inhibit root growth by limiting soil contact, which inhibits water and nutrient uptake. Such responses result in a relationship between soil compaction and root growth that is parabolic in nature (Rosenburg, 1964), having negative responses at both ends of the spectrum. With this in mind, it could be argued that some degree of compaction is actually an advantage under certain conditions when the soil is so loose that both water and nutrient uptake are inhibited.

The growth of turf can be greatly influenced by the degree of soil compaction. Root growth of ABG and perennial ryegrass is significantly reduced in heavily compacted soil (Sprague and Burton, 1937; Sills and Carrow, 1983) and high amounts of N (>0.5 kg N 100 m^{-2}) applied to compacted areas can further decrease root growth. This negative response can be seen on golf courses where managers attempt to alleviate decreased turf quality caused by compaction by applying nitrogen (Sills and Carrow, 1983).

Turf quality can be altered with increased frequency of lightweight rolling. Hartwiger et al. (2001) observed 14 to 15% and 24 to 26% reductions in turf quality of plots rolled four and seven times per week, respectively, compared to non-rolled plots, on both native soil and sand-based greens. However, it should be noted that the practice of topdressing was apparently not initiated in this experiment, which could greatly influence the results as noted by Nikolai (2004); putting greens can withstand more rolling when regularly topdressed. When topdressing, rolling three times per week seems to be a practical schedule that can increase BRD without affecting turf quality, soil compaction or water infiltration (Nikolai, 2002a; 2002b; 2004).

With advances in technology over the years, lightweight rollers have been improved offering a wide array of models which can vary considerably in weight, features, price, etc. Hartwiger (1996) referred to three roller types; the drum roller, which is generally a large, single roller pulled behind a vehicle; a triplex attachment, where the mowing reels are replaced with large rollers; and a dedicated roller, which is designed only to roll putting greens and possesses two to three rollers underneath the unit. One type of dedicated roller is the sidewinder, which consists of two or three rollers under the unit with the operator oriented perpendicular (sideways) to the direction of travel. Triplex attachments and dedicated rollers have become more popular within the last 15 years as lightweight rolling has become a more common practice (DiPaola and Hartwiger, 1994; Nikolai, 2004). Choosing a roller type depends on the needs of the manager or operator, but increases in BRD tend to be similar among many of the popular rollers used today. Nikolai (2004) showed that increases in BRD varied amongst roller type on the day of rolling and day after rolling; however, while the differences may have been significant, none where greater than 15 cm, which is a difference considered undetectable by golfers (Karcher et al., 2000).

Few studies have examined the relationship between disease and rolling frequency or roller type. While compaction of soil can decrease plant health and increase disease severity, it can also inhibit the ability of fungal hyphal growth through the soil (Skinner and Bowen, 1974). If fungal extension is limited, the potential for disease development could be reduced. Consistent rolling could also inhibit fungi growing on the surface of leaves, therefore reducing the potential for foliar disease, but this hypothesis has not been proven. Dollar spot has been observed to be lower in plots rolled three times per week compared to non-rolled turf (Nikolai et al., 2001). Nikolai et al. (2001) stated that rolling after early morning mowing could dissipate dew and gutation water which is rich in nutrients from plant leaves, and thus reduce disease severity. However, within this same study, pink patch, or pink snow mold, caused by *Microdochium nivale* (Fr.) Samuels & I.C. Hallett, was observed to be greater in rolled plots.

Initial research at Rutgers indicated that lightweight vibratory rolling either has no effect or can slightly reduce anthracnose disease severity (Inguagiato et al., 2009b).

However, this work did not assess other roller types or the impact of increased wear along the perimeter of a putting green caused by the directional change (turning) of equipment. This additional wear damage at the perimeter of a putting green may predispose the turf to anthracnose.

Sand Topdressing

Topdressing, as described by Beard (1973), is the application of a thin layer of selected or prepared soil to a specified turfgrass area. Its application can be employed for smoothing or leveling of the surface, modification of the surface soil, covering stolons or sprigs of vegetative plants, winter protection, and is an effective method to control thatch by encouraging the decomposition of organic matter (Beard, 1973; Ledeboer and Skogley, 1967). Initially, topdressing materials generally consisted of 1/3 peat, 1/3 sand and 1/3 soil, but more recently, topdressing material selection has adapted to better meet the needs of superintendents (Beard, 1973). Selection of topdressing material is often based on the existing soil properties. It is important to either match particle size of topdressing to the root zone, or place a coarser-textured material over finer-textured soil to ensure that water flow is not impeded by textural interfaces. If a finer-textured material is topdressed over a coarser-textured soil, water may be retained within the fine-textured material and impede water flow (Beard, 2002). Typically, topdressing on putting greens consists of straight sand or sand-based mixes. Applications can be light and frequent or heavy and less frequent depending on the situation and management (Beard, 2002). For example, larger amounts of sand are required to backfill coring holes, while smaller amounts are more suitable for routine topdressing during mid-season to maintain smoothness and modify surface thatch accumulation.

The application of sand topdressing can greatly influence the physical properties at the turf/soil surface. Altering the surface physical properties can influence the microenvironment and thus plant health. Sand topdressing can support a more upright growth habit of the turf leaves while providing more structural integrity at the base of the plant (Inguagiato et al., 2009a). The collection of sand around the base of the plant results in crowns that grow within a more soil-like environment rather than accumulating in the thatch (Inguagiato et al., 2009a). Crowns growing in thatch are subject to increased susceptibility to environmental stresses since temperature and water conditions vary more in thatch compared to the underlying soil (Beard, 1973). Hurto et al. (1980) also observed lower water retention in thatch of Kentucky bluegrass compared to an underlying silt loam soil. Sand topdressing can also create a firmer, more supportive surface that is less susceptible to mower scalp; reduced mower scalp from topdressing has been previously observed on creeping bentgrass (McCarty et al., 2007) and bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burtt-Davy] (White and Dickens, 1984). Additionally, firmer surface characteristics obtained through regular sand topdressing are thought to increase the effective height of cut; a slight increase in cutting height can significantly reduce anthracnose severity (Inguagiato et al., 2009b). However, sand topdressing can be an abrasive practice which can result in damage to the plant. Sub-angular and angular sands may cut leaves and sheaths when applied and incorporated as topdressing. Sand is typically incorporated into the canopy using brushing or dragging practices, which can also increase the damage caused from sand topdressing. Bruising or wounding damage to plant leaves could potentially result in increased infection by pathogens and low tolerance to environmental stresses (Agrios 2005; Beard, 1973).

Information regarding the relationship between sand topdressing and disease is somewhat inconsistent. There are reports of sand topdressing causing increased dollar spot activity on creeping bentgrass putting greens on sandy loam root zones (Engel and Alderfer, 1967) and coarse sand, or loamy-coarse sand root zones (Cooper and Skogley, 1981). However, other studies have suggested that sand topdressing had no effect on dollar spot disease development of both bermudagrass (Carrow et al., 1987) and creeping bentgrass putting greens (Stier and Hollman, 2003). Light frequent (e.g., 0.3 L m^{-2} every 7-d) sand topdressing can reduce anthracnose disease of ABG putting greens (Inguagiato, et al. 2009a). Moreover, incorporation methods (brushing, etc) have not affected anthracnose development. Carrow (1995) describes turf grown in sandy, well-drained soils as resistant to the problems associated with compaction, but poor in tolerance to wear. The poor wear tolerance may be related to the additional abrasive properties of golf spikes, thus accentuating the abrasion from sub-angular sands. It is not known whether the positive effects of sand topdressing in reducing anthracnose can be expected when the turf is also subject to intense foot traffic.

Foot Traffic

Foot traffic can cause both wear and compaction of the soil; however, the game of golf cannot be played without foot traffic. Putting greens can be severely compacted by the consistent foot traffic of golfers (Harban, 1922). Soil compaction, turfgrass wear, soil displacement, and divots can all result from foot traffic and are detrimental to turfgrass growth (Beard, 1973). Traffic that results in rutting or foot printing can compact soil and is more common on excessively wet areas (Beard, 1973). The negative effects associated with soil compaction have been previously discussed.

Wear of the turfgrass plants can cause problems as well. Beard (1973) defines turfgrass wear as direct pressure on the turf which can crush the leaves, stems, and crowns of the plant, and be accentuated by scuffing or tearing action associated with foot traffic. One problem commonly associated with wear is wounding. Wounding can come from abrasive golf shoes and divots from golf clubs, which provide an opening for fungi to cause infection (Agrios, 2005).

Turf species can differ greatly in the ability to withstand stress generated from wear and differences are normally correlated to differences in morphology; growth habit, stem thickness, leaf area, fresh and dry weight, and number of roots can all impact tolerance to traffic (Kuss, 1986). Cell wall constituents (i.e., total cell wall percentage, lignocellulose, cellulose, and lignin) directly impact the wear resistance of turfgrass species (Shearman and Beard, 1975b), thus influencing the degree of wounding that occurs under regular traffic. Additionally, morphology and cell wall constituents will vary amongst species; tall fescue (*Festuca arundinaceae* Schreb.) possesses more course leaf blades and is known to tolerate wheel traffic while Kentucky bluegrass has proven more tolerant to foot traffic (Shearman and Beard, 1975a). Younger (1961) previously reported that warm-season turfgrasses, such as bermudagrass and zoysiagrass (*Zoysia japonica* Steud, and *Zoysia matrella* L.), were more wear tolerant than cool-season turfs when subjected to the accelerated wear machine designed by Perry (1958); however, within the same study, 'Alta' tall fescue had wear tolerance similar to warm-season species, while 'Manhattan' perennial ryegrass and 'Merion' kentucky bluegrass were considered intermediate in tolerance. Additionally, Morrish and Harrison (1948) have previously reported Kentucky bluegrass, Canada bluegrass (*Poa compressa* L.), chewings fescue (*F. rubra* var. *commutata* Gaud.), sheep fescue (*F. ovina* L.), and tall fescue to be more tolerant to vehicular traffic than common forage species.

Within earlier literature, studies examining the wear tolerance of ABG are infrequent and inconsistent. In fact, previous studies examining the wear tolerance of putting green turf typically mention ABG as invasive, colonizing thinned areas subjected to wear stress (Canaway, 1981; Samaranayake et al., 2008). Carrow (1995) describes ABG as having a poor wear tolerance but excellent tolerance to soil compaction. Because of its ability to persist with short roots, ABG can spread easily into areas where compaction inhibits the growth of other species (Samaranayake et al., 2008). However, Canaway (1981) reported ABG had the best tolerance of wear, compared to other species, when using a differential-slip wear machine in the spring and winter. The low mowing height of ABG putting greens could also influence wear; Younger (1961) observed significantly lower wear resistance in grass mixtures maintained at 13 mm compared to 51 mm, but this may not be as problematic in greens-type ABG, as it is known to tolerate much lower mowing (Vargas and Turgeon, 2004).

Wear tolerance can be simulated in multiple ways as traffic on a golf course can come from both golfers and vehicles. Kimball developed a “simple one-paddle wear-testing machine” that later evolved into the first accelerated “mechanized turfgrass wear tester” (Perry, 1959). The accelerated wear tester was later used by Younger (1961) to test the wear resistance of cool-season turfgrasses. Evans (1988) utilized a commercially manufactured roller outfitted with feet to simulate human foot traffic, whereas Shearman and Beard (1974) developed a wear simulator constructed to rotate around a pivot point and powered by an electric motor. Fushtey et al. (1983) used a studded roller that resulted in severe mutilation of grass stands, and Bonos et al. (2001) developed a wear-simulator by modifying a walk behind power broom.

Of the wear trials that have been performed, few studies have examined the impact of actual human foot traffic on turf. Ferguson (1958; 1959) examined foot traffic of men wearing spiked, rubber cleated, or ripple soled shoes and later examined effects of turning by having golfers put and walk around a putting cup for an extended period of time; results showed reduced turf quality that was worse in areas where golfers turned around the cup. Hard metal spikes produced the most damage. Gibeault et al. (1983) observed hard spiked soles causing greater damage than rubber studded soles, which lead to the decline of using hard metal spikes for golf shoes (Bengeyfield, 1985). The negative effects of hard metal spikes on golf course turf are well known, and golfer's now use shoes equipped with soft-spikes, which has become a standard in the golf course industry (Gilhuly, 1992).

Traffic can result in open wounds of turf leaves and crowns, which has been commonly associated with plant disease; most fungi can enter plants through various types of wounds (Agrios, 2005). In examining the pathogenicity of *C. gloeosporioides* Penz. on torch ginger (*Etlingera elatior* (Jack) R.M. Smith), inoculation treatments that did not include mechanical wounding did not result in disease (Lins and Coelho, 2003). While wounding was not required for infection of corn (*Zea mays* L.) by *C. graminicola*, inoculation with mechanical wounding resulted in greater infection frequency and efficiency (Venard and Vaillancourt, 2007); 100% of inoculations with mechanical wounding resulted in infection while only 76% of unwounded inoculations became infected. Additionally, colonization of unwounded corn took up to 9 d while wounded inoculations were all fully colonized within 48 hrs post inoculation. In a one year study, Ebdon (2006) observed differences in anthracnose disease when various cultivars of velvet and creeping bentgrass were subjected to wear stress applied using a grooming brush; some cultivars had no disease while others were had disease levels below the minimum acceptable rating of 6. Traffic occurrence on or around putting greens is highly variable depending on where golfers approach and enter the green (Hathaway and Nikolai, 2005). However, greater amounts of disease tend to coincide with the most recent positioning of the flag stick on putting greens (Ferguson, 1963). The effect of human foot traffic on anthracnose severity has not been examined, although some have speculated that the additional stress of foot traffic in combination with sand topdressing could influence the disease. As foot traffic can be damaging, examination of how it influences disease could be useful for turfgrass management.

Summary

This thesis describes three field trials; two were initiated in 2006 and one was initiated in 2007. Previous research has shown irrigation to have a significant impact on numerous turfgrass diseases (Couch, 1966). Additionally, Danneberger et al. (1995) reported increased anthracnose on plants grown in a growth chamber and subjected to drought prior to inoculation; however the influence of daily irrigation on anthracnose in the field has not been previously examined. In 2006, an experiment was initiated to evaluate the effect of daily irrigation practices on anthracnose disease in the field by replacing various percentages of reference evapotranspiration (Chapter 1).

While previous research by Inguagiato et al. (2009b) observed lightweight rolling to have no effect or to slightly reduce anthracnose disease, only a triplex vibratory roller was evaluated. As different rollers are used in the management of putting greens, it is important to examine how different rolling equipment might impact anthracnose development. The use of a heavier dedicated roller may result in more or less stress on the surface through regular operation and turning thus impacting anthracnose differently from a vibratory roller. To further examine lightweight rolling, a study was initiated in 2006 to evaluate two lightweight rollers (dedicated sidewinder roller and triplex mounted vibratory roller) and non-rolled plots (Chapter 2). Within this same study, area of equipment operation was also examined since the turning of equipment (both rollers and/or mowing equipment) is believed to generate stress on turfgrass plants, thus possibly influencing anthracnose severity. Turning of equipment normally occurs at the perimeter of the putting green which is one area where anthracnose is commonly observed.

An additional trial in 2007 was designed to refine recommendations regarding sand topdressing and efforts to reduce anthracnose disease on ABG putting greens (Chapter 3). Research by Inguagiato et al. (2009a) reported reduced anthracnose on ABG putting green turf under both light and frequent, and heavy and infrequent applications of sand topdressing. Moreover, incorporation methods such as vibratory rolling and soft or stiff brushing did not affect anthracnose development. However, further evaluation is needed to determine whether foot traffic negates the beneficial effects of light frequent sand topdressing in reducing anthracnose severity. Wear from brushing alone has been reported to increase anthracnose severity on some bentgrass varieties (Ebdon, 2006), but the effect of human foot traffic on anthracnose disease has not yet been examined.

Research presented in this thesis can aid in the development of best management practices for the control of anthracnose. While these practices may not individually provide control of anthracnose disease, the combination these practices along with adequate nitrogen fertilization could significantly reduce the amount of fungicide used to control anthracnose on ABG putting greens.

REFERENCES

Agrios, G.N. 2005. Plant Pathology, Fifth Edition. Elsevier Academic Press. Burlington, MA.

Barnett, N.M., and A.W. Taylor. 1966. Amino acid and protein metabolism in bermudagrass during water stress. Plant Physio. 41:1222-1300.

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

Beard, J.B. 2002. Turf Management for Golf Courses. 2nd ed. Ann Arbor Press, Chelsea, MI.

Beard, J.B., P.E. Rieke, A.J. Turgeon, and J.M. Vargas Jr. 1978. Annual bluegrass (*Poa annua* L.) description, adaptation, culture, and control. Research Report 352. Michigan State Ag. Exp. Stat. 32 pp.

Bengeyfield, W.H. 1985. Golf shoes and turf wear - a story that won't go away! USGA Green Sec. Rec. 23:12

Bennett, O.L., and B.D. Doss. 1960. Effect of soil moisture level on root distribution of cool-season forage species. Agron. J. 52:204-207.

Bigelow, C.A., and K.S. Walker. 2007. Golf ball roll distance; a field exercise to explore management factors affecting putting green speed. J. of Nat. Resour. Life Sci. Educ. 36:112-119.

Blair, I.D. 1943. Behavior of the fungus *Rhizoctonia solani* Kühn in the soil. Ann. Appl. Biol. 30:118-127.

Bonos, S.A., E. Watkins, J.A. Honig, M. Sosa, T. Molnar, J.A. Murphy, and W.A. Meyer. 2001. Breeding cool-season turfgrasses for wear tolerance using a wear simulator. Int. Turfgrass Soc. Res. J. 9:137-145.

Canaway, P.M. 1981. Wear tolerance of turfgrass species. J. Sports. Turf Res. Inst. 57:65-83.

Carrow, R.N. 1980. Influence of soil compaction on three turfgrass species. Agron. J. 72:1038-1042.

Carrow, R.N. 1995. Wear stress on turfgrass. Golf Course. Manag. 63:49-53.

Carrow, R.N., B.J. Johnson, and R.E. Burns. 1987. Thatch and quality of Tifway bermudagrass turf in relation to fertility and cultivation. Agron. J. 79:524-530.

Clarke, B.B., P.R. Majumdar, L. Jepsen, J. Inguagiato, T. Flynn, A. Pitonak, D. Fitzgerald, M. Peacose, A. Scholz, T.J. Lawson, and J. Roberts. 2007. Impact of chemical and biological fungicides for the preventive control of anthracnose on an annual bluegrass green. Rutgers New Jersey Agricultural Experiment Station 2007 Turfgrass Proceedings 39:255-262.

Cooper, R.J., and C.R. Skogley. 1981. Putting green and sand/soil. U.S. Golf Assoc. Green Section Record 19:8-13.

Couch, H.B. 1966. Relationship Between Soil Moisture, Nutrition and Severity of Turfgrass Diseases. J. Sports Turf Res. Inst. 42:54-64.

Couch, H.B., and J.R. Bloom. 1960. Influence of environment on diseases of turfgrass II. effect of nutrition, pH, and soil moisture on sclerotinia dollar spot. Phytopathology. 50:761-763.

Crouch, J.A., B.B. Clarke, and B.I. Hillman. 2006. Unraveling evolutionary relationships among the divergent lineages of *Colletotrichum* causing anthracnose disease in turfgrass and corn. Phytopathology. 96:46-60.

DaCosta, M., and B. Huang. 2006. Deficit irrigation effects on water use characteristics of bentgrass species. Crop Sci. 46:1779-1786.

Danneberger, T.K., M.J. Carroll, J.M. Vargas, Jr., and P.E. Rieke. 1995. Susceptibility of *Poa annua* to anthracnose as influenced by water stress. J. of Turfgrass Manage. 1:19-24.

Das, A.C., and J.H. Western. 1959. The effect of inorganic manures, moisture and inoculum on the incidence of root disease caused by *Rhizoctonia solani* Kühn in cultivated soil. Ann. Appl. Biol. 47: 37-48.

Dernoeden, P.H. 2002. Creeping bentgrass management: summer stresses, weeds, and selected maladies. John Wiley & Sons, Inc., Hoboken, NJ.

DiPaola, J.M., and C.E. Hartwiger. 1994. Green speed, rolling and soil compaction. Golf Course Manage. 62:49-51, 78.

Doss, B.D., D.A. Ashley, and O.L. Bennett. 1960. Effect of soil moisture regime on root distribution of warm season forage species. Agron. J. 52:569-572.

Drew, M.C., and J.M. Lynch. 1980. Soil anaerobiosis, microorganisms, and root function. Ann. Rev. Phytopathology. 18:37-66.

Ebdon, J.S. 2007. Effects of species and cultivar on basal rot anthracnose under wear stress, 2006. Plant Disease Management Reports (online). Report 1:T040; The American Phytopathological Society, St. Paul, MN.

Endo, R.M., and P.F. Colbaugh. 1975. Drought stress as a factor triggering fungal disease of turfgrass. California Turfgrass Culture. 22:21-23.

Engel, R.E., and R.B. Alderfer. 1967. The effect of cultivation, topdressing, lime, N, and wetting agent on thatch development on 1/4-inch bentgrass turf over a 10-year period. New Jersey Agric. Exp. St. Bull. 818:32-45.

Evans, G.E. 1988. Tolerance of selected bluegrass and fescue taxa to simulated human foot traffic. J. Environ. Hort. 6:10-14.

Feil, W.S., E.E. Butler, J.M. Duniway, and W.D. Gubler. 2003. The effects of moisture and temperature on the survival of Colletotrichum acutatum on strawberry residue in soil. Can. J. Plant Path. 25:362-370.

Ferguson, M.H. 1958. Effects of golf-shoe soles on putting green turf. USGA J. Turf Manag. 35:25-28.

Ferguson, M.H. 1959. Turf damage from foot traffic. USGA J. Turf Manag. 36:29-32.

Ferguson, M.H. 1963. Effects of traffic on turf. USGA Green Sec. Rec. 1:3-5.

Fu, J.M., and P.H. Dernoeden. 2008. Carbohydrate metabolism in creeping bentgrass as influenced by two summer irrigation practices. J. Am. Soc. Hort. Sci. 133:678-683.

Fushtey, S.G., D.K. Taylor, and D. Fairey. 1983. The effect of wear stress on survival or turfgrass in pure stands and in mixtures. Can. J. Plant Sci. 63:317-22.

Gibeault, V.A., V.B. Younger, and W.H. Bengeyfield. 1983. Golf shoe study II. USGA Green Sec. Rec. 21:1-7.

Gilhuly, L.W. 1992. Search your sole – remove your spikes! USGA Green Sec. Rec. 30:24

Harban, W.S. The effect of trampling and rolling on turf. Bulletin of the Green Sec of the USGA. 2:148-150.

Harivandi, M.A. 2002. Turfgrass traffic and compaction: problems and solutions. Agriculture and Natural Resources Catalog for the University of California. 8080:1-6.

Hartwiger, C.E. 1996. The ups and downs of rolling putting greens. USGA Green Sec. Rec. 34:1-4.

Hartwiger, C.E., C.H. Peacock, J.M. DiPaola, and D.K. Cassel. 2001. Impact of light-weight rolling on putting green performance. Crop Sci. 41:1179-1184.

Hathaway, A.D., and T.A. Nikolai. 2005. A putting green traffic methodology for research applications established by in situ modeling. Int. Turfgrass Soc. Res. J. 10:69-70.

Henckel, P.A. 1964. Physiology of plant under drought. Ann. Rev. of Plant Physiol. 15:363-386.

Hongfei, J., J. Fry, and N. Tisserat. 1998. Assessing Irrigation Management for its Effects on Disease and Weed Levels in Perennial Ryegrass. Crop Sci. 38:440-445.

Huff, D.R. 2003. Annual bluegass (*Poa annua* L.), p. 39-51, *In* M. D. Casler and R. R. Duncan, eds. Turfgrass biology, genetics, and breeding. John Wiley & Sons, Inc., Hoboken, NJ. Hurto, K.A., A.J. Turgeon, and L.A. Spomer. 1980. Physical charecteristics of thatch as a turfgrass growing medium. Agron. J. 72:165-167.

Inguagiato, J.C., J.A. Murphy and B.B. Clarke. 2008. Anthracnose severity on annual bluegrass influenced by nitrogen fertilization, growth regulators, and verticutting. Crop Sci. 48:1595-1607.

Inguagiato, J.C. 2009a. Anthracnose severity influenced by cultural management of annual bluegrass putting green turf. Ph.D. Dissertation. Rutgers University, New Brunswick, NJ.

Inguagiato, J.C., J.A. Murphy, and B.B. Clarke. 2009b. Anthracnose disease and annual bluegrass putting green performance affected by mowing practices and lightweight rolling. Crop Sci. 49:1454-1462.

Jordan, J.E., R.H. White, D.M. Vietor, T.C. Hale, J.C. Thomas, and M.C. Engelke. 2003. Effect of irrigation frequency on turf quality, shoot density, and root length density of five bentgrass cultivars. Crop. Sci. 43:282-287

Karcher, D.E., Nikolai, T.A., and Calhoun, R.N. 2000. Green Speed: What do Golfers Know? Aus. Turfgrass Manage. 2:30-32.

Kemble, A.R., and H.T. Macpherson. 1954. Liberation of amino acids in perennial ryegrass during wilting. Biochem. J. 58:46-49.

Kim, K.S., and J.B. Beard. 1988. Comparative turfgrass evapotranspiration rates and associated plant morphological characteristics. Crop Sci. 28:328-331.

Kuss, F.R. 1986. A review of major factors influencing plant responses to recreation impacts. Environ. Manage. 10:637-650.

Landschoot, P., and B. Hoyland. 1995. Shedding some light on anthracnose basal rot. Golf Course Manage. 11:52-55.

Ledeboer, F.B., and C.R. Skogley, 1967. Investigations into the nature of thatch and methods for its decomposition. Agron. J. 39:320-323.

Lins, S.R.O., and R.S.B. Coelho. 2003. Anthracnose of torch ginger (*Etlingera elatior*): occurrence and inoculation methods. Summa Phytopathologica. 29:355-358.

Lull, H.W. 1959. Soil compaction on forest and range lands. USDA Forest Service Miscellaneous Publication 768, 33 pp.

Mann, R.L., and A.J. Newell. 2005. A survey to determine the incidence and severity of pests and diseases on golf course putting greens in England, Ireland, Scotland, and Wales. Int. Turfgrass Soc. Res. J. 10:224-229.

