ANTHRACNOSE OF ANNUAL BLUEGRASS PUTTING GREEN TURF AFFECTED BY SAND TOPDRESSING AND CULTIVATION

by

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ABSTRACT OF THE THESIS

Anthracnose of Annual Bluegrass Putting Green Turf Affected by Sand Topdressing and Cultivation

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Anthracnose, caused by the fungus *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman, is a devastating disease of annual bluegrass [*Poa annua* L. forma *reptans* (Hausskn.) T. Koyama] (ABG) putting green turf. Four field trials were conducted from 2009 to 2011 to examine the effects of sand topdressing and midseason cultivation on anthracnose severity of ABG turf mowed at 3.2-mm. Increased rate of spring (0, 1.2 and 2.4 L m^{-2}) and summer (0, 0.075, 0.15, 0.3 and 0.6 L m^{-2}) topdressing reduced disease severity linearly throughout most of 2009 and 2010. However, increased summer topdressing rate produced a quadratic decrease in disease severity by mid-2010; increased spring topdressing rate reduced the amount (rate) of summer topdressing needed to reduce disease. Sand topdressing during the onset of disease (approximately 10% of the plot area infested with *C. cereale*) in 2009 and 2010 caused a 9 to 14% increase in disease severity 16- to 18-d after treatments were initiated. However, these disease increases lasted only 6- to 9-d and continued sand topdressing reduced disease severity 13 to 20% by the end of each growing season. Verticutting, scarifying and solid-tining increased disease severity up to 18, 10 and 5%, respectively, when performed when symptoms were present (11 to 20% disease severity). These cultivation treatments reduced disease severity relative to the control before treatments were initiated again in 2010 (second trial-year); however, verticutting, scarifying and solid-tining increased disease once again by late-2010. Weekly grooming reduced disease severity up to 9% relative to the control during both trial-years. Cultivation typically did not affect disease severity when curative fungicide was also being applied. Deep vertical cutting (7.6-mm) increased disease 4% relative to the control and 5% relative to shallow vertical cutting (1.3-mm) on 6% of rating dates. Shallow vertical cutting produced small, marginally significant reductions in disease severity compared to the control on 16% of rating dates. Spring topdressing is a strategy for anthracnose suppression that may also reduce the rate of summer topdressing needed to reduce disease severity. Additionally, cultivation practices that only affect leaves, such as grooming, may slightly reduce anthracnose severity.

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TABLE OF CONTENTS

ABSTRACT OF THE THESIS ii

ACKNOWLEDGMENTS iv

TABLE OF CONTENTS v

LIST OF TABLES ix

LIST OF FIGURES xv

CHAPTER 1. Literature Review 1

Introduction 1

Anthracnose Disease 3

Symptomology 4

Causal Agent 5

Disease Cycle 7

Hemibiotrophy: Why does *C. cereale* switch lifestyles? 10

Epidemiology 12

Hosts 16

Chemical Control 20

Cultural Management Practices Affecting Anthracnose 22

Fertility 22

Growth Regulation 23

Mowing 24

Rolling 25

Irrigation 26

Sand Topdressing 26

Vertical Cutting....27
Cultural Practices for Thatch Management....30
Sand Topdressing....31
Cultivation....37
Summary....42
Research Objectives....43
References....45
CHAPTER 2. Anthracnose Disease Development on Annual Bluegrass Influenced by Spring and Summer Sand Topdressing Rate....62
Abstract....62
Introduction....64
Materials and Methods....67
Experimental Design and Treatments....67
Field Maintenance....68
Data Collection....69
Data Analysis....71
Results....73
Anthracnose Severity....73
Turf Quality....75
Incorporation of Summer Topdressing Sand....77
Volumetric Water Content....80
Surface Hardness....80
Turf Color....80

Thatch/Mat Layer Depth and Soil Nutrient Analysis 81
Discussion 83
References 88
CHAPTER 3. Anthracnose of Annual Bluegrass Affected by Sand Topdressing Rate
Applied During Disease Emergence 108
Abstract 108
Introduction 110
Materials and Methods 112
Experimental Design and Treatments 112
Field Maintenance 113
Data Collection and Analysis 115
Results and Discussion 117
Anthracnose Severity 117
Turf Quality 120
Conclusions 121
References 122
CHAPTER 4. Effects of Midseason Cultivation Practices on Anthracnose of Annual
Bluegrass Putting Green Turf 130
Abstract 130
Introduction 132
Materials and Methods 137
Experimental Design and Treatments 137
Field Maintenance 139

Data Collection and Analysis.....141
Results.....143
Anthracnose Severity.....143
Turf Quality.....145
Discussion.....148
References.....153
CHAPTER 5. Vertical Cutting Depth Effects on Anthracnose Severity of Annual Bluegrass Putting Green Turf.....170
Abstract.....170
Introduction.....171
Materials and Methods.....175
Experimental Design and Treatments.....175
Field Maintenance.....175
Data Collection and Analysis.....177
Results.....179
Anthracnose Severity.....179
Turf Quality.....180
Discussion.....181
References.....186
APPENDIX.....199
CURRICULUM VITAE.....209

LIST OF TABLES

Chapter 2:

Table 2.1. Particle size distribution of sand used for topdressing in 2009 and 2010...92

Table 2.2. Anthracnose severity response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009....................93

Table 2.3. Anthracnose severity response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010....................94

Table 2.4. Anthracnose severity response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009....................95

Table 2.5. Anthracnose severity response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009....................96

Table 2.6. Turf quality response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009....................97

Table 2.7. Turf quality response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010....................98

Table 2.8. Turf quality response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009 and 2010 99
Table 2.9. Sand incorporation response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ after three topdressing events in 2009 100
Table 2.10. Sand incorporation response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009....................101
Table 2.11. Number of days for topdressing sand to achieve an acceptable level of incorporation for spring and summer sand topdressing rates on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009....102
Table 2.12. Volumetric water content (measured at a 0-2.54 cm depth using time domain reflectometry) response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009 and 2010....................103
Table 2.13. Surface hardness response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010 104
Table 2.14. Turf color response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2011 105

Table 2.15. Turf color response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2011 106

Table 2.16. Results of nutrient analysis (performed by Mehlich III extraction) of the thatch fraction of two sand topdressing treatments on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ taken on 28 Nov. 2011...107

Table 2.17. Results of nutrient analysis (performed by Mehlich III extraction) of the soil fraction of two sand topdressing treatments on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ taken on 28 Nov. 2011 107

Chapter 3:

Table 3.1. Particle size distribution of sand used for topdressing in 2009 and 2010.125

Table 3.2. Anthracnose severity response to sand topdressing rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009 126

Table 3.3. Anthracnose severity response to sand topdressing rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010 127

Table 3.4. Turf quality response to sand topdressing rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009 128

Table 3.5. Turf quality response to sand topdressing rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010 129

Chapter 4:

Table 4.1. Anthracnose severity response to mid-season cultivation practices applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009. 160

Table 4.2. Anthracnose severity response to mid-season cultivation practices applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010 162

Table 4.3. Analysis of variance of anthracnose severity as affected by mid-season cultivation practices and fungicide applications applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010 163

Table 4.4. Anthracnose severity response to mid-season cultivation practices under no or curative fungicide programs applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010...164

Table 4.5. Anthracnose severity response to the main effect of mid-season cultivation practices applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010....165

Table 4.6. Turf quality response to mid-season cultivation practices applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009 166

Table 4.7. Turf quality response to mid-season cultivation practices applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010 167

Table 4.8. Analysis of variance of turf quality as affected by mid-season cultivation practices and fungicide applications applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010...168

Table 4.9. Turf quality response to mid-season cultivation practices under no or curative fungicide programs applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010...169

Chapter 5:

Table 5.1. Anthracnose severity response to depth of vertical cutting on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010....191

Table 5.2. Anthracnose severity response to depth of vertical cutting on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2011....193

Table 5.3. Anthracnose severity response to depth of vertical cutting on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2011....195

Table 5.4. Turf quality response to depth of vertical cutting on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2011....................197

Table 5.5. Turf quality response to depth of vertical cutting on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2011....................198

Appendix:

Table A.1. Anthracnose severity response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009 199

Table A.2. Anthracnose severity response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010 200

Table A.3. Anthracnose severity response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 13 Aug. 2009. ...201

Table A.4. Turf quality response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009 203

Table A.5. Turf quality response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010 204

Table A.6. Turf quality response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009 205

Table A.7. Turf quality response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010 207

LIST OF FIGURES

Chapter 4:

Figure 4.1. Anthracnose severity response to mid-season cultivation practices applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009. Grooming (1.3 mm depth, 1.5 mm blade width, 5 mm lateral blade spacing), verticutting (3.8 mm depth, 1.5 mm blade width, 10 mm lateral blade spacing), scarifying (7.6 mm depth, 1.5 mm blade width, 40 mm lateral blade spacing), and solid-tining (57 mm depth, 6 mm tine width, 38 by 38 mm spacing) were applied on 24 July and 14 Aug. 2009. Weekly grooming was applied every 7 d from 24 July to 28 Aug. 2009. Error bar indicates Fisher's protected LSD at α = 0.05 for treatment comparison on a specific rating date; no error bar indicates the date is not significant 161

Chapter 5:

Figure 5.1. Anthracnose severity response to depth of vertical cutting on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010. Vertical cutting was applied once on 23 July 2010 using blades that were 1.5 mm thick and spaced 40 mm apart. Error bar indicates Fisher's protected LSD at α = 0.05 for treatment comparison on a specific rating date; no error bar indicates a non-significant F test................................192

Figure 5.2. Anthracnose severity response to depth of vertical cutting on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2011. Vertical cutting was applied once on 6 July 2011 using blades that were

1.5 mm thick and spaced 40 mm apart. No error bar indicates a non-significant F test...194

Figure 5.3. Anthracnose severity response to depth of vertical cutting on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2011. Vertical cutting was applied once on 3 Aug. 2011 using blades that were 1.5 mm thick and spaced 40 mm apart. No error bar indicates a non-significant F test...196

Appendix:

Figure A.1. Anthracnose severity response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009. Sand topdressing applications were initiated on 28 July 2009 for both single (dashed trendline) and biweekly (solid trendline) frequencies. Biweekly applications continued to 24 August 2009...202

Figure A.2. Turf quality response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009. Sand topdressing applications were initiated on 28 July 2009 for both single (dashed trendline) and biweekly (solid trendline) frequencies. Biweekly applications continued to 24 August 2009. Nine (9) represents the best turf characteristic and 5 represents the minimally acceptable rating.......206

Figure A.3. Turf quality response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010. Sand topdressing applications were initiated on 24 May 2010 for both single (dashed trendline) and biweekly (solid trendline) frequencies. Biweekly applications continued to 19 July 2010. Nine (9) represents the best turf characteristic and 5 represents the minimally acceptable rating.............208

CHAPTER 1. Literature Review

INTRODUCTION

Anthracnose, caused by the fungus *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman (Crouch et al., 2006) is an important disease of cool-season grasses in temperate climates throughout the United States, Canada, Western Europe, South America, Southeast Asia, New Zealand, and Australia (Crouch and Beirn, 2009). Outbreaks of the disease increased in frequency and severity during the mid-1990s on annual bluegrass [*Poa annua* L. forma *reptans* (Hausskn.) T. Koyama] (ABG) and creeping bentgrass (*Agrostis stolonifera* L.) putting green turf. Annual bluegrass putting greens have been observed to be the most susceptible turf, possibly due to the weak perennial nature of the species and the stress of low cutting heights (Murphy et al., 2008). The disease produces symptoms on leaves, crowns, stolons and roots and can eventually cause death and severe thinning of the turf. Because thinned, symptomatic turf affects playability and aesthetics of putting greens, outbreaks of anthracnose can result in severe economic losses.

Control options are limited for the management of anthracnose on ABG. Host resistance to *C. cereale* is not available due to the instability of the greens-type phenotype in cultivated *Poa annua* L. (La Mantia and Huff, 2011). Thus, golf course superintendents rely upon applications of costly fungicides to obtain acceptable levels of disease control (Bigelow and Tudor Jr, 2012; Murphy et al., 2008; Young et al., 2010a). Repeated applications of fungicides with site-specific modes of action has resulted in resistance of *C. cereale* to the benzimidazole (Wong et al, 2008) and strobilurin (Wong et al., 2007) fungicide classes and reduced sensitivity has also been observed in the sterol demethylation inhibitor (DMI) class (Wong and Midland, 2007). However, superintendents can reduce the severity of serious anthracnose outbreaks through the implementation of improved cultural practices, such as increasing mowing height and providing adequate nitrogen fertility, irrigation and sand topdressing (Inguagiato et al., 2008; Inguagiato et al., 2009a; Inguagiato et al., 2012; Roberts et al., 2011). Because of the development of fungicide resistance and the inability of even the best fungicide programs to control the disease (Smiley et al., 2005), there is an ongoing need to develop and refine programmatic cultural practices, such as sand topdressing, to manage anthracnose on golf course putting green turf.

Anthracnose disease severity is enhanced when turf stands are stressed (Smiley et al., 2005). Scientists have found that the disease severity is greatest when ABG is weakened due to drought and heat stress (Danneberger et al., 1995; Roberts et al., 2011; Sprague and Evaul, 1930) and conditions that reduce plant vigor such as low nitrogen fertility and low mowing (Inguagiato et al., 2008; Inguagiato et al., 2009a). Furthermore, mechanical injury from abrasive cultural practices that create wounds may enable *C. cereale* to be more invasive (Smiley et al., 2005). However, results from field trials have shown that foot traffic, rolling, brushing, and double-cutting, all practices that wound turf, do not appear to increase anthracnose severity (Inguagiato et al., 2009a; Inguagiato et al., 2012; Roberts et al., 2012). Results on the effect of vertical cutting (VC) on anthracnose are conflicting. This practice consistently increased disease severity when applied to plots maintained at 2.0, 3.3 and 5.1 mm mowing heights (Uddin et al., 2008). In contrast, VC had no effect on the disease on an ABG fairway (Burpee and Goulty, 1984). Vertical cutting also had no effect on anthracnose severity on ABG putting green turf (3.2 mm mowing height) throughout most rating dates during a 3 yr. field trial conducted by Inguagiato et al. (2008); however, the practice did briefly reduce or increase disease during one year in this study. Sand topdressing, often thought of as an abrasive practice, has reduced disease severity on ABG putting green turf in several studies; however, brief increases were observed during the first years of these trials (Inguagiato et al., 2012; Inguagiato et al., 2013; Roberts, 2009). Although most previous research has suggested that wounding does not influence anthracnose development in ABG, results from the aforementioned trials indicate that wounding caused by VC or sand topdressing may, at times, enhance disease severity. However, more research is needed to test this hypothesis and determine under what conditions these practices might affect disease.

ANTHRACNOSE DISEASE

Anthracnose, meaning blackening (from anthrax = carbon = black), is the name applied to leaf diseases caused by fungi that produce their asexual spores (conidia) in an acervulus (Agrios, 2005; Smiley et al., 2005). These diseases, particularly those caused by members of the ascomycete genus *Colletotrichum*, occur worldwide and are very common and damaging on numerous crop and ornamental plants including at least 42 genera of plants in the family *Poaceae* (Agrios, 2005; Crouch and Beirn, 2009). The sexual state of *Colletotrichum* spp. is in the genus *Glomerella*, however the teleomorph is either rare or absent and have not been observed on infected turfgrasses in the field (Crouch and Beirn, 2009). The pathogen *C. cereale* lives saprophytically on residues in turf (e.g., thatch) and usually colonizes senescing leaves and tillers, although it may attack younger plant tissues (Smiley et al., 2005). The disease can occur at almost any time of year and is manifested as either a foliar blight or a basal rot of crown, stolon and root tissue.

Symptomology

Anthracnose foliar blight usually occurs during high temperatures in the summer and causes a yellowing or reddish brown discoloration of leaves and ultimately thinning of the canopy (Smiley et al., 2005). The foliar blight phase can also result in oblong, reddish brown leaf lesions. Distinctive acervuli (fruiting bodies) with black setae can be observed with a hand lens on green, yellow or tan acropetal tissue during this phase (Smiley et al., 2005; Smith et al., 1989). However, the presence of acervuli on residues in thatch does not indicate that healthy plants are infected (Smiley et al., 2005).

Anthracnose basal rot first appears on ABG putting greens during cool weather (winter or spring) as orange or yellow spots 6 to 12 mm in diameter that become large, irregularly shaped patches by late spring (Smiley et al., 2005). The disease progresses slowly throughout the summer, and yellowing begins on the oldest leaves from the tips progressing downward to sheaths (Smith et al., 1989). The youngest (central) leaf is the last to turn yellow and eventually red (Smiley et al., 2005). Thus, plants may display both green, healthy tillers and yellow-orange infected tillers during this phase Removing sheath tissues reveals black, rotting, water-soaked crown and stem tissues from which acervuli are produced (Murphy et al., 2008; Smiley et al., 2005). The blackening of these tissues is due to the dark-colored, dendroid hyphae and dense mycelial aggregates of the fungus (Smith et al., 1989). Anthracnose basal rot may not produce yellowing on leaf and sheath tissue until stem tissues have begun to rot (Smiley et al., 2005). Root systems of plants with basal rot are poor and necrotic, and plants usually die once they reach advanced stages of this phase of the disease (Smiley et al., 2005; Smith et al., 1989).

Causal Agent

The etiological agent of anthracnose of ABG*, C. cereale*, is also associated with 13 other genera of grasses with C3 (cool-season) photosynthetic pathways as either pathogens or endophytes (Crouch and Beirn, 2009). It was only recently that Crouch et al. (2006) resurrected the name *C. cereale* for the causal agent of anthracnose disease of the Poaceae, subfamily Pooideae including turfgrasses. The name *C. graminicola* sensu lato G.W. Wilson, causal agent of anthracnose of maize (*Zea mays* L.), was inappropriately employed to describe anthracnose of turfgrasses for the majority of the 20th century. The separation of maize-infecting isolates and pooid-infecting strains was performed using phylogenetic reconstructions with data sets from 107 *Colletotrichum* isolates at three variable loci using phylogenetic and network-based methodologies. Additionally, it was suggested that *C. cereale* may be a species group comprised of two or more species, rather than a single species, but further research is needed to test this hypothesis (Crouch et al., 2006).

Colletotrichum cereale was first described as a pathogen of grasses in Ohio, US during the early-20th century (Selby and Manns, 1909); however, Wilson (1914) grouped the pathogen with *C. graminicola* when he reported the fungus to be ubiquitous in cereal crops and bluegrasses (*Poa* spp.) in New Jersey. Severe outbreaks of the pathogen on ABG were reported (as *C. cereale*) in New Jersey in 1928 (Sprague and Burton, 1937; Sprague and Evaul, 1930). Researchers performed experiments documenting the pathogenicity of the fungus on ABG and other grass species during the middle of the 20th century (Smith, 1954; Sprague and Evaul, 1930; Wolff, 1947). The name *C. graminicola* given to the fungus by Wilson (1914) was upheld by von Arx (1957) during this time. Reports of increased disease severity during the late-1960s and early-1970s led researchers to consider *C. cereale* (reported as *C. graminicola*) to be a more serious pathogen of turfgrasses (Alexander, 1969; Couch, 1973). The first major epidemic of anthracnose of maize also occurred during the early-1970s, causing destruction of maize crops in north-central and eastern United States (Bergstrom and Nicholson, 1999). Controversy erupted during the late-1970s and early-1980s regarding whether summer decline of ABG was caused by *C. cereale* (reported as *C. graminicola*), environmental stress, a multipathogen complex/syndrome or by a combination of some or all of these factors (Bolton and Cordukes, 1981; Couch, 1979; Jackson and Herting, 1985; Vargas, 1980). However, Koch's postulates were fulfilled during the mid-1980s to confirm the pathogenicity of *C. cereale* (reported as *C. graminicola*) on ABG in the United States (Vargas and Detweiler, 1985). Anthracnose caused severe destruction to golf course putting greens in mid-western, northeastern and northwestern United States during the early-1990s and continues to be a major management issue for golf course superintendents worldwide (Murphy et al., 2012).

A distinct morphological feature of *C. cereale* is the presence of dark brown to black, melanized acervuli. Acervuli first appear immersed, then erumpent on shoot bases, leaf sheaths and leaves (Smith et al., 1989). Their diameters range from 20 to 200 µm when separate, but acervuli may become confluent in a dark, continuous stroma. Dark-brown, sterile setae (hair-like structures) develop around or within acervuli. Setae are irregularly septate with up to 7 septa, measure 32 to 120 µm x 6 to 8 µm, and their bases may be swollen or not swollen (Crouch et al., 2006). Colonies of *C. cereale* grown on potato dextrose agar may appear as a dark mat of setae, and heavy accumulations of conidia often cast an orange hue to the brown/black culture. Cultures of the fungus can exhibit hyphal (septate, hyaline, 2 to 5 µm wide) or mycelial (gray hue) growth, and mycelia usually overtake the entire culture as colonies age. Conidia are falcate or fusiform, apices acute, individually hyaline (salmon/orange color en mass), guttulate, and measure 6 to 34 µm in length and 2 to 6 µm in width. Conidia germinate to form hyaline germ tubes that produce dark brown to black, rounded and smooth or irregularly shaped appressoria (9 to 12 µm x 7 to 10 µm).

Disease Cycle

The source of primary inoculum for infection of leaf sheaths and stolons by *C. cereale* is conidia produced on overwintered residues in thatch (Crouch and Beirn, 2009; Settle et al., 2006). Conidia formed in acervuli are disseminated to the upper leaves or to nearby plants by splashing, blowing or mechanical means. Because little is known about the disease cycle of *C. cereale*, it is useful to summarize what has been reported for other *Colletotrichum* species or graminaceous hosts. In maize, conidia of *C. graminicola* are capable of long-term survival because they are surrounded by an extracellular mucilaginous matrix that contains self-inhibitor and antidessicant compounds that prevent premature germination and drying out, respectively (Bergstrom and Nicholson, 1999). This matrix also contains proline-rich proteins and several degrading enzymes that aid the fungus during the infection process.

To successfully colonize host tissue, *Colletotrichum* species form specific structures during pre- and post-invasive phases of the infection (Münch et al., 2008).

During host epidermal cell invasion, conidia adhere to host tissue and produce a germ tube from which a melanized appressorium forms. Appressoria can survive on the surface of plant tissues for an extended period of time before penetrating the cuticle, which may cause a delayed appearance of symptoms after inoculation (Bergstrom and Nicholson, 1999). A penetration peg, formed from the appressorium, directly invades epidermal cells through the cuticle and cell wall (Crouch and Beirn, 2009). This process is facilitated by a combination of enzymatic degradation and a powerful mechanical force equaling 17 μN (Bechinger et al., 1999; Bergstrom and Nicholson, 1999). Crouch and Clarke (2012) provided perspective on this forceful penetration stating, "if a force of 17 μN was exerted across the palm of a human hand, that individual would be able to lift a school bus weighing almost 17,000 pounds (7.7 metric tons)."

Following penetration, Colletotricha first establish an initial, short-lived biotrophic phase that is followed by a destructive nectrophoic phase. During its biotrophic phase, the fungus obtains nutrients from living host cells via primary hyphae that do not kill the host cell but rather become invaginated in the host plasma membrane (Bergstrom and Nicholson, 1999; Münch et al., 2008; Perfect et al., 1999). The fungus must employ strategies to suppress plant defense responses to achieve this biotrophic interaction with the host (Münch et al., 2008). One strategy used by *C. graminicola* is to convert the surface-exposed chitin of primary hyphae to chitosan via deacetylation to avoid detection and degradation by plant chitinases, which also prevents further host plant defense responses (El Gueddari et al., 2002). Additional strategies used by *Colletotrichum* species to avoid plant defense will be discussed in the next section.

The beginning of the destructive necrotrophic phase of Colletotricha is marked by the formation of secondary hyphae. These smaller hyphae kill the host cell by either secreting plant cell wall-degrading enzymes or inducing cell death by generating reactive oxygen species and then branch out within the necrotic tissue (Münch et al., 2008). Smith (1954) observed that once epidermal cells and the cortex of infected stems below the crown of ABG become overrun by *C. cereale* (reported as *C. graminicola*), the fungus invades the vascular system and plugs xylem and phloem cells with mycelium. However, studies with *C. graminicola* have provided no evidence that anthracnose is a vascular wilt pathogen of maize (Sukno et al., 2008; Venard and Vaillancourt, 2007a). Nevertheless, the likelihood of plant death increases greatly once *C. cereale* has entered advanced stages of infection (Smiley et al., 2005).

Conidia produced in acervuli on necrotic plant tissue serve as secondary inoculum to rapidly disperse the *C. graminicola* and cause repeated disease cycles on maize throughout the season (Bergstrom and Nicholson, 1999). When conditions are unfavorable for growth, *C. cereale* overwinters on infected residues (mycelium, conidia or acervuli in thatch) where it survives as a saprophyte (Crouch and Beirn, 2009). Survival of *Colletotrichum* species in the soil is heavily dependent on environmental conditions, temperature and other soil microflora. Cool temperatures favor survival of *C. graminicola*, which can overwinter for lengthy periods as long as sufficient plant debris is present (Crouch and Beirn, 2009; Smith et al., 1989; Vizvary and Warren, 1982). However, *C. graminicola* is a poor competitor with other soil organisms when not on plant residues (Lipps, 1983). Cultures of the fungus were killed within a few days when covered with field soil in absence of maize residue (Vizvary and Warren, 1982).

Hemibiotrophy: Why does *C. cereale* switch lifestyles?

Infection studies in maize show that of *C. graminicola* switches from a biotrophic to necrotrophic lifestyle 48 to 72 hours after inoculation, depending on environmental conditions (Bergstrom and Nicholson, 1999; Münch et al., 2008). However, the mechanisms responsible for this change are not fully understood and researchers have debated this topic for years (Mims and Vaillancourt, 2002; Perfect et al., 1999). Two recent studies analyzed the transcriptomes—the complete set of RNA transcripts in a cell and their quantity during a specific developmental stage or physiological condition (Wang et al., 2009)—of four *Colletotrichum* species, including *C. graminicola*, during various stages of the infection process to provide insights into this transition (Gan et al., 2013; McDowell, 2013). In both studies the transcript profiles of the biotrophic and necrotrophic phases were very different from one another.

During the biotrophic phase, the production of small, secreted proteins (SSPs; effector molecules) and secondary metabolism enzymes was up-regulated by *C. graminicola* (Gan et al., 2013; McDowell, 2013). The pathogen uses these molecules during colonization and biotrophy to reprogram plant host cells to avoid immune responses that may be triggered by conserved microbe-associated molecular patterns (MAMPS), such as chitin. Contrastingly, the switch to the necrotrophic phase is marked by the up-regulation of degrading enzymes, toxins and nutrient transporters. These findings relate to a previous study which found that a mutant strain of *C. graminicola* did not produce visible symptoms in colonized maize tissue because it did not secrete a sufficient quantity of cell wall degrading enzymes and, thus, could not make the transition from biotrophy to the necrotrophy (Mims and Vaillancourt, 2002).

Transcriptomic, histological and biochemical studies performed by Vargas et al. (2012) showed that maize cells induced defense mechanisms during infection by *C. graminicola*, even during its biotrophic phase. These findings suggest that the fungus does not completely suppress the plant defense mechanisms during its biotrophic phase, contrary to previous belief. Also, the switch to the necrotrophic lifestyle by *C. graminicola* was associated with the highest activation of defense responses in the maize plant. Thus, the authors suggest that the pathogen switches to the necrotrophic phase to escape the effect of the plant immune responses (e.g. production of reactive oxygen species) and continue its pathogenic activity (Vargas et al., 2012).

Several abscisic acid (ABA)-responsive genes were also up-regulated during infection by *C. graminicola* (Vargas et al., 2012), relating to previous work that indicated the involvement of ABA in the regulation of plant defense in maize (Jiang and Zhang, 2001). In a separate experiment, exogenous applications of ABA increased anthracnose disease severity in maize plants infected with *C. graminicola* (Vargas et al., 2012); the disease increase corresponded with the production of secondary hyphae by *C. graminicola*, indicating that the pathogen had switched to a necrotrophic lifestyle after the application of ABA. Increased ABA concentration has also been reported to enhance susceptibility of chili pepper fruits (*Capsicum annuum* cv. Nokkwang) to infection by *C. acutatum* (Hwang et al., 2008). The exact mechanisms responsible for the switch in lifestyles by *C. cereale* remain unknown, but there is increasing evidence that plant physiological responses play an important role in the transition. Bostock and Stermer (1989) outline extensive similarities between plant responses to wounding and infection by pathogens, which include increased levels of ABA and reactive oxygen species.

Therefore, it is possible that plant responses to wounding may also induce a lifestyle switch by *C. cereale* from biotrophic to necrotrophic resulting in increased disease severity; however, more research is needed to test this hypothesis.

Epidemiology

The basal rot phase of *C. cereale* can affect ABG putting greens during almost any time of the year, but the disease is generally most destructive during the hot, humid conditions during the summer in cool temperate climates (Smiley et al., 2005; Smith et al., 1989). Growth chamber, greenhouse and laboratory experiments have shown that increased temperature (25 to 33 C) and increased leaf wetting period (12 to 72 hours) are most conducive to infection by *C. cereale* (Bolton and Cordukes, 1981; Bruehl and Dickson, 1950; Smith, 1954; Sprague and Evaul, 1930; Vargas et al., 1992). A multiple regression model predicted greater foliar anthracnose severity of ABG at higher temperatures (18 to 28 C) and leaf wetness greater than 18 hr; however, the model was limited to an observed temperature range of 16 to 28 C (Danneberger et al., 1984). Conidial germination and appressorium formation by *C. graminicola* has a broad temperature range (15 to 35 C), but host penetration occurs within a much narrower temperature range (25 to 30 C) (Skoropad, 1967).

Anthracnose epidemics have been observed to develop rapidly on cool-season turf under overcast conditions (Smiley et al., 2005). These conditions promote high humidity and extended leaf wetness, which are known to enhance disease activity and are necessary for sporulation of *Colletotrichum* species (Bergstrom and Nicholson, 1999; Smiley et al., 2005). Anthracnose severity on ABG increased after a period of hot, humid weather caused by abnormally heavy rainfall and high temperatures in New Jersey in

1928 (Sprague and Evaul, 1930). Disease spread is obviously favored by rain because conidia are most easily dispersed by splashing raindrops (Bergstrom and Nicholson, 1999).

Overcast conditions reduce light intensity. Schall et al. (1980) reported that decreased light intensity in the greenhouse increased susceptibility of some maize genotypes to *C. graminicola*, and correspondingly, increased light intensity enhanced resistance of maize to anthracnose (Jenns and Leonard, 1985). Anthracnose resistance in maize involves biosynthesis of phenolic compounds, which is a light-dependent process (Nicholson and Hammerschmidt, 1992). However, conidia formation by *C. cereale* has been shown to be promoted by increased light intensity, perhaps due to increased temperature which is often associated with increased light intensity (Crouch and Clarke, 2012).

Stressful conditions are believed to be necessary for infection by *C. cereale*. Plants grown in soils that are compacted, drain poorly or exhibit nutrient (nitrogen, phosphorus or potassium) or water deficiencies are more susceptible to anthracnose (Smiley et al., 2005; Sprague and Burton, 1937). Stresses from heat, drought or low mowing are thought to cause ABG to be particularly susceptible to anthracnose (Smiley et al., 2005). Additionally, abrasive cultural management practices such as topdressing, aerification and vertical cutting create wounds which have been proposed to be means of ingress by *C. cereale*. However, research regarding the effect of wounding on the development of fungal diseases, especially anthracnose, on turfgrasses is contradictory.

A preliminary research study examined the effect of the type (puncture or abrasion) and location (leaf or crown) of wounding on the development of anthracnose basal rot on ABG plants grown in a greenhouse (Landschoot and Hoyland, 1995). Results of this experiment showed that plants that were crown-wounded prior to inoculation, regardless of the type of wound, resulted in faster development of anthracnose basal rot symptoms compared to unwounded, inoculated plants. However, plants that were wounded above the crown prior to inoculation did not produce anthracnose symptoms. In a laboratory experiment performed by Orshinsky et al. (2012), infection by the fungus *Sclerotinia homoeocarpa* F.T. Bennett, the causal agent of dollar spot disease, was more rapid in leaves of creeping bentgrass that were wounded immediately before inoculation compared to unwounded leaves. These results suggest that wounding, especially of crown tissue, might increase anthracnose severity of ABG, but more research should be performed to test this hypothesis.

A relationship may exist between the feeding and wounding activity of parasitic nematodes or insects and anthracnose severity of ABG (Jackson and Herting, 1985; Smiley et al., 2005). Anthracnose leaf blight was more severe in maize plants stressed by the root lesion nematode (*Pratylenchus hexincisus*) (Nicholson et al., 1985), and anthracnose stalk rot of maize has been associated with stem wounding by the European corn borer (*Ostrinia nubilalis* Hübner) (Bergstrom and Nicholson, 1999; White, 1999). Ingress of nonsenescent maize stem tissue by *C. graminicola* is thought to occur through wounds caused by the European corn borer (Bergstrom and Nicholson, 1999).

Muimba-Kankolongo (1991) observed that *C. graminicola* entered wound sites on maize plants via extremely long germ tubes and at times via hyphal strands. However, Bruehl and Dickson (1950) reported that germ tubes of the fungus did not penetrate leaves of Sudan grass (*Sorghum vulgare* var. sudanense (Piper) Hitchc.) through wounds or stomata; rather the fungus entered the host directly with a penetration peg. Wounding was also not necessary for *C. graminicola* to penetrate even the highly lignified fiber cells in rind tissue of maize, although penetration through wounds resulted in a more rapid and efficient infection (Venard and Vaillancourt, 2007b). Moreover, Smith (1954) determined that *C. cereale* (reported as *C. graminicola*) penetrated ABG directly and that wounds were not necessary for infection.

Fungal infection through wounds is transitory by nature. Anthracnose of maize and black dot of potato (*Solanum tuberosum* L.) [caused by *C. graminicola* and C. *coccodes* (Wallr.) S. J. Hughes, respectively] were dramatically reduced when inoculation was delayed by as little as 1 to 2 h after wounding compared to sites inoculated immediately after wounding (Johnson and Miliczky, 1993; Muimba-Kankolongo, 1991; Muimba-Kankolongo and Bergstrom, 1992; Muimba-Kankolongo and Bergstrom, 1990; Muimba-Kankolongo and Bergstrom, 2011). The decrease in disease severity observed when inoculation was delayed after wounding is thought to be a "wound healing" response (Muimba-Kankolongo, 1991; Muimba-Kankolongo and Bergstrom, 1992; Muimba-Kankolongo and Bergstrom, 1990; Muimba-Kankolongo and Bergstrom, 2011).

Wound healing has been reported to confer disease resistance in several plant/pathogen relationships (Bostock and Stermer, 1989; Lipetz, 1970). Monocots achieve disease resistance from wound healing by infusing cells adjacent to wounds with an extensive layer of lignin or other phenols (Bostock and Stermer, 1989). Venard and Vaillancourt (2007a) observed this response, reporting a thickening (lignification) of walls of parenchyma cells around wound sites of maize tissue infected with *C.*

graminicola. Moreover, anthracnose resistance in maize has been linked to the phenylpropanoid pathway, which produces lignin and numerous metabolites involved in defense responses (Bergstrom and Nicholson, 1999; Bostock and Stermer, 1989).

Resistance to *C. graminicola* from a wound healing response was demonstrated in a simple study that involved wounding maize plants at sites that were previously unwounded or wounded, then inoculating these sites with the fungus immediately after wounding (or re-wounding). Previously wounded sites produced significantly less anthracnose than previously unwounded sites (Muimba-Kankolongo and Bergstrom, 1990). In a similar study, Kim (2008) found that anthracnose of chili pepper was also reduced by a wound healing response. Thus, research in other *Colletotrichum spp.* suggests that ABG might achieve some level of resistance to *C. cereale* via a wound healing response; however, experiments need to be designed to test this hypothesis.

Hosts

The fungus *C. cereale* colonizes grasses of the subfamily Pooideae and is pathogenic to many common cool-season turfgrass species such as ABG, creeping bentgrass, fine fescues (*Festuca* spp.), Kentucky bluegrass (*Poa pratensis* L.), ryegrasses (*Lolium* spp.) and velvet bentgrass (*Agrostis canina* L.) (Crouch and Clarke, 2012). Isolates of *C. cereale* can display a high degree of host specificity, meaning that an isolate that is highly pathogenic to one turf species may not be pathogenic to another (Backman et al., 1999; Browning et al., 1999; Hsiang and Goodwin, 2001; Khan and Hsiang, 2003). The fungus is typically most destructive on ABG and creeping bentgrass putting greens, but is especially devastating to ABG possibly due to the weak perennial natures of the species (Murphy et al., 2008; Sprague and Burton, 1937; Sprague and Evaul, 1930).

Annual bluegrass (also known as annual meadow-grass in Europe) has the most widespread distribution of all managed turfgrasses but is most commonly found as an invasive, annual weed in maintained turf (Huff, 2003; Vargas and Turgeon, 2004). The value of ABG as a turfgrass has been debated for over a century, and literature on the subject can be segregated into two basic categories: (1) ABG as a turf or (2) ABG as a weed (Huff, 2003).