Marsh, A.R. 1969. Soil water-irrigation and drainage. In A.A. Hanson and F.V. Juska. Turfgrass Science. Agron. No. 14. Amer. Soc. Agron., Madison, WI.

McCarty, L.B., M.F. Gregg, and J.E. Toler. 2007. Thatch and mat management in an established creeping bentgrass golf green. Agron. J. 99:1530-1537.

Moore, L.D., H.B. Couch, and J.R. Bloom. 1963. Influence of environment on diseases of turfgrasses III. effect of nutrition, pH, soil temperature, air temperature, and soil moisture on pythium blight of highland bentgrass. Phytopathology. 53:53-57.

Morrish, R.H., and C.M. Harrison. 1948. The establishment and comparative wear resistance of various grasses and grass-legume mixtures to vehicular traffic. J. Am. Soc. Agron. 40:168-179.

Münch, S., U. Lingner, D.S. Floss, N. Ludwig, S. Norbert, and H.B. Deising. 2008. The hemibiotrophic lifestyle of *Colletotrichum* species. J. Plant Physio. 165: 41-51.

Murphy, J., F. Wong, L. Tredway, J. Crouch, J. Inguagiato, B. Clarke, T. Hsian, and F. Rossi. 2008. USGA Best management practices for anthracnose on annual bluegrass turf. Golf Course Manage. 76:93-104

Muse, R.R., and H.B. Couch. 1965. Influence of environment on disease of turfgrasses, IV. effect of nutrition and soil moisture on corticium red thread of creeping red fescue. Phytopathology. 55:507-510.

Nikolai, T.A., P.E. Rieke, J.N. Rogers, III, and J.M. Vargas, Jr., J.M. 2001. Turfgrass and soil responses to lightweight rolling on putting green root zone mixes. Int. Turfgrass Soc. Res. J. 9:604-609.

Nikolai, T.A. 2002a. Effects of rolling and fertility on putting green root zone mixes. Ph.D. dissertation. Michigan State University, East Lansing.

Nikolai, T.A. 2002b. More light on lightweight rolling, research is shedding light on rolling as a season-long maintenance practice. USGA Green Sec. Rec. 40:9-12.

Nikolai, T.A 2002c. Rollin', rollin', rollin, lightweight rollers can be used frequently to enhance putting green speed. Golf Course Manage. 72:121-124.

Nikolai, T.A. 2005. The Superintendents Guide to Controlling Putting Green Speed. John Wiley & Sons Inc., Hoboken, NJ. 125-127.

Papavizas, G.C., and C.B. Davey. 1961. Saprophytic behavior of *Rhizoctonia* in soil. Phytopathology. 52:693-699.

Perry, R.L. 1958. Standardized wear index for turfgrasses. Southern California Turfgrass Culture 8:30-31.

Piper, C.V., and R.A. Oakley. 1921. Rolling the turf. Bulletin Green Sec. USGA. 1:36.

Rosenburg, N.J. 1964. Response to plants to the physical effects of soil compaction. Advanced Agron. 16:181-196.

Samaranayake, H., T.J. Lawson, and J.A. Murphy. 2008. Traffic stress effects on bentgrass putting green and fairway turf. Crop Sci. 48:1193-1202.

Schoenweiss, D.F. 1978. Water stress as a predisposing factor in plant disease. Pgs. 61-99 in: Water Deficits and Plant Growth, Vol. 5. Edited by Kozlowski. Academic Press, New York.

Settle, D.M., A.D. Martinez-Espinoza, and L.L Burpee. 2006. Anthracnose of turfgrass. The Plant Health Instructor. DOI:10.1094/PHI-I-2006-1205-01.

Shearman, R.C., J.B. Beard, C.M. Hansen, and R. Apaclla. 1974. Turfgrass wear simulator for small plot investigations. Agron J. 66:332-334

Shearman, R.C., and J.B. Beard. 1975a. Turfgrass wear tolerance mechanisms: I. Wear tolerance of seven turfgrass species and quantitative methods for determining turfgrass wear injury. Agron. J. 67:208-11

Shearman, R.C., and J.B. Beard. 1975b. Turfgrass wear tolerance mechanisms: II. Effects of cell wall constituents on turfgrass wear tolerance. Agron. J. 67:211-215

Shimshi, D. 1963. Effect of soil moisture and phenylmercuric acetate upon stomatal aperture, transpiration, and photosynthesis. Plant Physiol. 38:713-721.

Sills, M.J., and R.N. Carrow. 1983. Turfgrass growth, N use, and water use under soil compaction and N fertilization. Agron. J. 75:488-492.

Skinner, M.F., and G.D. Bowen. 1974. The penetration of soil by mycelia stands of ectomychorrhizal fungi. Soil Bio. and Biochem. 6:57-61

Smiley, R.W. 1985. Soil and atmospheric moistures associated with fusarium crown rot and leaf blight of *Poa pratensis*. Plant Disease. 69:294-297.

Smiley, R.W., P.H. Dernoeden, and B.B. Clarke. 2005. Compendium of turfgrass diseases. 3rd ed. The American Pathological Society, St. Paul, MN.

Smith, J.D. 1954 A disease of *Poa annua.* J. Sports Turf Res. Inst. 8:3444-3453.

Smith, J.D. 1955 Turf disease notes. 1955. J. Sports Turf Res. Inst. 9:60-75.

Smith, J.D., N. Jackson, and A.R. Woolhouse. 1989. Fungal diseases of amenity turf grasses. 3rd ed. E. & F.N. Spon, London.

Sprague, N.B., and G.W. Burton. 1937. Annual bluegrass (*Poa annua* L.) and its requirements for growth. N.J. Ag. Exp. Station Bulletin. 630:1-24.

Sprague, H.B., and E.E. Evaul. 1930. Experiments with turf grasses in New Jersey. N.J. Ag. Exp. Station Bulletin. 497:1-55.

Stier, J.C., and A.B. Hollman. 2003. Cultivation and topdressing requirements for thatch management in A and G bentgrasses and creeping bluegrass. Hort. Science 38:1227-1231.

Turgeon, A.J. 2005. Turfgrass management 7th Ed. Pearson Education, Inc., Upper Saddle River, NJ.

Tutin, T.G. 1952. Origin of *Poa annua* L. Nature 169:160

Vaadia, Y., F.C. Raney, and R.M. Hagan. 1961. Plant water deficits and physiological processes. Ann. Rev. of Plant Physiol. 12:265-292.

Vargas, J.M., Jr., and A.J. Turgeon. 2004. *Poa annua*: physiology, culture, and control of annual bluegrass John Wiley & Sons, Inc, Hoboken, NJ.

Vavrek, B. 2002. Traffic…How much can you bare? USGA Green Sec. Rec. 40:1-5.

Venard, C. and L. Vaillancourt. 2007. Penetration and colonization of unwounded maize tissues by the maize anthracnose pathogen *Colletotrichum graminicola* and the related nonpathogen *C. sublineolum*. Mycologia 99: 368-377.

Vermeulen, P.H. 2003. Maybe it's time for a change. USGA Green Sec. Rec. 41:28.

Vivary, M.A., and H.L. Warren. 1982. Survival of *Colletotrichum graminicola* in Soil. Phytopathology. 72:522-525.

Weaver, J.E., and W.J. Himmel. 1930. Relation of increased water content and decreased aeration to root development of hydrophytes. Plant Physiol. 5:69-92.

White, R.H., and R. Dickens. 1984. Thatch accumulation in bermudagrass as influenced by cultural practices. Agron. J. 76:19-22.

Wilkinson, J.F., and D.T. Duff. 1972. Rooting of *Poa annua* L., *Poa pratensis* L., and *Agrostis palustris* Huds. at three soil bulk densities. Agron. J. 64:66-68.

Wilson, G.W. 1914. The identity of the anthracnose of grasses in the United States. Phytopathology 4:106-112.

Wong, F.P., and S. Midland. 2004. Fungicide-resistant anthracnose: bad news for greens management. Golf Course Manage. 72:75-80.

Wong, F.P., and S.L. Midland. 2007. Sensitivity distributions of California populations of Colletotrichum cereale to the DMI fungicides propiconazole, myclobutanil, tebuconazole, and triadimefon. Plant Disease. 91:1547-1555.

Wong, F.P., S.L. Midland, and K.A. Cerda. 2007. Occurrence and distribution of QoI-resistant isolates of *Colletotrichum cereale* from annual bluegrass in California. Plant Disease. 91:1536-1546.

Younger, V.B. 1961. Accelerated wear tests on turfgrasses. Agron. J. 53:217-18.

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

Zontek, S. 2004. Have we gone too far? The grass is talking to you. Are you listening? USGA Green Sec. Rec. 42:28.

Zontek, S.J. 2006. Understanding and managing mechanical damage. USGA Green Sec. Rec. 44:1-5.

CHAPTER 1. Irrigation Management Effects on Anthracnose Disease of Annual Bluegrass Putting Greens

ABSTRACT

Irrigation can influence both turf vigor and playability of putting greens. Anthracnose (*Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman) has become an increasingly destructive disease of annual bluegrass (ABG) [*Poa annua* L. f. *reptans* (Hausskn) T. Koyama] putting greens, particularly when turf is under stress. This 3-yr field study evaluated the effects of daily irrigation quantity [100, 80, 60 and 40% of reference evapotranspiration (ET_o)] on anthracnose severity of ABG mowed daily at 3.2-mm. Severe drought stress (40% ET_o) increased anthracnose severity in 2006, 2007 and 2008; anthracnose was less severe under 60% ET_o irrigation, and irrigating at 80% ET_o reduced severity compared to 60% ET_o. Irrigating at 100% ET_o initially reduced anthracnose severity compared to 40% ET_o, however, 100% ET_o resulted in similar disease severity later in the 2006 and 2008 seasons. While an increase late in the 2007 season was not apparent, plots maintained at 100% ET_o had turf quality similar to plots irrigated at 40% ET_o later in each year due in part to increased algal development. Irrigation to replace 80% ET_o typically resulted in the least amount of disease and the best turf quality throughout the trial. Thus, irrigation to provide adequate soil water and limit water stress is beneficial in reducing anthracnose and maintaining acceptable turf performance.

INTRODUCTION

Anthracnose is a serious disease of weakened or senescent turf caused by *Colletotrichum cereale* Manns sensu lato Crouch, Clarke and Hillman (Crouch et al., 2006). Although many turfgrass species are susceptible, the disease is particularly destructive on annual bluegrass (ABG) [*Poa annua* L. f. *reptans* (Hausskn) T. Koyama]. Two phases of the disease exist: a foliar blight, often problematic during high temperatures and humidity of summer, and a basal rot which can be observed throughout the year (Smiley et al., 2005). Anthracnose can cause severe thinning of putting green turf, which can greatly reduce playability and aesthetics.

Irrigation is essential to maintaining high performance of putting green turf as both plant health and playability are compromised if done improperly. The demand for firm, fast (long ball roll distance) playing surfaces requires that putting greens be kept at relatively low soil water availability. Thus, daily hand watering or syringing are often needed to manage drought stress and avoid permanent turf injury. Long-term (i.e., weeks, months) deficit irrigation can weaken and potentially predispose plants to anthracnose, especially ABG, which is intolerant of low soil water conditions (Marsh, 1969). Conversely, frequent, heavy irrigation increases the potential for mower scalp, algae and moss encroachment, susceptibility to traffic stresses (Beard, 2002), and is thought to increase anthracnose severity. In fact, some of the first observations of anthracnose on ABG putting greens in New Jersey associated increased disease severity with a previous period of heavy rainfall and compacted soil (Sprague and Evaul, 1930).

Soil water content has been reported to affect several diseases of cool-season turfgrasses. Creeping red fescue (*Festuca rubra* L. ‘Pennlawn’ and ‘Rainier’) grown in soil maintained at field capacity had greater severity of red thread [*Laetisaria fuciformis* (McAlpine) Burdsall reported as *Corticium fuciforme* (Berk.) Wakef.] than plants grown at ½ field capacity (Muse and Couch, 1965). *Pythium* blight, a foliar disease caused by *Pythium ultimum* Trow and *P. aphanidermatum* (Edson) Fitzpatrick (Syn. *P. butleri* Subrm), was more severe on highland bentgrass (*Agrostis tenuis* Sibth.) subjected to drought stress prior to rewetting the soil to field capacity compared to turf maintained continuously at ½ field capacity (Moore et al., 1963). Kentucky bluegrass (*Poa pratensis* L.) was more susceptible to dollar spot (*Sclerotinia homoeocarpa* F.T. Bennett) when subjected to moisture stress (i.e. extracting water to ¾ field capacity and below) compared to plants grown at constant field capacity (Couch and Bloom, 1960). Similarly, Papendick and Cook (1973) observed greater foot rot disease [*Fusarium roseum* (Lk.) emend. Snyd. & Hans. f. sp. *cerealis* (Cke.) Snyd. & Hans 'Culmorum'] on wheat (*Triticum aestivum* L.) subjected to drought stress, and Endo and Colbaugh (1972) found leaf spot and foot rot diseases [*Helminthosporium sativum* Pammel, C.M. King & G. Paxton] were more severe on Kentucky bluegrass that had experienced to drought stress.

Anthracnose incidence and severity on golf course putting greens has increased within the past decade (Dernoeden, 2002; Landschoot and Hoyland, 1995; Mann and Newell, 2005; Wong and Midland, 2004). Management practices commonly employed on golf courses during this period have been shown to enhance abiotic stress and are suspected of predisposing turf to anthracnose (Vermeulen, 2003; Zontek, 2004). Attempts to adjust cultural practices to improve turfgrass vigor (e.g. increased nitrogen fertilization) and reduce stress (increased mowing height) have been reported to reduce anthracnose development (Inguagiato et al., 2008; and 2009). Since plant health and vigor is greatly influenced by irrigation, it is important to determine whether irrigation influences anthracnose development. Previous work by Danneberger et al. (1995) in the growth chamber showed ABG plants subjected to drought stress before inoculation exhibited greater anthracnose disease. However, the effect of drought stress on anthracnose in the field has not been reported. Therefore, the objective of this field study was to evaluate the influence of irrigation quantity on anthracnose development of ABG putting green turf.

MATERIALS AND METHODS

General Management Practices

A 3-yr field study was initiated in 2006 on ABG turf grown on a Nixon sandy loam (fine, mixed, mesic Typic Hapludult) with a pH of 6.3 in North Brunswick, NJ. A monostand of ABG turf was established using seed indigenous to the site as well as seed introduced in 1992 from soil cores collected from golf course putting greens in Piscataway and Plainfield, NJ as described by Inguagiato et al. (2008). Turf was mown seven times wk^{-1} with a walk behind greens mower (models 220A and 220B, Deere & Co., Moline, IL) at a bench height of 3.2 mm. Nitrogen was sprayed using water soluble sources at N rates of either 4.9 or 9.8 kg ha^{-1}. When irrigation treatments where not being imposed, a N total of 73.2 kg ha^{-1} was applied from April to May 2006, 48.8 kg ha^{-1} from September to October 2006, 58.6 kg ha^{-1} from April to May 2007, 107.4 kg ha^{-1} from late August to October 2007, and 43.9 kg ha^{-1} from April to May 2008. While irrigation treatments were being imposed, N was applied totaling 48.8, 29.3, and 29.3 kg ha^{-1} from June to August 2006, 2007 and 2008, respectively. P and K were applied at 21.5 and 40.6 kg ha^{-1} in 2006, 16.1 and 30.4 kg ha^{-1} in 2007, and 0 and 56.3 kg ha^{-1} in 2008, respectively. The entire study area was topdressed with silica sand [sub-angular, medium(0.25 to 0.50 mm diameter)] at 1.83 m^3 ha^{-1} and incorporated with a cocoa mat drag (Ace Equipment and Supply Co., Henderson, CO) every 14 d from May to September each year. Trinexapac-ethyl [4-(cyclopropyl-α-hydroxy-methylene)-3.5-dioxocyclohexanecarboxylic acid ethylester] was applied at 0.048 kg a.i. ha^{-1} every 14 d from 22 May to 13 October 2006, 12 May to 9 September 2007, and 7 May to 13 October 2008. Dollar spot disease was prevented each year from May to October by alternating

14 d schedules of boscalid {3-pyridinecarboximide, 2-chloro-N-[4'chloro(1,1'-biphenyl)yl]} and vinclozolin [3-(3,5-dichlorophenyl)-5-ethenyl-5-methyl-2,4-oxazolidinedione] at 0.4 and 1.5 to 1.8 kg a.i. ha^{-1}, respectively. Flutolanil {N-[3-(1-methylethoxy)phenyl]-2-(trifluoromethyl)benzamide} was applied at 3.1 to 6.4 kg a.i. ha^{-1} for control of brown patch disease every 14 d from June through August. These fungicides were previously shown to be ineffective against anthracnose disease on ABG greens in New Jersey (Towers et al., 2002). ABG weevils [*Listronotus maculicollis* (Kirby)] were controlled with bifenthrin {[2-methyl(1,1'-biphenyl)-3-yl]methyl 3-[2-chloro-3,3,3-trifluoro-1-propenyl]-2,2-dimethyl-cyclopropanecarboxylate} applied at 0.13 kg a. i. ha^{-1} on 2 May 2006, 3 May and 19 June, 2007 and 13 May and 25 May, 2008. Algae was suppressed with mancozeb (ethylenebisdithiocarbamate) applied at 21.4 kg a.i. ha^{-1} on 31 May, 20 June, and 7, 22, and 28 July 2007.

The anthracnose epiphytotic was arrested after irrigation treatments were suspended each year to allow plots to recover during the fall and winter months. Chlorothalonil (tetrachloroisophthalonitrile) and thiophanate-methyl (dimethyl-4.4'–o-phenylenebis-[3-thioallophanate]) were applied at 18.1 kg a.i. ha^{-1} and 6.1 kg a.i. ha^{-1} on 26 October 2006, respectively. Chlorothalonil was applied at 16.1, 9.2 ,and 11.2 kg a.i. ha^{-1} on 10 September 2007, 16 September and 13 October 2008, respectively. Bentgrass encroachment was minimized with fluazifop-P-butyl {(R)-2-[4-[(5-(triflurometh yl)-2-pyridyloxy)phenoxy]propionic acid} applied at 0.21 kg a.i. ha^{-1} on 9 September 2006, 23 August and 5 September 2007 and 18 September 2008. Broadleaf weeds were controlled with mecoprop [2-(2-methyl-4-chlorophenoxy)] at 1.1 kg a.i. ha^{-1} on 23 August and 5 September 2007 and 18 September 2008. The experimental site had previously been inoculated in July 2002 with *C. cereale* isolate ValP-04 as described by Inguagiato et al. (2008) to ensure a uniform infection. Disease outbreaks occurred naturally in subsequent years. *C. cereale* was re-isolated from symptomatic leaf and stem tissue in treated plots each year in the current study to confirm the presence of the pathogen.

Treatment Design

This study was arranged as a randomized complete block design with five replications. Treatments were applied to 2.4 by 2.4-m plots and repeated in the same location each year. Irrigation quantity was the single factor studied; treatments consisted of daily irrigation quantities of 100, 80, 60 and 40% replacement of reference evapotranspiration (ET_o). A data logger (Model CR-10X, Campbell Scientific, Logan, UT) collected air temperature, relative humidity, wind speed and solar radiation parameters from an onsite weather station and calculated daily ET_o using the Penman Monteith equation (Allen et al., 1998). Respective treatment percentages of ET_o were transformed to a volume of daily irrigation for each 2.4 by 2.4-m plot, which was applied using a hand-held hose equipped with fan nozzle and digital flow meter (Catalog number 9978K75, McMaster-Carr Supply Co., New Brunswick, NJ). Treatments with greater deficit irrigation (that is, 60 and 40% ET_o) often required supplemental syringing to prevent prolonged wilt stress on days of high evaporative demand. Individual plots were syringed with no more than 0.6 mm of water when wilt stress was observed; syringing was repeated as necessary throughout each day.

Rain was not excluded from the experimental site; thus the irrigation treatments were suspended after rain based on the precipitation amount, soil water retention and evapotranspiration. Irrigation was withheld from each plot until the increase in soil water from rain had been depleted by drainage and evapotranspiration. Irrigation was withheld for no more than three days after a rain event.

Irrigation treatments were applied from 7 July to 25 August 2006 and from 31 May to 20 August 2007 and 26 August 2008. A 112-mm post treatment rainfall occurred from 25 August to 4 September 2006. A similar period of re-wetting was simulated with irrigation from 26 August to 4 September 2008, when plots were irrigated with 6.4 mm of water each night.

Data Collection and Analysis

Soil water content was measured daily with a surface neutron source gauge (Model 3411-B, Troxler Electronic Laboratories Inc., Research Triangle Park, NC). Anthracnose severity was determined periodically from July to September 2006, June to August 2007, and June to September 2008. The percent turf area infested with *C. cereale* was measured using a line intercept-grid count method described by Inguagiato et al. (2008) which had 273 intersections within a 1.4 m^2 $plot^{-1}$. The number of intersections observed over infested leaf tissue was recorded and transformed to a percentage using the formula: (*n*/273) x 100; where *n* represented the number of intersections observed over symptomatic leaf tissue. Turf quality was rated visually from June through August each year on a scale of 1 to 9, where 9 represented the best and 5 the minimum acceptable level of turf quality. Turf color, plant density, uniformity, and percent disease were all components of turf quality. Algal growth was visually estimated using a 1 to 9 scale (where 9 represented no algae) on 5 and 19 August 2006, and 20 June, 5, 13 and 19 July and 20 August 2007. All data were evaluated by analysis of variance using the General Linear Model procedure in the Statistical Analysis System software v. 9.1.3 (SAS

Institute, Cary, NC). Means were separated using Fisher's protected least significant difference at the 0.05 probability level.

RESULTS

Soil Water Content

As expected, soil water content varied among irrigation treatments in all 3 yr of the study and effects were observed soon after initiation of treatments (Figures 1, 2 and 3). Plots irrigated at 40% ET_o attained the lowest soil water content each year and increasing irrigation quantity produced a concurrent increase in soil water content. Visual wilt symptoms were observed soon after the initiation of 40% ET_o treatments in all years. Visual wilt was initially observed later in the season in plots receiving 60 and 80% ET_o replacement while plots receiving 100% ET_o did not produce visual wilt in all three years. The 40% ET_o irrigation plots required the most syringing events to relieve wilt symptoms: 53, 42, and 70 syringing events occurred in 2006, 2007 and 2008, respectively. Syringing events decreased as irrigation amount increased with 60% ET_o plots requiring 20, 8, and 26 events in 2006, 2007 and 2008, respectively; whereas the 80% and 100% ET_o plots received only 2 (2008) and 0 syringing events, respectively, over the 3 year study.

Rain increased the soil water for all treatments, but was dependent on the amount of rain as well as the antecedent soil water content. Soil water content decreased after each rain event and treatment differences became evident within a few days.

A 112 mm rainfall from 25 August to 4 September 2006 increased soil water content across all treatments. Soil water content in the 40, 60 and 80% ET_o plots was similar by 29 August; yet soil water content in the 40 and 60% ET_o plots was significantly lower than 100% ET_o plots (Figure 1). The study did not receive a large rainfall event at the end of the 2007 season and differences in soil water content between each ET_o treatment remained late into the season (Figure 2). In 2008, soil water content was increased in all plots by 28 August 2008 through irrigation to simulate the event of rainfall documented from 25 August to 4 September, 2006 (Figure 3). Plots receiving 40 and 60% ET_o had similar soil water content; however, soil water in these plots was significantly lower than plots receiving 80 and 100% ET_o, which were no different from one another.

Anthracnose Severity

Anthracnose was first observed as a natural infestation on 21 July 2006 (Table 1); peak levels (17 to 30%) were observed by 25 August. Disease developed earlier in 2007 (9 June) and progressed slowly by natural infection before increasing to a maximum of 30 to 58% turf area infested by 2 August (Table 2). Disease developed by mid-June in 2008 (Table 3) and gradually increased to 30 to 54% infested turf by 5 August.

Irrigation quantity affected anthracnose severity soon after disease symptoms became apparent in all 3 yrs. There was a linear or quadratic relationship between irrigation quantity and disease severity on 19 out of 21 rating dates over the 3 yrs of study (Tables 1, 2 and 3). Anthracnose severity was usually greatest in plots being irrigated at 40% ET_o in all years (Tables 1, 2 and 3). Increased irrigation quantity reduced disease by 28 July 2006, with plots irrigated at 60% ET_o having 6% less disease and plots irrigated at 80 and 100% ET_o having 11% less disease compared to plots irrigated at 40% ET_o (Table 1).

Anthracnose severity in plots irrigated at 100% ET_o became similar to turf irrigated at 40% ET_o by 25 August 2006; whereas, the moderate irrigation levels of 60 and 80% ET_o had the lowest disease severity (Table 1). Plots irrigated at 60 and 80%

ET_o had 5 to 8% less disease than plots irrigated at 100% ET_o and 10 to 13% less disease than plots irrigated at 40% ET_o, respectively, on this date.

Irrigation at 40% ET_o increased disease compared to 80 and 100% ET_o on all (8) rating dates in 2007 (Table 2). All irrigation quantities above 40% ET_o reduced disease by 20 June 2007 and the relative difference carried on through 20 August. Plots irrigated at 60% ET_o had 6 to 13% less disease than plots irrigated at 40% ET_o, and plots irrigated 80% ET_o had 4 to 15% less disease than plots irrigated at 60% ET_o from June to August 2007. Disease severity on plots irrigated at 100% ET_o was not different than plots irrigated at 80% ET_o, with the exception of 4 July 2007 when irrigation at 100% ET_o plots had 4% less disease.

Plots irrigated at 40% and 60% ET_o had the greatest anthracnose severity in 2008 on 7 of 11 rating dates (Table 3); however, plots irrigated at 60% ET_o had 7 to 10% lower disease severity than plots irrigated at 40% ET_o from 31 July to 13 August. Plots irrigated at 80 and 100% ET_o had similar disease severity from 17 June to 5 August 2008, which was lower than both 60 and 40% ET_o plots on all dates except 9 July. The disease severity of plots irrigated at 100% ET_o increased in mid-August becoming similar to 60% ET_o plots on 13 August and to 40 and 60% ET_o plots on 23 August. Plots irrigated at 80% ET_o had the lowest anthracnose severity on 13 and 23 August 2008.

Recovery

Plots irrigated at 40% ET_o (with most severe disease from 31 July through 23 August) were able to recover from anthracnose injury upon suspension of treatments and rewetting of plots through rain in 2006 (Table 1) and irrigation in 2008 (Table 3). Disease severity of plots irrigated at 40% ET_o decreased 18% in 9 days in 2006 (Table 1) when rainfall increased soil water content equivalent to the 60 and 80% ET_o irrigation treatments (Figure 1), while disease increased slightly (1 and 2%) during the same period for plots irrigated at 60 and 100% ET_o, respectively, and decreased 7% on 80% ET_o plots. Plots irrigated at 40% ET_o had significantly lower disease severity than all other treatments on 4 September 2006 (Table 1). Disease severity decreased by 8% on 40% ET_o plots after treatments were suspended and uniformly irrigated in 2008 (Table 3), while disease decreased 3% during the same period for plots irrigated at 60 and 80% ET_o and slightly increased 1% on 100% ET_o plots. There was no difference in disease severity among 40, 60 and 100% ET_o treatments although these had greater disease severity than the 80% ET_o treatment on 4 September 2008 (Table 3).

Turf Quality

There were linear and quadratic relationships between irrigation quantity and turf quality observed on 5 and 12 dates, respectively, out of 22 observations over the 3 yr trial (Tables 4-6). These responses generally indicated that increasing irrigation quantity improved turf quality; however, it was frequently observed that increasing irrigation beyond 80% ET_o was detrimental to turf quality.

Turf quality of plots irrigated at 40% ET_o became poorer than other treatments by 5 August 2006 (Table 4). Plots irrigated at 80% ET_o were among treatments with the higher turf quality with the exception of 8 September, when after rainfall, turf quality of both 40 and 60% ET_o treatments were higher than the 80% ET_o treatment. Turf quality on plots irrigated at 60% ET_o was generally higher in turf quality than the 40% ET_o plots except on 5 August and 8 September 2006. While turf quality of plots irrigated at 100% ET_o was initially better than at 40% ET_o on 5 August 2006, continued treatment increased algal development on plots irrigated at 100% ET_o (Table 7) and reduced turf quality to a level similar to plots irrigated at 40% ET_o by 11 August 2006 (Table 4).

Initially turf quality was the best on plots irrigated at 100% ET_o on 8 June 2007 (Table 5), but continued irrigation at 100% ET_o encouraged algal development by 5 August 2007 (Table 7) and thinning. Algal development contributed to the poor turf quality ratings (< 5) on plots irrigated at 80 and 100% ET_o from 19 June through 20 August 2007. The poor turf quality observed on plots irrigated at 40 and 60% ET_o from July through August 2007 (Table 5) was due to greater anthracnose severity (Table 2).

A more gradual development of anthracnose (Table 3) and lack of algal development in 2008 resulted in better turf quality and limited differences in quality during June and early July 2008 (Table 6). Plots irrigated at 80% ET_o were always among treatments with the best turf quality during 2008 and had better quality than all other treatments on 31 July and 5 and 23 August. While algae did not develop on plots during 2008, turf quality of plots irrigated at 100% ET_o decreased from 23 July through the end of the season due to chlorosis and thinning (data not shown).

Recovery

Post treatment effects on turf quality resulted in plots irrigated at 40% ET_o having the best turf quality while plots irrigated at 100% ET_o had the lowest turf quality on 8 September 2006 (Table 4). Moreover, treatments exhibited a linear relationship with turf quality on this date; turf quality decreased with increasing irrigation quantity. Post treatment effects were somewhat different in 2008 (Table 6) where plots irrigated at 80% ET_o had better turf quality than 100, 60 and 40% ET_o treatments. The quadratic relationship observed on this date indicated that both high (100% ET_o) and low (40 and

60% ET_o) irrigation decreased turf quality when compared to the best turf quality observed in 80% ET_o plots.

DISCUSSION

The lowest irrigation quantity (40% ET_o) resulted in the greatest disease severity in all three years of study. Severe deficit irrigation causes a low water potential to develop within a plant often without any visible signs of wilt (Papendick and Cook, 1973). It is likely that the stress generated from maintaining turf at low water potential increases susceptibility to disease. Danneberger et al. (1995) reported that ABG plants grown in a growth chamber and subjected to water stress 10 days prior to inoculation with *C. cereale* (reported as *C. graminicola*) exhibited greater disease severity compared to plants maintained at field capacity. Similarly, Kentucky bluegrass grown in soil and allowed to dry to a quarter of field capacity before irrigating the soil back to field capacity nearly doubled the incidence of dollar spot compared to plants maintained at field capacity (Couch and Bloom, 1960).

Prolonged drought stress can also impede or stop plant growth (Endo and Colbaugh, 1972) as wilting and withering of plant leaves can lead to abnormal or suppressed root growth (Wilson and Livingston, 1932). The inhibition of natural plant functions also causes disruptions in vital metabolic processes such as protein formation and carbohydrate storage. Wilting of perennial ryegrass has been shown to significantly reduce the amount of free amino acids, the building blocks of proteins (Kemble and Macpherson, 1954). Decreasing soil water can slow transpiration rates and greatly reduce photosynthesis (Shimshi, 1963). When photosynthesis is decreased, plants must rely on carbohydrate reserves to sustain growth, which are only stored when the demand is below the rate of production. Under slight drought stress, carbohydrates may actually accumulate due to reduced growth; deep irrigation at the first sign of leaf wilt increased carbohydrate content of creeping bentgrass compared to light frequent irrigation (Fu and Denoeden, 2008). However, more severe drought can arrest photosynthesis (Shao et al., 2008). If the carbohydrate reserves are depleted before photosynthesis fully recovers, turf may be vulnerable to infection (Zanoni et al., 1969). Moreover, leaf senescence is enhanced under drought stress (Boyer, 1976; Drew and Lynch, 1980) providing an opportunity for colonization of senescent tissue by *C. cereale*.

Prolonged drought stress can also adversely affect beneficial microorganisms in the soil and thatch. Endo and Colbaugh (1972) reported that lead spot, caused by *Bipolaris sorokiniana* (Sacc.) Shoemaker (reported as *H. sativum*), was enhanced by periods of drought, and associated increased disease severity with reduced microbial populations in the thatch and soil. It is possible that the enhanced anthracnose severity in the current study is associated with suppressed populations of beneficial microorganisms on ABG turf maintained under severe deficit irrigation (i.e., 40% ET_o), but this was not studied.

Previous work has shown that bentgrass (*Agrostis*) species irrigated at 40% ET_o exhibited significantly lower turf quality in the summer compared to the same species irrigated at 60, 80, and 100% ET_o (DaCosta and Huang, 2006). Turf quality of plots irrigated at 40% ET_o in our trial was negatively impacted by greater disease severity as well as chlorosis and thinning associated with severe deficit irrigation, despite frequent syringing to relieve wilt stress. As severe deficit irrigation inhibits plant growth, tiller production can decrease causing thinning and eventually voids within the turf canopy (Beard, 1973; Madison and Hagan, 1962). Reduced tiller density on plots irrigated at

40% ET_o was compounded by greater disease severity in our trial as infested plants senesced and created larger gaps in the canopy further reducing turf quality.

Increased irrigation was initially beneficial (reduced disease, better turf quality) each year of the current trial; however, continually irrigating at 100% ET_o eventually increased anthracnose severity by the end of 2006 and 2008 and increased algal development in 2006 and 2007. Increased algae development under irrigation at 100% ET_o would be expected since algae and moss are more common in areas of high soil water (Baldwin and Whitton, 1992). Greater irrigation can increase water vapor in and around the turf canopy (Beard, 1973) favoring germination of conidia, which can infect the plant (Agrios, 2005). Waterlogged soils also inhibit oxygen from reaching plant roots and cellular respiration and growth (Smith et al, 1989). Increased soil moisture has been shown to decrease root depth in both warm- (Doss et al., 1960) and cool-season turfgrass species (Bennett and Doss, 1960). Additionally, Jordan et al. (2003) reported that full replacement of ET_o daily decreased root length and shoot density of five bentgrass cultivars. Decreased root length and shoot density could explain the reduction in turf quality of plots receiving 100% ET_o replacement daily.

The breakdown of organic and inorganic acids in soil which can be phytotoxic to turf may also be inhibited under excessive soil water due to the inhibition of microorganisms that metabolize these compounds (Drew and Lynch, 1980). The breakdown of plant residues in waterlogged soils increases the organic acid content of soils as well as acetylaldehyde and ethanol (Drew and Lynch, 1980), which can accumulate to phytotoxic levels (Lynch, 1978). Accumulation of these phytotoxic chemicals within a soil can induce chlorosis of plant leaves (Drew and Lynch, 1980; Kramer, 1951) which was frequently observed in plots irrigated at 100% ET_o in 2008.

Irrigation to replace 80% ET_o typically resulted in the least amount of disease and the best turf quality throughout each season. This is similar to observations on bentgrass where the best turf performance occurred in plots irrigated at 60 to 80% ET_o (DaCosta and Huang, 2006). DaCosta and Huang (2006) also observed similar water use efficiency among turf irrigated at 60, 80 and 100% ET_o whereas irrigation at 40% ET_o resulted in decreased water use efficiency which can limit a plant's ability to recover from drought stress and possibly enhance a stress related disease such as anthracnose. In our study, irrigating at 60 and 80% ET_o presumably provided adequate oxygen levels in the soil without being detrimental to root growth. Air exchange between the soil and air is necessary to favor turf growth (Vargas and Turgeon, 2004). Jordan et al. (2003) reported that increasing the time interval between irrigation of bentgrass resulted in increased root length, shoot density, and turf quality compared to full replacement of ET_o daily. Additionally, Fu and Dernoeden (2008) observed increased water soluble and total non-structural carbohydrates in creeping bentgrass irrigated deep and infrequent compared to light frequent irrigation. Furthermore, Isolahti and Nissinen (2004) showed that increased fructan carbohydrate content in Timothy grass (*Phleum pratense* L.) increased resistance to *Typhula ishikariensis* Imai., the cause of gray snow mold.

While our study involved daily irrigation, applying water at a slight deficit (80% ET_o) allows the soil to dry more than full replacement of ET_o each day without development of drought. In our study, daily irrigation at 60 to 80% ET_o replacement was adequate to reduce anthracnose severity and also limit the development of algae and moss, and improve turf quality.

CONCLUSION

Anthracnose severity was greater on ABG subjected to extended periods of deficit irrigation, and repeated syringing was needed to relieve wilt stress. Additionally, applying greater amounts of irrigation (i.e., irrigation at 100% ET_o daily) can also increase anthracnose severity and encourage algae and moss development thus lowering turf quality. Daily irrigation at 80% of ET_o provided enough water to maintain satisfactory growth of ABG and reduce anthracnose severity on ABG putting green turf.

REFERENCES

Agrios, G.N. 2005. Plant Pathology. Elsevier Inc. San Diego, CA.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. Irr. & Drain. Paper 56. UN-FAO, Rome, Italy.

Baldwin, N.A., and B.A. Whitton. 1992. Cyanobacteria and eukaryotic algae in sports turf and amenity grasslands: a review. J. of App. Phycol. 4:39-47

Beard, J.B. 1973. Turfgrass science and culture. Prentice-Hall, Inc. Englewood Cliffs, NJ.

Beard, J.B. 2002. Turf management for golf courses. 2nd ed. Ann Arbor Press, Chelsea, MI.

Bennett, O.L., and B.D. Doss. 1960. Effect of soil moisture level on root distribution of cool-season forage species. Agron. J. 52:204-207.

Boyer, J.S. 1976. Water deficits and photosynthesis. *In* "Water Deficits and Plant Growth" (T.T. Kozlowski, ed.), Vol. 4 p. 153. Academic Press, New York.

Couch, H.B., and J.R. Bloom. 1960. Influence of environment on diseases of turfgrass II: Effect of nutrition, pH, and soil moisture on *Sclerotinia* dollar spot. Phytopathology. 50: 761-763

Crouch, J.A., B.B. Clarke, and B.I. Hillman. 2006. Unraveling evolutionary relationships among the divergent lineages of *Colletotrichum* causing anthracnose disease in turfgrass and corn. Phytopathology 96:46-60.

DaCosta, M., and B. Huang. 2006. Deficit irrigation effects on water use characteristics of bentgrass species. Crop Sci., 46:1779-1786.

Danneberger, T.K., M.J. Carroll, J.M. Vargas, Jr., and P.E. Rieke. 1995. Susceptibility of *Poa annua* to anthracnose as influenced by water stress. J. of Turfgrass Manage. 1:19-24.

Dernoeden, P.H. 2002. Creeping bentgrass management: summer stresses, weeds, and selected maladies John Wiley & Sons, Inc., Hoboken, NJ.

Drew, M.C., and J.M. Lynch. 1980. Soil anaerobisis, microorganisms, and root function. Ann. Rev. Phytopathol. 18:37-66.

Doss, B.D., D.A. Ashley, and O.L. Bennett. 1960. Effect of soil moisture regime on root distribution of warm season forage species. Agron. J. 52:569-572.

Endo, R.M., and P.F. Colbaugh. 1972. Drought stress as a factor triggering fungal disease of turfgrass. USGA Green Sec. Rec. 10:8-11.

Fu, J.M., and P.H. Dernoeden. 2008. Carbohydrate metabolism in creeping bentgrass as influenced by two summer irrigation practices. J. Am. Soc. Hort. Sci. 133:678-683.

Inguagiato, J.C., J.A. Murphy, and B.B. Clarke. 2008. Anthracnose severity on annual bluegrass influenced by nitrogen fertilization, growth regulators, and verticutting. Crop Sci. 48:1595-1607.

Inguagiato, J.C., J.A. Murphy, and B.B. Clarke. 2009. Anthracnose disease and annual bluegrass putting green performance affected by mowing practices and lightweight rolling. Crop Sci. 49:1454-1462.

Isolahti, M., and O. Nissinen. 2004. Role of storage carbohydrates in hardening and resistance of timothy genotypes to frost and *Typhula* spp. Proceedings of the 20th General Meeting of the European Grassland Federation, Luzern, Switzerland. pp.434-436

Jordan, J.E., R.H. White, D.M. Vietor, T.C. Hale, J.C. Thomas, and M.C. Engelke. 2003. Effect of irrigation frequency on turf quality, shoot density, and root length density of five bentgrass cultivars. Crop. Sci. 43:282-287

Kemble, A.R., and H.T. Macpherson. 1954. Liberation of amino acids in perennial rye grass during wilting. Biochemical J. 58:46-49.

Kramer, P.J. 1951. Causes of injury to plants resulting from flooding of the soil. Plant Physiol. 26:722-736.

Landschoot, P., and B. Hoyland. 1995. Shedding some light on anthracnose basal rot. Golf Course Manage. 11:52-55.

Lynch, J.M. 1978. Production and phytotoxicity of acetic acid in anaerobic soils containing plant residues. Soil Biol. Biochem. 10:131-135.

Madison, J.H., and R.M. Hagan. 1962. Extraction of soil moisture by Merion bluegrass (*Poa pratensis* l. 'Merion') turf, as affected by irrigation frequency, mowing height, and other cultural operations. Agron. J. 54: 157-160.

Mann, R.L., and A.J. Newell. 2005. A survey to determine the incidence and severity of pests and diseases on golf course putting greens in England, Ireland, Scotland, and Wales. Int. Turfgrass Soc. Res. J. 10:224-229.

Marsh, A.R. 1969. Soil water-irrigation and drainage. In A.A. Hanson and F.V. Juska. Turfgrass Science. Agron. Monograph No. 14. Amer. Soc. Agron., Madison, WI.

Moore, L.D., H.B. Couch, and J.R. Bloom. 1963. Influence of environment on diseases of turfgrasses III: effect of nutrition, pH, soil temperature, air temperature, and soil moisture on pythium blight of highland bentgrass. Phytopathology. 53:53-57.

Muse, R.R., and H.B. Couch. 1965. Influence of environment on disease of turfgrasses IV: effect of nutrition and soil moisture on *Corticium* red thread of creeping red fescue. Phytopathology 55:507-510.

Papendick, R.I., and R.J. Cook. 1973. Plant water stress and development of *Fusarium* foot rot in wheat subjected to different cultural practices. Phytopathology 64:358-363.

Shao, H.B, L.Y Chu, C.A. Jaleel, and C.X. Zhao. 2008. Water-deficit stress-induced anatomical changes in higher plants. C.R. Biologies 331:215-225.

Shimshi, D. 1963. Effect of soil moisture and phenylmercuric acetate upon stomatal aperture, transpiration, and photosynthesis. Plant Physiol. 38:713-721.

Smiley, R.W., P.H. Dernoeden, and B.B. Clarke. 2005. Compendium of turfgrass diseases. 3rd ed. The American Pathological Society, St. Paul, MN.

Smith, J.D., N. Jackson, and A.R. Woolhouse. 1989. Fungal diseases of amenity turf grasses. 3rd ed. E. & F.N. Spon, London.

Sprague, H.B., and E.E. Evaul. 1930. Experiments with turfgrasses in New Jersey. N.J. Ag. Exp. Station Bulletin. 497:1-55.

Towers, G., K. Green, E. Weibel, P. Majumdar, and B.B. Clarke. 2002. Evaluation of fungicides for the control of anthracnose basal rot on annual bluegrass, 2002.

Available at www.plant-managementnetwork.org/pub.trial/fntests/vol58/. Fungicide Nematicide Tests 58:T017

Vargas, J.M., Jr., and A.J. Turgeon. 2004. *Poa annua*: physiology, culture, and control of annual bluegrass John Wiley & Sons, Inc, Hoboken, NJ.

Vermeulen, P.H. 2003. Maybe it's time for a change. USGA Green Sec. Rec. 41:28.

Wilson, J.D., and B.E. Livingston. 1932. Wilting and withering of grasses in greenhouse cultures as related to the water-supplying power of the soil. Plant Physiol. 7:1-33.

Wong, F.P., and S. Midland. 2004. Fungicide-resistant anthracnose: bad news for greens management. Golf Course Manage. 72:75-80.

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

Zontek, S. 2004. Have we gone too far? The grass is talking to you. Are you listening? USGA Green Sec. Rec. 42:28

Figure 1. Soil water content response to irrigation quantities on an annual bluegrass turf grown on sandy loam and maintained at 3.2 mm in North Brunswick, NJ during 2006.

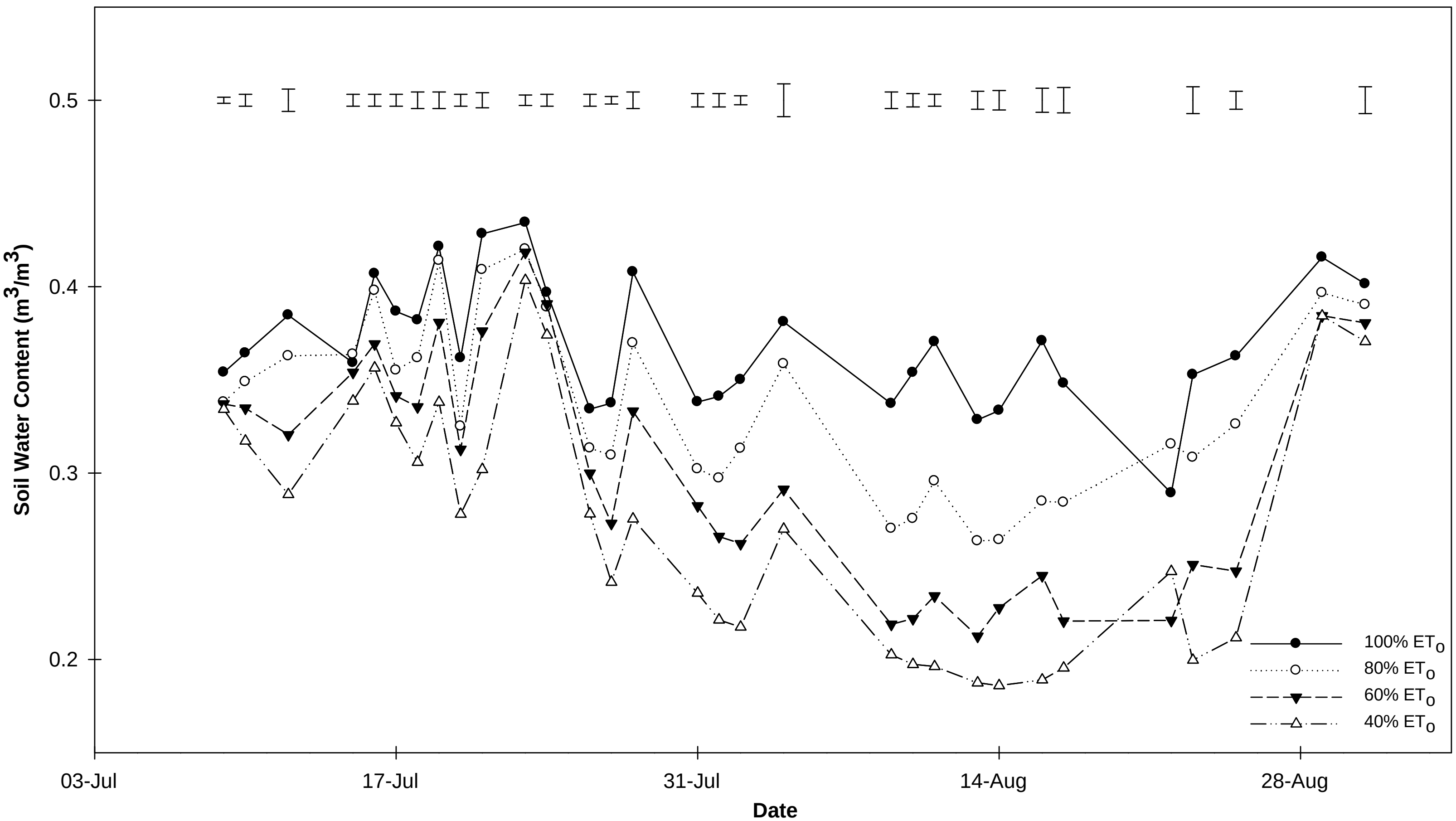

Figure 2. Soil water content response to irrigation quantities on an annual bluegrass turf grown on sandy loam and maintained at 3.2 mm in North Brunswick, NJ during 2007.

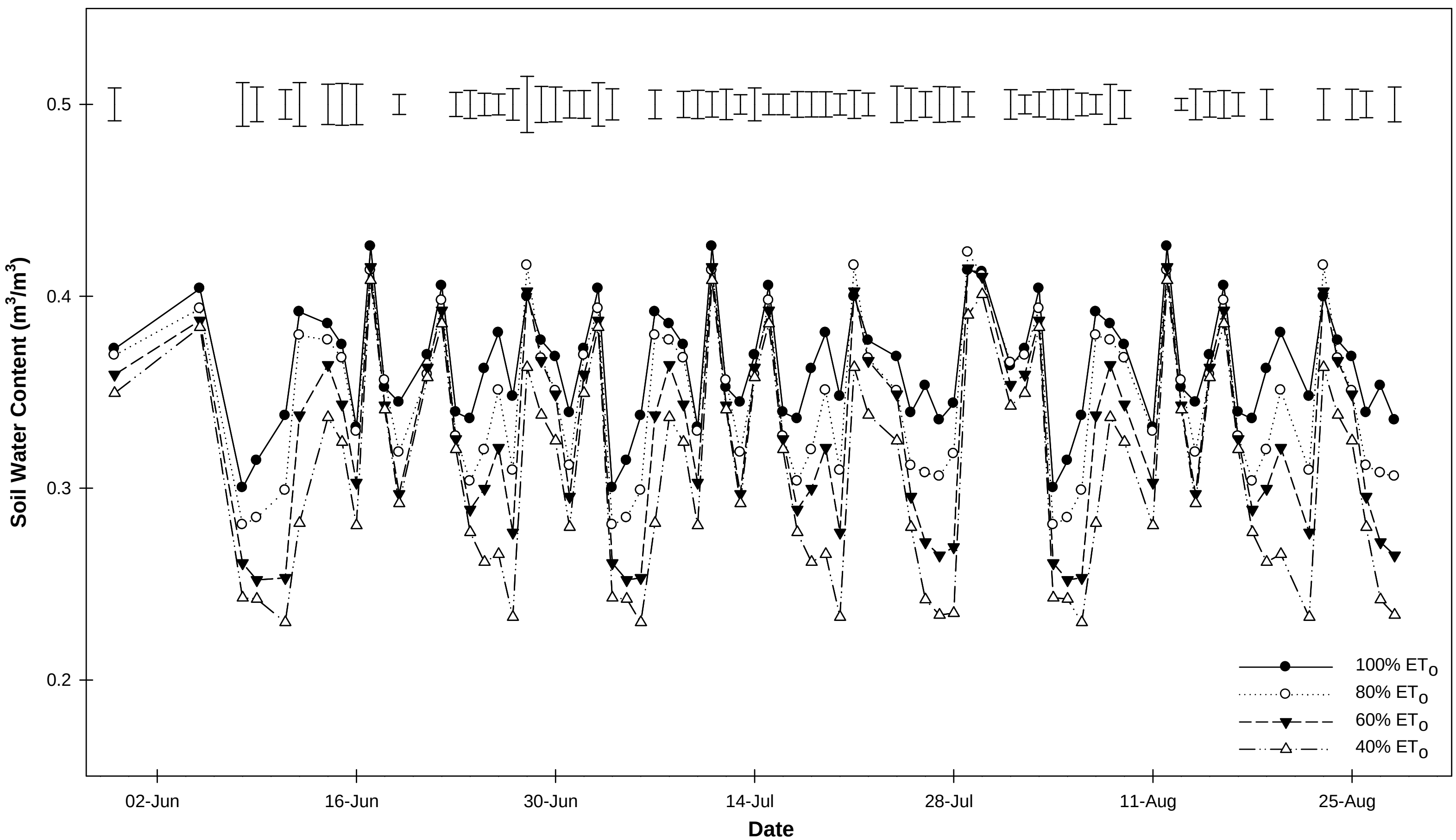

Figure 3. Soil water content response to irrigation quantities on an annual bluegrass turf grown on sandy loam and maintained at 3.2 mm in North Brunswick, NJ during 2008.