Although ABG can produce an excellent dense turf under favorable conditions, it has long been regarded as an undependable species (Sprague and Burton, 1937). Research performed during the 1930s provided insight into the requirements for growth of ABG (Sprague and Burton, 1937; Sprague and Evaul, 1930). The authors of these studies concluded that the primary reason of ABG failure during mid-summer is the lack of heat and drought tolerance of the species; thus, research emphasis was placed on discovering and implementing effective methods for ABG control. However, researchers during the late-1960s began to claim that that biotic stress from diseases and insects were often the primary cause of ABG failure rather than heat or drought stress (Alexander, 1969; Vargas Jr., 1976). Subsequent research has provided insight on the conditions under which ABG grows best and the measures necessary to control pest problems, which ultimately allowed superintendents to successfully maintain healthy ABG during the summer months (Beard et al., 1978; Vargas Jr., 1977). Thus, for the past half-century there has been increased effort to try to manage ABG as an important and reliable component of existing turfs (Huff, 1998; Vermeulen, 1989; Zontek, 1973). However, ABG is still regarded as a weed by most turf managers and is very rarely planted as the intended species in a sward (Vargas and Turgeon, 2004).

Annual bluegrass produces a fine-textured turf of high shoot density, uniformity, and overall quality when maintained under optimal growing conditions (Beard, 1970). Most major tournaments of the United States Golf Association (USGA) and Professional Golfers Association (PGA), and some European tournaments are played on greens composed, in whole or in part, of ABG (Vargas and Turgeon, 2004). Annual bluegrass can be described, generally, as a bunch-type or weakly-stoloniferous turf with folded vernation, an acute ligule (0.8 to 3 mm long), a prominent midrib on adaxial leaf surface, a boat-shaped leaf tip and no auricles (Huff, 2003). Panicle-shaped inflorescences are produced during most of the growing season, but are predominately visible in a flush during the spring (Huff, 2003). The prolific production of viable seed by ABG, even under close mowing, contributes to its competitive nature in putting greens (Huff, 1999).

Annual bluegrass is an allotetraploid (2n = 4x = 28) that is believed to have originated in Europe from a natural cross between the creeping perennial *P. supine* Schrad. (2n = 2x = 14) and the upright-growing *P. infirma* H.B.K. (2n = 2x = 14) (Nannfeldt, 1937; Tutin, 1952). *Poa annua* displays an extremely large level of variability within the species due to multiple hybridization and chromosome doubling events that have taken place during its evolution (Huff, 1999). The two primary morphological types of ABG are the bunch-type, upright growing annual type *(P. annua* f. *annua* L.) and the perennial type (*P. annua* f. *reptans* [Hausskn.] T. Koyama.) which has a more prostrate, spreading growth habit (Huff, 2003). The perennial type is preferred for golf greens because it provides a dense, uniform turf that produces fewer inflorescences and tolerates more environmental stress (Huff, 2003; Huff, 2004)

Annual bluegrass is known for its susceptibility to many turfgrass diseases such as anthracnose, dollar spot, summer patch (*Magnaporthe poae* Landschoot & Jackson), and brown patch (*Rhizoctonia solani* Kühn) (Huff, 2003; Smiley et al., 2005). Thus, plant breeders have sought for over fifty years to identify and develop strains of ABG that possess desirable traits such as disease resistance (Duff, 1978; Johnson et al., 1993; Youngner, 1959). Bolton and Cordukes (1981) identified two strains of ABG that demonstrated high levels of anthracnose resistance in the growth chamber. More recently, Huff (1999) discovered biotypes of ABG that exhibit excellent field resistance to anthracnose and dollar spot. However, there is an inadequate supply of commercially available ABG seed for superintendents who need it to repair or overseed existing ABG greens (Huff, 2004). The development of cultivated varieties ABG is challenged by the limitations of low seed yield and the indeterminacy of seed maturity (Huff, 2003). Another major issue with production of greens-type ABG is their reversion from a perennial type to an annual type when left unmowed as space plants in the breeding field (La Mantia and Huff, 2011).

Bonos et al. (2009) identified enhanced tolerance to anthracnose in the creeping bentgrass cultivars ‘Shark,’ ‘Penneagle II,’ ‘Runner,’ ‘Penn A-1,’ ‘Tyee’ and ‘Authority,’ and the velvet bentgrass (*A. canina* L.) cultivar ‘Greenwich’ and high susceptibility in the creeping bentgrass cultivars ‘Viper,’ ‘Providence,’ ‘Penncross,’ ‘Brighton,’ ‘Seaside II,’ and ‘Pennlinks II.’ However, the specific mechanisms of resistance to *C. cereale* identified in ABG and creeping bentgrass remain unknown . In maize, general responses to *C. graminicola* infection involve stimulation of phenolic compound biosynthesis, specifically phenylpropanoids, which triggers the fortification (lignification) of the cell wall near pre- and post-penetration infection sites to prevent penetration or expansion of the fungus, respectively (Bergstrom and Nicholson, 1999). Research to determine the mechanisms of anthracnose resistance in ABG and creeping bentgrass would advance breeding efforts to improve anthracnose resistance in these species.

Chemical Control

Superintendents who manage ABG rely on chemical and cultural options for control of anthracnose due to the lack of host resistance to *C. cereale*. Chemical control of anthracnose is best achieved with a preventative fungicide program (Murphy et al., 2008). In swards with a previous history of the disease, preventative fungicide programs should be initiated one month before anthracnose symptoms normally occur and continued biweekly throughout the growing season (Murphy et al., 2008; Young et al., 2010a). Depending on how early disease symptoms occur and the geographical location, fungicide programs for anthracnose control can extend from April through October and provide a significant cost for superintendents who battle this disease (Bigelow and Tudor Jr, 2012; Young et al., 2010a)

Currently, the most effective chemistries for the control of anthracnose include the nitriles (chlorothalonil), sterol-inhibitors (DMIs), strobilurins (QoIs) and benzimidazoles (where resistant isolates are not present), the antibiotic polyoxin-D, phosphonates (fosetyl-AL and the phosphites), the dicarboximide iprodione, and the phenylpyrrole fludioxonil (Murphy et al., 2008). Recently, Clarke et al. (2011) reported that two-component mixtures of chlorothalonil, phosphonates, and DMIs provided the best preventative control of anthracnose in NJ during severe disease epidemics. The authors also found that rotating among chemical families with different biochemical modes of action provided the best disease control compared to the sequential use of single chemistries (Clarke et al., 2011; Murphy et al., 2008). In general, superintendents should avoid sequential applications of the same chemistries, especially single-site inhibitors, due to the risk of fungicide resistance developing.

Unfortunately, fungicide resistance has developed in C. *cereale* to site-specific fungicides including the QoIs, benzimidazoles, and DMIs (Wong and Midland, 2004). Resistance to benomyl (benzimidazole) appeared as early as 1989 in Michigan (Detweiler et al., 1989). More recently, resistance to the fungicides azoxystrobin, thiophanate-methyl, and reduced sensitivity to propiconazole has been reported for *C. cereale* isolates collected from ABG and creeping bentgrass putting greens across the United States and Japan (Avila-Adame et al., 2003; Crouch et al., 2005; Mitkowski et al., 2009; Wong et al., 2008; Wong and Midland, 2007; Wong et al., 2007; Young et al., 2010a; Young et al., 2010b). Populations of *C. cereale* resistant to azoxystrobin and thiophanate-methyl developed rather quickly due to a G143A substitution in the cytochrome b protein and two mutations in ß-Tubulin 2 Gene, respectively (Avila-Adame et al., 2003; Wong et al., 2008; Wong et al., 2007; Young et al., 2010a; Young et al., 2010b). Whereas resistance to DMI fungicides, particularly propiconalzole, has developed gradually through reduced sensitivity (Wong and Midland, 2007).

Superintendents can delay resistance and achieve good disease control by: (1) rotating fungicide classes, (2) avoiding low-label-rate applications, (3) avoiding late curative applications, (4) using multi-site, contact fungicides and (5) tank-mixing fungicides (Murphy et al., 2008). Moreover, superintendents should use integrated disease management programs that emphasize cultural management practices that reduce host susceptibility to anthracnose (Brent and Hollomon, 2007).

CULTURAL MANAGEMENT PRACTICES AFFECTING ANTHRACNOSE

The emergence of anthracnose as a devastating pest of ABG turf during the 1990s has been associated with management practices employed by superintendents to improve playability and ball roll distance (green speed) (Landschoot and Hoyland, 1995; Mann and Newell, 2005; Vermeulen, 2003; Zontek, 2004). Numerous field studies have been conducted during the last decade to evaluate the effect of cultural management factors including N fertility, chemical growth regulation, mowing, rolling, irrigation, sand topdressing, and cultivation on anthracnose severity of ABG (Murphy et al., 2008; Murphy et al., 2012).

Fertility

Preceding the rise of anthracnose epidemics during the 1990s and 2000s, there was a trend among superintendents to decrease nitrogen fertility as a strategy to increase ball roll distance (Radko, 1985). Since then research has shown that low nitrogen fertility is one of the most important factors that predispose annual bluegrass to anthracnose. The exact mechanism responsible for disease reduction produced by increased nitrogen fertility is unknown, but improved plant vigor has been suggested (Murphy et al., 2008; White et al., 1978).

The most effective soluble-nitrogen programs for anthracnose suppression include light, frequent applications (e.g., 4.9 or 9.8 kg ha^{-1} every 7 or 14 d) throughout the summer (Inguagiato et al., 2008; Roberts et al., 2010). Roberts et al. (2010) found that initiating a low rate, summer soluble N program before symptom expression (mid-May) reduced disease compared to initiating N fertilization at the onset of disease (mid-June). Subsequent research has determined that increasing N rate up to 9.8 kg ha^{-1} every 7 d decreased disease; however, excessive N rates of 19.5 to 24.4 kg ha^{-1} every 7 d resulted in dramatic increases in anthracnose severity by mid-summer (Murphy et al., 2011). Research examining the effect of soluble N form found that potassium nitrate reduced disease compared to all other forms tested (urea, ammonium nitrate, calcium nitrate, ammonium sulfate); whereas ammonium sulfate had the greatest disease severity (Schmid et al., 2012a). Schmid et al. (2012b) reported that granular nitrogen (isobutylidene urea; IBDU) applied at rates 48.8 to 97.6 kg ha^{-1} was most effective when applied in the spring compared to autumn. Thus, best management practices (BMPs) for N fertility include applications of granular fertility in spring (48.8 to 97.6 kg ha^{-1}) and light, frequent applications of soluble N (e.g., 9.8 kg ha^{-1} every 7 d) during late spring and summer months (Murphy et al., 2012).

Growth regulation

Plant growth regulators (PGRs) have become an important tool used by many superintendents to improve shoot density, reduce shoot elongation, increase environmental stress tolerance, reduce ABG seedhead expression, and ultimately, enhance playability of putting greens (Danneberger, 2003; Dernoeden, 2012); however, the effect of PGRs commonly used on ABG [mefluidide (ME), ethephon (EP) and trinexapac-ethyl (TE)] on anthracnose severity were previously unknown prior to the early-2000’s (USDA-CSREES, 2005).

Inguagiato et al. (2008) found that ME and TE applications (0.106 and 0.050 kg a.i. ha^{-1} yr^{-1}, respectively) typically had no effect on anthracnose of ABG or, at times, inconsistently increased or decreased disease severity. Similarly, increased TE rate (0, 0.04, 0.05 and 0.08 kg a.i. ha^{-1} every 7 d) had little effect on anthracnose during a 3 yr trial or slightly reduced disease (linearly) during high disease pressure (Inguagiato et al., 2009b). Factorial studies that examined the effects of EP, ME and TE applied alone or in various combinations indicated that ME had little effect on the disease; whereas, EP treated plots had less disease than non-EP plots on 54% of rating dates and TE treated plots had less disease than non-TE-treated plots on 75% of rating dates (Inguagiato et al., 2010). Inguagiato et al. (2010) suggested that EP may reduce anthracnose by enhancing plant vigor (fewer seedheads) or inducing plant defense against disease. The authors also hypothesized that TE may reduce disease severity by increasing plant vigor and improving N use efficiency. Additional research is needed to test these hypotheses. Best management practices for PGRs include the frequent (every 7 to 14 d) application of these chemicals to maintain optimal quality and playability without concern that they may enhance disease severity on ABG putting greens (Murphy et al., 2012).

Mowing

Superintendents decrease cutting heights and increase mowing frequency to achieve faster green speeds (increased ball roll distance). Low mowing has been known for over a decade to increase anthracnose disease severity (Backman et al., 2002; Uddin and Soika, 2003). Recently, Inguagiato et al. (2009a) reported that increasing mowing height as little as 0.4 mm (e.g., 2.8 to 3.2 mm, or 3.2 to 3.6 mm) significantly reduced disease severity. The authors suggested that carbohydrates and rooting may have been enhanced at increased mowing heights, thus reducing plant stress and improving tolerance to anthracnose; however, the exact mechanism responsible for decreased disease severity observed with increased cutting height has yet to be confirmed.

Contrary to expectations, increased mowing frequency (double cutting) (Inguagiato et al., 2009a) and increased equipment traffic on the perimeter of a putting green (Roberts et al., 2012) did not increase anthracnose severity. Thus, BMPs for mowing to reduce anthracnose severity include maintaining cutting heights of 3.2 mm or greater and adopting practices such as double cutting or rolling to achieve faster green speeds (Murphy et al., 2012).

Rolling

Lightweight rolling is used to smooth and firm the surface of putting greens which can also increase green speed (Hartwiger et al., 2001). But like other cultural practice that may cause stress, rolling has been reputed to predispose turf to anthracnose (Smiley et al., 2005). However, recent research on ABG putting green turf showed that lightweight rolling (applied with a vibratory or sidewinder unit every other day) had no effect or reduced disease severity (Inguagiato et al., 2009a), even when traffic stress was increased due to changing direction of the roller at the perimeter of a putting green (Roberts et al., 2012). Additionally, lightweight rolling increased green speed without causing any detrimental effects to turf quality or soil bulk density (Inguagiato et al., 2009a; Nikolai et al., 2001; Roberts et al., 2012). Therefore, BMPs for rolling include lightweight rolling every other day to maintain acceptable green speed rather than decreasing N fertility or decreasing cutting height (Murphy et al., 2012).

Irrigation

Conditions that produce inadequate or excessive water can make ABG more susceptible to anthracnose (Danneberger et al., 1984; Danneberger et al., 1995; Smiley et al., 2005; Sprague and Evaul, 1930). Recent field research has provided insight on how different irrigation regimes [40, 60, 80, and 100% replacement of reference evapotranspiration (ET_o)] influence anthracnose disease severity. Turf subjected to frequent wilt stress during the summer (e.g. ≤ 60% ET_o) was most susceptible to anthracnose; however, replacing 100% ET_o also increased disease severity by the end of the summer (Roberts et al., 2011). Irrigation BMPs include applying sufficient irrigation (60 to 80% ET_o) to prevent wilt stress while also avoiding saturated soil conditions.

Sand Topdressing

Topdressing is the addition of a soil (usually sand) or soil mix to a turf surface which is usually incorporated by brushing, matting, raking, vibratory rolling and/or irrigating (Beard and Beard, 2005; Carrow, 1979; Foy, 1999). Light, frequent sand topdressing of putting greens has been a growing trend in the turfgrass industry since the 1970s (Madison et al., 1974). Wounding caused by sand topdressing and associated incorporation methods was thought to contribute to outbreaks of anthracnose, leading superintendents to forgo the practice when the disease was active (Backman et al., 2002; Smiley et al., 2005). Recent research has shown that although sand topdressing may cause small, brief increases in disease severity soon after applications are initiated, continued topdressing at 0.3 to 0.6 L m^{-2} every 7 to 14 d during the summer provided substantial disease reductions for the duration of the studies (Inguagiato et al., 2012; Inguagiato et al., 2013; Roberts, 2009). Topdressing at intervals of 21 or 42 d also reduced disease, but to a lesser extent than more frequent sand topdressing treatments (Inguagiato et al., 2012).

Sand topdressing has been suggested to reduce anthracnose by effectively raising the cutting height and burying and protecting crowns and leaf sheaths from environmental or mechanical stresses, thereby promoting plant vigor (Inguagiato et al., 2010). Initial increases in anthracnose observed during the first year of topdressing trials have been attributed to wounding of crowns that were not yet buried with sand (Inguagiato et al., 2013). However, more research is needed to determine the exact mechanisms responsible for the effects of sand topdressing observed on anthracnose.

Even under conditions of intense foot traffic equal to the amount of footsteps around the hole of a putting green that received 200 rounds of golf d^{-1} (327 footsteps m^{-2} d^{-1}), sand topdressing applied at 0.3 L m^{-2} every 7 d reduced disease severity compared to non-topdressed turf (Roberts, 2009). Moreover, methods of sand incorporation (vibratory rolling, stiff- or soft-bristled brush, or none) or sand particle shape (round vs. sub-angular) did not enhance disease severity (Inguagiato et al., 2013). In fact, sub-angular sand reduced disease severity compared to round sand on some rating dates throughout the trial (Inguagiato et al., 2013). Thus, best management practices for sand topdressing include topdressing at 0.3 to 0.6 L m^{-2} every 7 to 14 d throughout the summer to dilute thatch, create a better growing medium and develop a mat layer that provides protection of crowns (Murphy et al., 2008).

Vertical Cutting

Vertical cutting (VC) reduces puffiness and other problems caused by excessive thatch on putting green surfaces (Vargas and Turgeon, 2004). This practice has been suspected to enhance anthracnose severity by wounding, which may promote fungal ingress (Dernoeden, 2012; Landschoot and Hoyland, 1995; Smiley et al., 2005).

Contrary to previous suspicions, biweekly VC (3 mm depth) of an ABG putting green had little effect on anthracnose severity during a 3 yr trial; however, on one rating date VC increased disease on PGR-treated (TE) plots and decreased disease on low-N plots (Inguagiato et al., 2008). Burpee and Goulty (1984) hypothesized that turf cultivation (coring and verticutting) during the spring and fall might enhance anthracnose resistance of ABG fairway turf. But, similarly, no cultivation treatment affected disease development during their one year trial. *Colletotrichum* spp. in ABG and maize do not require wounds to penetrate their host (Bruehl and Dickson, 1950; Smith, 1954; Venard and Vaillancourt, 2007b). In fact, wound healing responses can often confer host resistance to fungal invasion (Bostock and Stermer, 1989; Lipetz, 1970), as demonstrated by enhanced resistance to *Colletotrichum* spp. via wound healing responses in maize and chili pepper (Kim, 2008; Muimba-Kankolongo, 1991; Muimba-Kankolongo and Bergstrom, 1992; Muimba-Kankolongo and Bergstrom, 1990; Muimba-Kankolongo and Bergstrom, 2011).

Contrastingly, increased depth (0, 3.3 and 5.1 mm) of VC increased anthracnose severity linearly on a mixed creeping bentgrass and ABG putting green inoculated with an aqueous suspension of *C. cereale* spores (10^4 conidia mL^{-1}) (Uddin et al., 2008). Based on Landschoot and Hoyland's (1995) observation that wounding ABG plants only at the crown, not leaves, immediately before inoculation resulted in increased disease, Inguagiato et al. (2008) hypothesized that VC to a depth that wounds crowns may increase anthracnose severity but VC to a depth that affects only leaves may not enhance the disease. Therefore, current BMPs include VC at shallow depths to only affect leaf tissue to prevent crown and stolon injury (Murphy et al., 2008).

Inoculation immediately after wounding potato (*Solanum tuberosum* L.) and maize plants resulted in increased infection by *Colletotrichum* spp.; whereas, wounded tissue was nearly as tolerant to pathogen ingress as unwounded tissue within 1 to 2 h after wounding (Johnson and Miliczky, 1993; Muimba-Kankolongo and Bergstrom, 1990). Uddin et al. (2008) did not specify the timing of inoculation in their study, but if the spore suspension was applied immediately after VC, then their report that VC increased disease would relate to the previous research regarding the timing of wounding and inoculation. Additional research is needed to confirm the influence of inoculation timing after wounding on anthracnose of ABG putting green turf.

Epidemics of *C. cereale* on golf course putting greens occur naturally, not by inoculation, during periods of high temperature, high humidity and prolonged leaf wetness (Bolton and Cordukes, 1981; Bruehl and Dickson, 1950; Danneberger et al., 1984; Smiley et al., 2005; Smith, 1954; Sprague and Evaul, 1930; Vargas et al., 1992). Vertical cutting is usually applied when the turf canopy is dry (Beard, 2002); thus, the timing of VC on golf courses typically would not typically occur in association with the timing of environmental conditions most conducive for infection by the pathogen. However, more research is needed to evaluate the how environmental conditions might affect the influence of VC on anthracnose disease severity of ABG putting green turf.

Vertical cutting removes thatch, which is where *C. cereale* is believed to survive on previously infected plant debris during unfavorable environmental conditions (Crouch and Clarke, 2012; Settle et al., 2006; Smiley et al., 2005). Thus, VC may help to contribute to reducing anthracnose by removing inoculated debris in thatch while also improving the surface medium for plant growth. Anthracnose severity in maize is less dramatic when plant debris is removed from field after harvest (Bergstrom and Nicholson, 1999). Thus, additional research is needed to evaluate the effect of removal of plant debris (thatch) on the severity of anthracnose on ABG putting green turf.

CULTURAL PRACTICES FOR THATCH MANAGEMENT

Superintendents commonly use cultural management practices such as sand topdressing and cultivation to control thatch accumulation. Thatch is an intermingled organic layer of dead and living shoots, stems, and roots that develops between the zone of green vegetation and the soil surface. Mat is an intermixed layer of thatch and mineral matter (e.g., sand) between the thatch and soil surface commonly found on greens and other areas that have been topdressed (Beard and Beard, 2005). Thatch develops when organic matter is produced at a rate faster than it is decomposed (Waddington, 1992). Therefore, thatch accumulation is stimulated by climatic, edaphic or biotic factors that promote organic matter production and/or inhibit its decomposition such as excessive N fertility, high soil water content, anaerobic conditions, inadequate cultivation and/or topdressing, and soil pH less than 6 (Beard, 1973; Carrow, 2003; Christians, 2011; Hurto et al., 1980; Waddington, 1992).

A thin layer of thatch ($\leq$ 6 mm) is considered beneficial to putting greens because it insulates the soil from temperature extremes, provides resiliency to turf, and increases wear tolerance (Beard, 1973). However, excessive thatch accumulation causes numerous management problems including increased incidence of hydrophobicity and localized dry spots, reduced water infiltration rates, reduced hydraulic conductivity, chlorosis, and reduced pesticide effectiveness (Beard, 1973; Beard, 2002; Christians, 2011; Waddington, 1992). Excess thatch is also associated with increased incidence of the diseases brown patch, dollar spot, leaf spot (caused by *Drechslera poae)*, snow molds (*Typhula* spp.), and stripe smut (caused by *Ustilago striiformis*) (Beard, 1973). Another deleterious effect of excess thatch is the elevation of crowns and reduction of rooting into the underlying soil, thus creating a puffy turf surface that is prone to scalping, high or low temperature stress, drought stress, foot printing and inconsistent ball roll (Beard, 1973; Christians, 2011; Hurto et al., 1980; Ledeboer and Skogley, 1967).

Recommendations for optimal levels of surface organic matter in putting greens range from 15 to 80 g kg^{-1} (Gaussoin et al., 2013); many authors recommend managing to maintain an organic matter level of 40 g kg^{-1} (Carrow, 2003; Moeller, 2008; O'Brien and Hartwiger, 2003). The three basic approaches to manage thatch accumulation are to: 1) enhance its degradation, 2) dilute it with topdressing, or 3) mechanically remove it via cultivation. Enhanced degradation involves using management practices or products that promote the microbial decomposition of thatch (Gaussoin et al., 2013). The following sections will discuss the secondary cultural management practices of sand topdressing and cultivation and how they influence the thatch and mat layer.

Sand Topdressing

Recognized benefits of a good topdressing program include a smooth, firm putting green surface; increased shoot density; reduced thatch; protection against winter injury; reduced grain; and better movement of air, water, nutrients and roots into soil (Beard, 2002; Cooper, 2004; Kowalewski et al., 2010; Zontek, 1979). Today the most common topdressing program involves light-rate, frequent applications of sand on putting greens, yet the widespread adoption of this program has only occurred within the last four decades (Cooper, 2004; Zontek, 1979).

The practice of topdressing is believed to have been invented by Old Tom Morris (1821-1908), pioneer of the game of golf and greenskeeper at St. Andrews Golf Course in Scotland (Labance and Witteveen, 2002). In those days topdressing was applied using wheelbarrows and shovels and applications were uneven, time-consuming and laborious (Aylward, 2010). In fact, Old Tom Morris was thought to have discovered the benefits of topdressing accidentally when he spilled a wheelbarrow of sand on a putting green and noted the increased quality of that green thereafter (Hurdzan, 2004).

Piper and Oakley (1917) were among the first to publish recommendations for topdressing in the United States, citing the benefits of “sanding” clay soil greens a few times per season at a rate of 1.65 L m^{-2} to improve surface characteristics and provide winter protection. Shortly after, agronomists from the U.S. Golf Association Green Section (1925) noted that heavy, infrequent applications of compost topdressing could be replaced more lighter-rate applications as often as every 7 d. The material used for topdressing varied greatly from location to location, but the majority of superintendents during this time were using a mix of sand, finer-textured soil and organic matter (Bengeyfield, 1969; Carrow, 1979). Regardless of the material used, most topdressing practices were suspended during the late-1930s and 1940s due to shortages in labor, equipment and materials caused by the second World War (Bengeyfield, 1969). The advent of the mechanical aerifier during the late-1940s also led to reduced topdressing because many managers incorporated soil removed during coring instead of topdressing (Bengeyfield, 1969). Although some scientists encouraged the use of frequent topdressing at rates of 1.65 L m^{-2} (Musser, 1950), putting greens were generally topdressed twice per year at most before the mid-1970s (Cooper, 2004).

The trend of frequent sand topdressing during the second half of the 20th century can be attributed primarily to research initiated by Dr. John Madison and coworkers at the University of California at Davis during the late-1950s. Similar to Old Tom Morris, Dr. Madison observed the benefits of sand topdressing accidentally when sand from a nearby pile blew onto the corner of a research field and enhanced the quality of the affected plots. Madison et al. (1974) promoted the use of a sand-only topdressing medium because it was cheaper, easier to apply, and provided better protection from the heavy traffic caused by increased play during the 1960s compared to sand-soil-peat mixes. The authors recommended applying sand at a rate of 0.91 L m^{-2} every 21 d to avoid creating alternating layers of sand and thatch. The advent of the first mechanized topdresser in 1960s made topdressing at these rates and frequencies practicable for superintendents, leading to the widespread adoption of the practice by the late-1970s (Aylward, 2010; Cooper, 2004; Zontek, 1979).

Hall (1979) warned against using sand-only mediums because of the potential to produce excessive water infiltration, excessive nutrient leaching, lower microbial activity, hydrophobic drying, lower water availability, and susceptibility to layering. However, proponents of a sand-only topdressing medium considered adding more organic matter to be illogical because a primary benefit from topdressing is to prevent excessive organic matter (thatch) accumulation (Cooper, 2004; Hummel, 1995). This debate continued into the mid-1990s, but today an overwhelming majority of superintendents use a sand-only medium for topdressing for the same reasons provided by Madison et al. (1974): sand is cheaper, easier to apply, resistant to compaction, and free of organic matter (Cooper, 2004; Hummel, 1995).

Topdressing has become as routine as fertilization (Hummel, 1995). Modern mechanized topdressers and material handlers allow for precise and accurate topdressing applications to 18 greens in less than an hour (Aylward, 2010). Additionally, modern equipment can apply sand at very low rates, allowing managers to topdress more frequently. O'Brien and Hartwiger (2003) reported that 0.15, 0.6 and 1.2 L m^{-2} are considered light, moderate and heavy rates of sand topdressing, respectively, and topdressing is now applied as often as every 7 d on golf course putting greens (Aylward, 2010). However, many superintendents still lack a basic understanding of the impact of topdressing programs on turfgrass health, good or bad, and the importance of choosing the correct material, rate, timing and frequency of application (Hummel, 1995). Additionally, superintendents lack a target quantity of sand needed to achieve the benefits gained from a sound topdressing program (O'Brien and Hartwiger, 2003).

The primary considerations for developing a topdressing program are the material, timing, frequency, rate, and method used for topdressing (Gaussoin et al., 2013). Labor, material and equipment expenditures must be allowed for a successful topdressing program; flawed programs can cause permanent damage that may require expensive reconstruction (Beard, 2002; Carrow, 1979; Christians, 2011)

Particle size distributions and chemical compositions can vary greatly among sands (Carrow, 1979), so it is recommended that only sands that meet USGA specifications for putting green root zone mix be used for topdressing (Green Section Staff, 2004). As a general rule, the texture of a topdressing material should be the same or coarser than the texture of the underlying soil (Christians, 2011); however, researchers have examined the effects, positive or negative, of using finer-textured sands for topdressing (Moeller, 2008; Murphy and Hempfling, 2011; Taylor, 1986).

Topdressing rates should be based on the amount of sand required to fill the thatch and the frequency of application should match the rate of thatch-verdure accumulation (Beard, 1978; Beard, 2002; Madison et al., 1974). Light, frequent topdressing reduces the production of alternate sand/thatch layers if matched with the rate of thatch accumulation and minimizes interruption to play caused by excess sand on the putting surface (Aylward, 2010; Cooper, 2004; Cooper and Skogley, 1981; Davis, 1977; Fermanian et al., 1985; Hummel, 1995; Madison et al., 1974; O'Brien and Hartwiger, 2003; Zontek, 1983).

The extent to which benefits from topdressing are achieved depends upon the frequency of application and the annual amount of sand applied to a putting green (Beard, 1978). O'Brien and Hartwiger (2003) outlined strategies to apply 12.2 to 15.2 L m^{-2} of sand per year, a sufficient annual amount to maintain the concentration of organic matter below a threshold of 40 g kg^{-1} (Carrow, 2003). The authors suggested applying 4.3 to 13.4 L m^{-2} of the annual sand amount as surface topdressing and the rest as back-fill after cultivation.

Research regarding the effect of topdressing on turf diseases is limited to incidental reports of disease outbreaks during trials with objectives unassociated with disease incidence. Some studies found that dollar spot severity of creeping bentgrass and velvet bentgrass putting green turf was increased by topdressing with sand, soil, or sand/soil mixes (Cooper and Skogley, 1981; Engel and Alderfer, 1967; Fermanian et al., 1985); whereas, Carrow et al. (1987) and Stier and Hollman (2003) reported that dollar spot severity of 'Tifway' bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* (Burtt-Davis)] managed as a homelawn and creeping bentgrass and ABG putting green turf were not affected by sand topdressing, and Henderson and Miller (2010) reported that sand topdressing reduced dollar spot on creeping bentgrass fairway turf. Outbreaks of pythium blight (caused by *Pythium* spp.) and brown patch were reported to be more severe on creeping bentgrass putting green turf that received a light, frequent sand topdressing compared to turf that received a heavy, infrequent sand topdressing (Shearman, 1984). Hawes (1980) reported that spring dead spot (*Ophiosphaerella* spp.) of bermudagrass (*Cynodon dactylon* L.) mowed at 1.9 cm was reduced by sand topdressing.

Recently, trials were initiated to evaluate the effects of sand topdressing anthracnose on ABG putting green turf (Inguagiato et al., 2012; Inguagiato et al., 2013; Roberts, 2009). Although topdressing briefly increased disease during the first year of these trials, results indicated that cumulative annual amounts of 2.4 to 4.8 L m^{-2} of sand applied every 7 to 14 d at rates of 0.3 to 0.6 L m^{-2} during the summer dramatically reduced anthracnose severity (Inguagiato et al., 2012). However, topdressing at these rates and frequencies during the summer can be an expensive and laborious practice for golf course superintendents and can potentially interrupt play on the golf course for several days after the application (Bigelow and Tudor Jr, 2012; O'Brien and Hartwiger, 2003; Vavrek Jr., 1995). Therefore, superintendents usually apply topdressing at rates and frequencies less than the programs outlined above during the summer (Inguagiato et al., 2012). It is apparent that more research is needed to identify sand topdressing programs (i.e., rates and timings) that reduce anthracnose and provide acceptable playing conditions throughout the summer.

Light, frequent topdressing during mid-summer is often supplemented with higher-rate topdressing applied alone or in conjunction with cultivation events during the spring and autumn when play is minimal (O'Brien and Hartwiger, 2003). Topdressing during the spring and autumn is generally less expensive to implement and less disruptive to play than summer topdressing programs. However, it is not known whether topdressing during these time affects anthracnose severity or the impact of summer topdressing on this disease. Also, more research is needed to explain the brief increases in anthracnose reported in previous topdressing trials.

Cultivation

Turf cultivation is a broad term that includes many mechanical practices used to modify the turf and/or root zone without destroying the turf (Bidwell, 1952; Dawson, 1934; Dawson and Ferro, 1939; Engel and Alderfer, 1967). Cultivation enhances growing conditions in the surface root zone by decreasing compaction of the soil and, thus, improving soil gas exchange, wetting and drying, water infiltration, root growth, and response to fertilizers (Christians, 2011; Turgeon, 2011). Methods of cultivation include tining (hollow or solid), spiking, slicing, drilling, vertical mowing (shallow; grooming and deep; scarifying), and injecting air or water (Gaussoin et al., 2013).

One of the most common and effective practices used to manage thatch and improve edaphic conditions is hollow tine cultivation, or coring (Beard, 1973; Christians, 2011). Coring is usually performed during the spring and/or autumn by using a machine equipped with hollow tines to remove cores of soil, which creates vertical channels in the surface root zone. The channels are typically back-filled with sand (Hartwiger and O'Brien, 2001; Murphy and Rieke, 1994). Coring is rarely practiced during midseason because it creates an uneven playing surface that can take several days or more to return to normal (Christians, 2011). However, cultivation practices such as solid-tining and VC can be used during midseason because they produce less disruption of the turf surface and require less equipment and labor expenses (McCarty et al., 2007; Murphy et al., 1993).

Solid-tine cultivation, synonymous with the terms "forking, needle-tining, punching, spiking, or venting," penetrates the soil with solid tines (6 to 19 mm diameter) mounted on the same machine used for coring and creates channels without removing soil or turf (Beard, 1973; Beard, 2002; Brotherton, 2011; Carrow, 2003; Carrow and Petrovic, 1992; Christians, 2011; Hartwiger and O'Brien, 2011). Benefits of solid-tining include increased saturated hydraulic conductivity, increased soil porosity, increased shoot density, increased overall turf quality, reduced soil electric conductivity, and reduced soil compaction (Carrow, 1996; Carrow, 2003; Green et al., 2001; Murphy et al., 1993).

Vertical cutting (VC), sometimes called "vertical mowing, verticutting, power raking, vertical slicing, or dethatching," can be performed with a variety of mechanical devices equipped with vertically rotating blades that cut into a turf at varying depths, blade spacings and blade thicknesses (Beard, 1973; Beard, 2002; Christians, 2011; Gaussoin et al., 2013; Turgeon, 2011).

Shallow VC, or grooming, mainly slices leaves and sometimes stolons and is most often performed to control grain, a condition where grass blades lay in a single direction and affect ball roll (Beard, 2002; Christians, 2011; Gaussoin et al., 2013). Frequent grooming also removes ABG seedheads and contributes to thatch control, especially when combined with sand topdressing (Beard, 2002). Grooming equipment usually has a thin blades (≤ 1 mm), a close blade spacing (5 to 19 mm), and a shallow operating depth (0.4 to 0.8 mm below the effective height of cut) (Beard, 2002).

Moderate VC, or verticutting, cuts deeper into the canopy than grooming and affects mostly leaf and stolon tissue but sometimes the crowns (Turgeon, 2011). Benefits from verticutting are similar to grooming; however, the greater depth of verticutting removes more thatch than grooming. Blades on verticutting equipment may be thicker (≤ 2 mm) and spaced wider apart (13 to 19 mm) than blades on grooming equipment (Beard, 2002).

Deep VC, or scarifying, cuts through leaves, stolons and crowns and into the upper root zone. Scarifying is useful for preparing turf surfaces for seeding during renovation procedures or for correcting serious thatch problems (Beard, 2002; Turgeon, 2011). Scarifying blades can be as thick as 3 mm and spaced up to 40 mm apart and are generally operated to depths up to 40 mm (Beard, 2002; Landreth et al., 2008). Research suggests that scarifying is the best option for thatch removal if the target area is within the first 40 mm depth of the turf surface (Lockyer, 2009). Landreth et al. (2008) reported that scarifying removed more organic matter from the surface 25 mm of a putting green rootzone than core cultivation. The greatest blade thickness (3 mm) removed the most organic matter; however, that treatment also required the most time for healing (nearly 60 days). Thus, intensive scarifying should only be practiced when large amounts of organic matter must be removed at once and a longer recovery time can be tolerated (Landreth et al., 2008).

Stresses caused by excessive thatch or soil compaction may predispose turfgrasses to diseases, thus cultivation practices are often recommended for disease management (Smiley et al., 2005). Tisserat and Fry (1997) reported that a combination of hollow-tine aeration plus VC to scarify the soil surface to a depth of 7 mm performed twice each year was moderately effective in reducing spring dead spot in bermudagrass. Summer patch was also reduced by deep and shallow coring on an ABG fairway (Clarke et al., 1995). Mechanical thatch removal by VC (unknown depth) reduced dollar spot disease of ‘Merion’ Kentucky bluegrass (*Poa pratensis* L.) (Halisky et al., 1981).