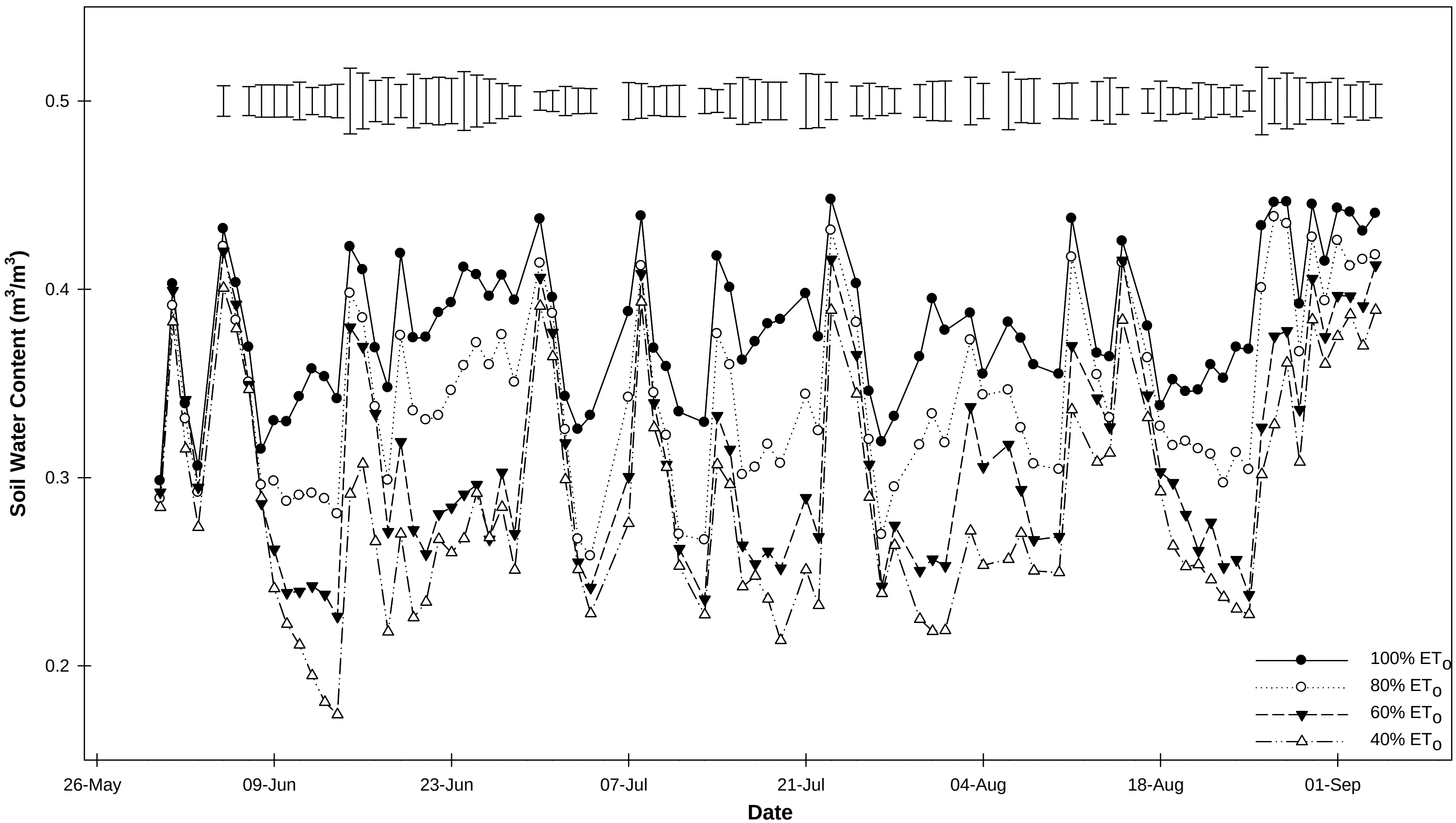

Table 1. Anthracnose severity as affected by irrigation quantity on annual bluegrass turf grown on a Nixon sandy loam and maintained at 3.2 mm in North Brunswick, NJ during 2006.

	Turf area infested			PT§
Irrigation quantity	21 Jul	28 Jul	25 Aug	4 Sep
	------------------------ % --------------------------			
100% ET_o†	6.8 a‡	5.9 c	25.2 ab	27.4 b
80% ET_o	6.6 a	6.3 c	16.7 c	23.7 b
60% ET_o	6.5 a	11.1 b	20.4 bc	21.0 b
40% ET_o	9.7 a	17.0 a	30.1 a	11.7 a
Source of Variation		ANOVA		
Treatment	NS¶	***	**	***
Planned *F*-tests				
Linear	NS	***	NS	**
Quadratic	NS	***	***	NS
CV (%)	33.9	25.3	22.0	30.4

**Significant at the 0.01 probability level

***Significant at the 0.001 probability level

†ET_o, % reference evapotranspiration, calculated daily using onsite weather data and the Penman-Monteith equation. Irrigation was applied daily in the absence of rain from 7 July to 25 Aug. 2006.

‡Means followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).

§PT, denotes post treatment evaluation, indicates that all plots were irrigated the same after 25 August 2006.

¶NS, not significant

Table 2. Anthracnose severity as affected by irrigation quantity on annual bluegrass turf grown on a Nixon sandy loam and maintained at 3.2 mm in North Brunswick, NJ during 2007.

	Turf area infested							
Irrigation quantity	9 Jun	20 Jun	29 Jun	4 Jul	14 Jul	19 Jul	2 Aug	20 Aug
	------------------------ % ------------------------							
100% ET_o[†]	1.7 b[‡]	2.0 c	3.4 c	6.3 d	12.7 c	18.8 c	30.4 c	16.3 c
80% ET_o	4.0 b	4.5 c	5.4 c	10.4 c	16.7 c	19.9 c	37.2 c	19.3 c
60% ET_o	9.7 a	9.3 b	9.7 b	15.6 b	30.2 b	31.9 b	47.9 b	34.1 b
40% ET_o	14.9 a	18.3 a	18.5 a	21.5 a	42.9 a	44.4 a	58.2 a	42.6 a
Source of Variation	ANOVA							
Treatment	**	***	***	***	***	***	***	***
Planned *F*-tests								
Linear	***	***	***	***	***	***	***	***
Quadratic	NS[§]	*	*	NS	*	**	NS	NS
CV (%)	53.9	35.9	30.8	21.6	14.8	11.6	11.5	14.9

*Significant at the 0.05 probability level

**Significant at the 0.01 probability level

***Significant at the 0.001 probability level

†ET_o, % reference evapotranspiration, calculated daily using onsite weather data and the Penman-Monteith equation. Irrigation was applied daily in the absence of rain from 31 May to 20 Aug. 2007.

‡Means followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).

§NS, not significant

Table 3. Anthracnose severity as affected by irrigation quantity on annual bluegrass turf grown on a Nixon sandy loam and maintained at 3.2 mm in North Brunswick, NJ during 2008.

	Turf area infested										PT[§]
Irrigation quantity	17 Jun	26 Jun	2 Jul	9 Jul	17 Jul	23 Jul	31 Jul	5 Aug	13 Aug	23 Aug	4 Sep
	%										
100% ET_o[†]	0.3 b[‡]	0.5 b	1.3 b	2.1 b	9.3 b	16.6 b	28.4 c	32.4 c	40.7 b	42.4 ab	43.7 a
80% ET_o	0.4 b	0.7 b	2.3 b	1.9 b	9.2 b	19.4 b	27.3 c	30.3 c	32.1 c	34.7 b	31.9 b
60% ET_o	0.8 a	1.2 a	4.7 a	2.9 ab	16.0 a	29.5 a	44.3 b	44.7 b	43.2 b	44.3 a	40.8 a
40% ET_o	1.0 a	1.2 a	5.1 a	3.6 a	17.6 a	34.1 a	52.4 a	54.4 a	50.0 a	48.4 a	40.7 a
Source of Variation						ANOVA					
Treatment	*	**	**	*	**	***	***	***	***	*	*
Planned *F*-tests											
Linear	**	***	***	**	***	***	***	***	***	0.06	NS
Quadratic	NS[¶]	NS	NS	NS	NS	NS	**	**	**	NS	*
CV (%)	52.5	30.8	39.1	29.9	24.8	19.5	7.0	10.3	10.3	15.6	15.3

*Significant at the 0.05 probability level

**Significant at the 0.01 probability level

***Significant at the 0.001 probability level

†ET_o, % reference evapotranspiration, calculated daily using onsite weather data and the Penman-Monteith equation. Irrigation was applied daily in the absence of rain from 31 May to 26 Aug. 2008.

‡Means followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).

§PT, Post treatment evaluation, indicates that all plots were watered the same after 26 August 2008

¶NS, not significant

Table 4. Turf quality response to irrigation quantity of annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2006.

	Turf quality				PT[§]
Irrigation quantity	21 July	5 Aug	11 Aug	19 Aug	8 Sep
	-----1-9; 9 = best-----				
100% ET_o[†]	6.0 a[‡]	6.2 ab	4.6 bc	3.2 b	2.4 c
80% ET_o	5.8 a	7.0 a	6.6 a	6.0 a	4.2 b
60% ET_o	5.8 a	6.0 b	5.4 ab	5.6 a	5.0 b
40% ET_o	5.0 a	4.4 c	3.4 c	4.0 b	7.0 a
Source of Variation			ANOVA		
Treatment	NS[¶]	***	**	***	***
Planned *F*-tests					
Linear	NS	***	*	NS	***
Quadratic	NS	**	***	***	NS
CV (%)	12.3	10.6	19.4	19.7	23.0

[*]Significant at the 0.05 probability level
[**]Significant at the 0.01 probability level
[***]Significant at the 0.001 probability level
ET_o, % reference evapotranspiration, calculated daily using onsite weather data and the Penman-Monteith equation. Irrigation was applied daily in the absence of rain from 7 July to 25 Aug. 2006.
[‡]Means followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).
[§]PT, denotes post treatment evaluation, indicates that all plots were irrigated the same after 25 August 2006.
[¶]NS, not significant

Table 5. Turf quality response to irrigation quantity of annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2007.

	Turf quality						
Irrigation quantity	8 Jun	19 Jun	5 Jul	13 Jul	19 Jul	2 Aug	20 Aug
	--------------------------------1-9; 9 = best --------------------------------						
100 % ET_o[†]	7.4 a[‡]	4.2 b	3.8 b	4.0 ab	3.0 a	3.8 a	3.4 b
80% ET_o	6.4 b	4.8 a	4.4 ab	4.4 ab	3.2 a	3.6 a	4.4 a
60% ET_o	5.4 c	5.0 a	4.8 a	4.6 a	4.0 a	3.8 a	4.4 a
40% ET_o	4.2 d	5.0 a	5.0 a	3.8 b	3.2 a	3.8 a	3.6 ab
Source of Variation				ANOVA			
Treatment	***	**	*	NS	NS	NS	NS
Planned *F*-tests							
Linear	***	***	**	NS	NS	NS	NS
Quadratic	NS[§]	*	NS	*	NS	NS	**
CV (%)	10.6	6.4	12.5	10.9	23.3	12.4	16.5

*Significant at the 0.05 probability level
**Significant at the 0.01 probability level
***Significant at the 0.001 probability level
† ET_o, % reference evapotranspiration, calculated daily using onsite weather data and the Penman-Monteith equation. Irrigation was applied daily in the absence of rain from 31 May to 20 Aug. 2007.
‡Means followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).
§NS, not significant

Table 6. Turf quality response to irrigation quantity of annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2008.

	Turf quality											PT[§]
Irrigation quantity	6 Jun	16 Jun	26 Jun	2 Jul	9 Jul	17 Jul	23 Jul	31 Jul	5 Aug	13 Aug	23 Aug	4 Sept
	-1-9; 9 = best-											
100% ET_o[†]	7.0 a[‡]	7.2 a	7.0 a	7.6 a	6.4 a	5.4 a	4.6 ab	4.0 b	4.0 b	3.0 b	3.6 b	3.0 b
80% ET_o	7.2 a	7.2 a	6.8 ab	7.8 a	6.8 a	5.8 a	5.2 a	5.6 a	4.6 a	3.8 a	4.6 a	4.4 a
60% ET_o	7.0 a	7.0 a	6.4 ab	6.4 b	6.2 a	5.4 a	4.6 ab	4.0 b	4.0 b	3.6 a	3.4 b	3.6 b
40% ET_o	7.2 a	6.2 b	6.2 b	6.0 b	6.0 a	4.8 b	4.0 b	4.0 b	3.4 c	3.0 b	3.4 b	3.6 b
Source of Variation						ANOVA						
Treatment	NS[¶]	**	0.06	***	NS	**	*	***	**	**	*	**
Planned *F*-tests												
Linear	NS	***	**	***	0.07	*	*	*	*	NS	NS	NS
Quadratic	NS	*	NS	NS	NS	*	*	***	**	***	0.08	**
CV (%)	4.6	5.3	6.9	5.9	7.2	7.0	10.7	6.2	9.9	9.4	16.0	13.2

*Significant at the 0.05 probability level
**Significant at the 0.01 probability level
***Significant at the 0.001 probability level
† ET_o, % reference evapotranspiration, calculated daily using onsite weather data and the Penman-Monteith equation. Irrigation was applied daily in the absence of rain from 31 May to 26 Aug. 2008.
‡Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05).
§PT, Post treatment evaluation, indicates that all plots were watered the same after 26 August 2008
¶NS, not significant

Table 7. Algae development in response irrigation quantity on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2006 and 2007.

	Algae						
	2006		2007				
Irrigation quantity	5 Aug	19 Aug	20 Jun	5 Jul	13 Jul	19 Jul	20 Aug
	-----1-9; 9 = least-----						
100% ET_o[†]	3.4 d[‡]	2.2 c	4.0 c[‡]	3.6 d	4.0 c	2.6 b	3.6 c
80% ET_o	5.2 c	6.2 b	4.4 c	4.6 c	4.4 c	3.0 b	5.8 b
60% ET_o	7.0 b	6.2 b	5.8 b	5.8 b	5.6 b	5.2 a	7.6 a
40% ET_o	9.0 a	8.8 a	6.8 a	7.4 a	8.6 a	6.0 a	8.2 a
Source of Variation	ANOVA						
Treatment	***	***	***	***	***	***	***
Planned *F*-tests							
Linear	***	***	***	***	***	***	***
Quadratic	NS[§]	NS	NS[§]	NS	***	NS	*
CV (%)	18.3	31.8	12.7	10.2	7.4	15.8	12.4

[*]Significant at the 0.05 probability level

[***]Significant at the 0.001 probability level

[†]ET_o, % reference evapotranspiration, calculated daily using onsite weather data and the Penman-Monteith equation. Irrigation was applied daily in the absence of rain from 7 July to 25 Aug. 2006 and 31 May to 20 August 2007.

[‡]Means followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).

[§]NS, not significant

CHAPTER 2. Lightweight Rolling Effects on Anthracnose Disease of Annual Bluegrass Putting Green Turf

ABSTRACT

Light-weight rolling can be effectively used to increase ball roll distance (BRD) and influence anthracnose development on annual bluegrass (ABG) [*Poa annua* L. f. *reptans* (Hausskn) T. Koyama] putting green turf. The objective of this 3-yr field trial was to evaluate the influence of roller type (i.e., sidewinder, triplex mounted vibratory and non-rolled) and location (center or perimeter) of equipment traffic on anthracnose severity and BRD of ABG turf maintained at 3.2 mm. Both roller types reduced disease 2 to 13% compared to non-rolled turf under moderate disease pressure in 2007 and 2008. The heavier sidewinder roller had less disease than the triplex mounted vibratory roller on 4 of 13 rating dates over the two years. Perimeter plots had less disease compared to center plots on 6 of 13 rating dates. The current study shows that rolling can be used to increase BRD, improve turf quality, and decrease anthracnose disease of ABG putting green turf under moderate disease severity.

INTRODUCTION

Anthracnose is a destructive disease of weakened or senescent turf resulting in extensive damage to golf course putting greens. *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman (Crouch et al., 2006) causes anthracnose on annual bluegrass (ABG) [*Poa annua* L. f. *reptans* (Hausskn) T. Koyama]. The disease may appear as a foliar blight that is normally problematic during summer months when temperatures and humidity are high, or a basal rot that can develop throughout the year. Anthracnose may eventually result in severe thinning of the turf sward greatly lowering the aesthetics and playability of putting green turf. The incidence and severity of anthracnose on putting greens has increased over the past two decades (Dernoeden, 2002; Inguagiato et al., 2008; Landschoot and Hoyland, 1995; Mann and Newell, 2005; Wong and Midland, 2004) and management practices commonly employed on golf courses (e.g. low cutting heights and N fertility) have been suggested as factors that may enhance abiotic stress and thus predispose turf to this disease (Vermeulen, 2003; Zontek, 2004). Plant health is known to significantly affect plant disease; thus it is important to understand how common management practices on putting greens might influence the development of anthracnose disease.

Rolling is a management practice routinely conducted after seeding to increase soil contact with seed, to smooth the putting surface after frost (Beard, 1973) and to increase ball roll distance (BRD) throughout the growing season on established greens. Early in the 20th century, rolling was regarded as a beneficial practice on putting greens, but research conducted in the mid-1900's associated this procedure with soil compaction causing mangers to discontinue its use (Beard, 2002). However, the introduction of lightweight rollers in the 1990's and the use of sand-based root-zones for putting greens reduced the potential for soil compaction (DiPaola and Hartwiger, 1994), thus encouraging superintendents to implement regular rolling practices to increase BRD and smoothness on putting greens. Rolling can increase BRD about 0.3 m for up to 48 hours compared to non-rolled plots (Nikolai, 2002a; 2002b; 2004). Increases in BRD can vary depending on roller type, soil moisture, cutting height and verdure of the putting surface (Nikolai, 2002a; 2004). Karcher et al. (2000) reported that differences in BRD needed to exceed 0.15 m to be detectable by golfers.

Hartwiger (1996) classified rollers into three types: the drum roller, which is generally a large, single roller pulled behind a utility vehicle; a triplex attachment (e.g. a lightweight vibratory roller), where the reels on a triplex mower are replaced with rollers; and a dedicated greens roller, which is a roller solely designed to roll putting greens, often possessing two to three rollers underneath the unit. One type of dedicated greens roller is the sidewinder, which consists of two solid rollers with the operator oriented perpendicular (sideways) to the direction of travel. Dedicated rollers and triplex attached vibratory rollers, are lightweight machines that have become frequently used on golf course putting greens within the last 15 years as the practice of lightweight rolling has become more widely accepted (DiPaola and Hartwiger, 1994).

Compaction is the compression of soil particles into a more dense soil mass (soil bulk density) (Beard, 1973). Compaction on a putting green is a function of the intensity of rolling, the weight of the rolling unit and the texture and water content of the soil. Thus, different root zone mixtures may respond differently to rolling. Compaction can intensify with increased lightweight rolling on native soil greens (DiPaola and Hartwiger, 1994; Hartwiger et al., 2001), but putting greens with high sand content root-zones can be rolled every day without detecting measureable changes in soil bulk density (Hamilton et al., 1994; Hartwiger et al., 2001). Rolling when the root-zone is wet can increase the potential for compaction. Therefore, some have concluded that the use of rollers when a finer-textured root zone is wet should be avoided (Piper and Oakley, 1921); however, this restriction may not be a problem on sand-based root-zones. Hartwiger et al. (2001) reported that turf quality can be reduced when frequent lightweight rolling is conducted on either sand based or fine-textured root zones; 14 to 15% and 24 to 26% reductions in turf quality were observed in such plots rolled four and seven times per week, respectively, compared to non-rolled plots. However, this research did not disclose whether topdressing had been applied which could have influenced the surface response to lightweight rolling. Conversely, Nikolai et al. (2001; 2002a; 2002b) concluded that rolling three times per week can increase BRD without affecting turf quality, soil compaction or water infiltration when a sand topdressing program is being implemented.

There is a parabolic relationship between soil compaction and root growth (Rosenburg, 1964) with negative root responses occurring under both loose and heavily compacted soils. Slight compaction can be beneficial by increasing root to soil contact, thus allowing for better extraction of nutrients such as N (Rosenburg, 1964). However, as compaction increases, turf quality typically declines. Previous research has shown that turf quality, shoot density and total non-structural carbohydrates decreased as compaction increased for kentucky bluegrass (*Poa pratensis* L.), tall fescue (*Festuca arundinacea* Schreb.) and perennial ryegrass plants [*Lolium perenne* L.] (Carrow, 1980). Additionally, root growth of ABG and perennial ryegrass maintained on a silt loam is significantly reduced in heavily compacted soil (Sprague and Burton, 1937; Sills and Carrow, 1983), and can be reduced further when turf is grown in compacted soil under high N fertilization. While soil compaction can result in a greater susceptibility to disease due to decreased plant health, compaction can also inhibit the ability of fungal hyphae (e.g., ectomycorrhizae) to growth through the soil profile (Skinner and Bowen, 1974). If fungal movement through the soil is limited, the potential for disease development could be reduced. Frequent rolling could also disrupt fungal growth on the surface of leaves, therefore reducing the potential for foliar infestation, but this has not been previously studied.

Few studies have examined the relationship between turf disease and rolling frequency or roller type. Dollar spot (caused by *Sclerotinia homoeocarpa* F.T. Bennett) incidence has been reported to be lower in ‘Penncross’ creeping bentgrass (*Agrostis stolonifera* L. reported as *Agrostis palustris* Huds.) plots rolled three times per week compared to non-rolled plots (Nikolai et al., 2001). The authors hypothesized that rolling after early morning mowing could further disperse dew and gutation water on plant leaves, thus reducing disease incidence. However, on one date within this same study, pink snow mold, another foliar disease caused by *Microdochium nivale* (Fr.) Samuels & I.C. Hallett, was found to be greater on rolled plots.

Lightweight rolling either had no effect or slightly reduced anthracnose severity on ABG maintained as putting green turf (Inguagiato, et al. 2008). The authors suggested that rolling produced a more prostrate growth habit that reduced the amount of plant tissue removed through daily mowing. Increased plant material left behind after mowing could enhance the photosynthetic capacity of the turf sward resulting in better plant health and disease suppression (Younger, 1969). However, Inguagiato et al. (2009) did not assess other roller types or the impact of increased equipment traffic along the perimeter of a putting green caused by the directional change (turning) of equipment. Since multiple roller types can be used on golf courses (Hartwiger, 1996), evaluation different rollers is important as they might have a differential effect on anthracnose development. Dedicated sidewinder rollers may generate more stress on plants due to their heavier weight and the turning action of the rollers. Moreover, sidewinder machines have the majority of their weight on the rollers, whereas the lightweight vibratory rollers are mounted on a triplex mower where a portion of the vehicle weight is distributed onto the tires. Having all of a unit's weight on the rollers instead of the tires could generate additional stress, particularly while turning. Additionally, some golf course superintendents have hypothesized that the additional equipment traffic stress present at the perimeter of a putting green may further predispose the turf to anthracnose, but this has yet to be determined. The objectives of this study were to determine i) impact of equipment traffic location and ii) the effect of lightweight roller type on anthracnose disease of ABG putting green turf.

MATERIALS AND METHODS

Treatment and Experimental Design

Treatments were arranged as a 2 x 3 factorial using a split-block (strip-plot) design with eight replications. Each replication consisted of two equivalent location blocks and three rolling treatment blocks arranged perpendicularly across each other. The plot size of intersecting perpendicular plots was 1.5- by 2.3-m. The equipment location factor was blocked to represent either the center or perimeter of a putting green. The center block received equipment traffic as single straight-line passes of rollers (as well as mower traffic). The perimeter block received additional traffic associated with the directional change or turning of rollers and mower as well as clean-up passes with the mower, which would be representative of equipment traffic at the perimeter of a putting green. Turf was mown 7 times wk^{-1} using a walk behind mower (model 220A and 220B, Deere & Co., Moline, IL) at a bench setting of 3.2 mm.

The three rolling treatment blocks consisted of one pass with a sidewinder roller (Tournament X-Press Greens Roller, SmithCo, Wayne, PA), a vibratory roller (Vibe V Vibratory, Turfline Inc., Moscow Hills, MO) mounted to a triplex mower (Model 300, The Toro Company, Bloomington, MN), or non-rolled. Rolling was performed every other day in the morning after mowing. Treatments were applied from 11 June to 19 September 2006, 10 May to 5 August 2007, and 13 May to 16 August 2008.

Field Inoculation

The experimental site had previously been inoculated with *C. cereale* isolate HFIIA using 20,000 conidia ml^{-1} on 2 August 2004 (Inguagiato et al., 2009). The inoculum was prepared and disseminated over the study as discussed by Inguagiato et al.

(2008). Subsequent disease outbreaks in the experimental area occurred naturally; *C. cereale* was re-isolated from symptomatic tissue each year from treated plot areas to verify disease causality.

General Management Practices

This 3-yr study was initiated in 2006 on an ABG putting green at the Rutgers Horticultural Farm II in North Brunswick, NJ. Turf was established on a Nixon sandy loam (fine-loamy, mixed, mesic Typic Hapludult) with a pH of 6.5 using seed indigenous to the site as well as seed introduced in 1998 from soil cores collected from golf course putting greens in Piscataway and Plainfield, NJ (Samaranayake et al., 2008).

Nitrogen was applied to the trial at either 4.9 or 9.8 kg ha^{-1} using a spray solution of water soluble sources [ammonium nitrate (34-0-0), calcium nitrate (15.5-0-0), urea (46-0-0), ammonium sulfate (21-0-0) or 20-20-20]. When treatments were not being imposed, N was applied to the trial area totaling 73.2 kg ha^{-1} from April to May 2006, 48.8 kg ha^{-1} from September to October 2006, 58.6 kg ha^{-1} from April to May 2007, 107.4 kg ha^{-1} from late August to October 2007, and 43.9 kg ha^{-1} from April to May 2008. While treatments were being conducted, N was applied totaling 48.8, 29.3, and 29.3 kg ha^{-1} from June to August 2006, 2007 and 2008, respectively. Based on soil test results, phosphorous and potassium were applied at 21.5 and 40.6 kg ha^{-1} in 2006, 16.1 and 30.4 kg ha^{-1} in 2007, and 0 and 56.3 kg ha^{-1} in 2008 as elemental P and K, respectively. Sub-angular silica sand topdressing conforming to USGA site specifications for sand root zones (Green Section Staff, 2004) was applied bi-weekly from May to September each year at 88.7 cm^3 m^{-2} to the entire study and immediately incorporated with a cocoa mat (Ace Equipment and Supply Co., Henderson, CO).