Cultivation may enhance resistance to diseases through a wound response mechanism. Moeller (2008) hypothesized that cored and topdressed creeping bentgrass putting green plots had reduced dollar spot severity compared to plots that were only topdressed because of increased production of phytoalexins, secondary metabolites involved in plant defense responses, in the cored plots. However, these results appear to contradict a previous report that coring had no effect on dollar spot incidence in creeping bentgrass or ABG putting green turf (Stier and Hollman, 2003).

Cultivation can induce plant stress and create wounds, both of which are thought to potentially enhance disease (Smiley et al., 2005). Carrow et al. (1987) reported that VC and coring may have weakened bermudagrass turf maintained as a homelawn and caused dollar spot to be more severe. Vertical cutting (2 mm depth) also increased dollar spot in ‘Tifeagle’ bermudagrass putting green turf (Unruh et al., 2005).

The research summarized immediately above and in previous sections suggests that cultivation practices may affect turf diseases, such as anthracnose, in a variety of ways. Cultivation may decrease disease severity by: 1) alleviating stresses that may promote disease caused by excess thatch or soil compaction or 2) producing a wound healing response. Contrastingly, cultivation may increase disease severity by: 1) promoting fungal ingress through wounds, 2) causing stress which can increase host susceptibility, or 3) inducing certain plant responses which may cause pathogens to become more destructive (e.g., triggering a hemibiotroph to become necrotrophic).

Summer cultivation has been suggested to improve summer stress tolerance of ABG (Green et al., 2001). However, observational reports from the field have claimed that anthracnose epidemics were enhanced after cultivation events (Landschoot and Hoyland, 1995; Raisch, 2003), presumably caused by increased invasion of *C. cereale* through wounds (Smiley et al., 2005). Field research has shown that VC, especially at increased depths, can enhance anthracnose disease severity (Uddin et al., 2008). Furthermore, wounding of ABG crown tissue resulted in more rapid disease development compared to wounding of leaf tissue or no wounding in a greenhouse study (Landschoot and Hoyland, 1995). Inguagiato et al. (2008) suggested that VC to a depth that injures crown tissue may increase disease severity; whereas, shallow VC that affects only leaf tissue should not affect disease. Additional research is needed to test this hypothesis. Moreover, there is a lack of research regarding the effect of other mid-season cultivation practices such as solid-tining initiated when symptoms of anthracnose first appear.

SUMMARY

The general aim of the research included in this thesis was to evaluate the effects of various sand topdressing programs and mid-season cultivation practices on anthracnose severity of ABG putting green turf. Previous work has shown that frequent, moderate-rate sand topdressing during the summer reduces anthracnose disease; however, this practice is associated with increased cost, labor and interruption to play. It is not known whether applying heavy-rate topdressing during periods of less play, such as spring, affects disease severity or the need for or benefits of summer topdressing.

Sand topdressing briefly enhanced disease severity during the first year of previous trials, presumably due to wounding of crowns not yet protected by a mat layer (Inguagiato et al., 2012; Inguagiato et al., 2013). Thus, researchers have suggested that increased anthracnose severity observed on golf course putting greens that have been topdressed may be an indication of insufficient topdressing rates or intervals (Inguagiato et al., 2012). Furthermore, it is often recommended that topdressing programs not be initiated during times when disease is active; however, research is needed to test this hypothesis.

Similarly, there have been observational and empirical reports that wounding caused by mid-season cultivation practices may increase anthracnose disease severity (Inguagiato et al., 2008; Landschoot and Hoyland, 1995; Raisch, 2003; Smiley et al., 2005; Uddin et al., 2008). Summer cultivation has been suggested to improve summer stress tolerance of ABG (Green et al., 2001); however managers often forgo these practices for fear of enhancing anthracnose disease severity especially when disease symptoms are present. Research regarding the effect of mid-season cultivation is limited and results are varied (Burpee and Goulty, 1984; Inguagiato et al., 2008; Uddin et al., 2008); thus, it would be helpful to provide information to managers regarding which cultivation practices, if any, affect anthracnose severity.

Previous greenhouse work showed that wounding ABG crown tissue increased anthracnose disease severity but wounding leaf tissue had no effect (Landschoot and Hoyland, 1995). Similarly, Uddin et al. (2008) found that increasing the depth (0, 3.3 and 5.1 mm) of VC caused a linear increase in anthracnose disease severity on a mixed stand of creeping bentgrass and ABG maintained as putting green turf; whereas, Inguagiato et al. (2008) found that VC an ABG putting green to a depth of 3 mm had little effect on the disease. Field research is needed to test whether VC to a depth that affects crowns (in addition to leaves and sheaths) influences disease compared to VC to a depth that only affects leaves.

Anthracnose of ABG causes severe damage to putting greens across the world, and options for control of this disease through host resistance or fungicide use are absent or becomingly increasingly limited, respectively. Therefore, it is important to find ways to augment these control methods by refining cultural management practices to decrease susceptibility of ABG putting green turf to anthracnose.

RESEARCH OBJECTIVES

Research was undertaken to determine the effects of sand topdressing and mid-season cultivation on anthracnose of ABG putting green turf beyond those previously studied by Inguagiato et al. (2008,2012,2013), Roberts (2009), and Uddin et al. (2008). This research will contribute meaningful information for golf course managers who battle anthracnose. The specific research objectives were to:

1. Determine the effect of spring topdressing on anthracnose severity as well as the potential for this factor to interact with the effects of summer topdressing (Chapter 2).
2. Assess the impact of biweekly sand topdressing on anthracnose disease severity when initiated during the early stages of disease symptoms (Chapter 3).
3. Evaluate the influence of grooming, verticutting, scarifying and solid-tining on anthracnose severity when applied at the onset of disease symptoms (Chapter 4)
4. Examine the effect of depth of VC on anthracnose disease severity (Chapter 5).

REFERENCES

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

Alexander, P.M. 1969. Anthracnose-Serious Disease Problem. U.S Golf Assoc. Green Section Record 7(5):8-9.

Avila-Adame, C., G. Olaya, and W. Köller. 2003. Characterization of *Colletotrichum graminicola* isolates resistant to strobilurin-related QoI fungicides. Plant Dis. 87(12):1426-1432.

Aylward, L. 2010. How topdressing became an art: Superintendents used to use wheelbarrows and shovels. How times have changed. Golfdom 66(2):38-40.

Backman, P., G. Stahnke, and E. Miltner. 2002. Anthracnose update: Cultural practices affect spread of disease in northwest. Turfgrass Trends 11:T1-T2, T4.

Backman, P.A., P.J. Landschoot, and D.R. Huff. 1999. Variation in Pathogenicity, Morphology, and RAPD Marker Profiles in *Colletotrichum graminicola* from Turfgrasses. Crop Sci. 39(4):1129-1135. DOI: 10.2135/cropsci1999.0011183X003900040030x.

Beard, J.B. 1970. An ecological study of annual bluegrass. U.S. Golf Assoc. Green Section Record 8(2):13-18.

Beard, J.B. 1973. Turfgrass: Science and culture. Prentice Hall, Englewood Cliffs, NJ.

Beard, J.B. 1978. Topdressing Overview. Proc. 48th Annu. Michigan Turfgrass Conf. 7:36-39.

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

Beard, J.B., and H.J. Beard. 2005. Beard's turfgrass encyclopedia for golf courses, grounds, lawns, sports fields. Michigan State Univ. Press, East Lansing, MI.

Beard, J.B., P.E. Rieke, A.J. Turgeon, and J.M. Vargas Jr. 1978. Annual bluegrass (*Poa annua* L.): description, adatpation, culture and control. Michigan State Univ. Agric. Exp. Stn. Res. Rep. 352.

Bechinger, C., K.-F. Giebel, M. Schnell, P. Leiderer, H.B. Deising, and M. Bastmeyer. 1999. Optical Measurements of Invasive Forces Exerted by Appressoria of a Plant Pathogenic Fungus. Science 285(5435):1896-1899. DOI: 10.1126/science.285.5435.1896.

Bengeyfield, W.H. 1969. This year: Top-dress greens and see the difference. U.S. Golf Assoc. Green Section Record 7(1):1-4.

Bergstrom, G.C., and R.L. Nicholson. 1999. The biology of corn anthracnose: knowledge to exploit for improved management. Plant Dis. 83(7):596-608.

Bidwell, W. 1952. Reducing thatch brings back healthy turf. Golfdom 26(3):78,80,82.

Bigelow, C.A., and W.T. Tudor Jr. 2012. Economic analysis of creeping bentgrass and annual bluegrass greens maintenance. Golf Course Manage. 80(10):76-78, 80, 82, 84, 86, 88, 90-93.

Bolton, A.T., and W.E. Cordukes. 1981. Resistance to *Colletotrichum graminicola* in strains of *Poa annua* and reaction of other turfgrasses. Can. J. Plant Pathol. 3(2):94-96.

Bonos, S.A., E.N. Weibel, T.J. Lawson, and B.B. Clarke. 2009. Tolerance of creeping bentgrass cultivars and selections to anthracnose in New Jersey. [Online]. Appl. Turfgrass Sci.(August):1-4.

Bostock, R.M., and B.A. Stermer. 1989. Perspectives on Wound Healing in Resistance to Pathogens. Annu. Rev. Phytopathol. 27(1):343-371. DOI: doi:10.1146/annurev.py.27.090189.002015.

Brent, K.J., and D.W. Hollomon. 2007. Fungicide resistance in crop pathogens: how can it be managed? FRAC Monogr. No. 1. Crop Life International, Brussels.

Brotherton, M.A. 2011. Influence of Cultural Practices on Creeping Bentgrass Putting Green Quality, Disease Incidence, and Organic Matter Dynamics. M.S. Thesis: North Carolina State Univ.

Browning, M., L.V. Rowley, P. Zeng, J.M. Chandlee, and N. Jackson. 1999. Morphological, pathogenic, and genetic comparisons of *Colletotrichum graminicola* isolates from Poaceae. Plant Dis. 83(3):286-292.

Bruehl, G.W., and J.G. Dickson. 1950. Anthracnose of cereals and grasses. USDA Tech. Bull. 1005:1-37.

Burpee, L.L., and L.G. Goulty. 1984. Influence of cultivation practices and fungicides on the development of anthracnose in a golf course fairway. Univ. of Guelph Turfgrass Res. Rep.:8-10.

Carrow, R.N. 1979. Topdressing: An essential management tool. Golf Course Manage. 47(6):26-28, 30-32.

Carrow, R.N. 1996. Summer decline of bentgrass greens: Understanding the cause of this problem not only helps you cure SBD, but also lets you initiate preventive maintenance. Golf Course Manage. 64(6):51-56.

Carrow, R.N. 2003. Surface organic matter in bentgrass greens. [Online]. USGA Turfgrass and Environ. Res. Online 2(17):1-12.

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(3):524-530. DOI: 10.2134/agronj1987.00021962007900030025x.

Carrow, R.N., and M.A. Petrovic. 1992. Effects of traffic on turfgrasses, In: D. V. Waddington, et al. (Eds.), Turfgrass, ASA, CSSA, & SSSA Inc., Madison, WI. pp. 285-330.

Christians, N. 2011. Fundamentals of turfgrass management. John Wiley & Sons, Inc., Hoboken, NJ.

Clarke, B.B., P. Majumdar, A. Pitonak, S. Flatley, S. Alea, C. Estler, M. Peacos, T.J. Lawson, C. Schmid, J.H. Hempfling, K. Clarke, R. Wang, W.K. Dickson, and J.B. Clark. 2011. Control of anthracnose with selected fungicides and biorational products on an annual bluegrass putting green turf. In: A. B. Gould, editor, Rutgers Turfgrass Proc., New Brunswick, NJ. pp. 220-250.

Clarke, B.B., D. Thompson, J.A. Murphy, and P. Majumdar. 1995. Development of an integrated summer patch control program for fine turf areas. Proc. of the Annu. Rutgers Turfgrass Symp. 4:18-19.

Cooper, R. 2004. Refining your putting green topdressing program. North Carolina Turfgrass:p. 14, 16-17.

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

Couch, H.B. 1973. Diseases of Turfgrasses. Krieger, New York.

Couch, H.B. 1979. Is it Anthracnose or is it wilt? The Greensmaster 15(5):3-6.

Crouch, J.A., and L.A. Beirn. 2009. Anthracnose of cereals and grasses. Fungal Diversity 39:19.

Crouch, J.A., and B.B. Clarke. 2012. Biology and pathology of turfgrass anthracnose. Golf Course Manage. 80(5):96-102.

Crouch, J.A., B.B. Clarke, and B.I. Hillman. 2005. Phylogenetic relationships and fungicide sensitivities of *Colletotrichum graminicola* isolates from turfgrass in North America. Int. Turfgrass Soc. Res. J. 10:186-195.

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(1):46-60. DOI: 10.1094/PHYTO-96-0046.

Danneberger, T., J. Vargas Jr, and A. Jones. 1984. A model for weather-based forecasting of anthracnose on annual bluegrass. Phytopathology 74(4):448-451.

Danneberger, T.K. 2003. Nobody could have predicted how vital PGRs have become. Golfdom 59(4):94.

Danneberger, T.K., M.J. Carroll, J.M. Vargas Jr, and P.E. Rieke. 1995. Susceptibility of *Poa annua* L. to anthracnose as influenced by water stress. J. of Turfgrass Manage. 1(2):19-24.

Davis, W.B. 1977. Sands and your putting green. California Turfgrass Culture 27(4):31-32.

Dawson, R.B. 1934. Forking as an aid to turf recovery after drought. J. of the Board of Greenkeeping Res. 3(11):233-241.

Dawson, R.B., and R.B. Ferro. 1939. Scarification and turf improvement. J. of the Board of Greenkeeping Res. 6(20):11-17.

Dernoeden, P.H. 2012. Creeping bentgrass management. CRC Press.

Detweiler, R.A., J.M. Vargas Jr, and W.L. Brendt. 1989. Resistance of *Colletotrichum graminicola* to benomyl. Proc. Int. Turf. Res. Conf. 6:359-362.

Duff, D.T. 1978. Disagreements arises over variant of annual bluegrass. Univ. of Rhode Island Turfgrass Res. Rev. 3:1-3.

El Gueddari, N.E., U. Rauchhaus, B.M. Moerschbacher, and H.B. Deising. 2002. Developmentally regulated conversion of surface-exposed chitin to chitosan in cell walls of plant pathogenic fungi. New Phytol. 156(1):103-112.

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

Fermanian, T.W., J.E. Haley, and R.E. Burns. 1985. The effects of sand topdressing on a heavily thatched creeping bentgrass turf. Proc. Int. Turf. Res. Conf. 5:439-448.

Foy, J. 1999. May the force be with you: An alternative method for incorporating topdressing sand into high-density putting green turf. U.S. Golf Assoc. Green Section Record 37(3):27.

Gan, P., K. Ikeda, H. Irieda, M. Narusaka, R.J. O'Connell, Y. Narusaka, Y. Takano, Y. Kubo, and K. Shirasu. 2013. Comparative genomic and transcriptomic analyses reveal the hemibiotrophic stage shift of *Colletotrichum* fungi. New Phytol. 197(4):1236-1249.

Gaussoin, R.E., W.L. Berndt, C.A. Dockrell, and R.A. Drijber. 2013. Characterization, development, and management of organic matter in turfgrass systems, In: J. C. Stier, Horgan, Brian P., Bonos, Stacy A., and Schmitt, Gail K. (Ed.), Turfgrass: Biology, Use, and Management, ASA, CSSA, & SSSA Inc., Madison, WI. pp. 1328.

Green, R.L., L. Wu, and G.J. Klein. 2001. Summer cultivation increases field infiltration rates of water and reduces soil electrical conductivity on annual bluegrass golf greens. HortScience 36(4):776-779.

Green Section Staff. 1925. General treatment in the upkeep of greens. Bull. of the U.S. Golf Assoc. Green Section 5(5):118.

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

Halisky, P.M., R.F. Myers, and R.E. Wagner. 1981. Relationship of thatch to nematodes, dollar spot and fungicides in Kentucky bluegrass turf. Proc. Int. Turf. Res. Conf. 4:415-420.

Hall, J.R.I. 1979. Avoid the temptation of sand topdressing. The Georgia Turf-Grass News 7(1):4-5.

Hartwiger, C., and P. O'Brien. 2011. Back to the basics: Plan now for next summer. Carolinas Green:14-15.

Hartwiger, C., and P. O’Brien. 2001. Core aeration by the numbers. U.S. Golf Assoc. Green Section Record 39(4):8-9.

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(4):1179-1184.

Hawes, D.T. 1980. Response of warm- and cool-season turfgrass polystands to nitrogen and topdressing. Proc. Int. Turf. Res. Conf. 3:65-74.

Henderson, J.J., and N.A. Miller. 2010. Importance of particle size distribution, application rate and sand depth in developing a fairway topdressing program. Univ. of Conn. Turfgrass Res. Rep. 5:41-49.

Hsiang, T., and P.H. Goodwin. 2001. Ribosomal DNA sequence comparisons of *Colletotrichum graminicola* from turfgrasses and other hosts. Eur. J. of Plant Pathol. 107(6):593-599.

Huff, D. 2003. Annual bluegrass (Poa annua L.). Turfgrass biology, genetics, and breeding. John Wiley and Sons, Hoboken, New Jersey:39-51.

Huff, D.R. 1998. The case for Poa annua on golf course greens. Golf Course Management 66(10):54-56.

Huff, D.R. 1999. For richer, for *Poa*. U.S. Golf Assoc. Green Section Record 37(1):11-14.

Huff, D.R. 2004. Developing annual bluegrass cultivars for putting greens. USGA Turfgrass and Environ. Res. Online 3(9):1-8.

Hummel, N.W. 1995. Topdressing for success. Cornell Univ. Turfgrass Times 5(4):8-9.

Hurdzan, M.J. 2004. Golf greens: History, design, and construction. John Wiley & Sons, Hoboken, NJ.

Hurto, K.A., A.J. Turgeon, and L.A. Spomer. 1980. Physical characteristics of thatch as a turfgrass growing medium. Agron. J. 72(1):165-167.

Hwang, S., J. Kim, Y.H. Kim, and H.T. Kim. 2008. ABA increases susceptibility of pepper fruits to infection of anthracnose by *Collectotrichum acutatum*. The Plant Pathol. J. 24(4):400-406.

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(4):1595-1607. DOI: 10.2135/cropsci2007.06.0343.

Inguagiato, J.C., J.A. Murphy, and B.B. Clarke. 2009a. Anthracnose Disease and Annual Bluegrass Putting Green Performance Affected by Mowing Practices and Lightweight Rolling. Crop Sci. 49(4):1454-1462. DOI: 10.2135/cropsci2008.07.0435.

Inguagiato, J.C., J.A. Murphy, and B.B. Clarke. 2009b. Anthracnose of annual bluegrass putting green turf influenced by trinexapac-ethyl application interval and rate. Int. Turfgrass Soc. Res. J. 11:207-218.

Inguagiato, J.C., J.A. Murphy, and B.B. Clarke. 2010. Anthracnose development on annual bluegrass affected by seedhead and vegetative growth regulators. Appl. Turf Sci. DOI: 10.1094/ATS-2010-0923-01-RS.

Inguagiato, J.C., J.A. Murphy, and B.B. Clarke. 2012. Sand Topdressing Rate and Interval Effects on Anthracnose Severity of an Annual Bluegrass Putting Green. Crop Sci. 52(3):1406-1415. DOI: 10.2135/cropsci2011.01.0010.

Inguagiato, J.C., J.A. Murphy, B.B. Clarke, and J.A. Roberts. 2013. Topdressing sand particle shape and incorporation effects on anthracnose severity of an annual bluegrass putting green. Int. Turfgrass Res. Soc. J. 12:(accepted).

Jackson, N., and V.J. Herting. 1985. *Colletotrichum graminicola* as an incitant of anthracnose/basal stem rotting of cool season turfgrasses. Int. Turfgrass Soc. Res. J. 5:647-656.

Jenns, A.E., and K.J. Leonard. 1985. Effect of illuminance on the resistance of inbred lines of corn to isolates of *Colletotrichum graminicola*. Phytopathology 75(3):281-286.

Jiang, M., and J. Zhang. 2001. Effect of abscisic acid on active oxygen species, antioxidative defence system and oxidative damage in leaves of maize seedlings. Plant Cell Physiol. 42(11):1265-1273.

Johnson, D.A., and E.R. Miliczky. 1993. Effects of wounding and wetting duration on infection of potato foliage by *Colletotrichum coccodes*. Plant Dis. 77(1):13-17.

Johnson, P.G., B.A. Ruemmele, P. Velguth, D.B. White, and P.D. Ascher. 1993. An overview of *Poa annua* L. reproductive biology. Int. Turfgrass Soc. Res. J. 7:798-804.

Khan, A., and T. Hsiang. 2003. The infection process of *Colletotrichum graminicola* and relative aggressiveness on four turfgrass species. Can. J. Microbiol. 49(7):433-442.

Kim, Y.H. 2008. Effect of delayed inoculation after wounding on the development of anthracnose disease caused by *Colletotrichum acutatum* on chili pepper fruit. The Plant Pathol. J. 24(4):392-399.

Kowalewski, A.R., J.N. Rogers, J.R. Crum, and J.C. Dunne. 2010. Sand topdressing applications improve shear strength and turfgrass density on trafficked athletic fields. HortTechnology 20(5):867-872.

La Mantia, J.M., and D.R. Huff. 2011. Instability of the Greens-Type Phenotype in Poa annua L. pp. 1784-1792.

Labance, B., and G. Witteveen. 2002. Keepers of the Green: A History of Golf Course Management. Ann Arbor Press, Chelsea, MI.

Landreth, J., D. Karcher, and M. Richardson. 2008. Cultivating to manage organic matter in sand-based putting greens: University of Arkansas researchers provide important insight for managing organic buildup on putting greens. U.S. Golf Assoc. Green Section Record 46(1):16-19.

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(4):320-323.

Lipetz, J. 1970. Wound healing in higher plants. Int. Rev. Cytol 27(1):1-28.

Lipps, P.E. 1983. Survival of *Colletotrichum graminicola* in infested corn residues in Ohio. Plant Dis. 67(1):102-104.

Lockyer, J. 2009. Successful fine turf organic matter management. Int. Turfgrass Bull. 244:9-11.

Madison, J.H., J.L. Paul, and W.B. Davis. 1974. Alternative method of greens management. Proc. Int. Turf. Res. Conf. 2:431-437. DOI: 10.2135/1974.proc2ndintlturfgrass.c65.

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(6):1530-1537. DOI: 10.2134/agronj2006.0361.

McDowell, J.M. 2013. Genomic and transcriptomic insights into lifestyle transitions of a hemi-biotrophic fungal pathogen. New Phytol. 197(4):1032-1034.

Mims, C.W., and L.J. Vaillancourt. 2002. Ultrastructural characterization of infection and colonization of maize leaves by *Colletotrichum graminicola*, and by a *C. graminicola* pathogenicity mutant. Phytopathology 92(7):803-812.

Mitkowski, N.A., A.M. Madeiras, A. Chaves, and A. Wick. 2009. Fungicide sensitivity of *Colletotrichum cereale* isolated from turfgrasses in the northeastern United States [Online]. Appl. Turfgrass Sci.:[1-10].

Moeller, A.C. 2008. Evaluation of Putting Green Surface Organic Matter Management Programs. M.S. Thesis: Purdue Univ.

Muimba-Kankolongo, A. 1991. Nature of resistance to anthracnose stalk rot associated with maize genotype, ontogeny, and wound response. PhD Thesis: Cornell Univ.

Muimba-Kankolongo, A., and G. Bergstrom. 1992. Wound predisposition of maize to anthracnose stalk rot as affected by internode position and inoculum concentration of *Colletotrichum graminicola*. Plant disease 76(2):188-195.

Muimba-Kankolongo, A., and G.C. Bergstrom. 1990. Transitory wound predisposition of maize to Anthracnose stalk rot. Can. J. Plant Pathol. 12(1):1-10.

Muimba-Kankolongo, A., and G.C. Bergstrom. 2011. Reduced Anthracnose Stalk Rot in Resistant Maize is Associated with Restricted Development of *Colletotrichum graminicola* in Pith Tissues. Phytopathology 159(5):329-341. DOI: 10.1111/j.1439-0434.2010.01766.x.

Münch, S., U. Lingner, D.S. Floss, N. Ludwig, N. Sauer, and H.B. Deising. 2008. The hemibiotrophic lifestyle of *Colletotrichum* species. J. Plant Physiol. 165(1):41-51.

Murphy, J., F. Wong, L. Tredway, J.A. Crouch, J. Inguagiato, B. Clarke, T. Hsiang, and F. Rossi. 2008. Best management practices for anthracnose on annual bluegrass turf. Golf Course Manage. 24:93-104.

Murphy, J.A., B.B. Clarke, C.J. Schmid, J.W. Hempfling, and R. Wang. 2011. Developing best management practices for anthracnose disease on annual bluegrass putting green turf. *In:* 2011 USGA Turfgrass Environ. Res. Summ. USGA Turfgrass and Environmental Research Online 10(23):2.

Murphy, J.A., and J.W. Hempfling. 2011. Impact of sand size and topdressing rate on surface firmness and turf quality of velvet bentgrass. USGA Turfgrass and Environmental Research Summary:39.

Murphy, J.A., J.C. Inguagiato, and B.B. Clarke. 2012. Best management practices for anthracnose on annual bluegrass. Golf Course Manage. 80(5):104-110.

Murphy, J.A., and P.E. Rieke. 1994. High pressure water injection and core cultivation of a compacted putting green. Agron. J. 86(4):719-724.

Murphy, J.A., P.E. Rieke, and A.E. Erickson. 1993. Core cultivation of a putting green with hollow and solid tines. Agron. J. 85(1):1-9.

Musser, H.B. 1950. Turf Management. McGraw-Hill Book Company, Inc., New York, NY.

Nannfeldt, J.A. 1937. The chromosome numbers of *Poa* sect. Ochlopoa A. & Gr. and their taxonomical significance. Botanisker Notiser:238-254.

Nicholson, R.L., G.B. Bergeson, F.P. DeGennaro, and D.M. Viveiros. 1985. Single and combined effects of the lesion nematode and *Colletotrichum graminicola* on growth and anthracnose leaf blight of corn. Phytopathology 75(6):654-661.

Nicholson, R.L., and R. Hammerschmidt. 1992. Phenolic compounds and their role in disease resistance. Annu. Rev. Phytopathol. 30(1):369-389.

Nikolai, T.A., P.E. Rieke, J.N. Rogers, 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.

O'Brien, P., and C. Hartwiger. 2003. Aeration and topdressing for the 21st century: Two old concepts are linked together to offer up-to-date recommendations. U.S Golf Assoc. Green Section Record 41(2):1-7.

Orshinsky, A.M., M.J. Boehm, and G.J. Boland. 2012. Plant wounding and *Ophiostoma mitovirus 3a* (OMV3a) influence infection of creeping bentgrass by *Sclerotinia homoeocarpa*. Can. J. Plant Pathol. 34:493.

Perfect, S.E., H.B. Hughes, R.J. O'Connell, and J.R. Green. 1999. *Colletotrichum*: A Model Genus for Studies on Pathology and Fungal–Plant Interactions. Fungal Genet. and Biol. 27(2):186-198.

Piper, C.V., and R.A. Oakley. 1917. Turf for golf courses. Macmillan, New York, NY.

Radko, A.M. 1985. Have we gone too far with low nitrogen on greens? U.S Golf Assoc. Green Section Record 23:26-28.

Raisch, T. 2003. Anthracnose: One club's three-year battle. Golf Course Manage. 71(11):76-78,80,82,84.

Roberts, J.A. 2009. Impact of cultural management on anthracnose severity of annual bluegrass putting green turf. M.S. Thesis: Rutgers Univ.

Roberts, J.A., J.C. Inguagiato, B.B. Clarke, and J.A. Murphy. 2011. Irrigation Quantity Effects on Anthracnose Disease of Annual Bluegrass. Crop Sci. 51(3):1244-1252. DOI: 10.2135/cropsci2010.07.0444.

Roberts, J.A., J.A. Murphy, and B.B. Clarke. 2010. Summer N-fertilization effects on annual bluegrass putting green turf. Phytopathology 100(65):S197.

Roberts, J.A., J.A. Murphy, and B.B. Clarke. 2012. Lightweight Rolling Effects on Anthracnose of Annual Bluegrass Putting Greens. Agron. J. 104(4):1176-1181. DOI: 10.2134/agronj2011.0269.

Schall, R.A., R.L. Nicholson, and H.L. Warren. 1980. Influence of light on maize anthracnose in the greenhouse. Phytopathology 70(10):1023-1026.

Schmid, C.J., B.B. Clarke, and J.A. Murphy. 2012a. Effect of Nitrogen Form on Anthracnose Disease of Annual Bluegrass Turf. Eur. Turfgrass Soc. Conf. Proc. 3:Unknown.

Schmid, C.J., J.A. Murphy, and B.B. Clarke. 2012b. Anthracnose severity of annual bluegrass putting green turf as influenced by nitrogen fertilization programming. Phytopathology 102(1):S1.7.

Selby, A.D., and T.F. Manns. 1909. Studies in diseases of cereals and grasses. Ohio Agric. Exp. Stn.

Settle, D.M., A.D. Martinez-Espinoza, and L.L. Burpee. 2006. Anthracnose of Turfgrass. The Plant Health Instructor [Online]:[1-6]. DOI: DOI:10.1094/PHI-I-2006-1205-01.

Shearman, R.C. 1984. Topdressing: Effects on cultural practices and disease incidence. Proc. of 54th Annu. Michigan Turfgrass Conf. 13:98-99.

Skoropad, W.P. 1967. Effect of temperature on the ability of *Colletotrichum graminicola* to form appressoria and penetrate barley leaves. Can. J. Plant Sci. 47(4):431-434.

Smiley, R.W., P.H. Dernoeden, and B.B. Clarke. 2005. Compendium of turfgrass diseases. APS press, St. Paul, MN.

Smith, J.D. 1954. A disease of *Poa annua*. J. Sports Turf Res. Inst. 8:344-353.

Smith, J.D., N. Jackson, and A.R. Woolhouse. 1989. Fungal diseases of amenity turf grasses. E. & FN Spon, New York, NY.

Sprague, H.B., and G.W. Burton. 1937. Annual bluegrass, *Poa annua* L. and its requirements for growth. New Jersey Agric. Exp. Stn. Bull.

Sprague, H.B., and E.E. Evaul. 1930. Experiments with turf grasses in New Jersey. New Jersey Agric. Exp. Stn. Bull.

Stier, J.C., and A.B. Hollman. 2003. Cultivation and topdressing requirements for thatch management in A and G bentgrasses and creeping bluegrass. HortScience 38(6):1227-1231.

Sukno, S.A., V.M. García, B.D. Shaw, and M.R. Thon. 2008. Root infection and systemic colonization of maize by *Colletotrichum graminicola*. Appl. Environ. Microbiol. 74(3):823-832.

Taylor, D.H. 1986. Points of caution: Sand size for topdressing golf greens. Golf Course Manage. 54(7):50, 52, 54, 58, 60, 62.

Tisserat, N.A., and J. Fry. 1997. Cultural practices to reduce spring dead spot (*Ophiosphaerella herpotricha*) severity in *Cynodon dactylon*. Int. Turf. Soc. Res. J. 8:931-936.

Turgeon, A.J. 2011. Turfgrass Management, Prentice Hall, Upper Saddle River, NJ.

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

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

Uddin, W., and M.D. Soika. 2003. Effects of turfgrass cultural management practices on severity of anthracnose basal rot in mixed annual bluegrass and creeping bentgrass greens. Phytopathology 93:S86.

Unruh, J.B., S.D. Davis, P.F. Colbaugh, B.J. Brecke, and D.O. Stephenson. 2005. Impact of various chemical and nutrient inputs and cultural treatments on 'Tifeagle bermudagrass (*Cynodon dactylon* x *C. transvaalensis*). Int. Turfgrass Soc. Res. J. 10(1):455-461.

USDA-CSREES. 2005. NE 1025: Biology, ecology and management of emerging pest of annual bluegrass on golf courses. Nat'l. Info. Mgt. and Support System. USDA-CSREES, Washington, DC.

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

Vargas, J.M. 1980. Anthracnose - rediscovering the wheel. GreenMaster 16(2):22-24.

Vargas, J.M., T.K. Danneberger, and A.L. Jones. 1992. Effects of temperature, leaf wetness duration and inoculum concentration on infection of annual bluegrass by

Colletotrichum graminicola. International Turfgrass Society Research Journal 7:324-328.

Vargas, J.M., and A.R. Detweiler. 1985. Anthracnose of *Poa annua*: the pathogenicity of *Colletotrichum graminicola*. Proc. Int. Turf. Res. Conf. 5:637-640.

Vargas Jr, J.M. 1976. Anthracnose: Disease poses threat to annual bluegrass. Golf Superintendent 44:42-45.

Vargas Jr., J.M. 1977. Maintaining annual bluegrass. Proc. of the Annu. Illinois Turfgrass Conf. 18:76-80.

Vargas, W.A., J.M.S. Martín, G.E. Rech, L.P. Rivera, E.P. Benito, J.M. Díaz-Mínguez, M.R. Thon, and S.A. Sukno. 2012. Plant defense mechanisms are activated during biotrophic and necrotrophic development of *Colletotricum graminicola* in maize. Plant physiology 158(3):1342-1358.

Vavrek Jr., R.C. 1995. A successful topdressing program requires consistency, commitment, and communication. U.S Golf Assoc. Green Section Record 33(5):8-10.

Venard, C., and L. Vaillancourt. 2007a. Colonization of fiber cells by *Colletotrichum graminicola* in wounded maize stalks. Phytopathology 97(4):438-447. DOI: 10.1094/phyto-97-4-0438.

Venard, C., and L. Vaillancourt. 2007b. Penetration and colonization of unwounded maize tissues by the maize anthracnose pathogen *Colletotrichum graminicola* and the related nonpathogen *C. sublineolum*. Mycologia 99(3):368-377.

Vermeulen, P. 1989. Consider *Poa annua* for your new green. U.S Golf Assoc. Green Section Record 27(5):17.

Vermeulen, P.H. 2003. Maybe it's time for a change. U.S Golf Assoc. Green Section Record 41:28.

Vizvary, M.A., and H.L. Warren. 1982. Survival of *Colletotrichum graminicola* in Soil. Phytopathology 72(5):522-525.

von Arx, J.A. 1957. Die Arten der Gattung *Colletotrichum* Cda. Phytopathologische Zeitschrift 29:414-468.

Waddington, D.V. 1992. Soils, soil mixtures, and soil amendments, In: D. V. Waddington, et al. (Eds.), Turfgrass, ASA, CSSA, & SSSA Inc., Madison, WI. pp. 331-383.

Wang, Z., M. Gerstein, and M. Snyder. 2009. RNA-Seq: a revolutionary tool for transcriptomics. Nature Rev. Genet. 10(1):57-63.

White, D.G. 1999. Compendium of corn diseases. American Phytopathological Society (APS Press).

White, D.G., R.G. Hoeft, and J.T. Touchton. 1978. Effect of nitrogen and nitrapyrin on stalk rot, stalk diameter, and yield of corn. Phytopathology 68:811-814.

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

Wolff, E.T. 1947. An Experimental Study of Colletotrichum Graminicolum on Fine Turf. PhD Thesis: Penn. State College.

Wong, F.P., K.A. de la Cerda, R. Hernandez-Martinez, and S.L. Midland. 2008. Detection and characterization of benzimidazole resistance in California populations of *Colletotrichum cereale*. Plant Dis. 92(2):239-246.

Wong, F.P., and S. Midland. 2004. Fungicide-resistant anthracnose: Bad news for greens management. Golf Course Manage. 72(6):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 Dis. 91(12):1547-1555.

Wong, F.P., S.L. Midland, and K.A. de la Cerda. 2007. Occurrence and distribution of QoI-resistant isolates of *Colletotrichum cereale* from annual bluegrass in California. Plant Dis. 91(12):1536-1546.

Young, J.R., M. Tomaso-Peterson, K. de la Cerda, and F.P. Wong. 2010a. Two mutations in β-tubulin 2 gene associated with thiophanate-methyl resistance in *Colletotrichum cereale* isolates from creeping bentgrass in Mississippi and Alabama. Plant Dis. 94(2):207-212.

Young, J.R., M. Tomaso-Peterson, L.P. Tredway, and K. de la Cerda. 2010b. Occurrence and molecular identification of azoxystrobin-resistant *Colletotrichum cereale* isolates from golf course putting greens in the Southern United States. Plant Dis. 94(6):751-757.

Youngner, V.B. 1959. Ecological studies on *Poa annua* in turfgrasses. Grass Forage Sci. 14(4):233-237.

Zontek, S.J. 1973. A positive approach to *Poa annua* management. U.S Golf Assoc. Green Section Record 11(2):1-5.

Zontek, S.J. 1979. Is sand topdressing right for you? Golf Course Manage. 47(6):15-17, 19-21.