Trinexapac-ethyl [4-(cyclopropyl-α-hydroxy-methylene)-3.5-dioxocyclohexanecarboxylic acid ethylester] was applied at 0.048 kg a.i. ha^{-1} every 14 d from 22 May to 13 October 2006, 12 May to 9 September 2007, and 7 May to 13 October 2008. Dollar spot was prevented each year with boscalid {3-pyridinecarboximide, 2-chloro-N-[4'chloro(1,1'-biphenyl)-2-yl]} at 0.4 kg a.i. ha^{-1} or vinclozolin [3-(3,5-dichlorophenyl)-5-ethenyl-5-methyl-2,4-oxazolidinedione] at 1.5 to 1.8 kg a.i. ha^{-1} every 14 d from May to October. Flutolanil {N-[3-(1-methylethoxy)phenyl]-2-(trifluoromethyl)benzamide} was applied at 3.1 to 6.4 kg a.i. ha^{-1} every 14 d from June through August each year for control of brown patch (caused by *Rhizoctonia solani* Kühn.). These fungicides were previously shown to provide ineffective control of anthracnose on ABG greens in New Jersey (Towers et al., 2002). Insect pests including ABG weevils [*Listronotus maculicollis* (Kirby)] were controlled with bifenthrin {[2-methyl(1,1'-biphenyl)-3-yl]methyl-3-[2-chloro-3,3,3-trifluoro-1-propenyl]-2,2-dimethyl-cyclopropanecarboxylate} applied at 0.13 kg a.i. ha^{-1} on 2 May 2006, 3 May and 19 June 2007, and 13 and 25 May 2008. Algae (cyanobacteria) development was suppressed with mancozeb (ethylenebisdithiocarbamate) applied at 21.4 kg a.i. ha^{-1} on 31 May, 20 June, and 7, 22 and 28 July 2007. Algae was present in sufficient concentrations to warrant control in 2006 and 2008.

When treatments were suspended each year, anthracnose development was arrested with chlorothalonil (tetrachloroisophthalonitrile) at 18.1 kg a.i. ha^{-1} on 26 October 2006, 16.1 kg a.i. ha^{-1} on 10 September 2007 and at 9.2 and 11.2 kg a.i. ha^{-1} on 16 September and 13 October 2008, respectively, so that plots could recover during the fall and winter months. Creeping bentgrass encroachment was prevented with fluazifop-

P-butyl {(R)-2-[4-[[5-(trifluromethyl)-2-pyridinyl]oxy]} applied at 0.21 kg a.i. ha^{-1} on 9 September 2006, 23 August and 5 September 2007, and 18 September 2008. Broadleaf weeds where controlled with MCPP [2-(2-methyl-4-chlorophenoxy)] at 1.1 kg a.i. ha^{-1} on 23 August and 5 September 2007, and 18 September 2008.

Data Collection and Analysis

Anthracnose severity was assessed regularly from August to September during 2006 and from June through August in 2007 and 2008 as the percent turf area infested with *C. cereale* by using the line intercept-grid method similar to that developed by Gaussoin and Branham (1989) and modified by Inguagiato et al. (2008) that yielded 273 observations over 1.4 m^2 $plot^{-1}$. Turf quality was rated visually from July through August 2006, May through August 2007, and June through August 2008 on a 1 to 9 scale, with 9 representing the best quality and 5 the minimum acceptable level. Turf color, density and disease severity were all considered when evaluating turf quality.

Soil bulk density was measured on 15 August 2007 and on 21 May, 3 and 17 June, 1 July, and 21 August 2008 using a surface-moisture-density gauge (Model 3411-B, Troxler Electronic Laboratories Inc., Research Triangle Park, NC) in the back scatter mode. BRD was measured between 1030 and 1500h from June to September 2006, on 5 June 2007, and from May to July 2008. Measurements for BRD were made across the center plots that only received straight line passes of the mower and rollers. BRD of perimeter plots was not measured as they received additional traffic due to turning of equipment and clean up mowing. BRD measurements were taken on days between rolling treatments by releasing three golf balls from the opposing directions within each plot using a Stimpmeter (United States Golf Association, 2004), and taking the average of all six ball rolls.

All data were subjected to analysis of variance to detect significant treatment effects using the General Linear Model (GLM) procedure for a strip-plot (anthracnose severity, turf quality and bulk density) or a randomized complete block (BRD) design in the Statistical Analysis System software v. 9.1.3 (SAS Institute, Cary, NC). Significance of treatment differences and interaction means were determined using Fisher's protected least significant difference at the 0.05 probability level.

RESULTS

Anthracnose Severity

Anthracnose was first observed on 18 June 2006 and developed slowly until mid-August when disease severity intensified (31 to 35%) on the first rating date (Table 1). Peak disease severity (42 to 48%) was observed on 11 September 2006 and this level of severity was sustained through 19 September. Initial disease symptoms were apparent the second year by 9 June 2007 (Table 2), with the greatest severity (58%) being observed on 2 August 2007. In 2008, anthracnose was initially observed on 17 June (Table 3); the disease progression was similar to 2007 with the greatest severity (62%) being observed on 6 August 2008.

The location factor affected disease severity on all rating dates in 2006 (Table 1). Anthracnose was initially lower (3%) in perimeter plots on 18 August, but continued treatment increased disease 6 and 8% in perimeter plots on 11 and 19 September, respectively, compared to center plots. Roller type only affected disease severity on one of three observations in 2006. Disease severity was slightly increased 5 and 6% by the sidewinder and vibratory rollers, respectively, compared to non-rolled plots on 11 September.

Perimeter plots in 2007 had slightly lower disease severity (3 and 6%) on 5 and 12 July, respectively (Table 2), compared to center plots. Both roller types reduced disease severity on 5 of 6 rating dates during 2007 (3 to 13%) compared to non-rolled plots. Reductions in disease severity were slightly greater with the sidewinder roller (4 to 5%) compared to the vibratory roller on 5 and 12 July, respectively, but no differences between roller type were evident on other rating dates in 2007.

In 2008, the location factor affected disease severity on 4 of 7 rating dates with perimeter plots having 6 to 9% less disease compared to center plots (Table 3). Lightweight rolling reduced anthracnose on all rating dates in 2008 (up to 8%) compared to non-rolled plots. Disease severity was slightly lower with the sidewinder roller on 2 rating dates (2 and 5% less disease on 16 July and 6 August, respectively) compared to plots treated with the vibratory roller; however an interaction on 16 July (Table 3b) indicated that this reduction was only observed in center plots.

Turf Quality

Turf quality of center and perimeter plots were only different on 25 August and 20 September 2006 (Table 4), where center plots had higher quality than perimeter plots. Turf quality was not influenced by lightweight rolling in 2006. Center and perimeter plots were no different in turf quality throughout 2007, but lightweight rolling plots had better turf quality than non-rolled plots on 13 and 19 July 2007 (Table 5); the sidewinder and vibratory rolled plots had similar turf quality on these dates. By 2 August, only sidewinder rolling improved turf quality compared to non-rolled plots. In 2008, perimeter plots had slightly higher turf quality on 16 July, whereas there was no difference between center and perimeter plots on other observation dates. The sidewinder roller increased turf quality on 16 July 2008 compared to both vibratory rolled and non-rolled plots (Table 6), while both sidewinder and vibratory rolling had better turf quality than non-rolled plots on 23 July. No interaction was observed between location and lightweight rolling for turf quality.

Soil Bulk Density and Ball Roll Distance

Soil bulk density was not affected by treatment on the one evaluation date (15 August) in 2007 (Table 7). Only the location factor influenced soil bulk density in 2008; perimeter plots had slightly greater density than center plots on 21 May and 1 July (Table 7). BRD was increased 15 to 31 cm by lightweight rolling on 3 of 9 dates in 2006 (6 and 25 July, and 7 August) compared to non-rolled plots (Table 8); the sidewinder and vibratory rolled plots had similar BRD on these dates. Rolled plots increased BRD compared to non-rolled plots on 15 June 2007 (Table 9); vibratory and sidewinder rolling increased BRD 24 and 38 cm, respectively. Rolling increased BRD on 17 June and 1 July 2008 (Table 9); the vibratory and sidewinder roller types increased BRD 12 to 16 cm, respectively, on 17 June, while only vibratory rolling increased BRD (18 cm) on 1 July compared to non-rolled plots.

DISCUSSION

Both forms of lightweight rolling impacted anthracnose disease severity, but the response varied across years of study. Initially, rolling slightly increased disease (5 to 6%) on one rating date in 2006, but later that year showed no effect. An increase in disease was surprising since previous work showed that lightweight rolling had either no effect or slightly reduced anthracnose disease severity (Inguagiato et al., 2009). Before the work of Inguagiato et al. (2009), potentially abrasive cultural management practices were thought to enhance anthracnose when the disease was active in the summer months (Dernoeden, 2002; Smiley et al., 2005). In our trial, rolling and mowing treatments were initiated relatively late into the 2006 season (11 June) a few days prior to disease observation; thus, disease was actively developing before treatment initiation. The addition of crushing and abrasive stresses to an already weakened and diseased plant could have increased expression of disease symptoms. While perimeter plots initially contained less disease than center plots in August 2006, disease severity became greater in perimeter plots in September 2006. This may have also been a result of the additional wear stress, caused by turning equipment and clean-up mowing, enhancing the expression of disease symptoms on already infested plants.

Mowing and rolling treatments were initiated earlier in the 2007 and 2008 seasons (10 May and 13 May, respectively) before the onset of disease symptoms (early to mid-June). This resulted in reduced disease severity on rolled plots, which was similar to the findings of Inguagiato et al. (2009). It is possible that initiating treatments earlier in the season, before the onset of disease, pre-conditioned the turf to stresses associated with rolling turf thus avoiding an increase and actually reduced symptom expression.

Reductions in disease severity may be related to the firming of the putting green surface caused lightweight rolling, which better supports the mower and reduces scalping (Inguagiato et al., 2009b). A firmer putting surface could also result in an increased effective height of cut, resulting less defoliation; however, actual cutting height was not measured in this study. Slight increases in cutting height have proven beneficial in reducing anthracnose severity; Inguagiato et al. (2009b) previously reported that mowing ABG at 3.6 mm reduced anthracnose disease 5 to 11% and 3 to 21% compared to mowing at 3.2 and 2.8 mm, respectively. Plants that sustain less defoliation will have more photosynthetic tissue allowing for increased carbohydrate storage; increased defoliation resulting from low mowing heights in kentucky bluegrass (*Poa pratensis* L.) decreased carbohydrates and increased summer patch disease (Davis and Dernoeden, 1991).

Proper rolling ensures good contact between plant tissue, including the crowns and the soil while also leveling the putting surface to avoid scalping (Beard, 2002). Thus, plant crowns are less susceptible to mower damage protecting the key storage organ necessary to support plant growth and development (Turgeon, 2005). Inguagiato et al. (2009a) reported that light and frequent sand topdressing also helped to improve the soil plant contact and maintain plant crowns lower in the edaphic layer (below the thatch and into the mat); turf managed in this way had decreased anthracnose severity. Moreover, rolling may reduce the tendency of crowns to become elevated into the thatch and leaf canopy layers, which could also decrease crown exposure to heat stress (Beard, 1973) thus, potentially making the plant less susceptible to disease.

Lightweight rolling can also increase surface water holding capacity (Nikolai, 2005), resulting in less wilt, or water stress, which has been previously shown to reduce anthracnose severity (Roberts et al., 2008). The sidewinder roller reduced disease severity more than the vibratory roller on 5 of 13 rating dates in 2007 and 2008. This response could be attributed to the greater mass of the sidewinder roller, which may have produced a firmer surface with less mower scalp than the vibratory roller. Since increases in soil bulk density were not detected and turf quality was often improved for the sidewinder and vibratory rolled treatments in 2007 and 2008, compaction associated with lightweight rolling should not be a major concern on ABG putting green turf.

Perimeter plots had significantly less disease on 6 of 13 rating dates in 2007 and 2008. Additionally, an interaction on 16 July 2008 showed that reduced disease in plots rolled with the sidewinder was only apparent in center plots indicating that the additional traffic in perimeter plots was able to firm up the surface and decrease disease in plots rolled with either the vibratory or sidewinder roller. Decreased disease in perimeter plots was not expected as clean-up mowing and turning of equipment generally increases wear stress on plant tissue. Wear stress can create wounds within the turf that may enable fungi to be more invasive, potentially enhancing disease (Smiley et al., 2005). However, only severe wounding (that is, deep verticutting) has previously been shown to increase anthracnose of ABG (Uddin et al., 2008) and maize (*Zea mays* L.) infected with *C. graminicola*; although wounding for the latter host was not required for infection (Venard and Vaillancourt, 2007). Essentially, perimeter plots were further rolled during mowing due to the presence of the drum roller on the mower. The observed reduction in anthracnose suggests that the combination of rolling and additional mowing (cleanup passes) in perimeter plots may have further firmed the surface thus reducing disease. Moreover, clean-up mowing in our study utilized straight-line passes, whereas normal clean-up mowing on putting greens is typically in an arc, which can cause increased wear. It is possible that clean-up mowing in straight-line passes may essentially firm the surface similar to a double-cut, which has been previously shown to have no effect or slightly reduce anthracnose (Inguagiato et al., 2009). Mowing along an arc could generate additional stress that might increase anthracnose; however, this technique was not examined in this study. Further research to evaluate the impact of mowing along a curved edge (i.e., a normal practice for putting green) on anthracnose would be informative, but our results illustrate that the turning of equipment (walk-behind mowers and lightweight rollers) on ABG greens does not enhance anthracnose severity.

Turf quality was acceptable (≥5) for all treatments in June each year, but quality generally became unacceptable in July and August when disease severity intensified. Turf quality of plots was either unaffected or increased by lightweight rolling in all three years of the study. Increased turf quality was likely a result of decreased anthracnose disease in the plots. These results were expected as sand-based putting greens can be rolled every other day (Nus, 1992; DiPaola and Hartwiger, 1994; Nikolai, 2002a, 2002b, 2004), and soil-based greens can be rolled three times per week, without observing negative effects on turf quality if a regular topdressing program is in place as was the case in our study (Nikolai, 2002b). Turf quality of center and perimeter plots only varied on 3 dates throughout the three years of study. The frequent absence of differences between treatments is likely due to the fact that plots not suffering from wear stress (e.g., center plots) had increased anthracnose that also lowered turf quality compared to perimeter plots. Decreased turf quality in the perimeter plots was expected as increased traffic from equipment and golfers can injure or thin turf if concentrated in a particular area (Beard, 1973)

Soil bulk density was not affected in plots that were rolled versus non-rolled in all three years of study. Additionally, bulk density of perimeter plots was only slightly increased on two dates (21 May and 1 July 2008) compared to center plots, and no negative effects of rolling treatments on anthracnose or turf quality were observed during that period. This supports previous recommendations that lightweight rolling can be conducted every other day (Nus, 1992; Nikolai, 2002a, 2002b, 2004; Nolan, 2008) without adversely affecting the putting surface. Rolling every other day often increased BRD; BRD increased 15 to 38 cm in rolled plots on days between rolling. This was somewhat higher than reported for previous work with similar roller types (Nikolai, 2004); however, rolling in the current study was performed in a manner conducive to increase putting green speed (BRD) and was similar to accepted golf course practices.

CONCLUSION

Unexpectedly, the perimeter location usually did not increase anthracnose development. This indicates that the wear associated with mowing and rolling along the perimeter of greens does not enhance anthracnose, but additional research utilizing a arc pattern of mowing would be required to confirm this observation. Lightweight rolling can be effectively used to increase BRD without adversely influencing and often reducing anthracnose severity. Moreover, lightweight rolling gives superintendents the option of raising the mowing height during summer stress, a practice that can significantly reduce disease severity (Inguagiato, et al., 2009). While lightweight rolling did not control anthracnose, the results provide evidence that lightweight rolling can be an integral part of a putting green maintenance program to increase BRD without intensifying this disease. The use of lightweight rolling in combination with adequate N fertilization can decrease disease severity and could potentially reduce the amount of fungicides used to control anthracnose on ABG putting greens.

REFERENCES

Beard, J.B. 1973. Turfgrass science and culture. Prentice-Hall, Inc. Englewood Cliffs, NJ.

Beard, J.B. 2002. Turf management for golf courses. 2nd ed. Ann Arbor Press, Chelsea, MI.

Carrow, R.N. 1980. Influence of soil compaction on three turfgrass species. Agron. J. 72:1038-1042.

Crouch, J.A., B.B. Clarke, and B.I. Hillman. 2006. Unraveling evolutionary relationships among the divergent lineages of *Colletotrichum* causing anthracnose disease in turfgrass and corn. Phytopathology. 96:46-60.

Davis, D.B., and P.H. Dernoeden. 1991. Summer patch and Kentucky bluegrass quality as influenced by cultural practices. Agron. J. 83:670-677.

Dernoeden, P.H. 2002. Creeping bentgrass management: summer stresses, weeds, and selected maladies John Wiley & Sons, Inc., Hoboken, NJ.

DiPaola, J.M., and C.E. Hartwiger. 1994. Green speed, rolling and soil compaction. Golf Course Manage. 62:49-51, 78.

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

Green Section Staff. 2004. USGA recommendations for a method of putting green construction. USGA Green Sec. Construction Educ. Program., Waco, TX.

Hamilton, G.W., D.W. Livingston, and A.E. Gover. 1994. The effects of light-weight rolling on putting greens. p.425-430. *In* A.J. Cochran and M.R. Farrally (ed.) Science and Golf II. Proceedings of the 1994 WorldScientific Congress of Golf, St. Andrews, Scotland. 4-8 July, 1994. E&FN Spon. London.

Hartwiger, C.E. 1996. The ups and downs of rolling putting greens. USGA Green Sec. Rec. 34:1-4.

Hartwiger, C.E., C.H. Peacock, J.M. DiPaola, and D.K. Cassel. 2001. Impact of light-weight rolling on putting green performance. Crop Sci. 41:1179-1184.

Inguagiato, J.C., J.A. Murphy and B.B. Clarke. 2008. Anthracnose severity on annual bluegrass influenced by nitrogen fertilization, growth regulators, and verticutting. Crop Sci. 48:1595-1607.

Inguagiato, J.C. 2009a. Anthracnose severity influenced by cultural management of annual bluegrass putting green turf. Ph.D. Dissertation. Rutgers University, New Brunswick, NJ.

Inguagiato, J.C., J.A. Murphy, and B.B. Clarke. 2009b. Anthracnose disease and annual bluegrass putting green performance affected by mowing practices and lightweight rolling. Crop Sci. 49:1454-1462

Karcher, D.E., T.A. Nikolai, and R.N. Calhoun. 2000. Green speed: what do golfers know? Australian Turfgrass Manage. 2:30-32.

Landschoot, P., and B. Hoyland. 1995. Shedding some light on anthracnose basal rot. Golf Course Manage. 11:52-55.

Mann, R.L., and A.J. Newell. 2005. A survey to determine the incidence and severity of pests and diseases on golf course putting greens in England, Ireland, Scotland, and Wales. Int. Turfgrass Soc. Res. J. 10:224-229.

Nikolai, T.A. 2002a. Effects of rolling and fertility on putting green root zone mixes. Ph.D. dissertation. Michigan State University, East Lansing.

Nikolai, T.A. 2002b. More light on lightweight rolling, research is shedding light on rolling as a season-long maintenance practice. USGA Green Sec. Rec. 40:9-12.

Nikolai, T.A 2004. Rollin', rollin', rollin, lightweight rollers can be used frequently to enhance putting green speed. Golf Course Manage. 72:121-124.

Nikolai, T.A., P.E. Rieke, J.N. Rogers, III, and J.M. Vargas, Jr. 2001. Turfgrass and soil responses to lightweight rolling on putting green root zone mixes. Int. Turfgrass Soc. Res. J. 9:604-609.

Nolan, C. 2008. Green speed-two modern techniques for preparing greens. Int. Turfgrass Bulletin. 239:12-16.

Nus, J. 1992. Rolling putting greens. Golf Course Manage. 60:16, 18, 20, 22.

Piper, C.V., and R.A. Oakley. 1921. Rolling the turf. Bulletin of the Green Section of the USGA. 1:36.

Roberts, J.A., J.C. Inguagiato, B.B. Clarke, and J.A. Murphy. 2008. Influence of irrigation management on anthracnose severity of annual bluegrass. 2008 Joint Annual Meeting of GSA, SSSA, ASA, CSSA, GCAGS, and HGS, Houston, TX. DOI:561-1

Rosenburg, N.J. 1964. Response to plants to the physical effects of soil compaction. Advanced Agron. 16:181-196.

Samaranayake, H., T.J. Lawson, and J.A. Murphy. 2008. Traffic stress effects on bentgrass putting green and fairway turf. Crop Sci. 48:1193-1202.

Sills, M.J., and R.N. Carrow. 1983. Turfgrass growth, N use, and water use under soil compaction and N fertilization. Agron. J. 75:488-492.

Skinner, M.F, and G.D. Bowen. 1974. The penetration of soil by mycelia strands of ectomycorrhizal fungi. Soil Bio. and Biochem. 6:57-61

Smiley, R.W., P.H. Dernoeden, and B.B. Clarke. 2005. Compendium of turfgrass diseases. 3rd ed. The American Pathological Society, St. Paul, MN.

Sprague, N.B., and G.W. Burton. 1937. Annual bluegrass (*Poa annua* L.) and its requirements for growth. NJ Ag. Exp. Station Bulletin. 630.

Towers, G., K. Green, E. Weibel, P. Majumdar, and B.B. Clarke. 2002. Evaluation of fungicides for the control of anthracnose basal rot on annual bluegrass, 2002. Available at www.plant-managementnetwork.org/pub.trial/fntests/vol58/. Fungicide Nematicide Tests 58:T017.

Turgeon, A.J. 2005. Turfgrass management 7th Ed. Pearson Education, Inc., Upper Saddle River, NJ.

Uddin, W., M. Soika, and D. Livingston. 2008. Vertical mowing and mowing height affect anthracnose basal rot. Golf Course Manage. 76:84-87.

United States Golf Association. 2004. Stimpmeter instruction booklet. *Greens Articles* 11 March 2009. http://www.usga.org/turf/articles/management/greens/stimpmeter.html.

Vermeulen, P.H. 2003. Maybe it's time for a change. USGA Green Sec. Rec. 41:28.

Venard, C., and L. Vaillancourt. 2007. Penetration and colonization of unwounded maize tissues by the maize anthracnose pathogen *Colletotrichum graminicola* and the related nonpathogen *C. sublineolum*. Mycologia 99: 368-377.

Wong, F.P., and S. Midland. 2004. Fungicide-resistant anthracnose: bad news for greens management. Golf Course Manage. 72:75-80.

Younger, V.B. 1969. Physiology of growth and development. *In* A.A. Hanson and F.V. Juska (ed.) Turfgrass Science. ASA, Madison, WI.

Zontek, S. 2004. Have we gone too far? The grass is talking to you. Are you listening? USGA Green Sec. Rec. 42:28.

Table 1. Anthracnose disease severity response to location and roller type on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2006.

Treatment	Turf area infested		
	18 Aug	11 Sep	19 Sep
Location (L)†	------------------	%	------------------
Center	34.5 a§	42.1 b	40.7 b
Perimeter	31.1 b	48.4 a	49.1 a
Lightweight Rolling (LR)‡			
Sidewinder Roller	34.7	47.7 a	49.4
Vibratory Roller	30.9	46.4 a	45.4
None	32.8	41.8 b	40.0
Source of Variation		ANOVA	
L	***	**	**
LR	NS¶	*	NS
L*LR	NS	NS	NS
CV (%)	13.5	38.0	27.2

*Significant at the 0.05 probability level
**Significant at the 0.01 probability level
***Significant at the 0.001 probability level
†Perimeter location similar to normal putting green perimeter (i.e., turning of mowing and rolling equipment minimized to perimeter plots as well as daily clean up passes from mowing)
‡Lightweight rolling performed every other day after morning mowing from 11 June to 19 Sept. 2006
§Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05).
¶NS, not significant

Table 2. Anthracnose disease severity response to location and roller type on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2007.

	Turf area infested					
Treatment	9 Jun	22 Jun	5 Jul	12 Jul	19 Jul	2 Aug
Location (L)†	------------------------------- % -------------------------------					
Center	10.5	20.3	24.4 a§	35.8 a	45.5	52.0
Perimeter	8.9	20.3	21.6 b	29.8 b	42.7	49.9
Lightweight Rolling (LR)‡						
Sidewinder Roller	8.3	17.6 b	17.9 c	26.8 c	39.4 b	47.8 b
Vibratory Roller	9.1	20.1 b	22.0 b	31.5 b	42.1 b	47.0 b
None	11.7	23.2 a	29.1 a	40.1 a	51.0 a	58.2 a
Source of Variation	ANOVA					
L	NS	NS	*	**	NS	NS
LR	NS¶	*	***	***	**	***
L*LR	NS	NS	NS	NS	NS	NS
CV (%)	24.1	17.0	14.5	14.0	5.8	7.6

*Significant at the 0.05 probability level
**Significant at the 0.01 probability level
***Significant at the 0.001 probability level
†Perimeter location similar to normal putting green perimeter (i.e., turning of mowing and rolling equipment minimized to perimeter plots as well as daily clean up passes from mowing)
‡Lightweight rolling performed every other day after morning mowing from 10 May to 5 Aug. 2007
§Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05).
¶NS, not significant

Table 3. Anthracnose disease severity response to location and roller type on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2008.

Treatment	Turf area infested						
	17 Jun	27 Jun	7 Jul	16 Jul	23 Jul	30 Jul	6 Aug
Location (L)[‡]	------------------------- % -------------------------						
Center	1.2	1.4	5.9	31.4 a[¶]	43.0 a	56.5 a	62.0 a
Perimeter	1.2	1.5	4.9	24.1 b	37.5 b	48.8 b	53.2 b
Lightweight Rolling (LR)[§]							
Sidewinder Roller	1.0 c	1.3 b	4.6 b	25.4 c	37.2 b	49.5 b	53.3 c
Vibratory Roller	1.2 b	1.4 b	5.3 ab	27.1 b	38.2 b	51.7 b	57.8 b
None	1.4 a	1.7 a	6.3 a	30.8 a	45.4 a	56.7 a	61.7 a
Source of Variation				ANOVA			
L	NS[#]	NS	NS	**	*	*	**
LR	**	*	0.058[†]	***	***	**	***
L*LR	NS	NS	NS	*	NS	NS	NS
CV (%)	18.7	20.2	14.4	5.8	8.4	5.9	4.3

[†]Significant at the 0.10 probability level
[*]Significant at the 0.05 probability level
[**]Significant at the 0.01 probability level
[***]Significant at the 0.001 probability level
[‡]Perimeter location similar to normal putting green perimeter (i.e., turning of mowing and rolling equipment minimized to perimeter plots as well as daily clean up passes from mowing)
[§]Lightweight rolling performed every other day after morning mowing from 13 May to 16 Aug. 2008
[¶]Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05).
[#]NS, not significant

Table 3b. Interaction between location and roller type on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ on 16 July 2008

	Turf Area Infested	
Lightweight Rolling	Center	Perimeter
	------------------ % ------------------	
Sidewinder Roller	28.07	22.71
Vibratory Roller	30.86	23.35
None	35.3	26.33
Type 1 - lsd†	1.58	
Type 2 - lsd‡	3.97	
Type 3 - lsd§	1.65	
Type 4 - lsd¶	1.68	

†Least significant difference to determine difference between two horizontal means (averaged over all vertical treatments

‡ Least significant difference to determine difference between two vertical means (averaged over all horizontal treatments

§ Least significant difference to determine difference between two horizontal means at the same level of vertical factor

¶ Least significant difference to determine difference between two vertical means at the same level of horizontal factor

Table 4. Turf quality response to location and roller type on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2006.

	Turf quality				
Treatment	19 Jul	4 Aug	25 Aug	8 Sep	20 Sep
Location (L)†	----------------------1-9; 9 = best ----------------------				
Center	5.1	5.2	3.9 a§	3.6	4.7 a
Perimeter	4.8	4.7	3.6 b	2.9	3.7 b
Lightweight Rolling (LR) ‡					
Sidewinder Roller	4.7	4.6	3.8	2.8	3.9
Vibratory Roller	4.9	5.1	4.1	3.2	4.1
None	5.2	5.1	3.5	3.8	4.6
Source of Variation			ANOVA		
L	NS	NS	**	NS	***
LR	NS¶	NS	NS	NS	NS
L*LR	NS	NS	NS	NS	NS
CV (%)	9.0	7.4	10.3	20.9	10.1

**Significant at the 0.01 probability level

***Significant at the 0.001 probability level

†Perimeter location similar to normal putting green perimeter (i.e., turning of mowing and rolling equipment minimized to perimeter plots as well as daily clean up passes from mowing)

‡Lightweight rolling performed every other day after morning mowing from 11 June to 19 Sept.2006

§Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05)

¶NS, not significant

Table 5. Turf quality response to location and roller type on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2007.

	Turf quality					
Treatment	25 May	8 Jun	19 Jun	13 Jul	19 Jul	2 Aug
Location (L) [†]	----------------------------1-9; 9 = best ----------------------------					
Center	6.7	5.8	5.8	3.4	3.7	3.1
Perimeter	6.7	5.5	5.6	2.9	3.4	2.9
Lightweight Rolling (LR)[‡]						
Sidewinder Roller	6.7	5.8	5.9	3.8 a[§]	4.0 a	3.3
Vibratory Roller	6.8	5.6	5.5	3.3 a	3.8 a	3.2
None	6.7	5.7	5.7	2.4 b	2.9 b	2.5
Source of Variation			ANOVA			
L	NS	NS	NS	NS	NS	NS
LR	NS[¶]	NS	NS	**	*	NS
L*LR	NS	NS	NS	NS	NS	NS
CV (%)	4.6	8.8	6.0	16.1	10.9	17.6

*Significant at the 0.05 probability level
**Significant at the 0.01 probability level
†Perimeter location similar to normal putting green perimeter (i.e., turning of mowing and rolling equipment minimized to perimeter plots as well as daily clean up passes from mowing)
‡Lightweight rolling performed every other day after morning mowing from 10 May to 5 Aug 2007
§Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05).
¶NS, not significant

Table 6. Turf quality response to location and roller type on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2008.

	Turf quality							
Treatment	6 Jun	16 Jun	27 Jun	7 Jul	16 Jul	23 Jul	30 Jul	6 Aug
Location (L)†	----------1-9; 9 = best ----------							
Center	6.2	6.2	6.4	5.6	3.7 b§	3.8	3.7	3.0
Perimeter	6.2	6.1	6.7	5.7	4.1 a	3.9	3.8	3.3
Lightweight Rolling (LR)‡								
Sidewinder Roller	6.3	6.2	6.7	5.8	4.3 a	4.0 a	3.8	3.3
Vibratory Roller	6.1	6.1	6.6	5.7	3.8 b	4.0 a	3.8	3.3
None	6.2	6.1	6.4	5.5	3.6 b	3.6 b	3.7	3.0
Source of Variation	ANOVA							
L	NS	NS	NS	NS	*	NS	NS	NS
LR	NS¶	NS	NS	NS	**	*	NS	NS
L*LR	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	5.0	5.8	5.5	6.9	10.3	4.3	9.1	16.8

*Significant at the 0.05 probability level

**Significant at the 0.01 probability level

†Perimeter location similar to normal putting green perimeter (i.e., turning of mowing and rolling equipment minimized to perimeter plots as well as daily clean up passes from mowing)

‡Lightweight rolling performed every other day after morning mowing from 13 May to 16 Aug. 2008

§Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05).

¶NS, not significant

Table 7. Soil bulk density response to location and roller type on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2007 and 2008.

	Soil bulk density					
	2007	2008				
Treatment	15 Aug	21 May	3 Jun	17 Jun	1 Jul	21 Aug
Location (L)†	---------------------------------- Mg/m^3 ----------------------------------					
Center	1.38	1.22 b§	1.31	1.29	1.29 b	1.35
Perimeter	1.39	1.24 a	1.32	1.30	1.31 a	1.36
Lightweight Rolling (LR)‡						
Sidewinder Roller	1.39	1.24	1.32	1.30	1.30	1.36
Vibratory Roller	1.38	1.22	1.31	1.29	1.30	1.36
None	1.39	1.23	1.32	1.30	1.30	1.35
Source of Variation			ANOVA			
L	NS	*	NS	NS	*	NS
LR	NS¶	NS	NS	NS	NS	NS
L*LR	NS	NS	NS	NS	NS	NS
CV (%)	3.25	2.19	1.41	1.27	1.73	1.86

*Significant at the 0.05 probability level

†Perimeter location similar to normal putting green perimeter (i.e., turning of mowing and rolling equipment minimized to perimeter plots as well as daily clean up passes from mowing)

‡Lightweight rolling performed every other day after morning mowing from 10 May to 5 Aug. 2007 and 13 May to 16 Aug. 2008

§Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05).

¶NS, not significant

Table 8. Ball roll distance response to lightweight roller type on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2006.

	Ball roll distance								
Treatment	13 Jun	21 Jun	6 Jul	25 Jul	7 Aug	15 Aug	21 Aug	25 Aug	5 Sep
Lightweight Rolling (LR)[†]	----------	----------	----------	----------	cm	----------	----------	----------	----------
Sidewinder Roller	285.2	300.2	280.7 a[‡]	316.2 a	309.6 a	316.2	309.9	325.1	311.9
Vibratory Roller	287.3	305.3	284.2 a	321.3 a	309.9 a	314.2	309.6	320.3	305.3
None	271.8	302.5	265.7 b	291.6 b	290.6 b	304.0	296.2	292.4	294.1
Source of Variation					ANOVA				
LR	NS[§]	NS	*	*	*	NS	NS	NS	NS
CV (%)	4.39	3.48	2.28	3.29	2.88	4.66	9.16	5.34	3.34

[*]Significant at the 0.05 probability level

[†]Lightweight Rolling performed every other day after morning mowing from 11 June to d19 Sept. 2006. Ball roll distance was only recorded on center plots that received straight line passes of the mower and rollers

[‡]Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05).

[§]NS, not significant

Table 9. Ball roll distance response to lightweight roller type on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2007 and 2008.

	Ball roll distance							
	2007	2008						
Treatment	15 Jun	15 May	28 May	11 Jun	17 Jun	23 Jun	1 Jul	8 Jul
Lightweight Rolling (LR)†	cm							
Sidewinder Roller	306.3 a‡	263.7	300.7	299.2	296.9 a	309.9	279.4 b	313.4
Vibratory Roller	320.8 a	271.8	305.6	303.3	292.4 a	309.1	294.6 a	320.3
None	282.4 b	266.4	298.2	285.2	280.7 b	304.0	275.8 b	315.7
Source of Variation	ANOVA							
LR	**	NS§	NS	NS	*	NS	*	NS
CV (%)	3.12	2.88	4.35	3.95	2.15	3.41	2.77	3.02

*Significant at the 0.05 probability level

**Significant at the 0.01 probability level

†Lightweight Rolling performed every other day after morning mowing from 10 May to 5 Aug. 2007 and 13 May to 16 Aug. 2008. Ball roll distance was only recorded on center plots that received straight line passes of the mower and rollers

‡Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05).

§NS, not significant

CHAPTER 3. Anthracnose Disease on Annual Bluegrass as Affected by Foot Traffic and Sand Topdressing

ABSTRACT

Sand topdressing on putting greens is applied to enhance the playability of the turf surface. Anthracnose is a devastating disease of annual bluegrass [*Poa annua* L. f. *reptans* (Hausskn) T. Koyama] (ABG) putting green turf, caused by *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman. The disease is more severe on weakened turf and has been thought to be enhanced by management practices that wound turf. A 2-yr field study was initiated in 2007 to evaluate the effects of foot traffic (0 and 327 footsteps m^{-2} d^{-1}) and sand topdressing (0 and 0.3 L m^{-2} every wk) on anthracnose severity of ABG mowed at 3.2 mm. Surprisingly, foot traffic reduced anthracnose severity as much as 28%, regardless of sand topdressing during both years. While sand topdressing initially increased disease severity in 2007, continued applications decreased disease severity by 9% by mid-August 2007 and again (3 to 7%) in 2008. The treatment combination of foot traffic 5 d wk^{-1} and weekly sand topdressing resulted in the best turf quality by the end of both seasons. Results indicate that the practice of sand topdressing may be continued even under conditions of intense foot traffic, when anthracnose develops on ABG putting greens.

INTRODUCTION

Anthracnose, caused by *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman (Crouch et al, 2006), is a destructive disease of putting green turf that can occur as either a foliar blight, often problematic during high temperatures and humidity of summer, or basal rot, which can be observed throughout the year. Anthracnose can cause severe thinning of putting green turf, which greatly reduces its aesthetic quality and playability. The disease is normally observed on annual bluegrass [*Poa annua* L. f. *reptans* (Hausskn) T. Koyama] (ABG), but bentgrass species (*Agrostis* spp.) can also become infested. The frequency and severity of anthracnose epiphytotics on ABG putting greens has increased over the past two decades (Dernoeden, 2002; Inguagiato et al., 2008a; Landschoot and Hoyland, 1995; Mann and Newell, 2005; Wong and Midland, 2004). While reasons for this increase are not fully understood, it has been hypothesized that management practices commonly employed on golf courses to improve playing conditions can increase abiotic stress, which may predispose the turf to anthracnose (Vermeulen, 2003; Zontek, 2004). Plant health is known to affect plant disease severity; thus it is important to understand how common management practices on putting greens can influence the development of anthracnose disease.

Topdressing, as described by Beard (1973), is the application of a thin layer of selected or prepared soil or sand to a turfgrass area. It is employed for smoothing or leveling of the playing surface, modification of the surface soil, covering stolons or sprigs of vegetative plants, winter protection and has been described as the most effective cultural practice to reduce and/or dilute thatch on putting greens (Beard, 1973; Ledeboer and Skogley, 1967). Typically, topdressing on putting greens consists of straight sand or sand/soil mixes, and applications can be light and frequent or heavy and less frequent (Beard, 2002). The amount of sand applied depends on the management objectives; for example, large quantities of topdressing are needed to backfill holes caused by cultivation and smaller amounts are often used for routine topdressing during mid-season to maintain smoothness of the putting green and to reduce surface thatch accumulation. Previous research has indicated that light frequent sand topdressing (e.g., 0.3 L m^{-2} every 7-d) can reduce anthracnose severity of ABG (Inguagiato et al., 2008b), while methods to incorporate the sand into the canopy (brushing, irrigation or rolling) did not affect anthracnose development.

Foot traffic can result in soil compaction, turfgrass wear, soil displacement and divots that are detrimental to turfgrass growth (Beard, 1973). Compaction resulting from foot traffic typically occurs where play is most concentrated, such as on tees, collars and around the cup of a putting green (Vavrek, 2002). Additionally, the potential for compaction is enhanced in excessively wet areas (Beard, 1973). The scuffing and tearing caused by frequent foot traffic can crush the leaves, stems and crowns of the plant (Beard, 1973). Wear is also more damaging at lower mowing heights; turfgrass mowed at 12.7 mm resulted in decreased wear tolerance compared to turfgrass mowed at 50.8 mm (Younger, 1962). The wounding and bruising resulting from wear has been associated with enhanced plant disease since it may provide an entry point for fungi to colonize plant tissue (Agrios, 2005; Beard, 1973). Although previous work has shown that wounding is not necessary to initiate anthracnose on corn (*Zea mays* L.), caused by *C. graminicola* (Ces.) C.G. Wils. (Venard and Vaillancourt, 2007), wounding has been reported to influence the pathogenicity of *C. gloeosporioides* Penz. on torch ginger

(*Etlingera elatior* (Jack) R.M. Smith) (Lins and Coelho, 2003). While Inguagiato et al. (2008b) indicated that sand topdressing can reduce anthracnose severity, superintendents have questioned whether this beneficial effect of sand topdressing might be negated by frequent foot traffic. Topdressing has been reported to reduce wear damage on perennial ryegrass maintained as a football field (Spring et al., 2007), but the effects of topdressing on wear potential of putting green turf have not been previously examined. For the current study, it was hypothesized that wear from regular foot traffic would increase anthracnose, but the beneficial effects of sand topdressing would still be observed. Therefore, the objectives of this study were: i) to evaluate the effect of foot traffic on the severity of anthracnose on ABG putting green turf and ii) to determine whether the effect of light frequent topdressing on anthracnose severity is independent of foot traffic.

MATERIALS AND METHODS

Treatment Design

The study used a split-plot design with a 2 by 2 factorial arrangement of treatments replicated four times. The main plot factor consisted of foot traffic [using Adidas Z-Traxion, soft-spike golf shoes (Adidas USA, Portland, OR)], which was initiated from eight starting positions at each end of a 0.25- by 3.66-m long traffic lane. The positions consisted of starting with either the left or right foot at 0, 0.20, 0.40 and 0.59 m from the beginning of each traffic lane and then repeating the process with the opposite foot. Thus, a complete subunit of foot traffic resulted in 16 total passes that distributed footsteps evenly over each traffic lane. Each main plot had four side-by-side traffic lanes creating a 1.02- by 3.66-m main plot. A total of four subunits of foot traffic were applied per day to each main plot resulting in a total of 64 total passes or 327 footsteps m^{-2} each day. Data from Hathaway and Nikolai (2005) indicated that 323 footsteps m^{-2} occured in the area around the hole on a putting green that received 200 rounds of golf d^{-1}. In the current study, foot traffic (0 and 327 footsteps m^{-2} d^{-1}) was initiated 14 June 2007 and 6 June 2008 and continued 5 d wk^{-1} through 4 September 2007 and 7 September 2008, respectively.

The sub-plot factor was comprised of topdressing plots with sub-angular silica sand (pH 7.0) at 0 or 0.3 L m^{-2} every week from 14 May through 28 August 2007 and 15 May through 29 August 2008. Topdressing sand conformed to the particle size distribution recommended for sand putting green root zones (USGA Staff, 2004) and was applied using a drop spreader (The Scotts Company, Marysville, OH). Sand was incorporated using a brush (91 by 23 cm) constructed of three broom heads having medium-stiff synthetic bristles (model 7436, Harper Brush Works, Inc., Fairfield, IA) mounted to a plywood base with two extended handles. Sand was incorporated into individual plots by dragging the brush over half of the plot four times and repeating the procedure on the opposite half.

General Maintenance Practices

The 2-yr field study was conducted on an ABG turf grown on a Nixon sandy loam (fine, mixed, mesic Typic Hapludult) with a pH of 6.3 at the Rutgers Horticultural Farm II in North Brunswick, NJ. The ABG turf was established in 1992 as described by Inguagiato et al. (2008a) using seed indigenous to the site as well as seed introduced in 1998 from soil cores collected from golf course putting greens in Piscataway and Plainfield, NJ (Samaranayake et al., 2008). Turf was mown 7 times wk^{-1} using a walk behind greens mower (model 220A and 220B, Deere & Co., Moline, IL) with a bench height setting of 3.2 mm. Irrigation was applied to avoid drought stress and maintain moderately dry soil conditions. When treatments were not being applied, nitrogen was applied as a foliar spray using water soluble sources at N rates of either 4.9 or 9.8 kg ha^{-1} totaling 58.6 kg ha^{-1} from April to May 2007, 107.4 kg ha^{-1} from late August to October 2007, and 43.9 kg ha^{-1} from April to May 2008. While treatments were being applied, the total N applied was 29.3 kg ha^{-1} from June to August 2007 and 2008. P and K were applied based on soil test results at 16.1 and 30.4 kg ha^{-1} in 2007 and 0 and 56.3 kg ha^{-1} in 2008, respectively. Trinexapac-ethyl [4-(cyclopropyl-α-hydroxy-methylene)-3.5-dioxocyclohexanecarboxylic acid ethylester] was applied at 0.048 kg a.i. ha^{-1} every 14 d from 12 May to 9 September 2007 and 7 May to 13 October 2008. Dollar spot (caused by *Sclerotinia homoeocarpa* F.T. Bennett) was prevented each year from May to October every 14 d by alternating boscalid {3-pyridinecarboximide, 2chloro-N-[4'chloro(1,1'-biphenyl)yl]} or vinclozolin [3-(3,5-dichlorophenyl)-5-ethenyl-5-methyl-2,4-oxazolidinedione] applications at 0.4 kg a.i. ha^{-1} and 1.5 to 1.8 kg a.i. ha^{-1}, resepectively. Brown patch (caused by *Rhizoctonia solani* Kuhn) was prevented with flutolanil {N-[3-(1-methylethoxy)phenyl]-2-(trifluoromethyl)benzamide} applied at 3.1 to 6.4 kg a.i. ha^{-1}. These fungicides were previously shown to be ineffective against anthracnose basal rot on ABG putting green turf in New Jersey (Towers et al., 2002). Algae was suppressed with mancozeb (ethylenebisdithiocarbamate) applied at 21.4 kg a.i. ha^{-1} on 31 May, 20 June, and 7, 22 and 28 July 2007. Mancozeb was not required in 2008 since algae was not prevalent.

The anthracnose epiphytotic was arrested after treatments were suspended each year to allow recovery of plots during the subsequent fall, winter and spring months. Chlorothalonil (tetrachloroisophthalonitrile) was applied at 16.1 kg a.i. ha^{-1} on 10 September 2007 and at 9.2 and 11.2 kg a.i. ha^{-1} on 16 September and 13 October 2008, respectively. Bentgrass encroachment was minimized with fluazifop-P-butyl {(R)-2-[4-[(5-(trifluromethyl)-2-pyridyloxy)phenoxy]propanoic acid} applied at 0.21 kg a.i. ha^{-1} on 23 August and 5 September 2007, and 18 September 2008. Broadleaf weeds were controlled with mecoprop [2-(2-methyl-4-chlorophenoxy)] at 1.1 kg a.i. ha^{-1} on 23 August and 5 September 2007, and 18 September 2008.

The experimental site was previously inoculated in July 2002 with *C. cereale* isolate ValP-04 as described by Inguagiato et al. (2008a). Disease outbreaks occurred naturally in subsequent years and *C. cereale* was re-isolated from symptomatic leaf and stem tissue each year to confirm the presence of the pathogen.

Data Collection and Analysis

Anthracnose severity was rated periodically from June to early September each year as the percent turf area infested with *C. cereale* using a line intercept-grid count method previously described by Inguagiato et al. (2008a) to obtain 273 intersections over each 1.4 m^2 $plot^{-1}$. The percent turf area infested with *C. cereale* was then calculated using the formula: (n/273) x 100; where n represents the number of intersections observed over symptomatic leaf tissue. Turf quality was rated visually from June through September each year using a scale of 1 to 9, where 9 represented the best quality and 5 the minimum acceptable quality. Turf density, uniformity and color were components of the turf quality rating; the density and uniformity components were strongly affected by disease severity. Similarly, turf color was rated from July to September 2007 and June through September 2008 on a scale of 1 to 9, where 6 represented normal green foliar color with ratings below and above representing lighter and darker green color, respectively.

To assess potential compaction from daily foot traffic, soil bulk density was measured on 2 September 2007 and on 21 May, 3 and 17 June, 2 July and 5 September 2008. Readings were taken at three in situ locations $plot^{-1}$ using a Troxler gamma-ray and neutron gauge (Model 3411-B, Troxler Electronic Laboratories Inc., Research Triangle Park, NC) operated in the backscatter mode.

All data were evaluated by analysis of variance to identify significant treatment effects using the General Linear Model procedure for a split-plot design in Statistical Analysis System software v. 9.1.3 (SAS Institute, Cary, NC). Means and significant interactions were separated using Fisher's protected least significant difference at the

0.05 probability level and using appropriate formulas described by Gomez and Gomez (1984).

RESULTS AND DISCUSSION

Disease was first observed on 6 June 2007 and progressed naturally to a maximum of 57% on 14 August 2007, after which disease severity declined to 49% during a period of rain and lower temperatures (Table 1). Disease severity increased again on 4 September as temperatures increased late in the summer. In 2008, disease severity was first observed on 15 June. The disease progressed slowly due to rain and low temperatures in early June, but increased steadily in mid-July reaching a maximum disease severity (55%) on 13 August (Table 2). Similar to 2007, rain and lower temperatures reduced disease severity on 20 August to 42%. Increased temperatures intensified disease severity (47%) again by 7 September 2008.

Anthracnose Severity

Foot traffic had a significant effect on disease severity on 14 of 22 rating dates across both years and reduced disease 15 to 28% (Table 1) and 2 to 24% (Table 2) in 2007 and 2008, respectively. The interaction on 12 July 2007 indicated that foot traffic alone, or in combination with sand topdressing, was not different from the check plots, whereas sand topdressing alone increased disease by 12% (Table 1b). It was initially hypothesized that foot traffic may increase disease severity via wounding and bruising, by providing fungal hyphae with a means to enter the plant (Beard, 1973; Agrios, 2005). However, work by Inguagiato et al. (2008a) indicated that light to moderate wounding had little effect on anthracnose severity; verticutting to a 3 mm depth of the turf canopy at 14 d intervals during the summer months and the incorporation of sand topdressing via vibratory rolling or stiff and soft brushes did not increase disease (Inguagiato et al., 2008b). Uddin et al. (2008) reported increased anthracnose severity after verticutting to a depth of 5.1 mm, but this reported a very deep cultivation treatment that caused extreme bruising that severely weakened the turf. Landschoot and Hoyland (1995) reported that anthracnose symptoms were not observed when leaf tissue was wounded, regardless of the type of wound. While environmental and mechanical stress have been suggested as factors which may increase anthracnose severity (Smiley et al., 2005), it appears that the routine and intense foot traffic stress does not enhance disease severity.

In our study, the compression of the turf surface imposed by foot traffic was very uniform over each plot and therefore it seems likely that foot traffic may have reduced disease in a manner similar to lightweight rolling. Lightweight rolling has been shown to reduce anthracnose severity on ABG (Inguagiato et al., 2009). Like rolling, foot traffic could be beneficial to a plant by pressing plant tissue, mainly the crowns, deeper in the soil medium (Beard, 2002) thus improving contact between plant roots and the soil and reducing scalping from mowers. This could result in improved plant health through increased nutrient and water uptake. Protection of the crown is essential since it is a key storage organ for the support and development of the plant (Turgeon, 2005). Hurto et al. (1980) observed lower water retention in thatch of Kentucky bluegrass (*Poa pratensis* L.) when compared to an underlying silt loam, and Roberts et al. (2008) previously observed increased anthracnose on water stressed ABG putting green turf. If the crown is maintained lower in the mat layer, or below the thatch, turf is less susceptible to temperature and drought stress (Beard, 1973) and potentially stressed related diseases such as anthracnose.

Additionally, stress generated from regular foot traffic could result in the accumulation of reactive oxygen species (ROS) in the turf. ROS are reduced derivatives of oxygen (O_2) such as hydrogen peroxide (H_2O_2) and nitric oxide (NO) that could potentially damage carbohydrates, lipids, nucleic acids and proteins in the turf (Han et al., 2008). ROS are typically considered toxic by-products; however, Mittler (2002) and Neill et al. (2002) state that, at low concentrations, ROS can be used by plants as signaling molecules for processes including systemic signaling and pathogen defense (e.g., systemic acquired resistance). ROS are typically degraded by scavenging antioxidants like catalase (CAT) and ascorbate peroxidase (APX) (Møller, 2001; Krieger-Liszkay, 2004), but Han et al. (2008) observed reduced peroxidase activity in response to simulated soccer traffic on Kentucky bluegrass (*Poa pratensis* L.), tall fescue (*Festuca arundinacea* Schreb.), and Japanese zoysiagrass (*Zoysia japonica* Steud.). Accumulation of ROS are common in stressed plants due to inundated scavenging systems (Mittler, 2002) and the accumulation of hydrogen peroxide (H_2O_2) has been previously observed to induce cell wall cross-linking and cellular protection and defense which can aid in pathogen avoidance (Delledonne et al., 1998). Orozco-Cardenas et al. (2001) has also observed ROS as messengers that activate defense genes like proteinase inhibitors showing that some ROS accumulation can be beneficial in the host-pathogen response. While ROS were not measured in our study, it is possible that regular traffic stress could induce ROS production similar to mowing and rolling as previously observed by Howieson (2005). Assuming that ROS did not accumulate to toxic levels, protein expression and defense responses may have aided in the reduction of anthracnose observed in trafficked plots. However, further research is needed to quantify ROS production in response to traffic stress and its potential role in reducing anthracnose severity on ABG turf. It is also possible that regular foot traffic could disrupt hyphal extension across turf plants or through the thatch thus inhibiting a disease like anthracnose; however, this hypothesis has also yet to be tested.