Zontek, S.J. 1983. Mismanagement in topdressing greens. Proc. of the 53rd Annu. Michigan Turfgrass Conf. 12:82-84.

Zontek, S.J. 2004. Have we gone too far? The grass is talking to you. Are you listening? U.S Golf Assoc. Green Section Record 48:28.

CHAPTER 2. Anthracnose Disease Development on Annual Bluegrass Influenced by Spring and Summer Sand Topdressing Rate

ABSTRACT

Anthracnose is a destructive disease of annual bluegrass [*Poa annua* L. f. *reptans* (Hausskn) T. Koyama] (ABG) turf caused by the fungus *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman. Sand topdressing during the summer can reduce anthracnose severity of ABG turf but the effect of spring topdressing on this disease remains unknown. A two year field study was initiated to evaluate the effect of spring topdressing on anthracnose severity as well as the potential for this factor to interact with the effects of summer topdressing on ABG maintained at 3.2-mm on a Nixon sandy loam in North Brunswick, NJ. The trial used a 3 x 5 factorial arranged as a RCBD with four replications. Spring topdressing was applied at rates of 0, 1.2 and 2.4 L m^{-2} as two split-applications on 20 April and 4 May 2009 and 14 and 28 April 2010. Summer topdressing was applied at rates of 0, 0.075, 0.15, 0.3 and 0.6 L m^{-2} every 14-d from 1 June to 24 August 2009 and 24 May to 17 August 2010. Generally, increased rate of spring and summer topdressing reduced anthracnose disease severity linearly throughout most of 2009 and 2010. However, the response to increased summer topdressing rate became a quadratic decrease in disease severity by the latter half of the 2010 season; the greatest summer topdressing rates had a diminishing effect on disease reduction. Interaction data from 2010 indicated that the rate of summer topdressing needed to reduce disease was decreased when the rate of spring topdressing was increased. Thus, spring topdressing is

an effective practice to reduce anthracnose disease severity and may enable the use of lower-rate summer topdressing to complement disease suppression.

INTRODUCTION

Anthracnose (*Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman) (Crouch et al., 2006) is a fungal disease that causes severe damage to annual bluegrass [*Poa annua* L. forma *reptans* (Hausskn.) T. Koyama] (ABG) and creeping bentgrass (*Agrostis stolonifera* L.) putting greens on golf courses in temperate climates across the world. The disease is most devastating on ABG, especially when the turf is maintained under stress-inducing cultural management programs to achieve faster green speeds (longer ball roll distance) (Dernoeden, 2012).

Topdressing is the distribution of a thin layer of soil onto a turfgrass area (Beard, 1973). Sand topdressing has been used to smooth the surface, modify accumulating thatch, improve surface soil root zones and provide winter protection of putting greens since the early days of golf (Bengeyfield, 1969; O'Brien and Hartwiger, 2003; Piper and Oakley, 1917). Previous research regarding the effect of topdressing on turf diseases is limited and results are varied. Cooper and Skogley (1981), Engel and Alderfer (1967), and Fermanian et al. (1985) found that topdressing (with coarse or loamy coarse sand, sandy loam, or sand and sand/soil mixes, respectively) on creeping bentgrass and velvet bentgrass putting green turf increased dollar spot (caused by *Sclerotnia homoeocarpa* F.T. Bennett) severity. Contrastingly, other studies on of ‘Tifway’ bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* (Burtt-Davis)] managed as a home lawn and creeping bentgrass and ABG putting green turf found that dollar spot severity was not affected by sand topdressing (Carrow et al., 1987; Stier and Hollman, 2003). Sand topdressing reduced dollar spot on creeping bentgrass fairway turf and spring dead spot (*Ophiosphaerella* spp.) in bermudagrass turf mowed at 1.9 cm (Hawes, 1980;

Henderson and Miller, 2010). No discussion was provided by the authors of these studies regarding the possible mechanism(s) responsible for the effects of topdressing on the severity of these diseases.

Contrary to the belief at the time that topdressing encouraged anthracnose (Smiley et al., 2005), Inguagiato et al. (2012) found that topdressing during the summer every 7 to 42 d at rates ranging from 0.3 to 1.2 L m^{-2} reduced anthracnose severity. Another study on the effect of sand particle shape on anthracnose showed that both sub-angular and round topdressing sand applied at 0.3 L m^{-2} every 14 d reduced the disease (Inguagiato et al., 2013). Most recently, Roberts (2009) observed that sand topdressing during the summer at 0.3 L m^{-2} every 7 d reduced disease severity even under conditions of intense foot traffic. Small increases in anthracnose severity from sand topdressing during the summer were observed early in the first year of each of these previous trials (Inguagiato et al., 2012; Inguagiato et al., 2013; Roberts, 2009). However, these initial increases in disease severity dissipated as sand topdressing treatments continued. Inguagiato et al. (2013) suggested that this initial increase in disease could have been caused by sand abrasion injury to exposed crowns, and that a critical level of sand accumulation (i.e., mat layer) must be achieved before sand topdressing could provide disease reductions.

Inguagiato et al. (2012) observed that cumulative amounts of 2.4 to 4.8 L m^{-2} of sand were needed to reduce anthracnose severity. Specifically, sand topdressing at rates of 0.3 to 0.6 L m^{-2} applied every 7 to 14 d during the summer provided the most rapid and substantial disease reduction. However, topdressing at these rates and frequencies during the summer can be an expensive and laborious practice for golf course superintendents and can potentially interrupt play on the golf course for several days after application (Bigelow and Tudor Jr, 2012; Vavrek, 1995). Therefore, there is a need to determine sand topdressing programs (i.e., rates and timings) that reduce anthracnose and provide more acceptable playing conditions throughout the summer.

Topdressing during the spring is generally less expensive to implement and less disruptive to play than summer topdressing programs. It is not known whether topdressing during the spring affects anthracnose severity or the impact of summer topdressing on this disease. Therefore, the objective of this trial was to determine the effect of spring topdressing on anthracnose severity as well as the potential for this factor to interact with the effects of summer topdressing.

MATERIALS AND METHODS

Experimental Design and Treatments

A 2-yr. field trial was initiated in March 2009 on ABG turf grown on a Nixon sandy loam (fine-loamy, mixed, semiactive, mesic Typic Hapludults, in some areas altered to fine-loamy, mixed, semiactive, mesic Ultic Udarents) at Horticultural Farm No. 2 in North Brunswick, NJ (40°28' N, 74°25' W). The ABG monostand was established in 2001 as described by Inguagiato et al. (2008) using the existing soil seed bank as well as seed introduced from soil cores collected from Rutgers Golf Course in Piscataway, NJ. The topdressing timing factors of spring and summer were arranged as a 3 x 5 factorial, respectively, in a randomized complete block design with four replications. Spring topdressing was applied at rates of 0, 1.2, and 2.4 L m^{-2} as split applications on 20 April and 4 May 2009 and 14 and 28 April 2010. Summer topdressing was applied at rates of 0, 0.075, 0.15, 0.3, and 0.6 L m^{-2} every 14 d from 1 June to 24 August 2009 and 24 May to 17 August 2010. Coring was not performed in combination with these treatments to avoid any potential confounding effects. Plot size was 1.8 by 1.8 m.

All topdressing treatments, except for the 0.075 L m^{-2} summer rate, were applied with a drop spreader (model SS-2, The Scotts Company, Marysville, OH) calibrated to uniformly apply each volume over the plot in 4 passes. The 0.075 L m^{-2} summer rate was applied uniformly with a shaker jar in 4 directions over the plot area. The topdressing material was a kiln dried subangular silica sand ("310" U.S. Silica, Co., Mauricetown, NJ) having a particle distribution that met USGA recommendations (2004) and a bulk density of 1.56 g cm^{-3} (Table 2.1). Treatments were applied between 1200 and 1700 h when the turf canopy was dry. Sand was incorporated using a soft-bristle brush as described by Inguagiato et al. (2012) followed by a light irrigation (hose) of the entire trial area.

Field Maintenance

The trial was mowed six times wk^{-1} between 0800 and 0930 h with a walk-behind greens mower (model 220A, Deere & Co., Moline, IL) set at a 3.2 mm bench setting. During the period that topdressing treatments were applied, 48.8 and 58.6 kg ha^{-1} of N was applied to the trial in 2009 and 2010, respectively. Once disease progress was arrested, N was applied at 93.7 and 112.8 kg ha^{-1} from September to October 2009 and September to November 2010, respectively. Irrigation was applied to maintain moderately-dry conditions and to prevent wilt stress. Soil pH, P and K were managed based on soil test recommendations common for putting greens in the northeastern United States.

Ethephon [(2-chloroethyl)phosphonic acid] was applied at 3.81 kg a.i. ha^{-1} on 25 March, 13 and 28 April 2009, and 19 March, 2 April, and 23 April 2010 to suppress ABG inflorescence expression. Trinexapac-ethyl [4-(cyclopropyl-α-hydroxy-methylene)-3,5-dioxocyclohexanecarboxylic acid ethylester)] was applied at 0.05 kg a.i. ha^{-1} every 14 d from 25 March until 2 October 2009 and from 19 March until 2 October 2010 to reduce vertical shoot growth and increase lateral tillering. Biweekly applications were made to control dollar spot disease with the fungicides vinclozolin [3-(3,5-dichlorophenyl)-5-ethenyl-5-methyl-2,4-oxazolidinedione] at 1.52 kg a.i. ha^{-1} or boscalid {3-pyridinecarboximide, 2-chloro-N-[4'chloro(1,1'-biphenyl)yl]} at 0.38 kg a.i. ha^{-1}. Brown patch (caused by *Rhizoctonia solani* Kühn) and summer patch (caused by *Magnaporthe poae* Landschoot & Jackson) were controlled using a biweekly rotation of the fungicides azoxystrobin (Methyl(E)-2-{2-[6-(2-cyanophenoxy)pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate)} at 0.61 kg a.i. ha^{-1}, flutolanil {N-[3-(1-methylethoxy)phenyl]-2-(trifluoromethyl)benzamide} at 6.41 kg a.i. ha^{-1}, and fluoxastrobin [(1E)-[2-[[6-(2-Chlorophenoxy)-5-fluoro-4-pyrimidinyl]oxy]phenyl](5,6-dihydro-1,4,2-dioxazin-3-yl) methanone-O-methyloxime] at 0.55 kg a.i. ha^{-1}. Mancozeb (ethylenebisdithiocarbamate) was applied as needed to control algae using rates ranging from 20.1 to 30.5 kg a.i. ha^{-1} in 2009 and 2010. These fungicides were found to have no effect on anthracnose isolates from this research location (Towers et al., 2003). Annual bluegrass weevils [*Listronotus maculicollis* (Kirby)] were controlled with indoxacarb {(S)-methyl 7-chloro-2,5-dihydro-2-[[(methoxycarbonyl)[4(trifluoromethoxy)phenyl]amino]-carbonyl]indeno[1,2-e][1,3,4]oxadiazine-4a-(3H)-carboxylate} applied at 0.27 kg a.i. ha^{-1} and chlorantraniliprole {3-Bromo-N-[4-chloro-2-methyl-6-[(methylamino)carbonyl]phenyl]-1-(3-chloro-2-pyridinyl)-1H-pyrazole-5-carboxamide} applied at 0.18 kg a.i. ha^{-1} on 14 June 2009 and 30 April 2010, respectively. Fluazifop-P-butyl {Butyl (R)-2-[4-[[5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoate} was applied at 0.21 kg a.i. ha^{-1} on 20 Sept. 2010 to suppress creeping bentgrass encroachment. Anthracnose disease was arrested at the end of each trial-year by applying chlorothalonil (tetrachloroisophthalonitrile) at 15.3 kg a.i. ha^{-1} on 3, 13 and 24 September 2009 and 18 September, 2 and 22 October 2010.

Data Collection

Anthracnose Disease Severity

Anthracnose severity was evaluated every 7 to 14 d when symptoms were present with a line-intercept grid count method that generated 273 observations per plot

(Inguagiato et al., 2008). A count of intersects that overlaid diseased ABG turf was recorded for each plot and transformed to a percentage using the equation:

$$(n/273) \times 100;$$

where n represented the count of intersects that overlaid of diseased ABG turf.

Visual Ratings

Turfgrass quality was rated visually every 7 to 14 d using a 1 to 9 scale (9 represented the best quality and 5 was the minimally acceptable rating). Turf density, uniformity, algae, and disease severity were considered when turf quality was evaluated. The extent of sand incorporation (SI) was assessed visually on 10 dates between 15 June and 27 July 2009 using a 1 to 9 scale [9 represented no visible sand on the canopy surface (=sand fully incorporated into the canopy) and 5 was the minimally acceptable amount of sand incorporated into the canopy). Additionally, the number of days required for all four replications of each topdressing treatment to reach an acceptable level of sand incorporation in the turf canopy was recorded after summer topdressing applications in 2009 and 2010. After the termination of the trial, turf color (1-9 scale; 9 represented the darkest green color and 5 was the minimally acceptable rating) was rated four times from March to November in 2011.

Volumetric Water Content

Volumetric water content (VWC) at the rootzone surface (0-7.5 cm depth) was measured on 6 dates in 2009 and 2 dates in 2010 using a portable soil probe equipped with time domain reflectometry (TDR), (Field Scout TDR 300 model, Spectrum Technologies, Inc., Plainfield, IL). The average of three measurements taken per plot was used for statistical analysis.

Surface Hardness

A Clegg Impact Soil Tester (CIST) (2.25 kg model, Lafayette Instrument Co., Lafayette, IN) and a USGA TruFirm device (TruFirm model, United States Golf Association, Far Hills, NJ) were used to measure surface hardness (SH). Readings were taken simultaneous with soil volumetric water content measurements of the upper 7.5 cm rootzone on 30 July and 30 August 2010. The impact hammers of the CIST and TruFirm devices were dropped from a 0.46 m height at three locations per plot and averaged for statistical analysis. Units were recorded in gravities (g_{max}) for the CIST and in centimeters for the TruFirm.

Thatch/Mat Layer Depth and Soil Nutrient Analysis

Samples for soil nutrient analysis were taken on 23 Nov. 2011 from plots that received a total of 0 and 6.6 L m^{-2} yr^{-1} of topdressing sand. Four soil cores were taken to a 17 cm depth using a 1.9 cm inside diameter probe. The thatch/mat layer of each core was measured for depth and separated from the underlying sandy loam portion of the sample. Verdure was removed from the thatch/mat portion. The thatch/mat and sandy loam portions of the four cores from each plot were composited separately, air-dried for 24 hours, and sent to the Rutgers Soil Testing Laboratory (New Brunswick, NJ) for analysis of soil pH and nutrient availability using the Mehlich III extraction method (Mehlich, 1984).

Data Analysis

Data were subjected to ANOVA using the General Linear Model procedure of the Statistical Analysis System (SAS) software v. 9.3 (SAS Institute, Cary, NC). Anthracnose severity data were transformed to area under the disease progress curve

(AUDPC) values to summarize disease epidemics for the evaluation periods in 2009 and 2010 (12 June to 3 Sept. and 19 May to 3 Sept., respectively) using the equation:

$$\text{AUDPC} = \sum_{i=1}^{n_i - 1} \left(\frac{y_i + y_{i+1}}{2} \right) (t_{i+1} - t_i)$$

where "t_i" is time in days, "i" is the order index for the ratings (and "n_i" is the number of ratings), "y" is the percent turf area infested at rating (Madden et al., 2007). Orthogonal polynomial contrasts for the main effects of spring (linear and quadratic) and summer (linear, quadratic, cubic, and quartic) topdressing rate were evaluated for the response variables of disease severity, AUDPC, turf quality, turf color, SI, VWC, and SH. Means of significant thatch/mat layer depth and soil nutrient analysis effects were separated using Fisher's protected least significant difference at the 0.05 probability level.

RESULTS

Anthracnose Severity

Disease symptoms were slow to develop in 2009; disease severity averaged no more than 3% on the four observation dates from 12 June to 23 July 2009 (Table 2.2). Disease severity increased to as much as 9% by 30 July 2009 and no treatment had a disease severity greater than 10% until early August. Maximum disease severity (35%) was reached by 27 Aug. 2009. In contrast, disease severity exceeded 10% on several treatments by 19 May 2010 and 25% on most plots on 28 June 2010 (Table 2.3). Maximum severity reached 72% by 3 Sept. 2010.

Area Under Disease Progress Curve

Accordingly, the area under the disease progress curve (AUDPC) values were much lower in 2009 than in 2010, due to the late onset of disease and the lower peak disease severity in 2009 (Tables 2.2 and 2.3). The AUDPC response to increased spring topdressing rate was a linear decrease in 2009 and 2010 (Tables 2.2 and 2.3). Similarly, increased summer topdressing rate produced a linear reduction in AUDPC in 2009 (Table 2.2); however, summer topdressing produced a quadratic decrease in AUDPC in 2010 (Table 2.3). The minimum AUDPC value in 2010 was obtained at a 0.39 L m^{-2} rate of summer topdressing as estimated from the quadratic polynomial equation.

Main Effects on Individual Observation Dates

Treatment differences on the first four rating dates in 2009 were not considered practically important because of the very low disease pressure (Table 2.2). Increased spring topdressing rate produced a linear reduction in disease severity on 6 August 2009 that continued from 20 Aug. through 3 Sept. 2009 providing up to a 10% reduction in severity. This effect of increased spring topdressing rate producing a linear reduction in anthracnose severity (6 to 21%) was observed from 28 May through 3 Sept. 2010 (Table 2.3).

Increased summer topdressing rate produced a strong linear reduction in disease severity from 30 July until 3 Sept. 2009; however, the response was quadratic on 13 August and depended on the spring topdressing rate on 20 August (Table 2.2). The quadratic response indicated that the minimum disease severity occurred at an estimated rate of 0.58 L m^{-2}.

Summer topdressing rate provided a strong linear reduction in disease severity on the first two rating dates in 2010; however, the response weakened and became quadratic by 19 June 2010 (Table 2.3). A quadratic response to summer topdressing rate was apparent from 15 July to 3 Sept. 2010 but the response depended on the spring topdressing rate on 15 July, 28 July and 3 Sept. Minimum disease severity occurred at an estimated summer topdressing rates of 0.36 and 0.39 L m^{-2} on 19 June and 16 Aug. 2010, respectively.

Interaction Effects on Individual Observation Dates

As mentioned, interactions between spring and summer topdressing rate were evident on 20 Aug. 2009 and 15 and 28 July and 3 Sept. 2010 (Tables 2.2 and 2.3). Increased summer topdressing rate produced a cubic, quadratic, and linear decrease in disease severity under the 0, 1.2, and 2.4 L m^{-2} rates of spring topdressing, respectively, on 20 Aug. 2009 (Table 2.4). The cubic response indicated that lower summer topdressing rates (0.075 and 0.15 L m^{-2}) caused a slight increase in disease (3-4%) that was maximized at an estimated summer rate of 0.08 L m^{-2}; whereas greater rates (0.3 and

0.6 L m^{-2}) reduced disease (14 to 24%) minimizing at an estimated rate of 0.5 L m^{-2}. The quadratic response under the spring topdressing rate of 1.2 L m^{-2} indicated that disease severity was lowest at an estimated summer topdressing rate of 0.54 L m^{-2}. Increased summer topdressing rate had the smallest reduction (linear) in disease severity under 2.4 L m^{-2} of spring topdressing probably because the disease severity was already low (19%) due to spring topdressing.

The interactions in July 2010 indicated that increased summer topdressing rate had the greatest effect (quadratic) on anthracnose severity under the 0 L m^{-2} spring topdressing level (Table 2.5). Minimum disease severity occurred at an estimated summer topdressing rate of 0.38 L m^{-2} for both 15 and 28 July 2010. The only other response to summer topdressing in July 2010 was a cubic response to summer topdressing under 1.2 L m^{-2} of spring topdressing on 15 July. This cubic response indicated that minimum disease severity occurred at an estimated summer topdressing rate of 0.13 L m^{-2}. On 3 Sept. 2010, the shape of the quadratic disease severity response to summer topdressing rate depended on the spring topdressing rate. Disease severity decreased as summer topdressing rate increased under no spring topdressing, and the lowest disease severity occurred at estimated summer topdressing rates of 0.52 L m^{-2}. In contrast, the quadratic response to summer topdressing under 1.2 and 2.4 L m^{-2} of spring topdressing suggested that increasing summer topdressing rates beyond 0.37 and 0.35 L m^{-2}, respectively, produced slight increases in disease severity.

Turf Quality

Turf quality of all treatments was acceptable (>5) on every rating date in 2009 due to the mild severity of the disease epiphytotic (Table 2.6). Turf quality was acceptable for all treatments until mid-July in 2010 when disease symptoms caused severe damage to the plots (Table 2.7).

Main Effects

Increased spring topdressing rate produced a linear improvement in turf quality in 2009 on 8 of 10 rating dates (Table 2.6). A quadratic response to spring topdressing rate was evident on 27 May 2009 when turf quality was maximized at an estimated spring topdressing rate of 1.6 L m^{-2}. Turf quality was not affected by spring topdressing on 16 July or 1 August 2009.

The turf quality response to increased spring topdressing rate was a quadratic improvement early in the 2010 growing season similar to 2009 (Table 2.7). The best turf quality was achieved at estimated spring topdressing rates of 1.3, 1.91 and 2.29 L m^{-2} on 19 May, 28 May and 4 June 2010, respectively. The turf quality response to increased spring topdressing rate became linear on 11 June and continued through 3 Sept. 2010.

Increased summer topdressing rate produced a linear improvement in turf quality by 24 June 2009 that continued, except for 6 and 16 July, until 17 Aug. 2009 (Table 2.6). The turf quality response depended on the spring topdressing rate on 6 July and was a quadratic improvement on 27 Aug. 2009, maximizing at an estimated summer topdressing rate of 0.6 L m^{-2}. Summer topdressing had no effect on turf quality on 16 July 2009.

Increased summer topdressing rate produced linear improvements in turf quality on most dates through 5 July 2010 (Table 2.7). Increased summer topdressing rate produced a quadratic improvement in turf quality on 19 June and 15 and 28 July, and the best turf quality occurred at estimated summer topdressing rates of 0.44, 0.46, and 0.36 L m^{-2}, respectively. The turf quality response to summer topdressing rate depended on the spring topdressing rate on 16 August and 3 Sept. 2010 ($pr > F = 0.055$).

Interaction Effects

Turf quality had a cubic response to summer topdressing rate when no spring topdressing was applied on 6 July 2009 (Table 2.8). The best turf quality occurred at an estimated summer topdressing rate of 0.47 L m^{-2}. Turf quality did not respond to summer topdressing rate when spring topdressing was 1.2 or 2.4 L m^{-2}. The interaction also indicated that there was not a benefit to turf quality from spring topdressing when summer topdressing was applied at 0.3 and 0.6 L m^{-2}.

Summer topdressing rate produced a quadratic improvement in turf quality on 16 Aug. 2010 at the 0 and 2.4 L m^{-2} spring topdressing rates, and the best turf quality occurred at estimated summer topdressing rates of 0.43 and 0.4 L m^{-2}, respectively (Table 2.8).

The spring by summer interaction was very close to statistical significance ($p=0.055$) and showed similar responses on 3 Sept. 2010 as the previous interactions (Table 2.8). The strongest positive response of turf quality to summer topdressing rate occurred when no spring topdressing was applied. The response to summer topdressing rate was quadratic under no spring topdressing, and the best turf quality was achieved at an estimated summer rate of 0.49 L m^{-2} on 3 Sept. The interaction also indicated that there was not a benefit to turf quality from spring topdressing when summer topdressing was applied at 0.3 and 0.6 L m^{-2}.

Incorporation of Summer Topdressing Sand

Main Effects

Spring topdressing rate affected the incorporation of sand into the turf canopy on five of ten dates in 2009, all of which occurred within 9 to 14 days after a summer topdressing application (Table 2.9). In general, increased spring topdressing rate reduced sand incorporation; however, this response was dependent on summer topdressing on 3 dates in 2009.

As expected, the 0 L m^{-2} summer topdressing rate had the best sand incorporation rating (9) on all dates because no topdressing sand was applied to these plots during the summer (Table 2.9). Also as expected, increasing the rate of summer sand topdressing decreased sand incorporation. The summer rates of 0.075 and 0.15 L m^{-2} provided acceptable sand incorporation ratings (>5) on all rating dates in 2009. Sand incorporation was often marginally acceptable at the 0.3 L m^{-2} summer topdressing rate and very poor at the 0.6 L m^{-2} summer topdressing rate.

Interaction Effects

Sand incorporation after summer topdressing depended on spring topdressing on 3 of 10 dates in 2009 (Table 2.9). The degree of the polynomial response was complicated but generally indicated that sand incorporation of summer topdressing became poorer as spring topdressing rate increased (Table 2.10). Sand incorporated well (ratings ≥ 7.8) for all summer topdressing rates under 0 L m^{-2} of spring topdressing on 15 June 2009. Sand incorporation of the 0.075 L m^{-2} summer topdressing rate was acceptable under 1.2 L m^{-2} of spring topdressing and only marginally acceptable under 2.4 L m^{-2} of spring topdressing. Sand incorporation was only marginally acceptable at summer topdressing rates of 0.15, 0.3 and 0.6 L m^{-2} when spring topdressing rate was 1.2 and 2.4 L m^{-2}.

On 11 July 2009, lower summer topdressing rates (0.075 and 0.15 L m^{-2}) had acceptable sand incorporation when no spring topdressing was applied; however, these summer topdressing rates incorporated more poorly under the 1.2 and 2.4 L m^{-2} spring rates (Table 2.10). Sand incorporation was only marginally acceptable for the summer topdressing rates of 0.3 and 0.6 L m^{-2} regardless of the spring topdressing rate.

The interaction on 27 July indicated that any effect of spring topdressing was very limited (Table 2.10). Lower summer topdressing rates (0.075 and 0.15 L m^{-2}) had acceptable sand incorporation under all spring rates. Only marginally acceptable incorporation of sand was observed at the summer topdressing rate of 0.6 L m^{-2} under all spring topdressing rates and at the 0.3 L m^{-2} summer topdressing rate under the 0 and 2.4 L m^{-2} spring topdressing rates.

Number of Days Required for Sand to Incorporate

The number of days after topdressing required for sand to reach an acceptable level of incorporation increased as summer topdressing rates increased in 2009 and 2010 (Table 2.11).

The summer topdressing rate of 0.075 L m^{-2} always incorporated to an acceptable level on the day of application during 2009 and 2010. Summer topdressing at 0.15 L m^{-2} required 0 to 2 days after topdressing to achieve an acceptable level of incorporation in 2009 and 2010. The number of days after topdressing required to achieve an acceptable level of incorporation increased from 2 to 6 from June to August 2009 and from 2 to 7 from May to August 2010 for the summer topdressing rate of 0.3 L m^{-2}. The summer topdressing rate of 0.6 L m^{-2} required from 6 to 14 days after topdressing from June to

August 2009 and from 7 to 14 days after topdressing from May to August 2010 to reach an acceptable level of incorporation.

Volumetric Water Content

Increased spring topdressing rate reduced volumetric water content (VWC) linearly on 30 July and 30 Aug. 2010 (Table 2.12). Similarly, increased summer topdressing rate produced a linear reduction in VWC on 30 July and 30 Aug. 2010. There was also an unexplainable, weak quartic response in VWC to summer topdressing rate on 30 Aug. 2010.

Surface Hardness

Spring topdressing rate had no effect on surface hardness measured on 30 July and 30 Aug. 2010 despite the presence of negatively linear VWC responses to increased spring topdressing rate (Table 2.13). Contrary to expectations, increased summer topdressing rate produced a slight linear reduction in surface hardness on 30 July, and this same response was close to statistical significance ($pr > F = 0.07$ for both CIST and TruFirm) on 30 August 2010 despite the negatively linear VWC response to increased summer topdressing rate.

Turf Color

Turf color was acceptable (>5) for all treatments on the four dates it was evaluated in 2011, after the conclusion of the study (Table 2.14). Generally, increased spring and summer topdressing rate produced linear reductions in turf color on both 9 May and 23 Nov. 2011. The spring by summer interaction on 23 Nov. 2011 indicated that the effect of increased summer topdressing rate on reducing turf color was primarily evident when spring topdressing rate was 2.4 L m^{-2} (Table 2.15).

Thatch/Mat Layer Depth and Soil Nutrient Analysis

Main Effects

The thatch/mat layer depth was 28 mm thicker in the treatment that received the greatest amount of sand (2.4 L m^{-2} spring rate and 0.6 L m^{-2} summer rate; 6.6 L m^{-2} yr^{-1}) compared to the treatment receiving no sand topdressing (Table 2.16). There were little differences in nutrient concentrations between the 0 and 6.6 L m^{-2} yr^{-1} treatments, and all nutrient concentrations in both treatments were within the same relative category for Mehlich III values (Heckman, 2006). However, there was a slightly greater concentration of boron (0.3 mg kg^{-1}) in the 6.6 L m^{-2} yr^{-1} treatment compared to no topdressing treatment. For both 0 and 6.6 L m^{-2} yr^{-1} treatments, P, K, Ca, and Fe were in the very low category, and Mg was in the low category. All other nutrients were in the high (optimal) category for both treatments. The categories of very low, low and medium are considered below optimum; high is considered optimum; and very high is considered above optimum (Heckman, 2006).

Accordingly, the depth of the soil fraction of the sample was 28 mm smaller in the 6.6 L m^{-2} yr^{-1} treatment compared to the 0 L m^{-2} treatment (Table 2.17). The pH (5.9) of the 0 L m^{-2} yr^{-1} treatment was higher than the pH (5.7) of 6.6 L m^{-2} yr^{-1} treatment, and concentrations of P, K, Ca, Mg, Mn, and Cu were also higher in the 0 L m^{-2} yr^{-1} treatment compared to the 6.6 L m^{-2} yr^{-1} treatment. Similar to the thatch/mat fraction, concentrations of all nutrients were found within the same relative level category for both treatments in the soil fraction. Boron was the only nutrient in the very low category, and Ca was the only nutrient in the low category. Potassium and Mg were in the medium category, and P, Zn, Mn, and Cu were all at acceptable concentrations. Iron was found at an above optimum level in the soil fraction.

DISCUSSION

Spring topdressing reduced anthracnose disease severity and occasionally reduced the rate of summer topdressing needed to decrease disease severity. This was evidenced by significant linear reductions in AUDPC and disease severity on individual observation dates caused by increased spring topdressing rate and by interaction data from the latter half of the 2010 season that indicated that the response to summer topdressing rate was less substantial under increased spring topdressing rate, respectively.

Findings of increased summer topdressing rate (0, 0.3, and 0.6 L m^{-2}) decreasing anthracnose severity were first reported by Inguagiato et al. (2012). Our results supported those previous reports and showed that increased summer topdressing rate decreased disease severity linearly during most of the 2009 season and the beginning of the 2010 season. However, the response to increased summer topdressing rate became a quadratic decrease in disease severity by late-2010 indicating that the greatest summer topdressing rates had a diminishing effect on disease suppression and maximum disease suppression was estimated to occur at rates lower than the highest summer topdressing rate evaluated in this study.

An interaction occurred on one date in 2009 where summer topdressing at 0.075 and 0.15 L m^{-2} slightly increased disease severity 3 to 4% when no spring topdressing was applied. However, this effect was only observed during the first trial-year and dissipated after continued sand topdressing applications, as reported in previous trials (Inguagiato et al., 2012; Inguagiato et al., 2013; Roberts, 2009). Inguagiato et al. (2013) hypothesized that initial increases in disease severity occurring shortly after the initiation of treatments during the first year of trials could have been caused by sand abrasion injury to crowns that were not yet buried and protected by a sand topdressing or mat layer. Landschoot and Hoyland (1995) reported that wounding ABG plants only at the crown, not leaves, immediately before inoculation resulted in increased severity of anthracnose basal rot. Penetration through wounds resulted in a more rapid and efficient infection of maize (*Zea mays* L.) by the closely related pathogen *C. graminicola*; however, wounds are not required to for penetration of maize stalks by *C. graminicola* (Venard and Vaillancourt, 2007) or ABG leaves, sheaths, and roots by *C. cereale* (reported as *Colletotrichum* spp.) (Smith, 1954). In fact, wound healing responses in monocots have been found to confer resistance to fungal invasion by the infusion of cells adjacent to wounds with an extensive layer of lignin or other phenols (Bostock and Stermer, 1989). Previously wounded sites produced significantly less anthracnose than unwounded sites on maize plants inoculated with *C. graminicola* (Muimba-Kankolongo and Bergstrom, 1990) and on chili pepper plants (*Capsicum annuum* cv. Nokkwang) inoculated with *C. acutatum* (Kim, 2008). Thus, it is possible that ABG plants in the current study may have gained a level of resistance against invasion by *C. cereale* through the healing of sites wounded by initial applications of sand topdressing.

Anthracnose survives unfavorable environmental conditions as saprophytic mycelium in thatch (Smiley et al., 2005). White and Dickens (1984) found that topdressing was the most effective practice to reduce thatch accumulation, and previous research has suggested that sand topdressing may reduce disease symptoms by the burying and dilution of disease inoculum (Madison et al., 1974; Sprague and Evaul, 1930). Thus, anthracnose severity may have been reduced by sand topdressing through modification of the thatch into a more suitable growth medium and through the burying and dilution of disease inoculum (mycelium) that survives in thatch.

Mat, an intermixed layer of thatch and mineral matter (e.g., sand) between the thatch and soil (Beard and Beard, 2005), provides a more desirable growth medium for plants than thatch alone because crowns growing in a mat layer are better protected from temperature and moisture fluctuations, conditions that enhance anthracnose disease severity, than crowns growing in thatch (Beard, 1973; Hurto et al., 1980; Smiley et al., 2005). Annual bluegrass plants observed in profile cores removed from topdressed plots in the current trial had longer leaf sheaths and more deeply buried crowns than plants taken from nontopdressed plots. A mat layer may also provide physical support to individual grass plants by adding new soil (sand) particles that surround tillers, crowns, and adventitious roots resulting in more erect plants and potentially enhancing photosynthesis. Protected crowns and adventitious roots are better able to support shoot vigor and help to create a tighter, finer textured turf (Beard, 2002; Bengeyfield, 1969; Hoos, 1981). Moreover, Inguagiato et al. (2012) suggested that a firmer turf surface improves tolerance to low mowing by increasing the effective cutting height, which can reduce anthracnose disease severity (Inguagiato et al., 2009).

Heavy-rate spring topdressing can provide an opportunity to incorporate large amounts of sand into the thatch during a period when the growth of the turf (thatch accumulation and canopy biomass development) is maximized and disruption to play is minimized (Beard, 1973; Turgeon, 2011). It is not uncommon for some managers to only apply sand topdressing once or twice a year during the spring and/or autumn, likely in conjunction with a cultivation event, and not apply topdressing during the summer. A beneficial mat layer could possibly be achieved through the sole use of sand topdressing during spring or autumn; however, this approach can also result in the formation of alternate layers of thatch and topdressing in the rootzone (Carrow, 1979; Fermanian et al., 1985). Rootzone layering can be prevented by making additional applications of sand in the summer at rates and frequencies that match the growth rate of the turf.

Sand incorporation data indicated that biweekly summer topdressing at 0.3 and 0.6 L m^{-2} left excess sand at the turf surface because these rates exceeded canopy biomass development, which is relatively low during the summer months for cool season grasses (Turgeon, 2011). This excess sand would likely interfere with play or mowing on a golf course and may have also been the reason that slight increases in disease severity were observed at these rates, compared to the 0.15 L m^{-2} summer topdressing rate when spring topdressing was applied at 1.2 or 2.4 L m^{-2} on interaction dates during late-2010. Excess sand from the 0.3 and 0.6 L m^{-2} summer topdressing rates may have buried green leaf tissue and reduced the amount of sunlight (light intensity) available to the plants, which has been reported to increase susceptibility of some maize genotypes to infection by *C. graminicola* (Schall et al., 1980). In contrast, the summer topdressing rates of 0.075 and 0.15 L m^{-2} did not result in excess sand at the turf surface and were more likely to match the growth of the turf (thatch accumulation and canopy biomass development).

The variation in disease response attributed to each main effect varied across years of study. Summer topdressing accounted for most (82%) of the disease response in 2009, whereas spring topdressing accounted for most (73%) of the disease response in 2010 (data not shown). The limited effect of spring topdressing on disease development in 2009 was probably due to the lack of disease symptoms early in the season. In contrast, anthracnose was active by mid-May 2010 and a spring topdressing effect was evident from May until the end of the season. In addition, the variation in response to each factor between years could also be attributed to differences in cumulative amounts of sand in plots. Inguagiato et al. (2012) concluded that disease reductions from sand topdressing occurred earlier in the second year of a trial because a mat layer was already been established from sand topdressing treatments applied during the first year.

On some dates in 2011 after the conclusion of the study, plots with greater cumulative amounts of sand demonstrated lower turf color than plots that received no sand. Results of soil nutrient analysis revealed no differences in nutrient concentrations in either the soil or thatch/mat fractions between plots receiving the highest and lowest annual cumulative sand (0 and 6.6 L m^{-2} yr^{-1}, respectively). Soil pH was slightly lower in the soil layer of the 6.6 L m^{-2} yr^{-1}sand plots compared to no sand plots, however the pH of both were within the acceptable range for *P. annua* (5.5 to 6.5) (Beard, 1973). These differences in turf color could have been caused by subtle changes in VWC and possibly drought stress among the high sand treatments. Plots that received 6.6 L m^{-2} yr^{-1} of sand had a deeper thatch/mat layer than the nontopdressed plots, providing a more sandy growth medium with lower water retention. Thus, it is likely that lower water retention in plot topdressed at 6.6 L m^{-2} yr^{-1} had less plant available water in the upper 80 mm of the profile than the no sand treatment and experienced greater drought stress.