Sand topdressing had a significant effect on disease severity on 8 of 11 rating dates in 2007 (Table 1) and 5 of 11 rating dates in 2008 (Table 2). Earlier literature has speculated that sand topdressing could increase plant stress resulting in increased anthracnose disease (Derneoden 2002: Smiley et al., 2005); however, this theory was not tested until recently. In June and July 2007, sand topdressing increased anthracnose severity up to 7% compared to non-topdressed plots (Table 1). This was not unexpected since Inguagiato et al. (2008b) showed similar increases (i.e., 8%) within the first few months of initiating a sand topdressing program. However, by 14 August 2007, the topdressed plots had less disease severity compared to non-topdressed plots. Sand topdressing reduced anthracnose severity 5 to 9% compared to non-topdressed plots on the final three rating dates of 2007, and 3 to 7% on all dates when topdressing affected this disease in 2008. The results from the current study indicate sand topdressing can consistently reduce anthracnose severity even under intense foot traffic once a sand layer has built up in the turf canopy.

Applications of sand topdressing promote a more upright growth habit of tillers and shoots by providing structural integrity at the base of the plant. The collection of sand around the base of a plant results in the crown developing in the growing media instead of accumulating in the thatch (Murphy et al., 2008) as sand topdressing has been previously shown to reduce thatch. Carrow et al. (1987) observed a 44 and 67% reduction in thatch depth for plots topdressed with 6.4 and 12.8 mm of sand, respectively, on bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. tranvaalensis* Burtt-Davy] putting green turf. Topdressing has also been shown to reduce mower scalp on creeping bentgrass [*Agrostis stoloniferous* L. var. *palustris* (Huds)] (McCarty et al., 2007) and bermudagrass (White and Dickens, 1984) turf maintained as putting greens. The application of sand creates a firmer, more supportive playing surface that is less susceptible to mower scalp as a firmer surface betters support the weight of the mower, thus preventing it from sinking into the canopy (essentially raising the effective height of cut) and removing additional plant material. Slight increases in cutting height have been shown to reduce anthracnose severity (Inguagiato et al., 2009).

Foot traffic and sand topdressing interacted three times during both years. The treatment interactions on 12 and 19 July 2007 (Table 1b) indicated that the transition to lower disease severity on topdressed plots began sooner on plots receiving foot traffic. Moreover, the interaction between foot traffic and topdressing on 22 July 2008 (Table 2b) indicated that the reduction in disease severity caused by topdressing was only evident on plots receiving foot traffic. These interactions indicate that the benefits of topdressing are influenced by frequent foot traffic. Foot traffic could be beneficial by better incorporating the sand into the canopy compared to plots that only received brushing. More effective sand incorporation could reduce sand loss by daily mowing, which, in addition to the smoothing effects on the playing surface, could partially explain the lower disease severity observed in plots receiving foot traffic; however, sand loss through mowing was not measured in this study. In light of these results, it is apparent that the addition of daily foot traffic to sand topdressed plots does not negate the beneficial effects of sand topdressing in reducing anthracnose severity, which had been hypothesized prior to conducting this study. Moreover, these results show that sand should be continually applied, even under heavy foot traffic, to reduce disease severity on ABG putting green turf.

Turf Quality

The main effect of foot traffic influenced turf quality on 3 of 8 rating dates during 2007 (Table 3); however, on one of these three dates the response to foot traffic was dependent on the level of topdressing. Generally, foot traffic had no effect on turf quality until later in the season (14 August to 4 September 2007) when quality was better in foot trafficked plots. The interaction on 14 August indicated that turf quality was improved by foot traffic only in topdressed plots (Table 3b).

The topdressing main effect influenced turf quality on 6 of 8 rating dates during 2007 (Table 3). And similar to anthracnose development, topdressing had a negative effect on turf quality from 19 June to 12 July, but then improved turf quality at the end of the season. The interactions observed on 14 August and 4 September indicated that topdressing improved quality only on foot trafficked plots (Table 3b).

Turf quality was affected by foot traffic and sand topdressing on 8 and 8 of 13 rating dates, respectively, during 2008 (Table 4). Generally, turf quality was initially reduced by foot traffic from 11 June to 9 July; however, the interactions on 11 June, and 2 and 9 July indicated this reduction in quality was frequently evident in only the non-topdressed plots (Table 4b). Turf quality was better under foot traffic from 30 July to 7 September, the same period when disease severity was also reduced by foot traffic (Table 2). The interactions observed on 30 July, 13 August and 7 September indicated that foot traffic and sand topdressing improved turf quality, but this effect frequently occurred only on plots that received both foot traffic and sand topdressing (Table 4b).

Turf quality ratings were rarely above the minimum acceptable level (≥5) during the study due to both wear stress and high disease levels. These results illustrate that foot traffic was applied in a manner conducive to decreased turf quality. Additionally, interactions illustrate that plots receiving foot traffic and sand topdressing were either no different or slightly better in turf quality compared to foot traffic alone, showing that ABG turf tolerates frequent traffic better when topdressing is applied. This is most likely due to sand topdressing providing a firmer surface that can better support foot traffic as was previously discussed for mowing practices. The promotion of upright growth provided by sand topdressing could also influence turf quality. If a mower is removing less of the plant (effectively raising the height of cut), then more plant material is left behind resulting in a more dense turf canopy. A more dense turf canopy will ultimately result in higher turf quality since turf color, density and uniformity are parameters often used to determine turf quality. Additionally, a more dense canopy will increase the photosynthesic capacity of the turf; Davis and Dernoeden (1991) observed increased carbohydrates and better turf quality in Kentucky bluegrass turf maintained at 7.6 cm compared to 3.8 cm. The increased height of cut could also increase rooting depth (Juska and Hanson, 1961; Lui and Huang, 2002) and tolerance to environmental stress (Beard and Daniel, 1966), a common problem that decreases turf quality of ABG in the summer. Since foot traffic is a common occurrence on golf course putting greens, sand topdressing should be applied to reduce the negative effects of foot traffic observed in our study.

Turf Color

Plots receiving daily foot traffic had decreased turf color on 12 of 20 rating dates during the 2-yr study (Tables 5 and 6) compared to non-trafficked plots. The reduction in turf color observed in trafficked plots from mid-July to late-August was due to wear stress, whereas the decrease in turf color on non-trafficked plots was more the result of high levels of anthracnose (Tables 1 and 2) that increased chlorotic tissue during this period.

Sand topdressing only affected turf color on 3 of 20 rating dates across both years. Turf color was actually reduced in sand topdressed plots on 19 July 2007 (Table 5); higher disease levels within these plots increased the amount of chlorotic tissue and color was further reduced in plots that also received foot traffic (Table 5b). On 16 June and 22 July 2008, turf color was increased in sand topdressed plots (Table 6). Similarly, Carrow et al. (1987) observed better turf color in topdressed bermudagrass, which they attributed to higher temperatures at the soil surface; temperatures at the soil surface were 1 to 2.5º C higher in the spring on topdressed plots allowing the turf to start growing and green-up faster than non-topdressed plots. However, our study was conducted in during the summer months on ABG, a cool season turf. Barton et al. (2009) also observed improved turf color with topdressing (5 mm) of Kikuyu [*Pennisetum clandestinum* (Hochst. Ex Chiov)] in May and November. Better turf color in plots receiving sand topdressing may also be related to the increased amount of photosynthetic tissue possibly achieved through increasing the effective cutting height, which would increase plant vigor thus, producing better turf color. Slight increases in cutting height (0.7 mm) have been reported to improve turf color of ‘TifEagle’ bermudagrass (Guertal and Evans, 2006).

Soil Bulk Density

Foot traffic increased the bulk density of the soil 1 to 9% by 2 September 2007 and all dates in 2008 (Table 7). Topdressing had no effect on bulk density throughout the study except when it interacted with foot traffic on 21 May and 3 June 2008 (Table 7b). On both dates, the combination of foot traffic and sand topdressing significantly increased bulk density, however, turf receiving either treatment alone had bulk densities similar to untreated check plots. It is possible that foot traffic on sand topdressed plots resulted in increased incorporation (packing) of sand thus increasing the bulk density. Increased soil bulk density is normally associated with negative effects including reduced root growth (Sprague and Burton, 1937; Sills and Carrow, 1983). However, the increased bulk density of trafficked plots in our study on 2 September and throughout 2008 was very small and such plots actually had decreased anthracnose severity compared to non-trafficked turf (Tables 1 and 2) suggesting that the degree of compaction was not great enough to adversely affect plant growth.

Breland and Hansen (1996) reported that retention of ^{15}N in soil organic matter and microbial biomass increased in a compacted sandy loam (bulk density of 1.3 g cm^{-3}). Since increased N fertilization is known to decrease anthracnose in ABG (Inguagiato et al., 2008a), it is also possible that the increase in soil bulk density reported in our study may have indirectly reduced anthracnose severity of trafficked plots (Tables 1 and 2). Additionally, compaction can inhibit ectomycorrhizal hyphae from extending within the soil (Skinner and Bowen, 1974). If the same were true for *C. cereale*, this may help explain the reduction in anthracnose observed in the current study on plots receiving foot traffic.

CONCLUSION

Regular foot traffic is a common occurrence on golf course putting greens. Although previous research generally highlights the negative aspects of traffic, results from our study show that regular foot traffic can reduce anthracnose disease on ABG putting green turf. Additionally, the negative aspects of foot traffic such as decreased turf quality can be minimized through regular applications of sand topdressing. With this in mind, it appears that the degree of wounding commonly associated with both foot traffic and sand topdressing are not severe enough to increase anthracnose, providing further evidence that wounding is not required for anthracnose to develop on turf. These results agree with previous research that shows the benefits of sand topdressing in reducing anthracnose disease. Thus, routine sand topdressing, even under heavy foot traffic, can be considered a component of best management practices for ABG putting green turf. While reductions in anthracnose severity are not always large, regular application of sand topdressing in combination with proper management, such as increased N fertilization, raising mowing heights and maintaining adequate soil water, can potentially reduce the amount of fungicide required to adequately control anthracnose disease on ABG putting greens.

REFERENCES

Agrios, G.N. 2005. Plant pathology. Elsevier Inc. San Diego, CA.

Barton, L., G.G.Y. Wan, R.P. Buck, and T.D. Comer. 2009. Effectiveness of cultural thatch-mat controls for young and mature kikuyu turfgrass. Agron. J. 101:67-74.

Beard, J.B. 1973. Turfgrass science and culture. Prentice-Hall, Inc. Englewood Cliffs, NJ.

Beard, J.B. 2002. Turf management for golf courses. 2nd ed. Ann Arbor Press, Chelsea, MI.

Beard, J.B., and W.H. Daniel. 1966. Relationship of creeping bentgrass (*Agrostis palustris* Huds.) root growth to environmental factors in the field. Agron. J. 58:337-339

Breland, T.A., and S. Hansen. 1996. Nitrogen mineralization and microbial biomass as affected by soil compaction. Soil Biol. And Biochem. 28:655-63.

Carrow, R.N., B.J. Johnson, and R.E. Burns. 1987. Thatch and quality of Tifway bermudagrass turf in relation to fertility and cultivation. Agron. J. 79:524-530.

Crouch, J.A., B.B. Clarke, and B.I. Hillman. 2006. Unraveling evolutionary relationships among the divergent lineages of *Colletotrichum* causing anthracnose disease in turfgrass and corn. Phytopathology. 96:46-60.

Davis, D.B., and P.H. Dernoeden. 1991. Summer patch and Kentucky bluegrass quality as influenced by cultural practices. Agron. J. 83:670-677.

Delledonne, M. Y. Xia, R.A. Dixon, and C. Lamb. 1998. Nitric oxide functions as a signal in plant disease resistance. Nature 394:585-588.

Dernoeden, P.H. 2002. Creeping bentgrass management: summer stresses, weeds, and selected maladies. John Wiley & Sons, Inc., Hoboken, NJ.

Gomez, K.A., and A.A. Gomez. 1984. Statistical procedures for agricultural research. 2nd ed. John Wiley & Sons, Inc., Hoboken, NJ

Guertal, E.A., and D.L. Evans. 2006. Nirtogen rate and mowing height effects on TifEagle bermudagrass establishment. Crop Sci. 46:1772-1778.

Han, L.B., G.L. Song, and X. Zhang. 2008. Preliminary observations on physiological responses of three turfgrass species to traffic stress. HortTechnology 18:139-143.

Hathaway, A.D., and T.A. Nikolai. 2005. A putting green traffic methodology for research applications established by in situ modeling. Int. Turfgrass Soc. Res. J. 10:69-70.

Howieson, M.J. Influence of mowing frequency and mower sharpness on efficiency of PSII and antioxidant and carbohydrate metabolism of creeping bentgrass. Ph.D. dissertation. Iowa State University, Ames, IO.

Hurto, K.A., A.J. Turgeon, and L.A. Spomer. 1980. Physical charecteristics of thatch as a turfgrass growing medium. Agron. J. 72:165-167.

Inguagiato, J.C., J.A. Murphy, and B.B. Clarke. 2008a. Anthracnose severity on annual bluegrass influenced by nitrogen fertilization, growth regulators, and verticutting. Crop Sci. 48:1595-1607.

Inguagiato, J.C., J.A. Murphy, B.B. Clarke, and J.A. Roberts. 2008b. Topdressing incorporation and sand shape effects on anthracnose severity of annual bluegrass. 2008 Joint Annual Meeting of GSA, SSSA, ASA, CSSA, GCAGS, and HGS, Houston, TX. DOI:561-5

Inguagiato, J.C., J.A. Murphy, and B.B. Clarke. 2009. Anthracnose disease and annual bluegrass putting green performance affected by mowing practices and lightweight rolling. Crop Sci. 49:1454-1462.

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

Krieger-Liszkay, A. 2004. Singlet oxygen production in photosynthesis. J. Exp. Bot. 56: 337-346.

Landschoot, P., and B. Hoyland. 1995. Shedding some light on anthracnose basal rot. Golf Course Manage. 11:52-55.

Ledeboer, F.B., and C.R. Skogley. 1967. Investigations into the nature of thatch and methods for its decomposition. Agron. J. 59:320-323.

Liu, X., and B. Huang. 2002. Mowing effects on root production, growth, and mortality of creeping bentgrass. Crop Sci. 42:1241-1250.

Lins, S.R.O, and R.S.B. Coelho. 2003. Anthracnose in torch ginger (*Etlingera elatior*): Occurrence and inoculation methods. Summa Phytopathologica 29:355-358.

Mann, R.L., and A.J. Newell. 2005. A survey to determine the incidence and severity of pests and diseases on golf course putting greens in England, Ireland, Scotland, and Wales. Int. Turfgrass Soc. Res. J. 10:224-229.

McCarty, L.B., M.F. Gregg, and J.E. Toler. 2007. Thatch and mat management in an established creeping bentgrass golf green. Agron. J. 99:1530-1537.

Mittler. R. 2002. Oxidative stress, antioxidants, and stress tolerance. Trends Plant Sci. 7:405-410.

Møller, I.M. 2001. Plant mitochondria and oxidative stress: electron transport, NADPH turnover, and metabolism of reactive oxygen species. Ann. Rev. Plant Physiol. Plant Mol. Biol. 52: 561-591.

Murphy, J., F. Wong, L. Tredway, J. Crouch, J. Inguagiato, B. Clarke, T. Hsian, and F. Rossi. 2008. USGA Best management practices for anthracnose on annual bluegrass turf. Golf Course Manage. 76:93-104

Niell, S.J., R. Desikan, A. Clarke, R.D. Hurst, and J.T. Hancock. 2002. Hydrogen peroxide and nitric oxide as signaling molecules in plants. J. Exp. Botany. 53:1237-1247.

Orozco-Cardenas M.L., J. Narvaez-Vasquez, and C.A. Ryan. 2001. Hydrogen peroxide acts as a second messenger for the induction of defense genes in tomato plants in response to wounding, systemin, and methyl jasmonate. Plant Cell. 13: 179-191.

Roberts, J.A., J.C. Inguagiato, B.B. Clarke, and J.A. Murphy. 2008. Influence of irrigation management on anthracnose severity of annual bluegrass. 2008 Joint Annual Meeting of GSA, SSSA, ASA, CSSA, GCAGS, and HGS, Houston, TX. DOI:561-1

Samaranayake, H., T.J. Lawson, and J.A. Murphy. 2008. Traffic stress effects on bentgrass putting green and fairway turf. Crop Sci. 48:1193-1202.

Sills, M.J., and Carrow, R.N. 1983. Turfgrass growth, N use, and water use under soil compaction and N fertilization. Agron. J. 75(3):488-492.

Skinner, M.F, and G.D. Bowen. 1974. The penetration of soil by mycelia strands of ectomycorrhizal fungi. Soil Bio. and Biochem. 6:57-61

Smiley, R.W., P.H. Dernoeden, and B.B. Clarke. 2005. Compendium of turfgrass diseases. 3rd ed. The American Pathological Society, St. Paul, MN.

Sprague, N.B., and Burton, G.W. 1937. Annual bluegrass (*Poa annua* L.) and its requirements for growth. NJ Ag. Exp. Station Bulletin. 630.

Spring, C.A., J.A. Wheater, and S.W. Baker. 2007. Fertiliser, sand topdressing, and aeration programmes for football pitches. I. Performance characteristics under simulated wear. J. of Turfgrass and Sports Surface Sci. 83:40-54

Towers, G., K. Green, E. Weibel, P. Majumdar, and B.B. Clarke. 2002. Evaluation of fungicides for the control of anthracnose basal rot on annual bluegrass, 2002. Fungicide Nematicide Tests 58:T017. Available at www.plant-managementnetwork.org/pub.trial/fntests/vol58/.

Turgeon, A.J. 2005. Turfgrass management. 5th ed. Reston Publishing Co., Inc., Reston, VA.

Uddin, W., M. Soika, and D. Livingston. 2008. Vertical mowing and mowing height affect anthracnose basal rot. Golf Course Manage. 76:84-87.

USGA, Staff. 2004. USGA recommendations for a method of putting green construction. U.S. Golf Assoc. Green Section Construction Educ. Progr. Waco, TX.

Vavrek, B. 2002. Traffic. How much can you bare? USGA Green Sec. Rec. 40:1-5.

Vermeulen, P.H. 2003. Maybe it's time for a change. USGA Green Sec. Rec. 41:28.

Venard, C., and L. Vaillancourt. 2007. Penetration and colonization of unwounded maize tissues by the maize anthracnose pathogen *Colletotrichum graminicola* and the related nonpathogen *C. sublineolum*. Mycologia 99: 368-377.

White, R.H., and R. Dickens. 1984. Thatch accumulation in bermudagrass as influenced by cultural practices. Agron. J. 76:19-22.

Wong, F.P., and S. Midland. 2004. Fungicide-resistant anthracnose: bad news for greens management. Golf Course Manage. 72:75-80.

Younger, V.B. 1962. Wear resistance of cool season turfgrasses: effects of previous mowing practices. Agron. J. 54:198-99.

Zontek, S. 2004. Have we gone too far? The grass is talking to you. Are you listening? USGA Green Sec. Rec. 42:28.

Table 1. Anthracnose disease severity response to foot traffic and sand topdressing on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2007.

	Turf area infested										
Main Effects	12 Jun	14 Jun	22 Jun	4 Jul	12 Jul	19 Jul	25 Jul	6 Aug	14 Aug	24 Aug	4 Sep
Foot Traffic (FT)†	----------	----------	----------	----------	----------	%	----------	----------	----------	----------	----------
200 rounds d^{-1}	7.3	10.8	17.2	17.6	17.3	15.3 b	18.9 b	25.4 b	29.3 b	25.4 b	28.3 b
None	7.9	13.4	18.4	21.3	23.5	31.5 a	33.9 a	49.9 a	56.8 a	48.5 a	55.7 a
Topdressing (T)‡											
Biweekly	11.2 a§	15.4 a	19.2	22.7 a	24.0 a	25.1 a	26.9	35.9	40.7 b	32.4 b	38.0 b
None	4.0 b	8.8 b	16.3	16.3 b	16.7 b	21.7 b	26.0	39.4	45.3 a	41.5 a	46.1 a
Source of Variation						ANOVA					
FT	NS¶	NS	NS	NS	NS	**	*	***	***	***	***
T	***	*	NS	*	**	*	NS	NS	*	**	***
FT*T	NS	NS	NS	NS	*	0.053	NS	NS	NS	NS	NS
CV (%)	17.7	28.8	28.9	22.6	12.9	12.9	13.8	8.5	6.0	10.3	6.0

*Significant at the 0.05 probability level
**Significant at the 0.01 probability level
***Significant at the 0.001 probability level
†Foot traffic consisted of either none or 64 straight-line passes of foot traffic (~200 rounds of golf) per day, 5 days per week, from 14 June to 4 Sept. 2007
‡Topdressing was applied biweekly at 0.3 L m^{-2} of sand from 14 May to 28 Aug. 2007
§Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05)
¶NS, not significant

Table 1b: Interaction means for anthracnose disease severity response to foot traffic and sand topdressing on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2007.

	Turf area infested										
Interaction Means	12 Jun	14 Jun	22 Jun	4 Jul	12 Jul	19 Jul	25 Jul	6 Aug	14 Aug	24 Aug	4 Sep
						%					
None	3.8	8.6	15.9	16.9	17.8 a	27.9	32.6	50.6	58.2	52.7	59.8
Traffic alone†	4.3	9.1	16.8	15.7	15.7 a	15.4	19.3	28.2	32.4	30.4	32.3
Sand alone‡	12.0	18.2	18.5	25.8	29.2 b	35.0	35.3	49.2	55.3	44.4	51.6
Traffic+sand	10.3	12.5	20.0	19.6	18.9 a	15.2	18.5	22.6	26.1	20.4	24.3
Type 1 - lsd¶	2.0	3.2	4.2	3.9	6.5	5.9	7.2	2.5	5.8	3.3	1.7
Type 2 - lsd#	1.6	4.3	6.3	5.4	3.2	3.7	4.5	3.9	3.2	4.7	3.1
Type 3 - lsd††	3.3	8.5	12.6	10.8	6.4	7.4	8.9	7.9	6.4	9.3	6.1
Type 4 - lsd‡‡	2.9	6.4	9.2	8.0	7.7	7.6	9.2	5.7	7.1	6.9	4.3
CV (%)	17.7	28.8	28.9	22.6	12.9	12.9	13.8	8.5	6.0	10.3	6.0

†Foot traffic consisted of either none or 64 straight-line passes of foot traffic (~200 rounds of golf) per day, 5 days per week, from 14 June to 4 Sept. 2007

‡Topdressing was applied biweekly at 0.3 L m^{-2} of sand from 14 May to 28 Aug. 2007

§Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05)

¶Type 1 least significant difference comparing two main plot means (averaged over all sub-plot treatments)

#Type 2 least significant different comparing two sub-plot means (averaged over all main-plot treatments)

††Type 3 least significant difference comparing two sub-plot means at the same main-plot treatment

‡‡Type 4 least significant difference comparing two main-plot means at the same or different sub-plot treatments

Table 2. Anthracnose disease severity response to foot traffic and sand topdressing on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2008.

	Turf area infested										
Main Effects	17 Jun	25 Jun	2 Jul	9 Jul	17 Jul	22 Jul	30 Jul	5 Aug	13 Aug	20 Aug	7 Sep
Foot Traffic (FT)[†]						%					
200 rounds d^{-1}	1.1	1.4	4.2	2.4 b[§]	15.5 b	19.1 b	36.9 b	33.1 b	30.3 b	21.8 b	23.3 b
None	1.2	1.5	4.3	4.6 a	25.7 a	29.3 a	50.7 a	53.0 a	54.6 a	41.1 a	46.7 a
Topdressing (T)[‡]											
Biweekly	1.0	1.4	4.0	3.4	19.3 b	22.8 b	42.4	41.6 b	42.2	29.1 b	31.5 b
None	1.3	1.5	4.6	3.5	21.9 a	25.6 a	45.2	44.4 a	42.6	33.7 a	38.5 a
Source of Variation						ANOVA					
FT	NS[¶]	NS	NS	**	*	**	*	*	**	***	**
T	NS	NS	NS	NS	**	*	NS	*	NS	*	**
FT*T	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
CV (%)	45.0	19.8	29.7	19.5	8.7	3.7	5.3	3.9	22.1	8.9	6.8

[*]Significant at the 0.05 probability level
[**]Significant at the 0.01 probability level
[***]Significant at the 0.001 probability level
[†]Foot traffic consisted of either none or 64 straight-line passes of foot traffic (~200 rounds of golf) per day, 5 days per week, from 6 June to 7 Sept. 2008
[‡]Topdressing was applied biweekly at 0.3 $L\ m^{-2}$ of sand from 15 May to 29 Aug. 2008
[§]Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05)
[¶]NS, not significant

Table 2b. Interaction means for anthracnose disease severity response to foot traffic and sand topdressing on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2008.

	Turf area infested										
Interaction Means	17 Jun	25 Jun	2 Jul	9 Jul	17 Jul	22 Jul	30 Jul	5 Aug	13 Aug	20 Aug	7 Sep
	%										
None	1.6	1.6	4.6	4.5	26.7	30.0 a	52.0	53.7	56.6	42.6	50.5
Traffic alone[†]	1.0	1.4	4.6	2.6	17.0	21.2 b	38.4	35.2	28.7	24.9	26.5
Sand alone[‡]	0.8	1.4	4.1	4.7	24.6	28.5 a	49.4	52.3	52.6	39.6	42.9
Traffic+sand	1.1	1.5	3.8	2.2	14.0	17.0 b	35.4	31.0	31.9	18.7	20.1
Type 1 - lsd[¶]	0.4	0.7	2.1	0.9	3.3	3.2	10.7	6.7	10.8	3.8	7.3
Type 2 - lsd[#]	0.6	0.4	1.6	0.8	2.2	0.3	2.9	2.0	11.5	3.4	2.2
Type 3 - lsd[††]	1.2	0.7	3.1	1.7	4.4	0.7	5.7	4.1	22.9	6.8	5.8
Type 4 - lsd[‡‡]	0.9	0.8	2.9	1.4	4.3	3.2	11.3	7.2	18.4	5.9	8.3
CV (%)	45.0	19.8	29.7	19.5	8.7	3.7	5.3	3.9	22.1	8.9	6.8

[†]Foot traffic consisted of either none or 64 straight-line passes of foot traffic (~200 rounds of golf) per day, 5 days per week, from 6 June to 7 Sept. 2008

[‡]Topdressing was applied biweekly at 0.3 L m^{-2} of sand from 15 May to 29 Aug. 2008

[§]Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05)

[¶]Type 1 least significant difference comparing two main plot means (averaged over all sub-plot treatments)

#Type 2 least significant different comparing two sub-plot means (averaged over all main-plot treatments)

[††]Type 3 least significant difference comparing two sub-plot means at the same main-plot treatment

[‡‡]Type 4 least significant difference comparing two main-plot means at the same or different sub-plot treatments

Table 3. Turf quality response to foot traffic and sand topdressing on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2007.