In conclusion, topdressing during spring can reduce anthracnose severity, and may decrease the rate of summer topdressing needed to achieve disease reductions. In future research, it will be important to determine whether autumn topdressing produces a similar effect.

REFERENCES

Beard, J.B. 1973. Turfgrass: Science and culture. Prentice Hall, Englewood Cliffs, NJ.

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

Beard, J.B., and H.J. Beard. 2005. Beard's turfgrass encyclopedia for golf courses, grounds, lawns, sports fields. Michigan State Univ. Press, East Lansing, MI.

Bengeyfield, W.H. 1969. This year: Top-dress greens and see the difference. U.S. Golf Assoc. Green Section Record 7(1):1-4.

Bigelow, C.A., and W.T. Tudor Jr. 2012. Economic analysis of creeping bentgrass and annual bluegrass greens maintenance. Golf Course Manage. 80(10):76-78, 80, 82, 84, 86, 88, 90-93.

Bostock, R.M., and B.A. Stermer. 1989. Perspectives on Wound Healing in Resistance to Pathogens. Annu. Rev. Phytopathol. 27(1):343-371. DOI: doi:10.1146/annurev.py.27.090189.002015.

Carrow, R.N. 1979. Topdressing: An essential management tool. Golf Course Manage. 47(6):26-28, 30-32.

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(3):524-530. DOI: 10.2134/agronj1987.00021962007900030025x.

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

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(1):46-60. DOI: 10.1094/PHYTO-96-0046.

Dernoeden, P.H. 2012. Creeping bentgrass management. CRC Press.

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

Fermanian, T.W., J.E. Haley, and R.E. Burns. 1985. The effects of sand topdressing on a heavily thatched creeping bentgrass turf. Proc. Int. Turf. Res. Conf. 5:439-448.

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

Hawes, D.T. 1980. Response of warm- and cool-season turfgrass polystands to nitrogen and topdressing. Proc. Int. Turf. Res. Conf. 3:65-74.

Heckman, J.R. 2006. Soil fertility test interpretation: Phosphorus, potassium, magnesium, and calcium. Fact Sheet FS719 Rutgers Cooperative Extension, New Jersey Agricultural Experimental Extension.

Henderson, J.J., and N.A. Miller. 2010. Importance of particle size distribution, application rate and sand depth in developing a fairway topdressing program. Univ. of Conn. Turfgrass Res. Rep. 5:41-49.

Hoos, D.D. 1981. Topdressing. U.S. Golf Assoc. Green Section Record 19:22.

Hurto, K.A., A.J. Turgeon, and L.A. Spomer. 1980. Physical characteristics of thatch as a turfgrass growing medium. Agron. J. 72(1):165-167.

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(4):1454-1462. DOI: 10.2135/cropsci2008.07.0435.

Inguagiato, J.C., J.A. Murphy, and B.B. Clarke. 2012. Sand Topdressing Rate and Interval Effects on Anthracnose Severity of an Annual Bluegrass Putting Green. Crop Sci. 52(3):1406-1415. DOI: 10.2135/cropsci2011.01.0010.

Inguagiato, J.C., J.A. Murphy, B.B. Clarke, and J.A. Roberts. 2013. Topdressing sand particle shape and incorporation effects on anthracnose severity of an annual bluegrass putting green. Int. Turfgrass Res. Soc. J. 12:(accepted).

Kim, Y.H. 2008. Effect of delayed inoculation after wounding on the development of anthracnose disease caused by *Colletotrichum acutatum* on chili pepper fruit. The Plant Pathol. J. 24(4):392-399.

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

Madden, L.V., G. Hughes, and F.Van den Bosch. 2007. The Study of Plant Disease Epidemics. The American Phytopathological Society, APS Press, St. Paul, MN.

Madison, J.H., J.L. Paul, and W.B. Davis. 1974. Alternative method of greens management. Proc. Int. Turf. Res. Conf. 2:431-437. DOI: 10.2135/1974.proc2ndintlturfgrass.c65.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Communications in Soil Sci. & Plant Analysis 15(12):1409-1416.

Muimba-Kankolongo, A., and G.C. Bergstrom. 1990. Transitory wound predisposition of maize to Anthracnose stalk rot. Can. J. Plant Pathol. 12(1):1-10.

O'Brien, P., and C. Hartwiger. 2003. Aeration and topdressing for the 21st century: Two old concepts are linked together to offer up-to-date recommendations. U.S Golf Assoc. Green Section Record 41(2):1-7.

Piper, C.V., and R.A. Oakley. 1917. Turf for golf courses. Macmillan, New York, NY.

Roberts, J.A. 2009. Impact of cultural management on anthracnose severity of annual bluegrass putting green turf. M.S. Thesis: Rutgers Univ.

Schall, R.A., R.L. Nicholson, and H.L. Warren. 1980. Influence of light on maize anthracnose in the greenhouse. Phytopathology 70(10):1023-1026.

Smiley, R.W., P.H. Dernoeden, and B.B. Clarke. 2005. Compendium of turfgrass diseases. APS press, St. Paul, MN.

Smith, J.D. 1954. A disease of *Poa annua*. J. Sports Turf Res. Inst. 8:344-353.

Sprague, H.B., and E.E. Evaul. 1930. Experiments with turf grasses in New Jersey. New Jersey Agric. Exp. Stn. Bull.

Stier, J.C., and A.B. Hollman. 2003. Cultivation and topdressing requirements for thatch management in A and G bentgrasses and creeping bluegrass. HortScience 38(6):1227-1231.

Towers, G., K. Green, E. Weibel, P. Majumdar, and B.B. Clarke. 2003. Evaluation of fungicides for the control of anthracnose basal rot on annual bluegrass. 2002. Fungicide and Nematicide Tests 58:T017.

Turgeon, A.J. 2011. Turfgrass Management, Prentice Hall, Upper Saddle River, NJ.

Vavrek Jr., R.C. 1995. A successful topdressing program requires consistency, commitment, and communication. U.S Golf Assoc. Green Section Record 33(5):8-10.

Venard, C., and L. Vaillancourt. 2007b. Penetration and colonization of unwounded maize tissues by the maize anthracnose pathogen *Colletotrichum graminicola* and the related nonpathogen *C. sublineolum*. Mycologia 99(3):368-377.

White, R.H., and R. Dickens. 1984. Thatch Accumulation in Bermudagrass as Influenced by Cultural Practices. Agron. J. 76:19-22. DOI: 10.2134/agronj1984.00021962007600010006x.

Table 2.1. Particle size distribution of sand used for topdressing in 2009 and 2010.

Sieve size opening							
2 mm	1 mm	500 µm	250 µm	149 µm	105 µm	53 µm	Pan
--- % retained (by weight) ---							
0	<0.1	31.3	65.1	3.3	0.2	<0.1	<0.1

Table 2.2. Anthracnose severity response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009.

Main effect	Turf Area Infested										AUDPC
	12 June	6 July	15 July	23 July	30 July	6 Aug.	13 Aug.	20 Aug.	27 Aug.	3 Sept.	
Spring rate (SP)‡	-----	-----	-----	-----	-----	%	-----	-----	-----	-----	
0	0.7	1.0	1.8	1.5	6.8	9.4	20.2	24.4	26.8	26.5	721
1.2 L m^{-2}	0.5	0.5	1.2	1.0	5.4	6.8	18.3	18.6	24.3	22.8	598
2.4 L m^{-2}	0.5	0.5	1.2	0.9	5.4	6.3	17.5	14.0	20.5	18.5	517
Summer rate (SU)§											
0	0.5	1.0	2.4	1.3	8.0	10.7	29.9	27.4	34.9	33.0	903
0.075 L m^{-2}	0.6	0.7	1.2	0.9	7.1	8.8	21.1	25.9	32.0	28.6	762
0.15 L m^{-2}	0.6	0.9	1.9	1.8	8.5	9.9	21.8	23.8	28.2	26.0	752
0.3 L m^{-2}	0.5	0.5	1.0	1.3	4.5	5.1	12.3	12.7	17.6	17.5	438
0.6 L m^{-2}	0.6	0.2	0.4	0.4	1.2	3.0	8.2	5.3	6.8	7.8	206
Source of variation						ANOVA					
SP	NS¶	0.06†	NS	NS	NS	*	NS	***	**	***	***
Linear	NS	*	NS	0.1	NS	*	NS	***	**	***	***
Quadratic	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
SU	NS	*	***	**	***	***	***	***	***	***	***
Linear	NS	**	***	*	***	***	***	***	***	***	***
Quadratic	NS	NS	NS	0.06	NS	NS	**	NS	NS	NS	0.07
Cubic	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS
Quartic	NS	NS	*	*	0.1	NS	*	NS	NS	NS	NS
SP x SU	NS	NS	NS	NS	NS	NS	NS	**	NS	NS	NS
CV, %	53.6	97.7	78.1	85.1	48.6	53.7	33.8	30.1	24.9	17.2	22.8

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
***Significant at the 0.001 probability level.
†Probability level ≤ 0.1.
‡The total spring topdressing rate was applied as split applications on 20 April and 4 May 2009.
§Summer topdressing rate was applied every 14 days from 1 June to 24 August 2009.
¶NS, not significant.

Table 2.3. Anthracnose severity response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010.

	Turf Area Infested											AUDPC
Main effect	19 May	28 May	4 June	11 June	19 June	28 June	5 July	15 July	28 July	16 Aug.	3 Sept.	
Spring rate (SP)[‡]	---	---	---	---	---	%	---	---	---	---	---	
0	10.4	18.9	29.3	24.3	25.1	32.8	43.8	35.4	38.3	56.6	71.5	3876
1.2 L m^{-2}	8.6	12.9	22.0	20.2	20.7	25.8	34.3	27.6	30.3	49.0	60.1	3163
2.4 L m^{-2}	11.2	12.2	17.9	16.7	16.5	21.9	27.8	22.2	24.3	41.0	50.3	2609
Summer rate (SU)[§]												
0	13.6	18.5	27.1	22.5	24.8	27.5	38.9	31.5	34.2	54.3	72.3	3619
0.075 L m^{-2}	11.2	17.2	24.0	22.8	23.6	27.5	36.0	29.5	31.7	49.1	64.6	3344
0.15 L m^{-2}	9.5	14.1	22.9	18.7	17.5	24.9	34.0	26.8	29.4	47.6	58.2	3059
0.3 L m^{-2}	8.6	13.1	19.7	19.2	17.5	27.2	34.2	26.1	28.9	46.1	52.7	2970
0.6 L m^{-2}	7.5	10.4	21.7	18.9	20.5	27.0	33.6	28.1	30.5	47.3	55.4	3085
Source of variation							ANOVA					
SP	NS[¶]	**	***	***	***	***	***	***	***	***	***	***
Linear	NS	***	***	***	***	***	***	***	***	***	***	***
Quadratic	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
SU	**	*	NS	NS	**	NS	0.06[†]	*	**	**	***	**
Linear	***	***	0.08	0.07	0.08	NS	*	0.08	*	*	***	**
Quadratic	0.08	NS	0.07	NS	**	NS	0.09	**	***	**	***	**
Cubic	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Quartic	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
SP x SU	NS	NS	NS	NS	NS	NS	NS	*	*	NS	*	NS
CV, %	40.0	41.4	31.5	26.4	27.7	20.0	13.9	14.2	11.0	11.8	12.1	12.1

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
***Significant at the 0.001 probability level.
†Probability level ≤ 0.1.
‡The total spring topdressing rate was applied as split applications on 14 April and 28 April 2010.
§Summer topdressing rate was applied every 14 days from 24 May to 17 August 2010.
¶NS, not significant.

Table 2.4. Anthracnose severity response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009.

	20 Aug. 2009				
	Spring rate‡, L m^{-2}				
Summer rate§	0	1.2	2.4	Spring rate	
L m^{-2}	--------------%-------------			Linear	Quad.
0	30.6¶	32.7	18.9	0.06†	NS#
0.075	34.4	27.1	16.3	**	NS
0.15	33.7	20.2	17.7	*	NS
0.3	16.2	8.8	13.0	NS	*
0.6	7.1	4.5	4.2	0.051	NS
Linear	***	***	***		
Quadratic	NS	*	NS		
Cubic	**	NS	NS		
Quartic	NS	NS	NS		

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
***Significant at the 0.001 probability level.
†Probability level ≤ 0.1.
‡The total spring topdressing rate was applied as split applications on 20 April and 4 May 2009.
§Summer topdressing rate was applied every 14 days from 1 June to 24 August 2009.
¶Within rows and columns, $LSD_{0.05}$ is 4.7 and 3.7, respectively.
#NS, not significant.

Table 2.5. Anthracnose severity response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009.

	15 July 2010					28 July 2010					3 Sept. 2010				
	Spring rate‡, L m^{-2}					Spring rate, L m^{-2}					Spring rate, L m^{-2}				
Summer rate§	0	1.2	2.4	Spring rate		0	1.2	2.4	Spring rate		0	1.2	2.4	Spring rate	
L m^{-2}	--------------%-------------			Linear	Quad.	--------------%-------------			Linear	Quad.	--------------%-------------			Linear	Quad.
0	41.5¶	30.3	22.6	**	NS#	46.2¶	32.4	24.1	***	NS	85.3¶	72.9	58.8	**	NS
0.075	36.6	25.5	26.2	**	*	40.4	30.2	24.5	***	NS	78.9	57.7	57.1	***	**
0.15	35.5	25.2	19.6	***	NS	35.5	29.9	22.9	***	NS	75.1	58.5	40.8	***	NS
0.3	29.3	29.4	19.6	*	0.09†	33.2	29.2	24.3	**	NS	59.8	53.7	44.7	**	NS
0.6	33.9	27.4	23.2	***	NS	36.0	29.7	25.8	**	NS	58.3	57.6	50.3	*	NS
Linear	**	NS	NS			***	0.08	NS			***	*	NS		
Quadratic	**	NS	NS			***	0.05	NS			**	**	*		
Cubic	NS	**	NS			NS	NS	NS			NS	NS	NS		
Quartic	NS	NS	NS			NS	NS	NS			NS	NS	NS		

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
***Significant at the 0.001 probability level.
†Probability level ≤ 0.1.
‡The total spring topdressing rate was applied as two applications on 14 April and 28 April 2010.
§Summer topdressing rate was applied every 14 days from 24 May to 17 August 2010.
¶$LSD_{0.05}$ within rows for 15 July, 28 July and 3 Sept. is 2.6, 2.2 and 4.7, respectively. $LSD_{0.05}$ within columns for 15 July, 28 July and 3 Sept. is 3.3, 2.8 and 6.1, respectively.
#NS, not significant.

Table 2.6. Turf quality response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009.

Main effect	27 May	15 June	24 June	6 July	16 July	26 July	1 Aug.	7 Aug.	17 Aug.	27 Aug.
Spring rate (SP)[‡]	--1–9 scale[§] --									
0	7.7	7.6	7.7	7.1	7.7	7.3	7.7	7.4	7.2	7.5
1.2 L m^{-2}	8.4	8.1	8.3	7.7	7.9	7.7	7.9	7.7	7.6	7.7
2.4 L m^{-2}	8.2	8.3	8.3	7.8	8.0	8.0	7.9	8.0	7.8	8.0
Summer rate (SU)[¶]										
0	8.1	8.1	8.0	7.3	7.8	7.1	7.5	7.3	6.8	6.7
0.075 L m^{-2}	8.1	7.8	7.9	7.3	8.0	7.4	7.7	7.3	7.3	7.4
0.15 L m^{-2}	8.2	8.0	7.8	7.2	7.6	7.3	7.6	7.4	7.2	7.6
0.3 L m^{-2}	8.1	7.8	8.3	7.8	7.9	8.0	8.3	8.0	7.9	8.1
0.6 L m^{-2}	8.0	8.1	8.5	8.0	8.0	8.5	8.1	8.5	8.3	8.8
Source of variation					ANOVA					
SP	**	**	**	**	NS[#]	**	NS	*	**	**
Linear	*	**	**	**	0.06[†]	***	NS	**	**	**
Quadratic	*	NS	0.06	NS	NS	NS	NS	NS	NS	NS
SU	NS	NS	*	*	NS	***	**	***	***	***
Linear	NS	NS	**	**	NS	***	***	***	***	***
Quadratic	NS	NS	NS	NS	NS	NS	0.08	NS	NS	*
Cubic	NS	NS	NS	NS	**	NS	NS	NS	NS	NS
Quartic	NS	NS	NS	NS	**	NS	NS	NS	0.08	NS
SP x SU	NS	NS	NS	*	NS	NS	NS	NS	NS	NS
CV, %	7.5	8.3	6.9	8.6	5.3	7.5	6.7	7.8	8.2	6.9

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

***Significant at the 0.001 probability level.

†Probability level ≤ 0.1.

‡The total spring topdressing rate was applied as split applications on 20 April and 4 May 2009.

§Nine (9) represents the best turf characteristic and 5 represents the minimally acceptable rating.

¶Summer topdressing rate was applied every 14 days from 1 June to 24 August 2009.

#NS, not significant.

Table 2.7. Turf quality response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010.

	May		June				July			Aug.	Sept.
Main effect	19	28	4	11	19	28	5	15	28	16	3
Spring rate (SP)‡	--1–9 scale§ --										
0	7.0	6.2	5.9	6.2	6.2	5.3	5.0	4.5	4.5	3.1	2.7
1.2 L m^{-2}	7.8	7.4	7.1	7.1	7.3	6.2	5.9	5.3	5.6	4.6	3.8
2.4 L m^{-2}	7.2	7.5	7.5	7.9	7.9	6.9	6.8	6.5	6.7	5.5	4.8
Summer rate (SU)¶											
0	7.1	6.5	6.3	6.7	6.4	5.7	5.4	5.0	4.8	3.3	2.5
0.075 L m^{-2}	7.1	7.0	6.7	6.8	6.9	5.8	5.6	5.2	5.5	4.3	3.8
0.15 L m^{-2}	7.6	7.1	6.8	7.0	7.3	6.2	6.0	5.5	5.8	4.6	4.1
0.3 L m^{-2}	7.3	7.3	7.1	7.3	7.4	6.3	6.1	5.8	6.2	4.9	4.2
0.6 L m^{-2}	7.6	7.2	7.3	7.5	7.5	6.6	6.3	5.6	5.7	4.8	4.3
Source of variation						ANOVA					
SP	***	***	***	***	***	***	***	***	***	***	***
Linear	NS#	***	***	***	***	***	***	***	***	***	***
Quadratic	***	*	*	NS	NS	NS	NS	NS	NS	0.09†	NS
SU	0.09	NS	**	**	***	**	**	*	***	***	***
Linear	*	NS	***	***	***	***	***	*	***	***	***
Quadratic	NS	NS	NS	NS	**	NS	NS	*	***	***	**
Cubic	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*
Quartic	0.09	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
SP x SU	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	0.055
CV, %	8.1	13.5	10.2	8.2	7.7	10.3	10.2	11.9	13.7	13.1	24.3

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
***Significant at the 0.001 probability level.
†Probability level ≤ 0.1.
‡The total spring topdressing rate was applied as split applications on 14 April and 28 April 2010.
§Nine (9) represents the best turf characteristic and 5 represents the minimally acceptable rating.
¶Summer topdressing rate was applied every 14 days from 24 May to 17 August 2010.
#NS, not significant

Table 2.8. Turf quality response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009 and 2010.

	6 July 2009					16 Aug. 2010					3 Sept. 2010 ($pr > F = 0.055$)				
	Spring rate‡, L m^{-2}					Spring rate, L m^{-2}					Spring rate, L m^{-2}				
Summer rate§	0	1.2	2.4	Spring rate		0	1.2	2.4	Spring rate		0	1.2	2.4	Spring rate	
L m^{-2}	---------1-9 scale¶---------			Linear	Quad.	---------1-9 scale---------			Linear	Quad.	---------1-9 scale---------			Linear	Quad.
0	6.5#	7.5	8.0	*	NS††	1.5#	3.8	4.8	***	NS	1.0#	3.0	3.5	*	NS
0.075	6.5	7.5	8.0	*	NS	2.8	5.0	5.0	***	**	2.0	4.0	5.3	***	0.08†
0.15	6.5	7.8	7.3	NS	0.08	3.3	4.8	5.8	***	NS	2.5	4.0	5.8	***	NS
0.3	8.0	7.8	7.5	NS	NS	4.0	4.8	6.0	**	NS	3.8	4.0	4.8	NS	NS
0.6	8.0	8.0	8.0	NS	NS	4.0	4.5	5.8	***	NS	4.0	4.0	4.8	NS	NS
Linear	***	NS	NS			***	NS	*			***	NS	NS		
Quadratic	NS	NS	NS			***	0.08	*			**	NS	NS		
Cubic	**	NS	NS			NS	NS	NS			NS	NS	0.07		
Quartic	NS	NS	NS			NS	NS	NS			NS	NS	NS		

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
***Significant at the 0.001 probability level.
†Probability level ≤ 0.1.
‡The total spring topdressing rate was applied as split applications on 20 April and 4 May 2009, and 14 April and 28 April 2010.
§Summer topdressing rate was applied every 14 days from 1 June to 24 August 2009, and 24 May to 17 August 2010.
¶Nine (9) represents the best turf characteristic and 5 represents the minimally acceptable rating.
#$LSD_{0.05}$ within rows for 6 July 2009 and 16 Aug. and 3 Sept. 2010 is 0.4, 0.4, and 0.6 respectively. $LSD_{0.05}$ within columns for 6 July 2009 and 16 Aug. and 3 Sept. 2010 is 0.5, 0.5, and 0.7 respectively.
††NS, not significant.

Table 2.9. Sand incorporation response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ after three topdressing events in 2009.

Main effect	15 June[‡]	17 June	24 June	29 June[‡]	30 June	6 July	11 July	14 July	16 July	27 July
Spring rate (SP)[§]	-----------------	-----------------	-----------------	-----------------	-------- 1–9 scale[¶]	--------	-----------------	-----------------	-----------------	-----------------
0	8.4	5.7	6.7	7.4	5.3	6.6	7.2	6.0	6.2	7.3
1.2 L m^{-2}	6.9	5.9	6.8	7.1	5.2	6.3	6.8	6.0	6.1	7.4
2.4 L m^{-2}	6.3	5.9	6.4	6.9	5.3	6.3	6.5	5.9	6.1	7.0
Summer rate (SU)[#]										
0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
0.075 L m^{-2}	7.1	7.2	7.4	7.7	6.3	7.5	7.3	7.3	7.3	8.0
0.15 L m^{-2}	7.1	5.8	7.2	7.4	5.5	7.0	7.1	6.4	6.6	7.7
0.3 L m^{-2}	6.5	5.0	6.0	6.3	3.6	5.2	5.7	4.8	4.9	6.3
0.6 L m^{-2}	6.3	2.2	3.6	5.2	2.0	3.3	5.0	2.2	2.8	5.0
Source of variation					ANOVA					
SP	***	NS[††]	*	***	NS	0.1[†]	***	NS	NS	**
Linear	***	NS	*	***	NS	0.06	***	NS	NS	*
Quadratic	*	NS	0.051	NS	NS	NS	NS	NS	NS	*
SU	***	***	***	***	***	***	***	***	***	***
Linear	***	***	***	***	***	***	***	***	***	***
Quadratic	***	***	*	***	***	***	***	***	***	***
Cubic	**	***	***	*	**	NS	NS	*	0.054	NS
Quartic	*	NS	**	**	**	*	**	NS	*	*
SP x SU	**	NS	NS	NS	NS	NS	*	NS	NS	**
CV, %	26.2	11.4	13.5	12.7	13.9	13.8	16.1	12.8	13.2	12.3

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
***Significant at the 0.001 probability level.
†Probability level ≤ 0.1.
‡Sand incorporation was evaluated before sand was applied on 15 June and 29 June 2009
§The total spring topdressing rate was applied as split applications on 20 April and 4 May 2009.
¶Nine (9) represents no sand visible and 5 represents the minimally acceptable rating.
#Summer topdressing rate was applied on 15 June, 29 June and 13 July 2009.
††NS, not significant.

Table 2.10. Sand incorporation response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009.

	15 June 2009					11 July 2009					27 July 2009				
	Spring rate[‡], L m^{-2}					Spring rate, L m^{-2}					Spring rate, L m^{-2}				
Summer rate[§]	0	1.2	2.4	Spring rate		0	1.2	2.4	Spring rate		0	1.2	2.4	Spring rate	
L m^{-2}	---------1–9 scale[¶]---------			Linear	Quad.	----------1–9 scale---------			Linear	Quad.	----------1–9 scale---------			Linear	Quad.
0	9.0[#]	9.0	9.0	NS[††]	NS	9.0[#]	9.0	9.0	NS	NS	9.0[#]	9.0	9.0	NS	NS
0.075	8.3	7.3	5.8	*	NS	8.0	7.5	6.5	*	NS	8.0	8.0	8.0	NS	NS
0.15	9.0	6.5	5.8	**	NS	8.0	6.8	6.5	*	NS	8.0	7.8	7.3	*	NS
0.3	7.8	6.0	5.8	**	NS	5.8	5.8	5.5	NS	NS	6.3	7.0	5.8	NS	0.06[†]
0.6	7.8	5.8	5.3	**	NS	5.3	5.0	4.8	NS	NS	5.0	5.0	5.0	NS	NS
Linear	**	**	***			***	***	***			***	***	***		
Quadratic	NS	*	***			**	***	**			**	NS	***		
Cubic	NS	NS	***			*	0.09	*			0.08	NS	NS		
Quartic	*	NS	*			*	NS	0.054			**	NS	NS		

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
***Significant at the 0.001 probability level.
†Probability level ≤ 0.1.
‡The total spring topdressing rate was applied as split applications on 20 April and 4 May 2009.
§Summer topdressing rate was applied every 14 days from 1 June to 24 August 2009.
¶Nine (9) represents no sand visible above turf canopy and 5 represents the minimally acceptable rating.
#$LSD_{0.05}$ within rows for 15 June, 11 July and 27 July is 0.5, 0.3 and 0.2, respectively. $LSD_{0.05}$ within columns for 15 June, 11 July and 27 July is 0.6, 0.4 and 0.3, respectively.
††NS, not significant.

Table 2.11. Number of days for topdressing sand to achieve an acceptable level of incorporation for spring and summer sand topdressing rates on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009.

		2009							2010						
Topdressing rate		June			July		August		May	June		July		August	
Spring†	Summer‡	1	15	29	13	27	10	24	24	7	21	5	19	2	17
----------L m^{-2}----------		days after topdressing													
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0.075	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0.15	0	0	1	1	1	1	2	0	0	1	1	1	1	2
0	0.3	2	2	3	3	4	5	6	2	2	3	3	5	6	7
0	0.6	6	8	8	9	10	12	14	6	8	8	10	11	13	14
1.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.2	0.075	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.2	0.15	0	0	1	1	1	1	2	0	0	1	1	1	1	2
1.2	0.3	2	2	3	3	4	5	6	2	2	3	3	5	6	7
1.2	0.6	6	8	9	9	10	12	14	6	8	9	10	11	13	14
2.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2.4	0.075	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2.4	0.15	0	0	1	1	1	1	2	0	0	1	1	1	1	2
2.4	0.3	2	2	3	3	4	5	6	2	2	3	4	5	6	7
2.4	0.6	6	9	9	9	10	12	14	7	9	10	10	11	13	14

†The total spring topdressing rate was applied as split applications on 20 April and 4 May 2009, and 14 April and 28 April 2010.

‡Summer topdressing rate was applied on 1 June, 15 June, 29 June, 13 July, 27 July, 10 Aug., 24 Aug. 2009; and 24 May, 7 June, 21 June, 5 July, 19 July, 2 Aug. 17 Aug. 2010.

Table 2.12. Volumetric water content (measured at a 0-7.5 cm depth using time domain reflectometry) response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009 and 2010.

	2009						2010	
Main effect	2 June	15 June	3 July	10 July	13 July	14 July	30 July	30 Aug.
Spring rate (SP)‡	----------	----------	----------	---------- $m^3\ m^{-3}$	----------	----------	----------	----------
0	21.3	28.5	19.1	15.5	30.9	28.8	25.4	24.5
1.2 L m^{-2}	20.8	28.0	18.3	15.2	30.0	28.9	24.5	23.5
2.4 L m^{-2}	20.5	27.3	17.6	15.1	30.5	27.9	22.8	20.6
Summer rate (SU)§								
0	20.7	28.3	17.3	15.6	30.3	28.3	25.3	22.8
0.075 L m^{-2}	21.3	28.1	19.3	14.1	30.7	28.4	25.6	24.7
0.15 L m^{-2}	20.8	28.0	17.7	15.6	30.9	29.0	23.5	22.5
0.3 L m^{-2}	21.7	27.9	19.0	16.7	30.7	28.7	24.1	23.5
0.6 L m^{-2}	19.8	27.3	18.3	14.3	29.7	28.2	22.8	21.0
Source of variation				ANOVA				
SP	NS¶	0.07†	0.06	NS	NS	NS	**	***
Linear	NS	NS	*	NS	NS	NS	**	***
Quadratic	NS	NS	NS	NS	NS	NS	NS	NS
SU	NS	NS	0.06	NS	NS	NS	**	*
Linear	NS	NS	NS	NS	NS	NS	**	*
Quadratic	NS	NS	NS	NS	NS	NS	NS	NS
Cubic	NS	NS	NS	0.09	NS	NS	NS	NS
Quartic	NS	NS	*	NS	NS	NS	NS	*
SP x SU	NS	NS	NS	NS	NS	NS	NS	NS
CV, %	10.3	7.7	10.2	18.0	7.5	8.1	10.2	10.5

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
***Significant at the 0.001 probability level.
†Probability level ≤ 0.1.
‡The total spring topdressing rate was applied as split applications on 20 April and 4 May 2009, and 14 April and 28 April 2010.
§Summer topdressing rate was applied every 14 days from 1 June to 24 August 2009, and 24 May to 17 August 2010.
¶NS, not significant

Table 2.13. Surface hardness response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010.

	Surface hardness‡		
	Clegg		TruFirm
Main effect	30 July	30 Aug.	30 Aug.
Spring rate (SP)§	----------------g_{max}----------------		-------cm------
0	5.79	5.00	1.38
1.2 L m^{-2}	5.77	4.90	1.41
2.4 L m^{-2}	5.80	4.88	1.41
Summer rate (SU)¶			
0	5.86	5.09	1.37
0.075 L m^{-2}	5.83	4.93	1.39
0.15 L m^{-2}	5.89	4.99	1.39
0.3 L m^{-2}	5.70	4.81	1.42
0.6 L m^{-2}	5.65	4.82	1.42
Source of variation		ANOVA	
SP	NS#	NS	NS
Linear	NS	NS	NS
Quadratic	NS	NS	NS
SU	*	0.07†	0.06
Linear	**	*	*
Quadratic	NS	NS	NS
Cubic	NS	NS	NS
Quartic	NS	NS	NS
SP x SU	NS	NS	NS
CV, %	3.7	5.5	3.6

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
†Probability level ≤ 0.1.
‡Surface hardness was measured using a Clegg Impact Soil Tester (2.25 kg model) and a USGA TruFirm at three locations per plot and averaged to one value.
§The total spring topdressing rate was applied as split applications on 14 April and 28 April 2010.
¶Summer topdressing rate was applied every 14 days from 24 May to 17 August 2010.
#NS, not significant.

Table 2.14. Turf color response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2011.

Main effect	2 Mar.	9 May	18 Aug.	23 Nov.
Spring rate (SP)‡	---------------------1–9 scale§---------------------			
0	6.0	7.7	5.9	7.3
1.2 L m^{-2}	6.2	6.8	6.1	7.0
2.4 L m^{-2}	6.6	6.4	5.9	6.7
Summer rate (SU)¶				
0	5.8	7.8	6.3	7.4
0.075 L m^{-2}	6.1	7.3	6.3	7.1
0.15 L m^{-2}	6.3	7.3	6.3	7.2
0.3 L m^{-2}	6.6	6.8	5.4	7.0
0.6 L m^{-2}	6.3	5.5	5.8	6.3
Source of variation		ANOVA		
SP	NS#	***	NS	**
Linear	NS	***	NS	***
Quadratic	NS	NS	NS	NS
SU	NS	***	NS	***
Linear	NS	***	0.07†	***
Quadratic	NS	NS	NS	NS
Cubic	NS	NS	NS	NS
Quartic	NS	NS	NS	NS
SP x SU	NS	NS	NS	*
CV, %	20.3	7.9	19.6	7.8

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
***Significant at the 0.001 probability level.
†Probability level ≤ 0.1.
‡The total spring topdressing rate was applied as split applications on 20 April and 4 May 2009, and 14 April and 28 April 2010.
§Nine (9) represented the darkest green color and 5 was the minimum acceptable rating.
¶Summer topdressing rate was applied every 14 days from 1 June to 24 August 2009, and 24 May to 17 August 2010.
#NS, not significant.

Table 2.15. Turf color response to spring and summer sand topdressing rate on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2011.

	23 November 2011				
	Spring rate‡, L m^{-2}				
Summer rate§	0	1.2	2.4	Spring rate	
L m^{-2}	--------1-9 scale¶--------			Linear	Quad.
0	7.3#	7.6	7.3	NS††	NS
0.075	7.5	7.3	6.5	**	NS
0.15	7.4	7.1	7.0	NS	NS
0.3	7.6	6.3	7.0	NS	*
0.6	6.8	6.8	5.5	0.07	NS
Linear	NS	0.052†	**		
Quadratic	0.09	0.06	0.1		
Cubic	NS	NS	NS		
Quartic	NS	NS	NS		

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
†Probability level ≤ 0.1.
‡The total spring topdressing rate was applied as split applications on 20 April and 4 May 2009, and 14 April and 28 April 2010.
§Summer topdressing rate was applied every 14 days from 1 June to 24 August 2009, and 24 May to 17 August 2010.
¶Nine (9) represented the darkest green color and 5 was the minimum acceptable rating.
#Within rows and columns, $LSD_{0.05}$ is 0.3 and 0.4, respectively.
††NS, not significant.

Table 2.16. Results of nutrient analysis (performed by Mehlich III extraction) of the thatch fraction of two sand topdressing treatments on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ taken on 28 Nov. 2011.

	Thatch/mat			Nutrient concentration								
Sand accumulation‡	depth§	pH	LRI¶	P	K	Ca	Mg	B	Zn	Mn	Cu	Fe
---L m^{-2} yr^{-1}---	--mm--			--------------------g cm^{-1}--------------------				--------------------------mg kg^{-1}--------------------------				
0	51	5.6	7.9	4.0	10.1	98.6	19.8	0.5	1.4	10.1	1.9	25.4
6.6	79	5.5	7.9	7.2	13.5	134.3	25.9	0.8	2.1	13.6	2.3	38.5
Source of variation						ANOVA						
Treatment	*	NS#	NS	NS	NS	NS	NS	*	0.07†	NS	NS	NS
CV, %	11.2	1.0	0.0	26.6	17.3	21.4	12.7	10.5	13.0	19.9	26.8	20.0

*Significant at the 0.05 probability level.

†Probability level ≤ 0.1.

‡The total annual sand was applied as spring topdressing applied as split applications on 20 April and 4 May 2009 and 14 April and 28 April 2010, and summer topdressing applied every 14 days from 1 June to 24 August 2009, and 24 May to 17 August 2010.

§Four cores were taken per plot to a 17 cm depth and were then separated into two fractions (layers) at the thatch/mat and native soil interface for bulk sampling. The thatch/mat layer depth was measured from the thatch/mat layer and native soil interface to the base of the verdure.

¶Liming requirement index

#NS, not significant

Table 2.17. Results of nutrient analysis (performed by Mehlich III extraction) of the soil fraction of two sand topdressing treatments on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ taken on 28 Nov. 2011.

				Nutrient concentration								
Sand accumulation‡	Soil depth§	pH	LRI¶	P	K	Ca	Mg	B	Zn	Mn	Cu	Fe
---L m^{-2} yr^{-1}---	--mm--			--------------------g cm^{-1}--------------------				--------------------------mg kg^{-1}--------------------------				
0	119	5.9	7.8	74.0	63.6	562.8	73.0	0.4	5.0	10.2	4.5	175.2
6.6	91	5.7	7.8	61.1	54.7	451.7	55.2	0.3	3.8	5.5	3.4	124.7
Source of variation						ANOVA						
Treatment	*	*	NS#	*	*	**	*	NS	NS	*	*	0.07†
CV, %	6.9	0.7	0.3	3.6	2.0	2.4	4.7	20.0	15.9	15.5	7.2	11.1

* and **Significant at the 0.05 and 0.01 probability level, respectively.

†Probability level ≤ 0.1.

‡The total annual sand was applied as spring topdressing applied as split applications on 20 April and 4 May 2009 and 14 April and 28 April 2010, and summer topdressing applied every 14 days from 1 June to 24 August 2009, and 24 May to 17 August 2010.

§Four cores were taken per plot to a 17 cm depth and were then separated into two fractions (layers) at the thatch/mat and native soil interface for bulk sampling. The soil depth was measured from the thatch/mat layer and native soil interface to the base of the sample.

¶Liming requirement index

#NS, not significant

CHAPTER 3. Anthracnose of Annual Bluegrass Affected by Sand Topdressing Rate Applied During Disease Emergence

ABSTRACT

Sand topdressing on putting green turf is suspected of increasing the severity of anthracnose disease, caused by the fungus *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman, of annual bluegrass [*Poa annua* L. f. *reptans* (Hausskn) T. Koyama] (ABG) turf. This field study was conducted to evaluate the effect of sand topdressing applied at the onset of disease symptoms on anthracnose severity of ABG turf. The turf was maintained at 3.2-mm on a Nixon sandy loam (fine-loamy, mixed, mesic Typic Hapludaults) in North Brunswick, NJ. Summer topdressing rates of 0, 0.075, 0.15, 0.30 and 0.6 L m^{-2} were applied (28 July 2009 and 24 May 2010) once disease severity had reached approximately 10% of the plot area infested with *C. cereale* and biweekly topdressing continued through 24 Aug. 2009 and 19 July 2010. Treatments were arranged in a RCBD with four replications. Sand topdressing at 0.15 and 0.3 L m^{-2} caused a 9 to 14% increase in disease severity 16 and 18 d after treatments were initiated in 2009 and 2010, respectively. Estimated topdressing rates of 0.25 and 0.34 L m^{-2} caused the greatest increases in disease severity in 2009 and 2010, respectively. These initial increases in disease severity were only apparent for 6- to 9-d and continued sand topdressing reduced disease severity 13 to 20% by the end of the trial during 2009 and 2010, respectively. Increased topdressing rate produced a quadratic reduction in disease severity by the end of the season in 2010, indicating that increasing topdressing rate beyond 0.15 L m^{-2} produced little benefit in the form of disease reduction. Summer topdressing applied at the onset of disease may cause relatively small, short-lived

increases in disease severity; however, continued sand topdressing can result in reductions in anthracnose severity that outweigh any initial disease increases.

INTRODUCTION

Anthracnose, caused by the fungus *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman (Crouch et al., 2006) is a problematic disease of annual bluegrass [*Poa annua* L. forma *reptans* (Hausskn.) T. Koyama] (ABG) and creeping bentgrass (*Agrostis stolonifera* L.) turf in many areas of United States and across the world. The disease is particularly damaging to ABG putting greens during warm and humid weather in the summer. Anthracnose severity has been reported to increase when turf is weakened from stressful management practices used to improve playability of golf turfs (Dernoeden, 2012).

Topdressing is the distribution of a thin layer of selected or prepared soil (often sand on putting greens) to a turfgrass area (Beard, 1973; Cooper and Skogley, 1981). The benefits of sand topdressing of putting greens include surface smoothing, thatch prevention and modification, surface soil modification, and winter protection (Beard, 1973). Recent research has indicated that sand topdressing at 0.3 L m^{-2} every 7 to 14 d during the summer can decrease anthracnose severity up to 47% on ABG turf maintained at 3.2 mm (Inguagiato et al., 2012; Inguagiato et al., 2013; Roberts, 2009). This reduction in disease severity produced by sand topdressing was attributed to the development of a sand (mat) layer that buries crowns of the plants and provides protection from abiotic and biotic stresses.

This previous research also reported that sand topdressing at these rates and frequencies increased disease severity 4 to 14% when first applied to turf that had received little to no previous sand topdressing during the growing season (Inguagiato et al., 2012; Inguagiato et al., 2013; Roberts, 2009). This initial increase in disease was observed early in the first year of these trials and was thought to have occurred due to sand induced wounding of the crown before sufficient sand had accumulated to bury and protect the crown in a mat layer (Inguagiato et al., 2013). In a greenhouse study, annual bluegrass tillers inoculated with *C. cereale* developed disease symptoms when wounded at the crown but not when wounded above the crown (Landschoot and Hoyland, 1995).

Inguagiato et al. (2012) speculated that topdressing programs which apply less sand than is needed to bury and protect crowns may intensify disease symptoms when one or more of the initial topdressings per season coincide with the early stages of disease symptoms. Information is lacking on the impact of initiating a topdressing program when disease symptoms first appear. Therefore, the objective of this study was to determine the impact of biweekly sand topdressing on anthracnose disease severity when initiated during the early stages of disease outbreaks.

MATERIALS AND METHODS

Experimental Design and Treatments

This field study was conducted on a putting green sward located at Horticultural Farm No. 2, North Brunswick, NJ (40°28' N, 74°25' W), during 2009 and 2010. The soil on this site is a modified Nixon sandy loam (fine-loamy, mixed, semiactive, mesic Typic Hapludults, in some areas altered to fine-loamy, mixed, semiactive, mesic Ultic Udarents). The turf was a seven-yr-old monostand of ABG that was established using seed native to the site and ABG introduced from Plainfield Country Club, Plainfield, NJ in 1998 (Inguagiato et al., 2009; Samaranayake et al., 2008). The site was previously inoculated with *C. cereale* isolate HFIIA using 20,000 conidia mL^{-1} on 2 Aug. 2004 using the procedures described by Inguagiato et al. (2009) to ensure uniform distribution of disease symptoms across the trial area, and subsequent outbreaks of the disease occurred naturally.

The trial used a randomized complete block design with four replications. The single factor studied was topdressing sand rate: 0, 0.075, 0.15, 0.3, and 0.6 L m^{-2}. Topdressing treatments were initiated when disease severity had reached approximately 10% of the plot area infested with *C. cereale* (28 July 2009 and 24 May 2010). Biweekly topdressing continued through 24 August 2009 (3 topdressings) and 19 July 2010 (5 topdressings). Plot size was 1.8 by 1.8 m.

The topdressing rates of 0.15, 0.3, and 0.6 L m^{-2} were applied with a drop spreader (model SS-2, The Scotts Company, Marysville, OH) calibrated to uniformly apply each volume over the plot in 4 passes. A shaker jar was used to apply the 0.075 L m^{-2} topdressing rate. The topdressing material was kiln dried silica sand (subangular)

("310" U.S. Silica, Co., Mauricetown, NJ) having a bulk density of 1.56 g cm^{-3} and a particle distribution that met USGA recommendations (2004) (Table 3.1). Topdressing was applied when the turf canopy was dry (between 1200 and 1700 h) and was incorporated via soft-bristle brushing as described by Inguagiato et al. (2012). The entire trial area received light hose-end irrigation after brushing.

Field Maintenance

Turf was mowed six times weekly between 0800 and 0930 h with a walking greens mower (model 1000, Toro Co., Bloomington,, MN) bench set at 3.2 mm and clippings were removed. Irrigation was applied to avoid wilt stress yet maintain moderately-dry conditions and to water-in fertilizer. Nitrogen was applied before treatments were initiated at 68.4 and 29.3 kg ha^{-1} from 7 Apr to 25 July 2009 and 21 Apr. to 17 May 2010 to complete recovery from the previous year's disease damage. During the period that topdressing treatments were applied and disease evaluations were performed, N was applied biweekly at 4.9 kg ha^{-1} totaling 9.8 and 29.3 kg ha^{-1} in 2009 and 2010, respectively. After disease progress was arrested, N was applied at 85 and 166 kg ha^{-1} from 7 Sept. to 6 Oct. 2009 and 17 Aug. to 11 Oct. 2010, respectively, to recover turf from disease damage. Phosphorus and potassium were applied based on soil test results at 30.3 and 143 kg ha^{-1} in 2009 and 26.9 and 45.2 kg ha^{-1} in 2010, respectively.

Dollar spot disease (caused by *Sclerotnia homoeocarpa* F.T. Bennett) was controlled with biweekly applications of the fungicides boscalid {3-pyridinecarboximide, 2-chloro-N-[4'chloro(1,1'-biphenyl)yl]} at 0.38 kg a.i. ha^{-1} or vinclozolin [3-(3,5-dichlorophenyl)-5-ethenyl-5-methyl-2,4-oxazolidinedione] at 1.52 kg a.i. ha^{-1}. The diseases summer patch (caused by *Magnaporthe poae* Landschoot & Jackson) and brown patch (caused by *Rhizoctonia solani* Kühn) were controlled using a rotation of the fungicides azoxystrobin (Methyl(E)-2-{2-[6-(2-cyanophenoxy)pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate)} at 0.61 kg a.i. ha^{-1}, flutolanil {N-[3-(1-methylethoxy)phenyl]-2-(trifluoromethyl)benzamide} at 6.41 kg a.i. ha^{-1}, and fluoxastrobin [(1E)-[2-[[6-(2-Chlorophenoxy)-5-fluoro-4-pyrimidinyl]oxy]phenyl](5,6-dihydro-1,4,2-dioxazin-3-yl) methanone-O-methyloxime] at 0.55 kg a.i. ha^{-1} applied every 14 d. Algal growth was controlled with mancozeb (ethylenebisdithiocarbamate) on 5, 11 and 27 June 2010 at 24.4 kg a.i. ha^{-1}, and at 15, 20 and 28 July 2010 at 30.5, 20.1 and 28.7 kg a.i. ha^{-1}, respectively. These fungicides were found to have no effect on anthracnose severity based on research conducted previously at this location (Towers et al., 2003). Annual bluegrass inflorescence expression was suppressed with the growth regulator ethephon [(2-chloroethyl)phosphonic acid] at a rate of 3.81 kg a.i. ha^{-1} on 25 March, 13 and 28 April 2009 and 19 March, 2 April, and 23 April 2010. Trinexapac-ethyl [4-(cyclopropyl-α-hydroxy-methylene)-3,5-dioxocyclohexanecarboxylic acid ethylester)] was applied at 0.05 kg a.i. ha^{-1} every 14 d from 25 March until 2 October 2009 and from 19 March until 2 October 2010 to regulate vegetative growth. The insecticides chlorantraniliprole {3-Bromo-N-[4-chloro-2-methyl-6-[(methylamino)carbonyl]phenyl]-1-(3-chloro-2-pyridinyl)-1H-pyrazole-5-carboxamide} at 0.18 kg a.i. ha^{-1} and indoxacarb {(S)-methyl 7-chloro-2,5-dihydro-2-[[(methoxycarbonyl)[4(trifluoromethoxy)phenyl]amino]-carbonyl]indeno[1,2-e][1,3,4]oxadiazine-4a-(3H)-carboxylate} at 0.27 kg a.i. ha^{-1} were applied on 14 June 2009 and 30 April 2010, respectively, to control annual bluegrass weevils [*Listronotus maculicollis* (Kirby)]. Creeping bentgrass was eliminated from the study area with fluazifop-P-butyl {Butyl (R)-2-[4-[[5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoate} at 0.21 kg a.i. ha^{-1} on 20 Sept. 2010. Anthracnose disease progress was arrested on 3 Sept. 2009 and 17 Aug. 2010 using chlorothalonil (tetrachloroisophthalonitrile) at 12.9 and 14.7 kg a.i. ha^{-1}, respectively.

Data Collection and Analysis

Anthracnose disease severity was evaluated on 9 dates from July to Sept. 2009 and on 10 dates from May to Aug. 2010 as the percent turf area infested with *C. cereale* using a line-intercept grid count method that generated 273 observations per plot (Inguagiato et al., 2008). Percent turf area infested with *C. cereale* was calculated using the equation:

$$(n/273) \times 100;$$

where n represented the count of intersects that overlaid ABG turf infested with *C. cereale*. Area under the disease progress curve (AUDPC) values were calculated using the equation:

$$\mathrm{AUDPC} = \sum_{i=1}^{n_i - 1} \left(\frac{y_i + y_{i+1}}{2} \right) (t_{i+1} - t_i)$$

where "t_i" is time in days, "i" is the order index for the ratings (and "n_i" is the number of ratings), "y" is the percent turf area infested at rating (Madden et al., 2007). Turfgrass quality was rated visually every 7 to 14 d using a 1 to 9 scale (9 represented the best quality and 5 was the minimally acceptable rating). Turf density, uniformity, algae, topdressing sand incorporation and disease severity were all considered when turf quality was evaluated.

Analysis of variance was performed by partitioning treatment effects into orthogonal comparisons using CONRAST statements within the General Linear Model procedure of the Statistical Analysis System (SAS) software v. 9.3 (SAS Institute, Cary, NC). Trend comparison analysis was performed for topdressing rate effects by partitioning topdressing rate sums of squares for disease severity and turf quality into linear, quadratic and lack of fit components by orthogonal polynomial contrasts (Steel et al., 1997; Yourstone, 1991). When the polynomial orthogonal contrasts were significant, appropriate regression equations were fitted to the topdressing rate response data. Orthogonal polynomial coefficients were computed by the ORPOL function using the IML procedure in SAS. Treatment effects were considered significant if $p \leq 0.05$.

RESULTS AND DISCUSSION

Anthracnose Severity

Initial symptoms of anthracnose basal rot developed as a natural infestation in early July 2009. Disease severity was relatively low, no more than 18%, throughout July and early August due to unfavorable environmental conditions for anthracnose development (rain and mild temperatures). Disease severity increased during mid-August and maximum disease severity (40%) was reached on 28 Aug. 2009, after which disease severity declined to 31% on 3 Sept. due to cooler temperatures and lower humidity (Table 3.2). Anthracnose symptoms developed earlier in 2010 and disease severity was moderate (22 to 32%) by 28 May (Table 3.3). Disease severity progressed slowly through June to early-July 2010 and increased to peak levels (41 to 61%) in mid-August.

There were no significant differences in AUDPC among any treatments in 2009 or 2010 because treatment effects during early- and late-season were opposite and offset each other when integrating over time (Tables 3.2 and 3.3).

Similar to results from previous work (Inguagiato et al., 2012; Inguagiato et al., 2013; Roberts, 2009), sand topdressing caused a slight increase in disease compared to nontopressed turf on one rating date during 2009. Increased topdressing rate produced a quadratic increase in disease severity on 13 Aug. 2009, after two topdressing applications (Table 3.2). Maximum disease severity occurred at a sand rate of 0.25 L m^{-2} as estimated from the quadratic polynomial equation. However, the quadratic response also indicated that disease severity was reduced to a level lower than the non-topdressed control when topdressing rate was increased to 0.6 L m^{-2} on 13 Aug. As reported in other trials, this initial increase in disease observed on 13 Aug. was short-lived and continued sand topdressing reduced disease severity linearly by the end of the first year of the trial on 3 Sept. 2009 (Inguagiato et al., 2012; Inguagiato et al., 2013; Roberts, 2009). Quadratic and lack-of-fit effects were also significant on 3 Sept. due to the 0.15 L m^{-2} rate producing a greater disease reduction than the 0.3 L m^{-2} rate.

Anthracnose severity response to topdressing rate in 2010 was similar to 2009; increased topdressing rate produced a quadratic increase in disease severity on 11 June 2010 after two topdressing applications, and maximum disease severity occurred at an estimated rate of 0.34 L m^{-2} (Table 3.3). Increased topdressing rate produced a quadratic reduction in anthracnose severity on 28 July and 11 Aug. 2010, and minimum disease severity occurred at estimated rates of 0.4 and 0.41 L m^{-2}, respectively.

Previously, increases in disease severity caused by sand topdressing have only been reported during the first year of a trial (Inguagiato et al., 2012; Inguagiato et al., 2013; Roberts, 2009). As mentioned before, Inguagiato et al. (2013) attributed these initial increases in disease observed in under-topdressed turf to the wounding of unprotected crowns based on Landschoot and Hoyland's (1995) reports that only wounding of the crown, not leaves, increased anthracnose. The cumulative sand amounts needed to reduce disease severity in first year of previous topdressing trials were within the range of 2.4 to 4.8 L m^{-2} (Inguagiato et al., 2012). In those trials, crowns of plants in topdressed plots were already buried and protected within a mat layer before topdressing was initiated in the second year. Cumulative sand totals ranged from 0.23 to 1.8 L m^{-2} after the first year of the current trial. Therefore, crowns in topdressed plots were probably not thoroughly surrounded and protected by sand within the mat layer and, thus, were subject to wounding from sand topdressing applications during the second year.

Although mechanical stress is typically expected to increase anthracnose severity (Smiley et al., 2005), species in the *Colletotrichum* genus do not require wounds or existing openings to penetrate their host (Bruehl and Dickson, 1950; Smith, 1954; Venard and Vaillancourt, 2007). Some studies have shown that infection by *C. graminicola* was enhanced from indirect penetration through wounds (Venard and Vaillancourt, 2007; Bergstrom and Nicholson, 1999). However, Crouch and Beirn (2009) suggested that practices that incite injury must be evaluated individually as wounding does not always facilitate infection from *Colletotrichum* spp. Recent research has shown that wounding caused by verticutting (3 mm depth every 14 d) had little effect on disease severity (Inguagiato et al., 2008), and foot traffic (equivalent to 200 rounds d^{-1}) caused substantial reductions in disease severity (Roberts et al., 2013). Data from the current trial indicate that crown wounding caused by applying sand to previously nontopdressed turf during the emergence of disease symptoms slightly increased disease severity. However, these increases were brief and not any greater than the increases observed in previous trials. Moreover, continued sand topdressing reduced disease severity by the end of each season, similar to other trials. These results suggest that practitioners may initiate a biweekly sand topdressing program on ABG putting green turf during the early stages of disease development to achieve disease reductions that will outweigh any brief increases in disease severity that may result from initial topdressing applications.

Turf Quality

Turf quality was acceptable (≥5) for all treatments throughout 2009 (Table 3.4) and until early-July 2010 (Table 3.5) under low or moderate levels of disease severity (Tables 3.2 and 3.3). Any treatment differences on the first three rating dates in 2009 were considered random effects because treatments were not initiated until 28 July 2009 (Table 3.4).

Increased topdressing rate produced a linear reduction in turf quality on 1 and 7 Aug 2009 (Table 3.4). Turf quality did not respond to topdressing rate on any other date in 2009. This linear reduction could be due to random effects; however, although not significant, disease severity means of turf treated with the 0.3 and 0.6 L m^{-2} rates were slightly higher than the control on 1 Aug. 2009 (6 and 1%, respectively) and 7 Aug. 2009 (2 and 1%, respectively) (Table 3.2).

Increased topdressing rate improved turf quality linearly on 21 June 2010 (Table 3.5). Topdressing rate did not affect turf quality again until 11 Aug., when the response to increased topdressing rate was quadratic. The best turf quality occurred at an estimated rate of 0.41 L m^{-2}. The quadratic responses in turf quality and disease severity on 11 Aug 2010 were similar, and there was little improvement to turf quality or disease reduction when topdressing rate was increased beyond 0.15 L m^{-2} on 11 Aug 2010 (Tables 3.3 and 3.5).

CONCLUSIONS

Sand topdressing at rates of 0.15 and 0.3 L m^{-2} applied during the early stages of disease outbreaks caused small, short-lived increases in disease severity. However, continued biweekly sand topdressing applications caused reductions in disease severity by the end of each trial-year that were greater than any increase in disease severity observed soon after treatments were initiated. These data suggest that initiating a biweekly sand topdressing program when disease symptoms are present can be a beneficial tool for anthracnose disease reduction, despite transient increases in disease severity which may be observed shortly after the initiation of the program.

REFERENCES

Beard, J.B. 1973. Turfgrass: Science and culture. Prentice Hall, Englewood Cliffs, NJ.

Bergstrom, G.C., and R.L. Nicholson. 1999. The biology of corn anthracnose: knowledge to exploit for improved management. Plant Dis. 83(7):596-608.

Bruehl, G.W., and J.G. Dickson. 1950. Anthracnose of cereals and grasses. USDA Tech. Bull. 1005:1-37.

Cooper, R.J., and C.R. Skogley. 1981. An evaluation of several topdressing programs for *Agrostis palustris* Huds. and *Agrostis canina* L. putting green turf. Proc. Int. Turf. Res. Conf 4:129-136.

Crouch, J.A., and L.A. Beirn. 2009. Anthracnose of cereals and grasses. Fungal Diversity 39:19.

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(1):46-60. DOI: 10.1094/PHYTO-96-0046.

Dernoeden, P.H. 2012. Creeping bentgrass management. CRC Press.

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

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(4):1595-1607. DOI: 10.2135/cropsci2007.06.0343.

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(4):1454-1462. DOI: 10.2135/cropsci2008.07.0435.

Inguagiato, J.C., J.A. Murphy, and B.B. Clarke. 2012. Sand Topdressing Rate and Interval Effects on Anthracnose Severity of an Annual Bluegrass Putting Green. Crop Sci. 52(3):1406-1415. DOI: 10.2135/cropsci2011.01.0010.

Inguagiato, J.C., J.A. Murphy, B.B. Clarke, and J.A. Roberts. 2013. Topdressing sand particle shape and incorporation effects on anthracnose severity of an annual bluegrass putting green. Int. Turfgrass Res. Soc. J. 12:(accepted).

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

Madden, L.V., G. Hughes, and F. Van den Bosch. 2007. The Study of Plant Disease Epidemics. The American Phytopathological Society, APS Press, St. Paul, MN.

Roberts, J.A. 2009. Impact of cultural management on anthracnose severity of annual bluegrass putting green turf. M.S. Thesis: Rutgers Univ.

Samaranayake, H., T.J. Lawson, and J.A. Murphy. 2008. Traffic Stress Effects on Bentgrass Putting Green and Fairway Turf. Crop Sci. 48(3):1193-1202. DOI: 10.2135/cropsci2006.09.0613.

Smiley, R.W., P.H. Dernoeden, and B.B. Clarke. 2005. Compendium of turfgrass diseases. APS press, St. Paul, MN.

Smith, J.D. 1954. A disease of *Poa annua*. J. Sports Turf Res. Inst. 8:344-353.

Steel, G.D., J.H. Torrie, and D.A. Dickey. 1997. Procedures and principles of statistics: A biometrical approach, McGraw-Hill, New York, NY.

Towers, G., K. Green, E. Weibel, P. Majumdar, and B.B. Clarke. 2003. Evaluation of fungicides for the control of anthracnose basal rot on annual bluegrass. Fungicide and Nematicide Tests 58:T017.

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(3):368-377.

Yourstone, K.S. 1991. Partitioning Variance and Comparing Treatment Means with Contrast and Estimate. Proc. of the Northeast SAS User Group Conf. 4:288-293.

Table 3.1. Particle size distribution of sand used for topdressing in 2009 and 2010.

Sieve size opening							
2 mm	1 mm	500 µm	250 µm	149 µm	105 µm	53 µm	Pan
-- % retained (by weight) --							
0	<0.1	31.3	65.1	3.3	0.2	<0.1	<0.1

Table 3.2. Anthracnose severity response to sand topdressing rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009.

Topdressing rate‡	7 July	15 July	24 July	1 Aug.	6 Aug.	13 Aug.	20 Aug.	28 Aug.	3 Sept.	AUDPC
L m^{-2}	----------	----------	----------	----------	percent turf area infested	----------	----------	----------	----------	
0	0.4	2.3	9.8	12.8	8.3	25.3	25.9	40.4	30.8	828
0.075	0.4	2.0	8.1	12.7	8.3	29.2	27.2	38.1	25.6	834
0.15	0.5	1.1	8.3	11.9	8.0	34.1	25.2	36.3	20.5	820
0.3	0.7	1.1	13.3	18.3	10.7	28.9	24.2	38.1	23.1	830
0.6	0.5	0.7	13.4	13.5	9.2	20.7	18.9	35.8	18.2	680
Source of Variation	----------	----------	----------	----------	----------	$P > F$	----------	----------	----------	----------
Treatment	NS§	NS	NS	NS	NS	*	NS	NS	***	NS
Planed F-Test										
Linear	NS	0.09†	0.06	NS	NS	0.06	NS	NS	***	0.07
Quadratic	0.09	NS	NS	NS	NS	*	NS	NS	*	NS
Lack-of-fit	NS	NS	NS	NS	NS	NS	NS	NS	**	NS
CV, %	59.3	85.8	34.9	34.2	25.1	18.7	28.9	9.6	9.3	14.6

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

***Significant at the 0.001 probability level.

†Probability level ≤ 0.1.

‡Topdressing rate was applied every 14 days from 28 July to 24 August 2009.

§NS, not significant.

Table 3.3. Anthracnose severity response to sand topdressing rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010.

Topdressing rate‡	19 May	28 May	4 June	11 June	21 June	28 June	7 July	15 July	28 July	11 Aug.	AUDPC
L m^{-2}	---------- percent turf area infested ----------										
0	12.2	24.8	23.9	16.3	21.7	29.0	35.1	30.5	41.4	60.7	2412
0.075	15.1	31.9	27.7	26.6	27.4	35.0	42.9	30.6	40.0	53.8	2647
0.15	9.0	22.4	21.6	22.6	24.8	30.9	34.0	28.8	30.8	41.8	2180
0.3	13.2	28.9	24.1	30.4	28.8	34.3	37.1	28.7	31.4	41.0	2375
0.6	11.6	25.0	27.8	22.5	30.3	38.6	38.2	30.7	32.0	41.1	2406
Source of Variation	---------- *P* > *F* ----------										
Treatment	NS§	NS	NS	0.06†	NS	NS	NS	NS	*	***	NS
Planed F-Test											
Linear	NS	NS	NS	NS	0.07	0.09	NS	NS	*	***	NS
Quadratic	NS	NS	NS	*	NS	NS	NS	NS	*	**	NS
Lack-of-fit	NS	NS	NS	NS	NS	NS	0.08	NS	NS	NS	NS
CV, %	38.8	32.7	22.9	25.0	21.1	20.1	14.6	13.1	13.0	12.0	14.0

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

***Significant at the 0.001 probability level.

†Probability level ≤ 0.1.

‡Topdressing rate was applied every 14 days from 24 May 2010 to 19 July 2010.

§NS, not significant

Table 3.4. Turf quality response to sand topdressing rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009.

Topdressing rate‡	9 July	16 July	24 July	1 Aug.	7 Aug.	17 Aug.	27 Aug.
L m^{-2}				------1–9 scale§------			
0	7.0	7.5	8.3	8.0	8.3	6.3	7.5
0.075	6.8	7.3	7.8	8.3	8.0	6.8	7.5
0.15	6.5	7.3	7.8	8.3	7.8	6.8	8.0
0.3	6.3	6.7	6.7	7.7	7.0	6.7	8.0
0.6	6.3	6.5	6.8	7.5	7.5	7.0	7.8
Source of Variation				------$P > F$------			
Treatment	NS¶	NS	0.07†	NS	NS	NS	NS
Planed F-Test							
Linear	0.09	*	**	*	*	NS	NS
Quadratic	NS	NS	NS	NS	0.08	NS	0.09
Lack-of-fit	NS	NS	NS	NS	NS	NS	NS
CV, %	9.0	9.4	10.2	5.8	7.1	10.3	5.2

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

†Probability level ≤ 0.1.

‡Topdressing rate was applied every 14 days from 28 July to 24 August 2009.

§Nine (9) represents the best turf characteristic and 5 represents the minimally acceptable rating.

¶NS, not significant.

Table 3.5. Turf quality response to sand topdressing rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010.

Topdressing rate‡	19 May	28 May	4 June	11 June	21 June	28 June	7 July	15 July	28 July	11 Aug.
L m^{-2}	----------	----------	----------	----------	1–9 scale§	----------	----------	----------	----------	----------
0	6.0	6.5	5.8	6.8	6.3	5.8	4.8	5.8	3.8	3.0
0.075	5.5	5.8	5.8	5.8	6.3	5.5	4.5	5.0	4.0	3.8
0.15	6.5	6.5	6.3	6.5	6.5	5.8	5.3	6.0	5.0	4.5
0.3	5.8	5.8	6.0	6.3	6.5	5.5	5.3	5.0	4.5	5.0
0.6	6.3	6.0	6.3	6.3	7.0	6.0	5.5	5.0	4.5	4.8
Source of Variation	----------	----------	----------	----------	$P > F$	----------	----------	----------	----------	----------
Treatment	NS¶	NS	NS	NS	NS	NS	NS	NS	NS	0.06†
Planed *F*-Test										
Linear	NS	NS	NS	NS	*	NS	NS	NS	NS	*
Quadratic	NS	NS	NS	NS	NS	NS	NS	NS	NS	*
Lack-of-fit	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV, %	12.5	13.5	10.8	12.1	7.6	14.8	15.9	14.7	25.0	21.8

*Significant at the 0.05 probability level.

†Probability level ≤ 0.1.

‡Topdressing rate was applied every 14 days from 24 May 2010 to 19 July 2010.

§Nine (9) represents the best turf characteristic and 5 represents the minimally acceptable rating.

¶NS, not significant

CHAPTER 4. Effects of Midseason Cultivation Practices on Anthracnose of Annual Bluegrass Putting Green Turf

ABSTRACT

Annual bluegrass [*Poa annua* L. forma *reptans* (Hausskn.) T. Koyama] (ABG) putting greens are particularly susceptible to the disease anthracnose, caused by the fungus *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman. Mechanical injury from cultivation practices has been reputed to enhance ABG susceptibility to anthracnose via wounding, particularly if cultivation is conducted when symptoms are present. The effect of midseason cultivation applied at the onset of disease symptoms on anthracnose severity was studied on ABG turf maintained at 3.2-mm on a Nixon sandy loam in North Brunswick, NJ. Treatments of no cultivation, grooming, verticutting, solid-tining, scarifying and weekly grooming were arranged in a RCBD with four replications in 2009. Treatments were initiated (24 July 2009 and 2 June 2010) when 11 to 20% of the trial area was infested with *C. cereale* and were applied every 21-d thereafter, except for weekly grooming which was applied every 7-d. The experimental design was modified to a strip-plot design in 2010; cultivation plots were horizontally stripped with a second factor of fungicide control (treated or untreated). Without fungicide applications, verticutting increased disease severity 4 to 18% on 54% of rating dates and scarifying increased disease 2 to 10% on 31% of rating dates during the treatments periods of 2009 and 2010. Solid-tining was the only treatment to increase disease severity (5%) on turf under fungicide control in 2010. Grooming reduced disease relative to the control during both trial-years, especially when applied weekly under fungicide control. Surprisingly, all cultivation practices reduced disease severity relative

to the control before the treatment period began again in 2010; however, verticutting, scarifying and solid-tining increased disease by the end of the 2010 season in the absence of fungicide. Midseason cultivation does not appear to greatly enhance the risk of anthracnose on ABG turf under a fungicide program commonly used to control the disease.

INTRODUCTION

Anthracnose, incited by the fungus *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman, is a destructive disease of annual bluegrass [*Poa annua* L. forma *reptans* (Hausskn.) T. Koyama] (ABG) and creeping bentgrass (*Agrostis stolonifera* L.) putting greens (Crouch et al., 2006). Annual bluegrass is particularly susceptible to anthracnose, possibly due to the weak perennial nature of the species and its susceptibility to environmental stress (Murphy et al., 2008; Smiley et al., 2005). Severe anthracnose outbreaks emerged during the early-1990s in North America and have continued to appear ubiquitously throughout temperate climates across the world (Crouch et al., 2006; Landschoot and Hoyland, 1995; Mann and Newell, 2005). Infection by *C. cereale* can often result in death of ABG and, ultimately, severe loss of turf (Smiley et al., 2005). Chemical control options have become increasingly limited due to the emergence of resistant strains of *C. cereale* to several fungicide chemistries (Avila-Adame et al., 2003; Crouch et al., 2005; Wong et al., 2008; Wong and Midland, 2007; Wong et al., 2007; Young et al., 2010a; Young et al., 2010b). Thus, recent research has focused on the effects, positive or negative, of cultural management practices on anthracnose severity of ABG.

Management practices that enhance playability (ball roll distance) for golfers but reduce plant vigor have been suspected to increase anthracnose severity (Vermeulen, 2003; Zontek, 2004). Research has proven that low mowing heights, low nitrogen fertility, and limited irrigation increase damage of ABG from anthracnose (Inguagiato et al., 2008; Inguagiato et al., 2009; Roberts et al., 2011). Cultivation practices have also been suspected to increase anthracnose severity because wounding and increased plant stress are believed to increase ABG susceptibility to anthracnose (Landschoot and Hoyland, 1995; Smiley et al., 2005). However research is limited regarding the effects of mechanical wounding caused by mid-season cultivation practices such as vertical cutting (VC) and solid-tining on anthracnose of ABG.

Turf cultivation is a general term that describes mechanical practices that modify the turf and/or root zone without destroying the sward (Bidwell, 1952; Dawson, 1934; Dawson and Ferro, 1939; Engel and Alderfer, 1967). Cultivation decreases soil compaction and, thus, enhances growing conditions in the surface root zone by improving soil gas exchange, wetting and drying, water infiltration, root growth, and response to fertilizers (Christians, 2011; Turgeon, 2011). Coring is a common and effective method of cultivation that uses hollow tines to remove soil cores and create vertical channels in the surface root zone that are typically back-filled with sand or sandy soil (Beard, 1973; Christians, 2011; Hartwiger and O'Brien, 2001; Murphy and Rieke, 1994). Coring is often performed during spring and/or autumn but rarely during midseason because it can create an uneven playing surface that can take many days to return to normal (Christians, 2011).

Alternatively, solid-tining and VC are cultivation practices that are often used during midseason because they are less disruptive to play and have reduced equipment and labor costs compared to coring (McCarty et al., 2007; Murphy et al., 1993). Solid-tine cultivation penetrates the soil and creates channels without removing soil or turf (Murphy et al., 1993). Benefits of solid-tining include increased shoot density and reduced soil compaction, which can increase saturated hydraulic conductivity and soil porosity and, thus, indirectly reduce soil electric conductivity as well (Carrow, 1996; Carrow, 2003; Green et al., 2001; Murphy et al., 1993).

Vertical cutting (VC) removes thatch, controls turf grain, a condition where grass blades lay in a single direction and affect ball roll, and reduces canopy biomass by slicing into a turf surface with mechanical devices equipped with vertically rotating blades (Beard and Beard, 2005). Depending on the objective, VC machines may have different blade spacings (5 to 40 mm) and thicknesses (1 to 3 mm) set to varying depths (0 to 40 mm) (Landreth et al., 2008; Lockyer, 2009; Moore, 2005). Shallow VC, or grooming, smoothes putting surfaces by reducing puffiness caused by the high shoot density of ABG (Vargas and Turgeon, 2004). Grooming equipment usually has thin blades (≤ 1 mm), close blade spacing (5 to 19 mm), and a shallow cutting depth (0.4 to 0.8 mm below the effective height of cut) (Beard, 2002). Moderate VC, hereinafter referred to as verticutting, cuts deeper into the canopy than grooming and affects mostly leaf and sheath tissue but sometimes affects crowns (Turgeon, 2011). Verticutting improves smoothness of a putting surface but provides greater thatch removal than grooming due to its increased depth. Blades on verticutting equipment may be thicker (≤ 2 mm) and spaced wider apart (13 to 19 mm) than blades on grooming equipment (Beard, 2002). Deep VC, or scarifying, removes large amounts of thatch, readies surfaces for renovation/overseeding and reduces compaction of the surface soil (Beard, 2002; Turgeon, 2011). Scarifying blades can be as thick as 3 mm, are spaced up to 40 mm apart and operated to depths up to 40 mm (Beard, 2002; Landreth et al., 2008). Scarifying is rarely performed during midseason because of the extensive amount of time required for turf to recover from the disruption caused by this practice (Landreth et al., 2008; Lockyer, 2009).

Putting greens with excessive thatch and poor soil conditions are more susceptible to disease (Beard, 1973; Smiley et al., 2005); therefore, cultivation can be an important part of disease management programs (Smiley et al., 2005). Clarke et al. (1995) reported that both deep and shallow coring reduced summer patch (caused by *Magnaporthe poae* Landschoot & Jackson) on an ABG fairway. Spring dead spot (caused by *Ophiosphaerella herpotricha* (Fr.:Fr.) J. Walker) on bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burtt-Davy] maintained at a 13 mm mowing height was moderately reduced by hollow-tine aerating and VC twice per year (Tisserat and Fry, 1997). Vertical cutting reduced dollar spot (caused by *Sclerotinia homoeocarpa* F.T. Bennett) severity on Kentucky bluegrass (*Poa pratensis* L.) (Halisky et al., 1981). Dollar spot was also reduced by coring a bentgrass putting green (Moeller, 2008) during spring and late-summer; however, Stier and Hollman (2003) reported that coring once (October) or four times annually (May, July, September, October) had no effect on dollar spot incidence in creeping bentgrass or ABG putting green turf. Carrow et al. (1987) reported that VC and coring may have weakened bermudagrass turf maintained as a homelawn and caused dollar spot to be more severe. Unruh et al. (2005) also reported that VC increased dollar spot severity on bermudagrass putting green turf.

Cultivation during midseason has been suggested to improve summer stress tolerance of ABG (Green et al., 2001). Additionally, thatch removal from midseason cultivation may reduce disease because primary inoculum for infection by pathogens such as *C. cereale* is produced on overwintered residues in thatch (Couch, 1973).