	Turf quality							
Main Effects	19 Jun	5 Jul	12 Jul	19 Jul	2 Aug	14 Aug	24 Aug	4 Sep
Foot Traffic (FT)[†]	---------------------------------------1-9; 9 = best ---							
200 rounds d^{-1}	5.4	4.4	4.9	4.0	4.5	4.8 a	4.5 a	5.3 a
None	5.5	4.4	4.3	3.6	3.8	3.9 b	3.3 b	3.9 b
Topdressing (T)[‡]								
Biweekly	5.0 a[§]	4.0 a	4.1 a	3.8	4.0	4.5 a	4.3 a	4.9 a
None	5.9 b	4.8 b	5.0 b	3.9	4.3	4.1 b	3.5 b	4.3 b
Source of Variation	ANOVA							
FT	NS[¶]	NS	NS	NS	NS	*	**	***
T	*	*	*	NS	NS	*	***	***
FT*T	NS	NS	NS	NS	NS	**	NS	*
CV (%)	8.8	8.1	10.5	16.5	23.2	5.8	7.4	5.5

[*]Significant at the 0.05 probability level
[**]Significant at the 0.01 probability level
[***]Significant at the 0.001 probability level
[†]Foot traffic consisted of either none or 64 straight-line passes of foot traffic (~200 rounds of golf) per day, 5 days per week, from 14 June to 4 Sept. 2007
[‡]Topdressing was applied biweekly at 0.3 L m^{-2} of sand from 14 May to 28 Aug. 2007
[§]Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05)
[¶]NS, not significant

Table 3b. Interaction means for turf quality response to foot traffic and sand topdressing on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2007.

	Turf quality							
Interaction Means	19 Jun	5 Jul	12 Jul	19 Jul	2 Aug	14 Aug	24 Aug	4 Sep
	-----------------------------------1-9; 9 = best -------------------------------------							
None	6.0	4.8	4.8	3.8	4.0	4.0 a	3.0	3.8 a
Traffic alone†	5.8	4.8	5.3	4.0	4.5	4.3 a	4.0	4.8 b
Sand alone‡	5.0	4.0	3.8	3.5	3.5	3.8 a	3.5	4.0 a
Traffic+sand	5.0	4.0	4.5	4.0	4.5	5.3 b	5.0	5.8 c
Type 1 - lsd¶	1.2	1.1	1.0	0.8	1.0	0.8	0.5	0.4
Type 2 - lsd#	0.6	0.4	0.6	0.8	1.2	0.3	0.4	0.3
Type 3 - lsd††	1.2	0.9	1.2	1.5	2.3	0.6	0.7	0.6
Type 4 - lsd‡‡	1.4	1.3	1.3	1.3	1.8	0.9	0.7	0.6
CV (%)	8.8	8.1	10.5	16.5	23.2	5.8	7.4	5.5

†Foot traffic consisted of either none or 64 straight-line passes of foot traffic (~200 rounds of golf) per day, 5 days per week, from 14 June to 4 Sept. 2007

‡Topdressing was applied biweekly at 0.3 L m^{-2} of sand from 14 May to 28 Aug. 2007

§Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05)

¶Type 1 least significant difference comparing two main plot means (averaged over all sub-plot treatments)

#Type 2 least significant different comparing two sub-plot means (averaged over all main-plot treatments)

††Type 3 least significant difference comparing two sub-plot means at the same main-plot treatment

‡‡Type 4 least significant difference comparing two main-plot means at the same or different sub-plot treatments

Table 4. Turf quality response to foot traffic and sand topdressing on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2008.

	Turf quality												
Main Effects	6 Jun	11 Jun	16 Jun	25 Jun	2 Jul	9 Jul	17 Jul	22 Jul	30 Jul	5 Aug	13 Aug	20 Aug	7 Sep
Foot Traffic(FT)[†]	---1-9; 9 = best ---												
200 rounds d^{-1}	6.9	6.5	6.4 b[§]	6.0 b	5.5 b	5.5 b	4.3	4.3	4.5 a	4.6 a	4.6 a	5.3 a	4.1
None	7.0	6.9	7.1 a	7.1 a	6.0 a	6.0 a	4.3	4.0	4.0 b	3.8 b	3.3 b	3.9 b	3.8
Topdressing (T)[‡]													
Biweekly	7.0	7.0 a	7.1 a	6.6	6.0 a	6.0 a	4.4	4.3	4.5 a	4.5 a	4.1 a	4.8	4.5 a
None	6.9	6.4 b	6.4 b	6.5	5.5 b	5.5 b	4.1	4.0	4.0 b	3.8 b	3.8 b	4.4	3.4 b
Source of Variation	ANOVA												
FT	NS[¶]	NS	*	**	***	***	NS	NS	***	**	*	**	NS
T	NS	**	**	NS	***	***	NS	NS	***	*	*	NS	**
FT*T	NS	*	NS	NS	***	***	NS	NS	***	NS	*	NS	*
CV (%)	3.6	3.7	5.2	3.8	0.0	0.0	6.8	7.0	0.0	9.1	6.3	8.4	9.7

*Significant at the 0.05 probability level

**Significant at the 0.01 probability level

***Significant at the 0.001 probability level

[†]Foot traffic consisted of either none or 64 straight-line passes of foot traffic (~200 rounds of golf) per day, 5 days per week, from 6 June to 7 Sept. 2008

[‡]Topdressing was applied biweekly at 0.3 L m^{-2} of sand from 15 May to 29 Aug. 2008

[§]Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05)

[¶]NS, not significant

Table 4b. Interaction means for turf quality response to foot traffic and sand topdressing on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2008.

	Turf quality												
Interaction Means	6 Jun	11 Jun	16 Jun	25 Jun	2 Jul	9 Jul	17 Jul	22 Jul	30 Jul	5 Aug	13 Aug	20 Aug	7 Sep
	------1-9; 9 = best------												
None	6.8	6.8 b	6.8	7.0	6.0 b	6.0 b	4.3	4.0	4.0 a	3.5	3.3 a	3.8	3.5 a
Traffic alone[†]	7.0	6.0 a	6.0	6.0	5.0 a	5.0 a	4.0	4.0	4.0 a	4.3	4.3 b	5.0	3.3 a
Sand alone[‡]	7.0	7.0 b	7.5	7.3	6.0 b	6.0 b	4.3	4.0	4.0 a	4.0	3.3 a	4.0	4.0 a
Traffic+sand	7.0	7.0 b	6.8	6.0	6.0 b	6.0 b	4.5	4.5	5.0 b	5.0	5.0 c	5.5	5.0 b
Type 1 - lsd[¶]	0.4	0.4	0.5	0.4	0.0	0.0	1.1	0.5	0.0	0.4	1.0	0.4	0.8
Type 2 - lsd[#]	0.3	0.3	0.4	0.3	0.0	0.0	0.4	0.4	0.0	0.5	0.3	0.5	0.5
Type 3 - lsd[††]	0.8	0.8	1.1	0.8	0.0	0.0	0.9	0.9	0.0	1.2	0.8	1.2	1.2
Type 4 - lsd[‡‡]	0.6	0.6	0.7	0.6	0.0	0.0	1.2	0..65	0.0	0.7	1.1	0.7	1.0
CV (%)	3.6	3.7	5.2	3.8	0.0	0.0	6.8	7.0	0.0	9.1	6.3	8.4	9.7

[†]Foot traffic consisted of either none or 64 straight-line passes of foot traffic (~200 rounds of golf) per day, 5 days per week, from 6 June to 7 Sept. 2008
[‡]Topdressing was applied biweekly at 0.3 L m^{-2} of sand from 15 May to 29 Aug. 2008
[§]Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05)
[¶]Type 1 least significant difference comparing two main plot means (averaged over all sub-plot treatments)
#Type 2 least significant different comparing two sub-plot means (averaged over all main-plot treatments)
[††]Type 3 least significant difference comparing two sub-plot means at the same main-plot treatment
[‡‡]Type 4 least significant difference comparing two main-plot means at the same or different sub-plot treatments

Table 5. Turf color response to foot traffic and sand topdressing on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2007.

	Turf color						
Main Effects	5 Jul	12 Jul	19 Jul	2 Aug	14 Aug	24 Aug	4 Sep
Foot Traffic(FT)[†]	-----------------------------1-9; 9 = Darkest Green -----------------------------						
200 rounds d^{-1}	5.9 a[§]	5.5	3.0 b	5.1	4.4 b	5.3	6.3
None	5.0 b	4.8	5.6 a	5.5	5.5 a	5.1	6.4
Topdressing (T)[‡]							
Biweekly	5.5	5.0	4.1 b	5.4	5.0	5.4	6.8
None	5.4	5.3	4.5 a	5.3	4.9	5.0	5.9
Source of Variation				ANOVA			
FT	*	NS	**	NS	*	NS	NS
T	NS[¶]	NS	*	NS	NS	NS	NS
FT*T	NS	NS	*	NS	NS	NS	NS
CV (%)	4.6	5.6	1.0	9.0	10.7	10.8	8.9

[*]Significant at the 0.05 probability level
[**]Significant at the 0.01 probability level
[†]Foot traffic consisted of either none or 64 straight-line passes of foot traffic (~200 rounds of golf) per day, 5 days per week, from 14 June to 4 Sept. 2007
[‡]Topdressing was applied biweekly at 0.3 L m^{-2} of sand from 14 May to 28 Aug. 2007
[§]Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05)
[¶]NS, not significant

Table 5b. Interaction means for turf color response to foot traffic and sand topdressing on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2007.

	Turf color						
Interaction Means	5 Jul	12 Jul	19 Jul	2 Aug	14 Aug	24 Aug	4 Sep
	-----------------------------1-9; 9 = Darkest Green -----------------------------						
None	5.8	5.0	6.0 c	5.5	5.5	5.0	5.8
Traffic alone†	5.0	5.5	3.0 a	5.0	4.3	5.0	6.0
Sand alone‡	5.0	4.5	5.3 b	5.5	5.5	5.3	7.0
Traffic+sand	5.0	5.5	3.0 a	5.3	4.5	5.5	6.5
Type 1 - lsd¶	0.4	1.4	0.4	1.0	0.8	0.4	1.0
Type 2 - lsd#	0.3	0.4	0.3	0.6	0.6	0.7	0.7
Type 3 - lsd††	0.6	0.7	0.6	1.2	1.2	1.4	1.4
Type 4 - lsd‡‡	0.6	1.5	0.6	1.3	1.1	1.0	1.3
CV (%)	4.6	5.6	1.0	9.0	10.7	10.8	8.9

†Foot traffic consisted of either none or 64 straight-line passes of foot traffic (~200 rounds of golf) per day, 5 days per week, from 14 June to 4 Sept. 2007

‡Topdressing was applied biweekly at 0.3 L m^{-2} of sand from 14 May to 28 Aug. 2007

§Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05)

¶Type 1 least significant difference comparing two main plot means (averaged over all sub-plot treatments)

#Type 2 least significant different comparing two sub-plot means (averaged over all main-plot treatments)

††Type 3 least significant difference comparing two sub-plot means at the same main-plot treatment

‡‡Type 4 least significant difference comparing two main-plot means at the same or different sub-plot treatments

Table 6. Turf color response to foot traffic and topdressing on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2008.

	Turf color												
Main Effects	6 Jun	11 Jun	16 Jun	25 Jun	2 Jul	9 Jul	17 Jul	22 Jul	30 Jul	5 Aug	13 Aug	20 Aug	7 Sep
Foot Traffic (FT)[†]	--------------------1-9; 9 = Darkest Green--------------------												
200 rounds d^{-1}	8.0	7.0 b[§]	7.3	7.0 b	5.6 b	6.0 b	4.0 b	4.5 b	5.3 b	5.1 b	4.8	4.4 b	4.1 b
None	8.0	8.0 a	8.3	8.8 a	7.0 a	7.3 a	5.0 a	6.3 a	6.0 a	6.1 a	5.0	6.3 a	5.3 a
Topdressing (T)[‡]													
Biweekly	8.0	7.5	8.0 a	8.0	6.4	6.6	4.5	5.6 a	5.8	5.9	5.0	5.4	4.9
None	8.0	7.5	7.5 b	7.8	6.3	6.6	4.5	5.1 b	5.5	5.4	4.8	5.3	4.5
Source of Variation	ANOVA												
FT	NS[¶]	***	NS	**	*	*	***	**	*	*	NS	**	*
T	NS	NS	*	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
FT*T	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	0.0	0.0	5.3	3.7	4.0	0.0	0.0	7.6	5.1	9.6	10.3	14.1	11.9

*Significant at the 0.05 probability level

**Significant at the 0.01 probability level

***Significant at the 0.001 probability level

[†]Foot traffic consisted of either none or 64 straight-line passes of foot traffic (~200 rounds of golf) per day, 5 days per week, from 6 June to 7 Sept. 2008

[‡]Topdressing was applied biweekly at 0.3 L m^{-2} of sand from 15 May to 29 Aug. 2008

[§]Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05)

[¶]NS, not significant

Table 7. Soil bulk density response to foot traffic and topdressing on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2007 and 2008.

	Soil bulk density					
	2007	2008				
Main Effects	2 Sep	21 May	3 Jun	17 Jun	2 Jul	5 Sep
Foot Traffic (FT)†	------------------------------------ Mg/m^3 ------------------------------------					
200 rounds d^{-1}	1.40 a§	1.2140 a	1.2973 a	1.3196 a	1.4091 a	1.3726 a
None	1.33 b	1.1943 b	1.2805 b	1.2736 b	1.2934 b	1.3031 b
Topdressing (T)‡						
Biweekly	1.37	1.2082	1.2932	1.3055	1.3578	1.3452
None	1.36	1.2001	1.2846	1.2877	1.3447	1.3306
Source of Variation	ANOVA					
FT	**	*	***	*	***	***
T	NS¶	NS	NS	NS	NS	NS
FT*T	NS	**	*	NS	NS	NS
CV (%)	1.19	0.7	0.7	2.0	2.5	2.3

*Significant at the 0.05 probability level

**Significant at the 0.01 probability level

***Significant at the 0.001 probability level

†Foot traffic consisted of either none or 64 straight-line passes of foot traffic (~200 rounds of golf) per day, 5 days per week, from 14 June to 4 Sept. 2007 and 6 June to 7 Sept. 2008

‡Topdressing was applied biweekly at 0.3 L m^{-2} of sand from 14 May to 28 Aug. 2007 and 15 May to 29 Aug. 2008

§Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05)

¶NS, not significant

Table 7b. Interaction means for soil bulk density response to foot traffic and topdressing on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2007 and 2008.

	Soil bulk density					
	2007	2008				
Interaction Means	2 Sep	21 May	3 Jun	17 Jun	2 Jul	5 Sep
	-- Mg/m^3 --					
None	1.33	1.20 a	1.28 a	1.28	1.28	1.31
Traffic alone†	1.39	1.20 a	1.29 a	1.30	1.41	1.39
Sand alone‡	1.33	1.19 a	1.28 a	1.27	1.31	1.30
Traffic+sand	1.41	1.23 b	1.31 b	1.34	1.41	1.36
Type 1 - lsd¶	0.02	0.02	0.01	0.03	0.05	0.04
Type 2 - lsd#	0.02	0.01	0.01	0.03	0.08	0.08
Type 3 - lsd††	0.04	0.02	0.02	0.06	0.08	0.08
Type 4 - lsd‡‡	0.03	0.02	0.01	0.05	0.08	0.06
CV (%)	1.19	0.7	0.7	2.0	2.5	2.3

†Foot traffic consisted of either none or 64 straight-line passes of foot traffic (~200 rounds of golf) per day, 5 days per week, from 14 June to 4 Sept. 2007 and 6 June to 7 Sept. 2008

‡Topdressing was applied biweekly at 0.3 L m^{-2} of sand from 14 May to 28 Aug. 2007 and 15 May to 29 Aug. 2008

§Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05)

¶Type 1 least significant difference comparing two main plot means (averaged over all sub-plot treatments)

#Type 2 least significant different comparing two sub-plot means (averaged over all main-plot treatments)

††Type 3 least significant difference comparing two sub-plot means at the same main-plot treatment

‡‡Type 4 least significant difference comparing two main-plot means at the same or different sub-plot treatments

APPENDIX

Table 1. Turf color response to irrigation quantity of annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2006.

	Turf Color		
Irrigation quantity	21 Jul	28 Jul	25 Aug
	------1-9; 9=Darkest Green------		
100% ET_o[†]	6.2 c[‡]	5.4 c	4.8 c
80% ET_o	6.8 b	6.2 b	6.2 b
60% ET_o	7.2 b	7.2 a	7.2 a
40% ET_o	8.0 a	7.8 a	7.4 a
Source of Variation		ANOVA	
Treatment	***	***	***
Planned *F*-tests			
Linear	***	***	***
Quadratic	NS[§]	NS	*
CV (%)	33.9	25.3	22

[*]Significant at the 0.05 probability level
[***]Significant at the 0.001 probability level
[†]ET_o, % reference evapotranspiration, calculated daily using onsite weather data and the Penman-Monteith equation. Irrigation was applied daily in the absence of rain from 7 July to 25 Aug. 2006.
[‡]Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05).
[§]NS, not significant

Table 2. Turf color response to irrigation quantity of annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2007.

	Turf color						
Irrigation quantity	8 Jun	19 Jun	5 Jul	13 Jul	19 Jul	2 Aug	20 Aug
	--------------------------1-9; 9 = Darkest Green --------------------------						
100 % ET_o †	7.8 a‡	7.8 a	8.0 a	8.6 a	8.2 a	9.0 a	7.8 a
80% ET_o	6.6 b	6.8 b	7.0 b	7.2 b	7.2 b	8.0 b	7.0 b
60% ET_o	5.8 bc	5.6 c	6.0 c	6.0 c	6.4 c	7.0 c	6.0 c
40% ET_o	5.2 c	4.6 d	5.4 d	5.0 d	5.4 d	5.8 d	5.2 d
Source of Variation				ANOVA			
Treatment	***	***	***	***	***	***	***
Planned *F*-tests							
Linear	***	***	***	***	***	***	***
Quadratic	NS§	NS	NS	NS	NS	NS	NS
CV (%)	10.6	6.4	12.5	10.9	23.3	12.4	16.5

***Significant at the 0.001 probability level

† ET_o, % reference evapotranspiration, calculated daily using onsite weather data and the Penman-Monteith equation. Irrigation was applied daily in the absence of rain from 31 May to 20 Aug. 2007.

‡Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05).

§NS, not significant

Table 3. Turf color response to irrigation quantity of annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2008.

	Turf color											PT[§]
Irrigation quantity	6 Jun	16 Jun	26 Jun	2 Jul	9 Jul	17 Jul	23 Jul	31 Jul	5 Aug	13 Aug	23 Aug	4 Sep
	--------------------------------	-----------------------	1-9; 9 = Darkest Green	-----------------------								--------------------------------
100% ET_o[†]	8.0	8.4 ab[‡]	8.0 a	7.4	7.0	5.4 ab	4.0 c	4.2 c	4.0 c	4.0 c	4.0 b	4.4 b
80% ET_o	8.0	8.8 a	8.0 a	7.6	7.0	5.8 a	5.6 a	6.4 a	6.4 a	5.8 a	5.4 a	6.6 a
60% ET_o	8.0	8.0 b	7.0 b	7.2	7.0	5.4 ab	5.0 b	6.0 a	6.6 a	5.4 a	4.6 ab	6.0 a
40% ET_o	8.0	8.0 b	7.0 b	7.2	7.0	5.0 b	4.8 b	5.4 b	5.4 b	4.6 b	4.4 b	6.2 a
Source of Variation						ANOVA						
Treatment	NS[¶]	*	***	NS	NS	0.05	***	***	***	***	*	**
Planned *F*-tests												
Linear	NS	*	***	NS	NS	NS	**	***	***	NS	NS	**
Quadratic	NS	NS	NS	NS	NS	*	***	***	***	***	*	**
CV (%)	0	4.7	0	8.5	0	7.4	6.5	7.8	9.4	8.2	13	11.7

[*]Significant at the 0.05 probability level

[**]Significant at the 0.01 probability level

[***]Significant at the 0.001 probability level

[†] ET_o, % reference evapotranspiration, calculated daily using onsite weather data and the Penman-Monteith equation. Irrigation was applied daily in the absence of rain from 31 May to 26 Aug. 2008.

[‡]Means followed by the same letter are not significantly different according to Fisher's protected LSD.

[§]PT, Post treatment evaluation, indicates that all plots were watered the same after 26 August 2008

[¶]NS, not significant

Table 4. Plant tissue nitrogen content in response to irrigation quantity of annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2007 and 2008.

	Nitrogen Content				
	2007		2008		
Irrigation quantity	22 Jun	12 Jul	4 Jun	3 Jul	14 Aug
	% N				
100% ET_o[†]	2.1	2.0 a[‡]	1.3	2.1	1.9
80% ET_o	2.2	2.0 a	1.1	2.2	2.2
60% ET_o	2.0	1.7 b	1.2	1.6	1.6
40% ET_o	2.1	1.7 b	1.4	2.3	2.0
Source of Variation			ANOVA		
Treatment	NS[§]	*	NS	NS	NS
Planned *F*-tests					
Linear	NS	*	NS	NS	NS
Quadratic	NS	NS	NS	NS	NS
CV (%)	6.8	10.0	16.9	31.3	27.7

[*]Significant at the 0.05 probability level

[†]ET_o, % reference evapotranspiration, calculated daily using onsite weather data and the Penman-Monteith equation. Irrigation was applied daily in the absence of rain from 31 May to 20 Aug. 2007 and 31 May to 26 Aug. 2008.

[‡]Means followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).

[§]NS, not significant

Table 5. Turf color response to location and roller type on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2007.

Treatment	Turf color 13 Jul	19 Jul	2 Aug
Location (L)[†]	----1-9; 9 = Darkest Green ------		
Center	5.7 a[§]	5.4 a	5.3 a
Perimeter	5.0 b	4.1 b	4.4 b
Lightweight Rolling (LR)[‡]			
Sidewinder Roller	5.5 a	5.2 a	5.1 a
Vibratory Roller	5.4 ab	4.8 ab	5.1 a
None	5.2 b	4.4 b	4.3 b
Source of Variation		ANOVA	
L	NS[¶]	NS	**
LR	NS	NS	NS
L*LR	NS	NS	NS
CV (%)	9	7.4	10.3

[*]Significant at the 0.05 probability level
[**]Significant at the 0.01 probability level
[†]Perimeter location similar to normal putting green perimeter (i.e., turning of mowing and rolling equipment minimized to perimeter plots as well as daily clean up passes from mowing)
[‡]Lightweight Rolling performed every other day after morning mowing from 10 May to 5 Aug 2007
[§]Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05).
[¶]NS, not significant

Table 6. Turf quality response to location and roller type on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2008.

	Turf color								
Treatment	6 Jun	16 Jun	27 Jun	7 Jul	16 Jul	23 Jul	30 Jul	6 Aug	16 Aug
Location (L)†	--1-9; 9 = Darkest Green --								
Center	8.00	7.94	8.00	7.00	6.94	4.94	5.61	4.89	4.61
Perimeter	8.00	8.00	8.00	7.00	6.78	5.22	5.61	4.83	4.33
Lightweight Rolling (LR)‡									
Sidewinder Roller	8.00	7.92	8.00	7.00	6.92	5.17 a§	5.67 a	4.92	4.67
Vibratory Roller	8.00	8.00	8.00	7.00	6.92	5.17 a	5.83 a	5.08	4.42
None	8.00	8.00	8.00	7.00	6.75	4.92 b	5.33 b	4.58	4.33
Source of Variation					ANOVA				
L	NS¶	NS	NS	NS	NS	NS	NS	NS	NS
LR	NS	NS	NS	NS	NS	*	*	NS	NS
L*LR	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	0	2.1	0	0	4.6	6	4.6	7.8	5.5

*Significant at the 0.05 probability level

†Perimeter location similar to normal putting green perimeter (i.e., turning of mowing and rolling equipment minimized to perimeter plots as well as daily clean up passes from mowing)

‡Lightweight rolling performed every other day after morning mowing from 13 May to 16 Aug. 2008

§Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05).

¶NS, not significant

Curriculum Vita

JOSEPH ANTHONY ROBERTS

Education:

August 2003 - May 2007 ***North Carolina State University***
- Bachelors of Science in Biological Sciences, 2007
- Bachelors of the Arts in Chemistry, 2007

September 2007 - Present ***Rutgers, The State University of New Jersey***
- Master's student in Plant Biology (expected graduation date October 2009)
- Thesis topic – Management factors of annual bluegrass that may predispose turf to anthracnose

Occupations:

June 2007 - Present ***Graduate Research Assistant* -** Rutgers University Department of Plant Biology

Publications:

June 2007 **Roberts, J.A.**, and Tredway, L.P. 2007. *Curvularia*, a ubiquitous fungus with potential for high pathogenicity. A study of various *Curvularia* isolates involving molecular characterization and effects on multiple cultivars of zoysiagrass. Explorations Journal. 2: pp. 1-7

January 2008 **Roberts, J.A.**, and Tredway, L.P. 2008. First report of *Curvularia* blight of zoysiagrass caused by *Curvularia lunata* in the United States. Plant Disease. 92(1): p. 173.

September 2008 **Roberts, J.A.,** and Tredway, L.P. 2008. First report of curvularia blight of zoysiagrass caused by *Curvularia lunata* in the U.S. Golf Course Management.78(9):pp. 91-92