However, observational reports from the field have associated cultivation with enhanced anthracnose severity (Landschoot and Hoyland, 1995; Raisch, 2003), presumably by facilitating invasion of *C. cereale* through wounds (Smiley et al., 2005). Thus, many turf managers avoid the use of cultivation practices when anthracnose is active (Landschoot and Hoyland, 1995; Smiley et al., 2005). Research regarding the effect of midseason cultivation on anthracnose is limited and results have been conflicting. Increasing verticutting depth up to 5.1 mm increased anthracnose severity linearly on a mixed stand of creeping bentgrass and ABG putting green turf in a trial conducted by Uddin et al. (2008); whereas, Inguagiato et al. (2008) reported found that VC to a 3 mm depth on an ABG putting green had little effect on anthracnose. Wounding (puncture or abrasion) of ABG crown tissue prior to inoculation with *C. cereale* resulted in more rapid disease development in a greenhouse trial compared to wounding of leaf tissue or no wounding (Landschoot and Hoyland, 1995). Therefore, Inguagiato et al. (2008) suggested that deep VC (e.g., scarifying) of crown tissue may increase disease severity; whereas, shallow VC (e.g., grooming) of only leaf tissue may not affect anthracnose severity. Research is needed to test how these unique VC practices and other midseason cultivation practices such as solid-tining affect anthracnose. Therefore, a trial was initiated in 2009 on ABG putting green turf to evaluate the influence of grooming, verticutting, scarifying and solid-tining on anthracnose severity when applied at the onset of disease symptoms.

MATERIALS AND METHODS

Experimental Design and Treatments

This field study was conducted on a seven-yr-old monostand of ABG turf grown on a Nixon sandy loam (fine-loamy, mixed, semiactive, mesic Typic Hapludults, in some areas altered to fine-loamy, mixed, semiactive, mesic Ultic Udarents) capped with a 50 to 60 mm deep sand topdressing layer at Horticultural Farm No. 2, North Brunswick, NJ (40°28’ N, 74°25’ W). The sward was established in 2002 from seed indigenous to the location as well as from soil cores introduced from Plainfield Country Club, Plainfield, NJ in 1998 (Inguagiato et al., 2009; Samaranayake et al., 2008). The study location was inoculated with a spore suspension (20,000 conidia mL^{-1}) of *C. cereale* isolate HFIIA on 2 Aug. 2004 (Inguagiato et al., 2009). Subsequent anthracnose outbreaks, including those during the current trial, occurred naturally.

Cultivation technique was the single factor evaluated during 2009. Treatments included no cultivation, grooming (1.3 mm depth, 1.5 mm blade width, 5 mm lateral blade spacing), verticutting (3.8 mm depth, 1.5 mm blade width, 10 mm lateral blade spacing), scarifying (7.6 mm depth, 1.5 mm blade width, 40 mm lateral blade spacing), solid-tining (57.2 mm depth, 6.3 mm tine width, 38.1 by 38.1 mm tine spacing), and weekly grooming. Grooming, verticutting and scarifying were applied using a triplex mower (model 3150, Toro Co., Bloomington, MN) equipped with specialized reel-chassis (model TA3TORO Thatch-Away Supa-System, Turfline Inc., Moscow Mills, MO) with cassette-inserts designed for each practice (models TA3CAS GROTORO, TA3CAS VERTORO, TA3CAS SCATORO, respectively, Turfline Inc., Moscow Mills, MO). Solid-tining was performed using a walking aerator (model ProCore 648, Toro Co., Bloomington, MN). All cultivation treatments were applied between 1300 and 1600 hr when turf was dry. Treatments were applied every 21 d from 24 July to 14 Aug. 2009 (2 applications) and from 2 June to 19 July 2010 (3 applications), except for weekly grooming which was applied every 7 d from 24 July to 28 Aug. 2009 (5 total applications) and from 2 June to 11 Aug. 2010 (10 total applications). Disease severity was 11% and 20% of the trial area infested with *C. cereale* when treatments were initiated in 2009 and 2010, respectively. The trial area was rolled with a sidewinder roller (Tournament X-Press Greens Roller, SmithCo, Wayne, PA) to smooth the surface after cultivation treatments were applied. No sand topdressing was applied during treatments periods.

Treatments were arranged in a randomized complete block design with four replications and plots dimensions were 1.5 by 3.7 m during 2009. Fungicide control was included as a second factor in the same study location during 2010 to examine the effect of cultivation treatments under reduced disease severity. A strip-plot design was used to incorporate the fungicide control factor by dividing blocks (9.1 by 3.7 m) of the vertically-aligned cultivation treatments (1.5 by 3.7 m) into two horizontal-strip plots (9.1 by 1.8 m) of fungicide treatments (treated or untreated). Fungicide treated plots received curative applications of chlorothalonil (tetrachloroisophthalonitrile) and fosetyl-Al [Aluminum tris (O-ethyl phosphonate)] at the rates of 12.6 and 9.8 kg ha^{-1}, respectively, as a tank mix on 3 and 11 June and then every 14 d thereafter until 4 Aug. 2010. Fungicides were applied using a gas-powered backpack sprayer (Model SHR-210, ECHO Incorporated, Lake Zurich, IL) operated at 379 kPa of pressure to produce a water carrier volume of 815 L ha^{-1}. The sprayer boom (The Broyhill CO, Dakota City, NE) was equipped with 5 flat fan spray nozzles (Model XR8003, Tee Jet Technologies, Carol Stream, IL) affixed to constant flow valves (Model CFValve G11-16SY, GATE LLC., Sebastian, FL) that were spaced 25.4 cm apart.

Field Maintenance

Mowing was performed 6 times wk^{-1} between 0800 and 0930 h with a walking greens mower (model 1000, Toro Co., Bloomington, MN) bench set at a 3.2 mm height of cut and clippings were removed. Moderately-dry conditions were maintained by irrigating to avoid wilt stress and water-in fertilizer. Before treatments were initiated, N was applied at 63.5 and 34.2 kg ha^{-1} from 7 Apr to 12 July 2009 and 21 Apr. to 27 May 2010 to complete recovery from disease damage from the previous year. When cultivation treatments were being performed, N was applied every 14 d at 4.9 kg ha^{-1} totaling 14.7 and 29.3 kg ha^{-1} from 25 July to 23 Aug. 2009 and 11 June to 4 Aug. 2010, respectively. After treatments were curtailed and disease progress was arrested with fungicides, N was applied at 84.9 and 166 kg ha^{-1} from 7 Sept. to 6 Oct. 2009 and 17 Aug. to 11 Oct. 2010, respectively, to encourage recovery from disease damage. Phosphorus and K were applied based on soil test results during the spring or autumn at 30.3 and 143 kg ha^{-1} in 2009 and 26.9 and 45.2 kg ha^{-1} in 2010, respectively. Anthracnose epidemics were stopped at the conclusion of each trial year using the fungicide chlorothalonil applied at 12.9 and 14.7 kg a.i. ha^{-1} on 3 Sept. 2009 and 17 Aug. 2010, respectively.

The plant growth regulator ethephon [(2-chloroethyl)phosphonic acid] was applied at a rate of 3.81 kg a.i. ha^{-1} on 25 March, 13 and 28 April 2009 and 19 March, 2 April, and 23 April 2010 to suppress ABG inflorescence expression. Vegetative growth was controlled with biweekly applications of the plant growth regulator trinexapac-ethyl [4-(cyclopropyl-α-hydroxy-methylene)-3,5-dioxocyclohexanecarboxylic acid ethylester)] at 0.05 kg a.i. ha^{-1} from 25 March until 2 October 2009 and from 19 March until 2 October 2010. Annual bluegrass weevils [*Listronotus maculicollis* (Kirby)] were controlled with the insecticides chlorantraniliprole {3-Bromo-N-[4-chloro-2-methyl-6-[(methylamino)carbonyl]phenyl]-1-(3-chloro-2-pyridinyl)-1H-pyrazole-5-carboxamide} applied at 0.18 kg a.i. ha^{-1} and indoxacarb {(S)-methyl 7-chloro-2,5-dihydro-2-[[(methoxycarbonyl)[4(trifluoromethoxy)phenyl]amino]-carbonyl]indeno[1,2-e][1,3,4]oxadiazine-4a-(3H)-carboxylate} applied at 0.27 kg a.i. ha^{-1} on 14 June 2009 and 30 April 2010, respectively. Encroachment of creeping bentgrass was suppressed with fluazifop-P-butyl {Butyl (R)-2-[4-[[5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoate} applied at 0.21 kg a.i. ha^{-1} on 20 Sept. 2010.

A preventative program using fungicides that have been shown to not affect anthracnose isolates from this research location was used to selectively control unwanted diseases from 30 May to 19 Aug. 2009 and from 14 May to 14 Aug. 2010 (Towers et al., 2003). Dollar spot disease was controlled with biweekly applications of the fungicides boscalid {3-pyridinecarboximide, 2-chloro-N-[4'chloro(1,1'-biphenyl)yl]} at 0.38 kg a.i. ha^{-1} or vinclozolin [3-(3,5-dichlorophenyl)-5-ethenyl-5-methyl-2,4-oxazolidinedione] at 1.52 kg a.i. ha^{-1}. Summer patch and brown patch (caused by *Rhizoctonia solani* Kühn) were controlled using a biweekly rotation of the fungicides azoxystrobin (Methyl(E)-2-{2-[6-(2-cyanophenoxy)pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate)} at 0.61 kg a.i. ha^{-1}, flutolanil {N-[3-(1-methylethoxy)phenyl]-2-(trifluoromethyl)benzamide} at 6.41 kg a.i. ha^{-1}, and fluoxastrobin [(1E)-[2-[[6-(2-Chlorophenoxy)-5-fluoro-4-

pyrimidinyl]oxy]phenyl](5,6-dihydro-1,4,2-dioxazin-3-yl) methanone-O-methyloxime] at 0.55 kg a.i. ha^{-1} Algal growth was controlled as needed with mancozeb (ethylenebisdithiocarbamate) applied at rates ranging from 20.1 to 30.5 kg a.i. ha^{-1} only during 2010.

Data Collection and Analysis

Anthracnose disease severity was assessed on 11 dates from 12 June to 3 Sept. 2009 and on 9 dates from 19 May to 13 Aug. 2010 as the percent turf area infested with *C. cereale* using a line-intercept grid count method modified from Inguagiato et al. (2008) that generated 546 observations per plot for 12 June to 3 Sept. 2009 and 19 and 28 May 2010 and 273 observations per plot for 7 June to 13 Aug. 2010. Percent turf area infested was calculated using the equations:

$$(n/546) \text{ x } 100, \text{ and } (n/273) \text{ x } 100;$$

where *n* represented the count of intersects that overlaid ABG turf infested with *C. cereale*. Area under the disease progress curve (AUDPC) values were calculated using the equation:

$$\text{AUDPC} = \sum_{i=1}^{n_i - 1} \left(\frac{y_i + y_{i+1}}{2} \right) (t_{i+1} - t_i)$$

where "t_i" is time in days, "i" is the order index for the ratings (and "n_i" is the number of ratings), and "y" is the percent turf area infested at rating (Madden et al., 2007). Turfgrass quality was rated visually using a 1 to 9 scale (9 represented the best quality and 6 was the minimally acceptable rating) on 7 dates from 9 July to 27 Aug. 2009 and on 9 dates from 19 May to 13 Aug. 2010. Turf density, uniformity, algae, disease severity, and surface disruption caused by cultivation were considered when turf quality was evaluated. Data were subjected to ANOVA using the General Linear Model procedure (PROC GLM) in the Statistical Analysis System software v. 9.3 (SAS Institute, Cary, NC). Means were separated using Fisher's protected least significant difference ($p \leq 0.05$) using the appropriate error terms and formulae described by Gomez and Gomez (1984).

RESULTS

Anthracnose Severity

Anthracnose basal rot was slow to develop from June to mid-July 2009 and gradually increased during late-July and August to a maximum severity (17 to 27%) on 3 Sept. 2009 (Table 4.1 and Fig. 4.1). Any treatment differences from 12 June to 24 July 2009 were considered random effects; cultivation treatments were not initiated until after disease assessments were made on 24 July. Anthracnose symptoms developed earlier during 2010 and disease severity reached 14 to 26% by 28 May 2010 (Table 4.2). Anthracnose severity did not increase greatly during June (Tables 4.3, 4.4 and 4.5); however, dramatic increases occurred during July and August and maximum disease severity ranged from 33 to 69% by 13 Aug. 2010 (Table 4.4).

The area under the disease progress curve (AUDPC) was much smaller in 2009 compared to 2010 due to the late onset of anthracnose and the lower maximum disease severity during 2009 (Tables 4.1, 4.3 and 4.4). Verticutting increased and weekly grooming decreased AUDPC compared to uncultivated turf during 2009. Midseason cultivation interacted with fungicide control to affect AUDPC during 2010 (Table 4.3); no cultivation treatment was different than the control under either level of fungicide, but fungicide application reduced AUDPC in verticutting plots (Table 4.4).

When disease was analyzed for each observation date, the pooled effects of cultivation increased disease severity 1 to 2% compared to no cultivation on 3 of 6 rating dates during the treatment period of 1 Aug. to 3 Sept. 2009 (Table 4.1). However, verticutting and scarifying were the only two treatments to increase disease severity compared to the uncultivated control during 2009 (Table 4.1 and Fig. 4.1). Verticutting increased anthracnose disease 6% relative to the control on 6 Aug. 2009. Verticutting and scarifying increased disease severity compared to no cultivation on 23 Aug. (4 and 2%, respectively) and 31 Aug. (6 and 2%, respectively) 2009. Verticutting was the only cultivation treatment to increase disease severity (9%) relative to the control on 3 Sept. 2009.

A residual effect of cultivation treatments applied in 2009 appeared during spring 2010, as evidenced by the pooled effects of cultivation reducing disease severity compared to the uncultivated control on 19 and 28 May 2010 (Table 4.2). All cultivation treatments reduced disease severity by 4 to 5% on 19 May. Verticutting, scarifying and weekly grooming reduced disease 8 to 11% relative to the control on 28 May 2010.

Curative fungicide applications reduced disease severity on 3 of 7 rating dates during cultivation treatments in 2010 (Table 4.3). Fungicide-treated plots had 5% less disease than plots that received no fungicide on 7 June 2010. Similarly, fungicides reduced disease severity by 8 and 17% compared to the untreated control on 28 July and 13 Aug. 2010, respectively.

Cultivation affected disease severity on 5 of 7 rating dates during the treatment period in 2010 and interacted with the fungicide factor on 4 of those dates (Table 4.3). There was a fungicide by cultivation interaction on 7 June 2010; the pooled effects of cultivation significantly reduced disease 5% compared to no cultivation under no fungicide but this response was nonsignificant under fungicide control (Table 4.4). The individual treatments of grooming, verticutting and weekly grooming reduced disease severity 4, 11 and 9% relative to the control, respectively, under no fungicide on 7 June. In fungicide-treated plots, grooming was the only treatment that reduced disease (5%)

relative to the control on 7 June. The main effect of cultivation on 12 June 2010 indicated that grooming and verticutting reduced disease severity (7 and 5%, respectively) and solid-tining increased disease severity by 5% compared to no cultivation (Table 4.5). Cultivation did not affect disease severity on 22 or 28 June, but cultivation by fungicide interactions occurred on the final three rating dates of 15 and 28 July and 13 Aug 2010 (Table 4.3). Verticutting increased disease by 5% compared to no cultivation under no fungicide on 15 July (Table 4.4). In fungicide-treated plots, solid-tining increased disease by 5% and weekly grooming decreased disease by 5% relative to the control on 15 July. Verticutting increased disease by 9 and 18% and scarifying increased disease by 10% under no fungicide on 28 July and 13 Aug. 2010, respectively. In fungicide-treated plots, weekly grooming reduced disease severity by 6 and 7% compared to no cultivation on 28 July and 13 Aug. 2010, respectively.

Turf Quality

Turf quality was acceptable (≥ 6) for all treatments until mid-Aug. 2009 (Table 4.6) due to the low to moderate disease severity (Table 4.1). Turf quality was generally poorer during 2010 due to the early onset of disease symptoms (Table 4.2) and turf quality was already unacceptable for some treatments on the first two rating dates in 2010 (Table 4.7).

Cultivation did not affect turf quality on 9, 16 and 24 July 2009 because treatments were not initiated until after visual ratings were made on 24 July (Table 4.6). The combined effects of cultivation treatments reduced turf quality compared to no cultivation on 2 of 4 rating dates from 1 to 27 Aug. 2009. Solid-tining improved turf quality and verticutting reduced turf quality compared to the uncultivated control on 1

Aug. 2009. Weekly grooming and verticutting were the two individual treatments that reduced turf quality compared to the control on 7 and 17 Aug. 2010. Grooming every 21 d also decreased turf quality compared to the control on 17 Aug. Verticutting was the only treatment to reduce turf quality compared to the uncultivated control on 27 Aug. 2009.

Before treatments were applied in 2010, the pooled residual effects of cultivation treatments during 2009 improved turf quality compared to no cultivation on 19 and 28 May 2010 (Table 4.7). No individual treatment effects were significant on these dates.

During the treatment period in 2010, the main effect of fungicide on turf quality was significant on 2 of 7 rating dates (Table 4.8). Curative fungicide applications improved turf quality compared to no fungicide on 28 July and 13 Aug. 2010.

Cultivation interacted with fungicide to affect turf quality on 5 of 7 rating dates in 2010 (Table 4.8). The pooled effect of cultivation improved turf quality compared to no cultivation under the curative fungicide program on 22 June 2010; all cultivation treatments improved turf quality compared to the control except solid-tining (Table 4.9). Under no fungicide, scarifying produced unacceptable turf quality that was significantly lower than the uncultivated control on 22 June. On 28 June, turf quality was unacceptable in verticutting and scarifying plots and was significantly lower than the control under no fungicide. In fungicide-treated plots, grooming, verticutting and weekly grooming improved turf quality on 28 June. Verticutting reduced turf quality compared to the control under no fungicide on 15 July. In fungicide-treated plots, solid-tining reduced turf quality and weekly grooming improved turf quality compared to the control on 15 July. Weekly grooming under curative fungicide was the only treatment to have acceptable turf quality on 15 July and no treatment had acceptable turf quality by 28 July. Verticutting and scarifying decreased turf quality compared to the control under no fungicide and, similar to previous rating dates, weekly grooming improved turf quality compared to no cultivation in fungicide-treated plots on 28 July and 13 Aug. 2010.

DISCUSSION

Results from this trial indicated that midseason cultivation influenced anthracnose disease severity when applied at the onset of disease symptoms; however, the effect depended on the type of cultivation applied. Verticutting, scarifying and solid-tining were the only cultivation practices to increase anthracnose severity. Verticutting to a 3.8 mm depth primarily injured ABG leaf and sheath tissue, as evidenced by visual observation of these tissues in the mower bucket after treatments were applied. However, this treatment also injured crown tissue since the verticutting equipment was set to cut 0.6 mm deeper than the 3.2 mm mowing height. Previous greenhouse work indicated that wounding crowns of ABG tillers prior to inoculation with *C. cereale* enhanced anthracnose severity (Landschoot and Hoyland, 1995). Verticutting to a depth of 5.1 mm, which likely injured crowns, increased anthracnose severity relative verticutting to a depth of 3.3 mm (Uddin et al., 2008). Moreover, our verticutting equipment had a blade width and blade spacing that affected 15% of the turf surface and caused extensive defoliation. Low mowing has been associated with enhanced outbreaks of *C. cereale* due, in part, to defoliation of ABG turf (Backman et al., 2002; Inguagiato et al., 2009). Similarly, the defoliation of maize plants enhanced infection by *C. graminicola* (Dodd, 1980; Mortimore and Ward, 1964).

Scarifying did not produce as frequent or as large increases in disease severity as verticutting, despite the greater cutting depth of scarifying. Scarifying affected only 4% of the turf area due to the wider blade spacing (40 mm), which would have injured fewer crowns and caused substantially less defoliation than verticutting. Similarly, the limited effect of solid-tining on disease was probably due to this practice affecting only 2% of the turf surface area compared to 15 and 4% of the turf surface area affected by verticutting and scarifying, respectively.

Disease reductions produced by grooming, verticutting and scarifying may have been due to the removal of viable *C. cereale* inoculum in the thatch. These practices may have also created a microenvironment in the turf canopy that was less favorable for disease development (i.e., less wet and shady) by initially removing canopy biomass, which may have increased leaf tissue drying and sunlight (Smiley et al., 2005). Solid-tining can reduce soil compaction (Murphy et al., 1993) and, thus, may have reduced the susceptibility of the turf to anthracnose on the infrequent occasions when this practice was found to decrease disease severity (Smiley et al., 2005). Solid-tining and vertical cutting have been reported to stimulate the growth of juvenile shoots (Carrow, 1996; Schery, 1966), which are more tolerant to anthracnose than older, senescing ABG shoots (Settle et al., 2006). Additionally, cultivation also may have increased ABG resistance to infection by *C. cereale* by triggering a wound healing response. Wound healing responses have provided resistance to infection by *C. graminicola* in maize and *C. acutatum* in chili pepper (*Capsicum annuum* cv. Nokkwang) via upregulated chemical defenses and lignification of cell walls in plant hosts (Bergstrom and Nicholson, 1999; Kim, 2008; Mims and Vaillancourt, 2002; Muimba-Kankolongo and Bergstrom, 1990). Many plants gain resistance to fungal invasion from wound healing responses (Bostock and Stermer, 1989; Lipetz, 1970).

Grooming and weekly grooming provided the most consistent disease reductions probably because these practices only affected leaf tissue and, therefore, were less likely to increase disease severity. Shallow VC (grooming) to a 3 mm depth every 14 d did not greatly affect anthracnose disease development on ABG maintained at 3.2 mm mowing height (Inguagiato et al., 2008). Moreover, wounding leaves of ABG tillers prior to inoculation in the greenhouse did not enhance anthracnose disease severity (Landschoot and Hoyland, 1995). Grooming also affected the most turf surface area (30%), which likely enhanced one or more of the plausible causes of disease reduction described above. Similarly, weekly grooming probably enhanced disease reductions compared to grooming every 21 d due to the increased frequency of this practice.

Based on our findings that cultivation practices typically did not increase disease severity under fungicide control, we can speculate that the increased disease symptoms observed in verticutting, scarifying and solid-tining plots under no fungicide control were due to actual increases in anthracnose severity rather than "injury/yellowing" caused by mechanical wounding. Moreover, these results suggest that midseason cultivation may not be a great risk for enhancing anthracnose on golf courses where fungicide programs are commonly employed to control anthracnose. It would have been useful to conduct the current trial for a third year to provide two years of data including the fungicide factor; however, renovation of the trial area was necessary after 2010 due to the extensive damage caused by the disease.

Results from this trial suggest that the location of wounding of ABG plants and the percent of the turf surface affected by midseason cultivation practices are factors that influence anthracnose disease development. However, the factors of wounding location and percent turf surface area affected (e.g., blade spacing) were confounded among the grooming, verticutting and scarifying treatments in the current study. To prove this hypothesis conclusively, additional studies to examine the effect of vertical cutting depth using the same blade spacing and/or the effect of blade spacing using the same vertical cutting depth on disease severity are needed. Findings from the current trial also lead us to speculate that thatch removal may be an important tool for managing anthracnose; however, cultivation practices that remove thatch, such as verticutting and scarifying, increased disease severity in our study when performed during the onset of disease under no fungicide control. Alternatively, frequent grooming may be a better substitute for verticutting or scarifying for midseason thatch removal because this practice either had no effect or reduced disease severity and also caused less of a reduction to turf quality during our trial. Although not as effective as deep vertical cutting to remove thatch, grooming can prevent thatch accumulation when combined with sand topdressing (Gaussoin et al., 2013). Moreover, disease reductions caused by grooming may be enhanced when grooming is performed in conjunction with sand topdressing, which dilutes thatch (Callahan et al., 1998; Carrow et al., 1987; White and Dickens, 1984) and reduces anthracnose disease severity (Inguagiato et al., 2012; Inguagiato et al., 2013; Roberts, 2009). However, more research is needed to test this hypothesis.

In summary, the cultivation practices of verticutting and scarifying often increased anthracnose disease severity when performed at the onset of disease symptoms. Verticutting resulted in the greatest and most frequent disease increases. Solid-tining also increased disease severity, but not as frequently or as substantially as verticutting or scarifying. All cultivation practices had lower disease severity compared to the control during the beginning of the second trial-year; however, verticutting, scarifying and solid-tining increased disease as the 2010 season progressed. Weekly grooming produced the most consistent effect of reducing disease relative to the control during both trial-years.

These results suggest that turf managers can reduce the risk of increasing disease severity by avoiding the use of midseason cultivation practices that wound crowns when anthracnose is active. Furthermore, fungicides also appeared to negate the potential for disease enhancement caused by midseason cultivation. Midseason cultivation practices that wound leaf tissue, such as grooming, do not appear to increase disease severity and may slightly reduce disease, especially when applied weekly and in combination with fungicides.

REFERENCES

Avila-Adame, C., G. Olaya, and W. Köller. 2003. Characterization of *Colletotrichum graminicola* isolates resistant to strobilurin-related QoI fungicides. Plant Dis. 87(12):1426-1432.

Backman, P., G. Stahnke, and E. Miltner. 2002. Anthracnose update: Cultural practices affect spread of disease in northwest. Turfgrass Trends 11:T1-T2, T4.

Beard, J.B. 1973. Turfgrass: Science and culture. Prentice Hall, Englewood Cliffs, NJ.

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

Beard, J.B., and H.J. Beard. 2005. Beard's turfgrass encyclopedia for golf courses, grounds, lawns, sports fields. Michigan State Univ. Press, East Lansing, MI.

Bergstrom, G.C., and R.L. Nicholson. 1999. The biology of corn anthracnose: knowledge to exploit for improved management. Plant Dis. 83(7):596-608.

Bidwell, W. 1952. Reducing thatch brings back healthy turf. Golfdom 26(3):78,80,82.

Bostock, R.M., and B.A. Stermer. 1989. Perspectives on Wound Healing in Resistance to Pathogens. Annu. Rev. Phytopathol. 27(1):343-371. DOI: doi:10.1146/annurev.py.27.090189.002015.

Callahan, L.M., W.L. Sanders, J.M. Parham, C.A. Harper, L.D. Lester, and E.R. McDonald. 1998. Cultural and Chemical Controls of Thatch and Their Influence on Rootzone Nutrients in a Bentgrass Green. Crop Sci. 38(1):181-187. DOI: 10.2135/cropsci1998.0011183X003800010030x.

Carrow, R.N. 1996. Summer decline of bentgrass greens: Understanding the cause of this problem not only helps you cure SBD, but also lets you initiate preventive maintenance. Golf Course Manage. 64(6):51-56.

Carrow, R.N. 2003. Surface organic matter in bentgrass greens. [Online]. USGA Turfgrass and Environ. Res. Online 2(17):1-12.

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(3):524-530. DOI: 10.2134/agronj1987.00021962007900030025x.

Christians, N. 2011. Fundamentals of turfgrass management. John Wiley & Sons, Inc., Hoboken, NJ.

Clarke, B.B., D. Thompson, J.A. Murphy, and P. Majumdar. 1995. Development of an integrated summer patch control program for fine turf areas. Proc. of the Annu. Rutgers Turfgrass Symp. 4:18-19.

Couch, H.B. 1973. Diseases of Turfgrasses. 2nd ed. Kriger Publishing Co., Inc., Malabar, FL.

Crouch, J.A., B.B. Clarke, and B.I. Hillman. 2005. Phylogenetic relationships and fungicide sensitivities of *Colletotrichum graminicola* isolates from turfgrass in North America. Int. Turfgrass Soc. Res. J. 10:186-195.

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(1):46-60. DOI: 10.1094/PHYTO-96-0046.

Dawson, R.B. 1934. Forking as an aid to turf recovery after drought. J. of the Board of Greenkeeping Res. 3(11):233-241.

Dawson, R.B., and R.B. Ferro. 1939. Scarification and turf improvement. J. of the Board of Greenkeeping Res. 6(20):11-17.

Dodd, J.L. 1980. Grain sink size and predisposition of *Zea mays* to stalk rot. Phytopathology 70:534-535.

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

Gaussoin, R.E., W.L. Berndt, C.A. Dockrell, and R.A. Drijber. 2013. Characterization, development, and management of organic matter in turfgrass systems, In: J. C. Stier, Horgan, Brian P., Bonos, Stacy A., and Schmitt, Gail K. (Ed.), Turfgrass:

Biology, Use, and Management, ASA, CSSA, & SSSA Inc., Madison, WI. pp. 1328.

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

Green, R.L., L. Wu, and G.J. Klein. 2001. Summer cultivation increases field infiltration rates of water and reduces soil electrical conductivity on annual bluegrass golf greens. HortScience 36(4):776-779.

Halisky, P.M., R.F. Myers, and R.E. Wagner. 1981. Relationship of thatch to nematodes, dollar spot and fungicides in Kentucky bluegrass turf. Proc. Int. Turf. Res. Conf. 4:415-420.

Hartwiger, C., and P. O'Brien. 2001. Core aeration by the numbers. U.S. Golf Assoc. Green Section Record 39(4):8-9.

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(4):1595-1607. DOI: 10.2135/cropsci2007.06.0343.

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(4):1454-1462. DOI: 10.2135/cropsci2008.07.0435.

Inguagiato, J.C., J.A. Murphy, and B.B. Clarke. 2012. Sand Topdressing Rate and Interval Effects on Anthracnose Severity of an Annual Bluegrass Putting Green. Crop Sci. 52(3):1406-1415. DOI: 10.2135/cropsci2011.01.0010.

Inguagiato, J.C., J.A. Murphy, B.B. Clarke, and J.A. Roberts. 2013. Topdressing sand particle shape and incorporation effects on anthracnose severity of an annual bluegrass putting green. Int. Turfgrass Res. Soc. J. 12:(accepted).

Kim, Y.H. 2008. Effect of delayed inoculation after wounding on the development of anthracnose disease caused by *Colletotrichum acutatum* on chili pepper fruit. The Plant Pathol. J. 24(4):392-399.

Landreth, J., D. Karcher, and M. Richardson. 2008. Cultivating to manage organic matter in sand-based putting greens: University of Arkansas researchers provide important insight for managing organic buildup on putting greens. U.S. Golf Assoc. Green Section Record 46(1):16-19.

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

Lipetz, J. 1970. Wound healing in higher plants. Int. Rev. Cytol 27(1):1-28.

Lockyer, J. 2009. Successful fine turf organic matter management. Int. Turfgrass Bull. 244:9-11.

Madden, L.V., G. Hughes, and F. Van den Bosch. 2007. The Study of Plant Disease Epidemics. The American Phytopathological Society, APS Press, St. Paul, MN.

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(6):1530-1537. DOI: 10.2134/agronj2006.0361.

Mims, C.W., and L.J. Vaillancourt. 2002. Ultrastructural characterization of infection and colonization of maize leaves by *Colletotrichum graminicola*, and by a *C. graminicola* pathogenicity mutant. Phytopathology 92(7):803-812.

Moeller, A.C. 2008. Evaluation of Putting Green Surface Organic Matter Management Programs. M.S. Thesis: Purdue Univ.

Moore, D. 2005. The supa greens maintenance cassette system. Int. Turfgrass Bull. 228:21, 23.

Mortimore, C.G., and G.M. Ward. 1964. Root and stalk rot of corn in southwestern Ontario: III. sugar levels as a measure of plant vigor and resistance. Can. J. Plant Sci. 44:451-457.

Muimba-Kankolongo, A., and G.C. Bergstrom. 1990. Transitory wound predisposition of maize to Anthracnose stalk rot. Can. J. Plant Pathol. 12(1):1-10.

Murphy, J., F. Wong, L. Tredway, J.A. Crouch, J. Inguagiato, B. Clarke, T. Hsiang, and F. Rossi. 2008. Best management practices for anthracnose on annual bluegrass turf. Golf Course Management 24:93-104.

Murphy, J.A., and P.E. Rieke. 1994. High pressure water injection and core cultivation of a compacted putting green. Agron. J. 86(4):719-724.

Murphy, J.A., P.E. Rieke, and A.E. Erickson. 1993. Core cultivation of a putting green with hollow and solid tines. Agron. J. 85(1):1-9.

Raisch, T. 2003. Anthracnose: One club's three-year battle. Golf Course Manage. 71(11):76-78,80,82,84.

Roberts, J.A. 2009. Impact of cultural management on anthracnose severity of annual bluegrass putting green turf. M.S. Thesis: Rutgers Univ.

Roberts, J.A., J.C. Inguagiato, B.B. Clarke, and J.A. Murphy. 2011. Irrigation Quantity Effects on Anthracnose Disease of Annual Bluegrass. Crop Sci. 51(3):1244-1252. DOI: 10.2135/cropsci2010.07.0444.

Samaranayake, H., T.J. Lawson, and J.A. Murphy. 2008. Traffic Stress Effects on Bentgrass Putting Green and Fairway Turf. Crop Sci. 48(3):1193-1202. DOI: 10.2135/cropsci2006.09.0613.

Schery, R.W. 1966. Remarkable Kentucky bluegrass. Southern California Turfgrass Culture. 8:30-31.

Settle, D.M., A.D. Martinez-Espinoza, and L.L. Burpee. 2006. Anthracnose of Turfgrass. The Plant Health Instructor [Online]:[1-6]. DOI: DOI:10.1094/PHI-I-2006-1205-01.

Smiley, R.W., P.H. Dernoeden, and B.B. Clarke. 2005. Compendium of turfgrass diseases. APS press, St. Paul, MN.

Stier, J.C., and A.B. Hollman. 2003. Cultivation and topdressing requirements for thatch management in A and G bentgrasses and creeping bluegrass. HortScience 38(6):1227-1231.

Tisserat, N.A., and J. Fry. 1997. Cultural practices to reduce spring dead spot (*Ophiosphaerella herpotricha*) severity in *Cynodon dactylon*. Int. Turf. Soc. Res. J. 8:931-936.

Towers, G., K. Green, E. Weibel, P. Majumdar, and B.B. Clarke. 2003. Evaluation of fungicides for the control of anthracnose basal rot on annual bluegrass. Fungicide and Nematicide Tests 58:T017.

Turgeon, A.J. 2011. Turfgrass Management, Prentice Hall, 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.

Unruh, J.B., S.D. Davis, P.F. Colbaugh, B.J. Brecke, and D.O. Stephenson. 2005. Impact of various chemical and nutrient inputs and cultural treatments on 'Tifeagle bermudagrass (*Cynodon dactylon* x *C. transvaalensis*). Int. Turfgrass Soc. Res. J. 10(1):455-461.

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

Vermeulen, P.H. 2003. Maybe it's time for a change. U.S Golf Assoc. Green Section Record 41:28.

White, R.H., and R. Dickens. 1984. Thatch Accumulation in Bermudagrass as Influenced by Cultural Practices. Agron. J. 76(1):19-22. DOI: 10.2134/agronj1984.00021962007600010006x.

Wong, F.P., K.A. de la Cerda, R. Hernandez-Martinez, and S.L. Midland. 2008. Detection and characterization of benzimidazole resistance in California populations of *Colletotrichum cereale*. Plant Dis. 92(2):239-246.

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 Dis. 91(12):1547-1555.

Wong, F.P., S.L. Midland, and K.A. de la Cerda. 2007. Occurrence and distribution of QoI-resistant isolates of *Colletotrichum cereale* from annual bluegrass in California. Plant Dis. 91(12):1536-1546.

Young, J.R., M. Tomaso-Peterson, K. de la Cerda, and F.P. Wong. 2010a. Two mutations in β-tubulin 2 gene associated with thiophanate-methyl resistance in *Colletotrichum cereale* isolates from creeping bentgrass in Mississippi and Alabama. Plant Dis. 94(2):207-212.

Young, J.R., M. Tomaso-Peterson, L.P. Tredway, and K. de la Cerda. 2010b. Occurrence and molecular identification of azoxystrobin-resistant *Colletotrichum cereale* isolates from golf course putting greens in the Southern United States. Plant Dis. 94(6):751-757.

Zontek, S.J. 2004. Have we gone too far? The grass is talking to you. Are you listening? U.S Golf Assoc. Green Section Record 48:28.

Table 4.1. Anthracnose severity response to mid-season cultivation practices applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009.

Source of Variation	12 June	22 June	7 July	15 July	24 July	1 Aug.	6 Aug.	13 Aug.	23 Aug.	31 Aug.	3 Sept.	AUDPC
	-- $p > F$ --											
Treatment	*	0.06†	NS‡	NS	0.08	0.06	**	NS	***	***	***	**
CV, %	67.8	60.5	122.9	49.1	20.8	21.7	21.9	13.2	4.4	6.7	6.8	9.1
Orthogonal Contrast	-- percent turf area infested --											
No Cultivation vs	2.2	0.8	0.5	2.2	13.1	13.9	10.8	18.5	16.8	16.3	17.6	1470.1
Cultivation	0.8 **	0.3 **	0.2 NS	1.1 **	10.5 0.06	13.0 NS	11.6 NS	19.3 NS	17.9 *	18.0 *	19.5 *	1432.8 NS
Cultivation Type§												
No Cultivation	2.2a	0.8a	0.5	2.2	13.1a	13.9ab	10.8b	18.5	16.8cd	16.3cd	17.6bc	1470b
Grooming	0.7b	0.3b	0.2	1.3	12.2ab	12.5ab	10.2b	19.4	16.4d	16.4cd	16.7c	1389bc
Verticutting	0.8b	0.3b	0.1	1.2	9.4b	15.8a	16.8a	22.3	20.4a	22.2a	26.6a	1678a
Solid-tining	1.1b	0.4b	0.2	1.2	9.0b	10.9b	11.0b	17.9	17.7bc	17.7bc	17.9bc	1344bc
Scarifying	0.5b	0.3b	0.2	0.8	12.4ab	15.6a	11.5b	19.3	18.6b	18.3b	19.3b	1505ab
Weekly Grooming	1.0b	0.3b	0.2	1.0	9.5b	10.2b	8.4b	17.5	16.4d	15.6d	17.0c	1249c
$LSD_{0.05}$	1.1	0.4	0.4	0.9	3.4	4.3	3.8	3.8	1.2	1.8	2.0	198

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

***Significant at the 0.001 probability level.

†Probability level ≤ 0.1.

‡NS, not significant

§Grooming (1.3 mm depth, 1.5 mm blade width, 5 mm lateral blade spacing), verticutting (3.8 mm depth, 1.5 mm blade width, 10 mm lateral blade spacing), scarifying (7.6 mm depth, 1.5 mm blade width, 40 mm lateral blade spacing), and solid-tining (57 mm depth, 6 mm tine width, 38 by 38 mm spacing) were applied on 24 July and 14 Aug. 2009. Weekly grooming was applied every 7 d from 24 July to 28 Aug. 2009.

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Figure 4.1. Anthracnose severity response to mid-season cultivation practices applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009. Grooming (1.3 mm depth, 1.5 mm blade width, 5 mm lateral blade spacing), verticutting (3.8 mm depth, 1.5 mm blade width, 10 mm lateral blade spacing), scarifying (7.6 mm depth, 1.5 mm blade width, 40 mm lateral blade spacing), and solid-tining (57 mm depth, 6 mm tine width, 38 by 38 mm spacing) were applied on 24 July and 14 Aug. 2009. Weekly grooming was applied every 7 d from 24 July to 28 Aug. 2009. Error bar indicates Fisher's protected LSD at α = 0.05 for treatment comparison on a specific rating date; no error bar indicates the date is not significant.

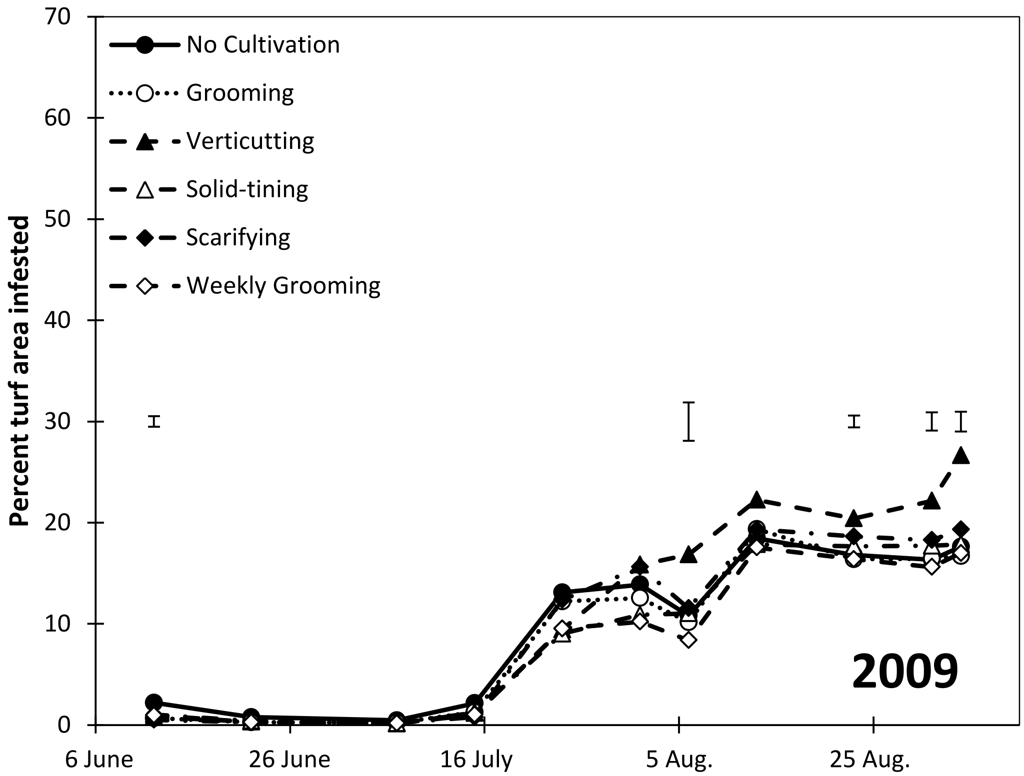

Table 4.2. Anthracnose severity response to mid-season cultivation practices applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010.

Source of Variation	19 May	28 May
	---------------------------------- $p > F$ ----------------------------------	
Treatment	*	0.07†
CV, %	28.4	25.5
Orthogonal Contrast	--------------------- percent turf area infested ---------------------	
No Cultivation vs	11.3	25.7
Cultivation	6.7 **	18.3 *
Cultivation Type‡		
No Cultivation	11.3a	25.7a
Grooming	7.1b	20.1abc
Verticutting	6.2b	17.4bc
Solid-tining	7.6b	22.2ab
Scarifying	6.6b	17.6bc
Weekly Grooming	6.0b	14.3c
$LSD_{0.05}$	3.2	7.5

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

†Probability level ≤ 0.1.

‡Grooming (1.3 mm depth, 1.5 mm blade width, 5 mm lateral blade spacing), verticutting (3.8 mm depth, 1.5 mm blade width, 10 mm lateral blade spacing), scarifying (7.6 mm depth, 1.5 mm blade width, 40 mm lateral blade spacing), and solid-tining (57 mm depth, 6 mm tine width, 38 by 38 mm spacing) were applied on 2 June, 23 June and 19 July 2010. Weekly grooming was applied every 7 d from 2 June to 11 Aug. 2010.

Table 4.3. Analysis of variance of anthracnose severity as affected by mid-season cultivation practices and fungicide applications applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010.

Source of Variation	7 June	12 June	22 June	28 June	15 July	28 July	13 Aug.	AUDPC
	---------- $p > F$ ----------							
Fungicide (F)	*	NS‡	0.08†	NS	NS	*	***	*
Cultivation§ (C)	**	***	NS	NS	NS	**	*	*
C x F	**	NS	NS	NS	***	**	***	***
CV, %	10.4	15.8	10.9	15.5	7.8	7.8	9.2	5.0
<u>Fungicide</u>	---------- percent turf area infested ----------							
Curative Fungicide¶	17.9	19.3	18.7	27.8	32.5	42.8	37.3	2064
No Fungicide	22.9	21.5	21.2	27.1	33.0	51.0	54.4	2370

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

***Significant at the 0.001 probability level.

†Probability level ≤ 0.1.

‡NS, not significant

§Grooming (1.3 mm depth, 1.5 mm blade width, 5 mm lateral blade spacing), verticutting (3.8 mm depth, 1.5 mm blade width, 10 mm lateral blade spacing), scarifying (7.6 mm depth, 1.5 mm blade width, 40 mm lateral blade spacing), and solid-tining (57 mm depth, 6 mm tine width, 38 by 38 mm spacing) were applied on 2 June, 23 June and 19 July 2010. Weekly grooming was applied every 7 d from 2 June to 11 Aug. 2010.

¶Fungicide treated plots curative received applications of chlorothalonil (tetrachloroisophthalonitrile) and fosetyl-Al [Aluminum tris (O-ethyl phosphonate)] at the rates of 12.6 and 9.8 kg ha^{-1}, respectively, as a tank mix on 3 and 11 June 2010 and then every 14 d thereafter until 4 Aug. 2010.

Table 4.4. Anthracnose severity response to mid-season cultivation practices under no or curative fungicide programs applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010.

	7 June		15 July		28 July		13 Aug.		AUDPC	
Orthogonal Contrasts	No Fungicide	Curative Fungicide†	No Fungicide	Curative Fungicide	No Fungicide	Curative Fungicide	No Fungicide	Curative Fungicide	No Fungicide	Curative Fungicide
	---------- percent turf area infested ----------									
No Cultivation vs	27.0	19.0	33.4	33.0	48.9	44.4	51.0	39.8	2328	2183
Cultivation	22.1 *	17.7 NS‡	32.9 NS	32.4 NS	51.5 NS	42.4 NS	55.1 NS	36.8 NS	2379 NS	2041 NS
<u>Cultivation Type</u>§										
No Cultivation	27.0	19.0	33.4	33.0	48.9	44.4	51.0	39.8	2328	2183
Grooming	22.6	14.2	29.5	34.5	45.0	41.5	48.4	36.1	2077	2000
Verticutting	16.3	15.1	38.0	29.9	57.4	40.7	69.0	35.3	2608	1903
Solid-tining	27.6	22.7	33.7	37.8	49.7	49.1	51.0	42.5	2417	2371
Scarifying	25.8	19.6	31.8	32.0	58.9	42.2	61.2	37.2	2654	2117
Weekly Grooming	18.0	16.9	31.7	27.7	46.3	38.6	45.8	32.7	2137	1812
$LSD_{0.05}$ within columns	4.3		4.4		5.1		6.8		626	
$LSD_{0.05}$ within rows	4.5		4.3		7.8		6.7		617	

*Significant at the 0.05 probability level.

†Fungicide treated plots received curative applications of chlorothalonil (tetrachloroisophthalonitrile) and fosetyl-Al [Aluminum tris (O-ethyl phosphonate)] at the rates of 12.6 and 9.8 kg ha^{-1}, respectively, as a tank mix on 3 and 11 June 2010 and then every 14 d thereafter until 4 Aug. 2010.

‡NS, not significant

§Grooming (1.3 mm depth, 1.5 mm blade width, 5 mm lateral blade spacing), verticutting (3.8 mm depth, 1.5 mm blade width, 10 mm lateral blade spacing), scarifying (7.6 mm depth, 1.5 mm blade width, 40 mm lateral blade spacing), and solid-tining (57 mm depth, 6 mm tine width, 38 by 38 mm spacing) were applied on 2 June, 23 June and 19 July 2010. Weekly grooming was applied every 7 d from 2 June to 11 Aug. 2010.

Table 4.5. Anthracnose severity response to the main effect of mid-season cultivation practices applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010.

Orthogonal Contrast	12 June
	----------------- % -----------------
No Cultivation vs	21.2
Cultivation	20.2 NS†
Cultivation Type‡	
No Cultivation	21.2bc
Grooming	14.5d
Verticutting	16.7d
Solid-tining	26.5a
Scarifying	25.3cd
Weekly Grooming	18.3cd
$LSD_{0.05}$	4.3

†NS, not significant

‡Grooming (1.3 mm depth, 1.5 mm blade width, 5 mm lateral blade spacing), verticutting (3.8 mm depth, 1.5 mm blade width, 10 mm lateral blade spacing), scarifying (7.6 mm depth, 1.5 mm blade width, 40 mm lateral blade spacing), and solid-tining (57 mm depth, 6 mm tine width, 38 by 38 mm spacing) were applied on 2 June, 23 June and 19 July 2010. Weekly grooming was applied every 7 d from 2 June to 11 Aug. 2010.

Table 4.6. Turf quality response to mid-season cultivation practices applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009.

Source of Variation	9 July	16 July	24 July	1 Aug.	7 Aug.	17 Aug.	27 Aug.
	----------	----------	----------	$p > F$	----------	----------	----------
Treatment	NS[†]	NS	NS	**	**	***	***
CV, %	8.7	5.9	7.1	6.2	7.4	6.3	11.0
Orthogonal Contrasts	----------	----------	----------	1–9 scale[‡]	----------	----------	----------
No Cultivation vs	6.5	6.5	7.5	7.0	7.8	7.3	6.5
Cultivation	6.7 NS	6.7 NS	7.2 NS	7.0 NS	7.0 *	6.4 **	5.9 NS
Cultivation Type[§]							
No Cultivation	6.5	6.5	7.5	7.0bc	7.8a	7.3a	6.5ab
Grooming	6.8	6.5	7.0	7.5ab	7.3ab	6.5b	6.5ab
Verticutting	6.8	6.5	6.8	6.3d	6.3c	5.5c	4.0c
Solid-tining	7.0	6.8	7.5	7.8a	7.5a	7.0ab	6.3ab
Scarifying	6.3	6.5	7.3	6.5cd	7.3ab	7.0ab	5.8b
Weekly Grooming	6.8	7.0	7.5	6.8cd	6.5bc	5.8c	7.0a
$LSD_{0.05}$	0.9	0.6	0.8	0.7	0.8	0.6	1.0

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

***Significant at the 0.001 probability level.

†NS, not significant

‡Nine (9) represents the best turf characteristic and 6 represents the minimally acceptable rating.

§Grooming (1.3 mm depth, 1.5 mm blade width, 5 mm lateral blade spacing), verticutting (3.8 mm depth, 1.5 mm blade width, 10 mm lateral blade spacing), scarifying (7.6 mm depth, 1.5 mm blade width, 40 mm lateral blade spacing), and solid-tining (57 mm depth, 6 mm tine width, 38 by 38 mm spacing) were applied on 24 July and 14 Aug. 2009. Weekly grooming was applied every 7 d from 24 July to 28 Aug. 2009.

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Table 4.7. Turf quality response to mid-season cultivation practices applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010.

Source of Variation	19 May	28 May
	---------- $p > F$ ----------	
Treatment	NS†	NS
CV, %	11.0	13.5
Orthogonal Contrast	---------- 1–9 scale‡ ----------	
No Cultivation vs	5.0	5.0
Cultivation	5.9 *	6.1 *
Cultivation Type§		
No Cultivation	5.0	5.0
Grooming	5.8	6.0
Verticutting	6.0	6.0
Solid-tining	6.0	5.8
Scarifying	6.0	6.3
Weekly Grooming	5.8	6.3
$LSD_{0.05}$	1.0	1.2

*Significant at the 0.05 probability level.

†NS, not significant

‡Nine (9) represents the best turf characteristic and 6 represents the minimally acceptable rating.

§Grooming (1.3 mm depth, 1.5 mm blade width, 5 mm lateral blade spacing), verticutting (3.8 mm depth, 1.5 mm blade width, 10 mm lateral blade spacing), scarifying (7.6 mm depth, 1.5 mm blade width, 40 mm lateral blade spacing), and solid-tining (57 mm depth, 6 mm tine width, 38 by 38 mm spacing) were applied on 2 June, 23 June and 19 July 2010. Weekly grooming was applied every 7 d from 2 June to 11 Aug. 2010.

Table 4.8. Analysis of variance of turf quality as affected by mid-season cultivation practices and fungicide applications applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010.

Source of Variation	7 June	12 June	22 June	28 June	15 July	28 July	13 Aug.
	---------- p > F ----------						
Fungicide (F)	0.06[†]	NS[‡]	NS	0.1	0.06	*	**
Cultivation (C)[§]	NS	NS	0.09	0.08	*	**	0.06
C x F	NS	NS	*	*	*	***	**
CV, %	8.0	5.2	6.6	7.0	12.8	10.3	13.6
<u>Fungicide</u>	---------- 1–9 scale[¶] ----------						
Curative Fungicide[#]	6.7	6.4	6.9	6.8	5.4	4.6	4.5
No Fungicide	5.9	6.3	6.5	6.3	4.4	3.5	3.2

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

***Significant at the 0.001 probability level.

†Probability level ≤ 0.1.

‡NS, not significant

§Grooming (1.3 mm depth, 1.5 mm blade width, 5 mm lateral blade spacing), verticutting (3.8 mm depth, 1.5 mm blade width, 10 mm lateral blade spacing), scarifying (7.6 mm depth, 1.5 mm blade width, 40 mm lateral blade spacing), and solid-tining (57 mm depth, 6 mm tine width, 38 by 38 mm spacing) were applied on 2 June, 23 June and 19 July 2010. Weekly grooming was applied every 7 d from 2 June to 11 Aug. 2010.

¶Nine (9) represents the best turf characteristic and 6 represents the minimally acceptable rating.

#Fungicide treated plots received curative applications of chlorothalonil (tetrachloroisophthalonitrile) and fosetyl-Al [Aluminum tris (O-ethyl phosphonate)] at the rates of 12.6 and 9.8 kg ha^{-1}, respectively, as a tank mix on 3 and 11 June and then every 14 d thereafter until 4 Aug.

Table 4.9. Turf quality response to mid-season cultivation practices under no or curative fungicide programs applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010.

	22 June		28 June		15 July		28 July		13 Aug.	
Orthogonal Contrasts	No Fungicide	Curative Fungicide[‡]	No Fungicide	Curative Fungicide	No Fungicide	Curative Fungicide	No Fungicide	Curative Fungicide	No Fungicide	Curative Fungicide
	---------- 1-9 scale[§] ----------									
No Cultivation vs	6.5	6.3	6.5	6.3	4.8	5.3	4.0	4.5	3.8	4.3
Cultivation	6.5 NS[¶]	7.1 *	6.3 NS	6.9 0.08[†]	4.4 NS	5.4 NS	3.5 NS	4.6 NS	3.1 0.08	4.6 NS
<u>Cultivation Type</u>[#]										
No Cultivation	6.5	6.25	6.5	6.25	4.75	5.3	4.0	4.5	3.8	4.3
Grooming	7.0	7.0	7.0	7.0	5.0	5.5	4.5	4.8	3.8	4.8
Verticutting	6.25	7.5	5.5	7.0	3.5	5.8	2.5	4.8	2.3	4.8
Solid-tining	6.5	6.5	6.25	6.25	4.5	4.3	3.8	4.0	3.5	4.0
Scarifying	5.75	7.0	5.75	6.75	4.0	5.3	2.3	4.0	2.3	4.3
Weekly Grooming	7.0	7.25	7.0	7.25	4.8	6.3	4.3	5.5	3.8	5.3
$LSD_{0.05}$ within columns	0.66		0.74		0.8		0.7		0.8	
$LSD_{0.05}$ within rows	0.8		0.77		1.2		0.8		0.8	

*Significant at the 0.05 probability level.

†Probability level ≤ 0.1.

‡Fungicide treated plots received curative applications of chlorothalonil (tetrachloroisophthalonitrile) and fosetyl-Al [Aluminum tris (O-ethyl phosphonate)] at the rates of 12.6 and 9.8 kg ha^{-1}, respectively, as a tank mix on 3 and 11 June and then every 14 d thereafter until 4 Aug.

§Nine (9) represents the best turf characteristic and 6 represents the minimally acceptable rating.

¶NS, not significant

#Grooming (1.3 mm depth, 1.5 mm blade width, 5 mm lateral blade spacing), verticutting (3.8 mm depth, 1.5 mm blade width, 10 mm lateral blade spacing), scarifying (7.6 mm depth, 1.5 mm blade width, 40 mm lateral blade spacing), and solid-tining (57 mm depth, 6 mm tine width, 38 by 38 mm spacing) were applied on 2 June, 23 June and 19 July 2010. Weekly grooming was applied every 7 d from 2 June to 11 Aug. 2010.

CHAPTER 5. Vertical Cutting Depth Effects on Anthracnose Severity of Annual Bluegrass Putting Green Turf

ABSTRACT

Wounding of annual bluegrass [*Poa annua* L. f. *reptans* (Hausskn) T. Koyama] (ABG) turf has produced varying responses to anthracnose disease (caused by the fungus *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman). A field study was conducted to evaluate the effect of vertical cutting depth on anthracnose severity of ABG turf mowed at 3.2-mm in North Brunswick, NJ. Treatments included vertical cutting (VC) to 1.3- and 7.6-mm depths, shallow and deep, respectively. An untreated control was also included. Treatments were applied once at the initiation of each of three trial runs on 23 July 2010, 6 July 2011 and 3 Aug. 2011 using a VC reel having 1.5-mm wide blades spaced 40 mm laterally. Treatments were arranged in a RCBD with ten replications. Disease was assessed at intervals no greater than 5-d apart at the same 10 positions along each of three 25-cm transects for a total of 30 observations within each plot. The three transects were established directly over VC channels in treated plots and randomly positioned over turf in the untreated plots. Deep VC produced a 4% increase in disease relative to the control and a 5% increase in disease severity relative to shallow VC on 2 of 32 observation dates in 2010 and 2011. Shallow VC produced small, marginally significant reductions in disease severity on 1 to 3 rating dates per trial run (5 of 32 total rating dates). The subtle, short-lived increases caused by deep VC during one trial run indicated that deep VC may play a minor role in enhancing disease development; whereas, shallow VC appears to either have no effect or slightly reduce disease severity.

INTRODUCTION

Anthracnose of annual bluegrass [*Poa annua* L. forma *reptans* (Hausskn.) T. Koyama] (ABG) is caused by the fungus *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman (Crouch et al., 2006). Symptoms of infected turf appear as either a foliar blight, which occurs during hot, humid summer periods of mid-summer or a basal rot that can occur year-round (Smiley et al., 2005). The disease thins turf and causes severe losses to ABG putting greens in temperate climates throughout the United States, Canada, Western Europe, South America, Southeast Asia, New Zealand, and Australia (Crouch and Beirn, 2009).

Stressful conditions can increase susceptibility of ABG putting greens to infection by *C. cereale* (Smiley et al., 2005). Increased occurrence and severity of the disease during the last two decades have been directly linked to management practices that increase putting green playability (ball roll distance or “green speed”) but decrease plant vigor, such as low mowing height, low N fertility, and limited irrigation (Inguagiato et al., 2008; Inguagiato et al., 2009; Roberts et al., 2011).

Vertical cutting (VC) is a cultivation practice that involves slicing into a turf surface for the purpose of removing excess thatch, controlling turf grain and reducing canopy biomass (Beard and Beard, 2005). This practice can be performed with a variety of mechanical devices equipped with vertically rotating blades that cut into a turf surface at varying depths (0 to 40 mm), blade spacings (5 to 40 mm), and blade thicknesses (1 to 3 mm) (Landreth et al., 2008; Lockyer, 2009; Moore, 2005). Vertical cutting to a shallow depth is often performed to create a smoother putting surface by reducing puffiness caused by the high shoot density of ABG (Vargas and Turgeon, 2004). Shallow VC is also used for thatch removal, particularly when combined with sand topdressing (Beard, 2002; Christians, 2011; Gaussoin et al., 2013). Deep VC can be used to prepare turf surfaces for renovation, remove thatch, and alleviate compaction of the surface soil (Beard, 2002; Turgeon, 2011). Research suggests that deep VC is the most effective option for thatch removal if the target area is within the first 40 mm depth of the surface (Landreth et al., 2008; Lockyer, 2009).

Excess thatch accumulation and poor soil conditions predispose turf to disease (Beard, 1973; Smiley et al., 2005). Thus, cultivation practices such as VC are often recommended for disease management (Smiley et al., 2005). A combination of aeration plus VC (7 mm depth) performed twice each year was moderately effective in reducing spring dead spot (caused by *Ophiosphaerella herpotricha* (Fr.:Fr.) J. Walker) of 'Midlawn' bermudagrass turf [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burtt-Davy] maintained at a 13 mm mowing height (Tisserat and Fry, 1997). Mechanical thatch removal by VC (unknown depth) reduced dollar spot disease (caused by *Sclerotinia homoeocarpa* F.T. Bennett) of 'Merion' Kentucky bluegrass (*Poa pratensis* L.) turf maintained at 38 mm (Halisky et al., 1981). However, VC can also create wounds and enhance plant stress, both of which are thought to facilitate pathogen invasion (Agrios, 2005; Smiley et al., 2005). Dollar spot was increased by coring and VC to a depth just above the soil surface on 'Tifway' bermudagrass turf maintained at 19 mm (Carrow et al., 1987). Vertical cutting (2 mm depth) also increased dollar spot in 'Tifeagle' bermudagrass maintained at 2.8 or 3.6 mm (Unruh et al., 2005). In a laboratory study, dollar spot developed more rapidly in wounded leaves of creeping bentgrass (*Agrostis stolonifera* L.) than unwounded leaves (Orshinsky et al., 2012).

Work on the effect of VC on anthracnose has produced conflicting results. Biweekly VC (3 mm depth) of an ABG maintained at 3.2 mm had little effect on anthracnose severity; however, on one rating date, VC increased disease when applied to plots treated with the plant growth regulators trinexapac-ethyl or mefluidide or decreased disease when applied to plots treated with low N fertility (Inguagiato et al., 2008). Spring or autumn VC (unknown depth) applied alone or in conjunction with coring did not affect anthracnose of ABG fairway turf (Burpee and Goulty, 1984). Conversely, increased depth (0, 3.3 and 5.1 mm) of weekly VC caused a linear increase in anthracnose severity of a mixed stand ABG and creeping bentgrass turf inoculated with *C. cereale* and maintained at 2.0, 3.0 and 4.3 mm mowing heights (Uddin et al., 2008).

Although wounding is not required for *C. cereale* to infect ABG tissue (Bruehl and Dickson, 1950; Smith, 1954), results from a greenhouse experiment showed that wounding (puncture or abrasion) of ABG crown tissue immediately prior to inoculation resulted in more rapid disease development of anthracnose basal rot symptoms compared to unwounded, inoculated ABG plants (Landschoot and Hoyland, 1995). Similarly, inoculation of wounded maize (*Zea mays* L.) tissue with the closely related pathogen *C. graminicola* resulted in more rapid and efficient anthracnose disease development compared to unwounded, inoculated maize tissue (Venard and Vaillancourt, 2007). In contrast, disease did not develop any faster when wounds were made to ABG leaf tissue prior to inoculation by *C. cereale* (Landschoot and Hoyland, 1995). Therefore, researchers have suggested that VC to a depth that injures crown tissue may increase disease severity; whereas, shallow VC should not influence disease because it only affects leaf tissue (Inguagiato et al., 2008). However, no field studies examining VC depth alone have tested this hypothesis. Therefore, the objective of this study was to evaluate the effect of depth of VC on anthracnose severity of ABG putting green turf.

MATERIALS AND METHODS

Experimental Design and Treatments

This field research study was conducted in one location in 2010 and repeated twice in different locations in 2011 at Horticultural Farm No. 2 in North Brunswick, NJ (40°28' N, 74°25' W). The experimental area was an established greens-type ABG turf grown on a sand topdressing layer (50 to 60 mm deep) overlaying a Nixon sandy loam (fine-loamy, mixed, semiactive, mesic Typic Hapludults, in some areas altered to fine-loamy, mixed, semiactive, mesic Ultic Udarents). Treatments were arranged in a randomized complete block design with ten replications. Plots were 0.5 by 1.5 m in size. Treatments included a control, shallow VC (1.3 mm depth), and deep VC (7.6 mm depth). Vertical cutting was applied once per trial run (23 July 2010, 6 July 2011 and 3 Aug 2011) between 1300 and 1600 hr when the turf canopy was dry using one gang of a triplex mower (model 3150, Toro Co., Bloomington, MN). The gang was a specialized reel-chassis (model TA3TORO Thatch-Away Supa-System, Turfline Inc., Moscow Mills, MO) equipped with a reel-cassette (model TA3CAS SCATORO, Turfline Inc., Moscow Mills, MO) that had 1.5 mm wide blades spaced 40 mm laterally and a total working width of 455 mm. Disease severity averaged 5% of the trial area infested with *C. cereale* when treatments were applied during the first and second trial runs and 27% during the third trial run.

Field Maintenance

Mowing was performed 6 times wk^{-1}with a triplex greens mower (model 3150, Toro Co., Bloomington,, MN) set at a bench mowing height setting of 3.2 mm and clippings were removed. Soil water content was maintained similar to a golf course putting green (moderately-dry conditions) by applying irrigation to avoid wilt stress and water-in fertilizer. Topdressing (medium-coarse, subangular silica sand; "310" U.S. Silica, Co., Mauricetown, NJ) was applied biweekly at 0.18 L m^{-2} and incorporated with a cocoa mat drag (Ace Equipment and Supply Co., Henderson, CO) from April to Oct. in 2010 and May to Oct. 2011. Before treatments were initiated, N was applied at 53.7, 29.3, and 48.8 kg ha^{-1} from 12 Apr to 7 July 2010, 8 Apr. to 3 June 2011, and 8 Apr. to 25 July 2011 for trial runs 1, 2, and 3, respectively. Biweekly applications at 4.9 kg ha^{-1} of N totaled 14.7, 19.5, and 9.8 kg ha^{-1} for trial runs 1, 2, and 3, respectively, during the period that disease evaluations were performed. After disease observations ended, N was applied at 169, 107, and 119 kg ha^{-1} from 6 Sept. to 12 Nov. 2010, 13 Aug. to 14 Oct. 2011, and 3 Sept. to 14 Oct. 2011 at the end of trial runs 1, 2, and 3, respectively. Phosphorus was applied at 53.8, 6.4, and 4.3 kg ha^{-1} and K was applied at 45.2, 41.0, and 106.7 kg ha^{-1} during late-summer or early-autumn for trial runs 1, 2, and 3, respectively, based on soil test results. Plant growth regulators were applied similar to golf course practices: ethephon [(2-chloroethyl) phosphonic acid] was applied at 3.81 kg a.i. ha^{-1} on 19 Mar., 2 Apr., and 23 April 2010 and 22 Mar., and 6 and 20 Apr. 2011 to regulate ABG inflorescence expression and trinexapac-ethyl [4-(cyclopropyl-α-hydroxy-methylene)-3,5-dioxocyclohexanecarboxylic acid ethylester)] was applied biweekly at 0.05 kg a.i. ha^{-1} from 19 Mar. to 2 Oct. 2010 and 22 Mar. to 26 Oct. 2011 to regulate vegetative growth.

Biweekly applications of the fungicides boscalid {3-pyridinecarboximide, 2-chloro-N-[4'chloro(1,1'-biphenyl)yl]} at 0.38 kg a.i. ha^{-1} or vinclozolin [3-(3,5-dichlorophenyl)-5-ethenyl-5-methyl-2,4-oxazolidinedione] at 1.52 kg a.i. ha^{-1} were made to preventatively control dollar spot disease from 14 May to 28 Aug. 2010 and 14 Apr. to

1 Sept. 2011. Patch diseases caused by *Magnaporthe poae* Landschoot & Jackson and *Rhizoctonia solani* Kühn were controlled using a biweekly rotation of the fungicides azoxystrobin (Methyl(E)-2-{2-[6-(2-cyanophenoxy)pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate)} at 0.61 kg a.i. ha^{-1}, flutolanil {N-[3-(1-methylethoxy)phenyl]-2-(trifluoromethyl)benzamide} at 6.41 kg a.i. ha^{-1}, and fluoxastrobin [(1E)-[2-[[6-(2-Chlorophenoxy)-5-fluoro-4-pyrimidinyl]oxy]phenyl](5,6-dihydro-1,4,2-dioxazin-3-yl) methanone-O-methyloxime] at 0.55 kg a.i. ha^{-1} from 25 Mar to 28 Aug 2010 and 6 May to 1 Sept. 2011. These fungicides have not been shown to affect anthracnose isolates from this research location (Towers et al., 2003). Chlorothalonil (tetrachloroisophthalonitrile) was applied at 12.6 kg a.i. ha^{-1} to arrest anthracnose disease progress at the end of trial runs 1, 2, and 3 on 18 Sept. 2010, 6 Aug. 2011, and 21 Sept. 2011, respectively. Annual bluegrass weevils [*Listronotus maculicollis* (Kirby)] were controlled with the insecticide chlorantraniliprole (3-Bromo-N-[4-chloro-2-methyl-6-[(methylamino)carbonyl]phenyl]-1-(3-chloro-2-pyridinyl)-1H-pyrazole-5-carboxamide) applied at 0.18 kg a.i. ha^{-1} on 30 April 2010 and 3 May 2011. Algal growth was suppressed as needed using mancozeb (ethylenebisdithiocarbamate) applied at rates ranging from 20.1 to 30.5 kg a.i. ha^{-1} during 2010. Creeping bentgrass was controlled with fluazifop-P-butyl {Butyl (R)-2-[4-[[5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoate} applied at 0.21 kg a.i. ha^{-1} on 20 Sept. 2010.

Data Collection and Analysis

Anthracnose severity was evaluated every 0 to 5 d after VC was applied from 23 July to 31 Aug. 2010, 6 July to 1 Aug. 2011, and 4 Aug. to 2 Sept. 2011 for trial runs 1, 2, and 3, respectively. Disease development was monitored at 10 positions along each of three 25 cm transects within each plot (30 observations per plot). Transects directly overlaid the VC channels of treated plots and were randomly positioned over turf in non-scarified plots. Ends of each transect were marked so that disease observations could be performed at the same transect-positions (every 2.5 cm) by aligning the ends of a measuring ruler with the ends of the transect. A count of transect-positions where acervuli were present on ABG leaf, stolon or crown tissue was recorded for each plot and transformed to a percentage using the following equation:

$$(n/30) \text{ x } 100;$$

where n represented the count of transect positions that contained acervuli. Turfgrass quality was assessed during the second and third runs of the trial on a 1 to 9 scale where 9 represented the best quality and 6 was the minimally acceptable rating. Turf density, turf uniformity, turf color, anthracnose disease severity, and the healing of VC channels were considered when turf quality was evaluated. Data were subjected to analysis of variance using the General Linear Model procedure (PROC GLM) in the Statistical Analysis System software v. 9.3 (SAS Institute, Cary, NC). Means were separated using Fisher's protected least significant difference at the 0.05 probability level.

RESULTS

Anthracnose Severity

Anthracnose severity was low (≤ 8%) for the first three rating dates during trial run 1 (Table 5.1 and Fig. 5.1). The disease progressed steadily until reaching peak levels (57 to 58%) on 31 Aug. 2010. Disease severity was similarly low (≤ 8%) during the first three rating dates of trial run 2; higher peak levels (66 to 71%) were reached during late-Aug. (Table 5.2 and Fig. 5.2). Trial run 3 was initiated when disease severity was moderate (23 to 31%) (Table 5.3 and Fig. 5.3). However, disease severity did not change greatly throughout the duration of trial run 3, and peak levels reached only 27 to 34% by 2 Sept. 2011.

Deep VC slightly increased (4%) disease severity compared to shallow VC and the control on 31 July 2010 (8 d after VC was applied); however, the effect was no longer apparent on 3 Aug. 2010 (Table 5.1 and Fig. 5.1). Deep VC increased disease (5%) compared to shallow VC on 7 Aug. 2010, but neither VC treatment was different than the control. In contrast, shallow VC produced a marginally significant ($pr > F = 0.08$) disease reduction (5%) compared to the control on 11 Aug., which continued as a non-significant trend until 20 Aug. 2010.

Deep VC did not affect disease severity on any of the 13 rating dates during trial run 2; whereas, shallow VC produced a marginally significant ($pr > F = 0.09$) reduction (4%) in disease severity compared to no VC on 8 July 2011, and a similar but non-significant response was apparent on 14 July, 16 July, and 1 Aug. 2011 (Table 5.2 and Fig. 5.2).

Similarly, deep VC had no effect on disease severity during trial run 3. However, shallow VC produced a marginally significant (*pr* > *F* = 0.08, 0.09, and 0.06) disease reduction compared to no VC on 4, 15 and 17 Aug. 2011, respectively, which appeared as a non-significant trend on all other rating dates during this trial run. (Table 5.3 and Fig. 5.3)

Turf Quality

In general, the control and shallow VC treatments had acceptable turf quality (≤ 6) on all dates; whereas, the surface disruption caused by deep VC produced unacceptable turf quality for 12 to 3 d after VC during trial runs 2 and 3, respectively (Tables 5.4 and 5.5).

Deep VC reduced turf quality compared to all other treatments from 6 to 22 July and on 27 July 2011 during trial run 2 (Table 5.4). Shallow VC immediately decreased turf quality compared to the control on 6 July 2011 (0 d after VC); however, these plots were not different than the control for remainder of trial run 2. Turf quality was not affected by VC on 24 July or 1 Aug. 2011.

Deep VC plots had lower turf quality than other treatments from 4 to 8 Aug. 2011 during trial run 3 and continued to have marginally significant (*pr* > *F* = 0.06 and 0.09) lower turf quality compared to the control on 11 and 15 Aug 2011 (Table 5.5). This effect was also evident when deep VC plots had lower turf quality compared to all other treatments on 25 Aug. and 2 Sept. 2011 (*pr* > *F* = 0.06), respectively. Shallow VC briefly reduced turf quality compared to the control for 1 and 3 d after VC was applied on 3 Aug. 2011 during trial run 3.

DISCUSSION

The results of this study indicated that VC depth may play a role in disease development, albeit subtle and inconsistent. Additionally, deep and shallow VC appeared to have contrasting effects. Deep VC (7.6 mm) produced small, transitory increases in disease severity (4 to 5%) compared to other treatments on 2 of 10 rating dates during the first trial-run but did not affect disease severity on any of the remaining 22 rating dates during the second and third trial-runs; whereas, shallow VC (1.3 mm) appeared to occasionally reduce anthracnose severity in our study. Uddin et al. (2008) reported that 5.1 mm deep VC increased anthracnose disease severity more than 3.3 mm deep VC. In the greenhouse, anthracnose basal rot developed in inoculated ABG tillers that were wounded at the crown, but not in those tillers wounded above the crown (Landschoot and Hoyland, 1995). Thus, Inguagiato et al. (2008) hypothesized that deep VC may increase anthracnose severity because it wounds crowns; whereas, shallow VC may not because only leaf and sheath tissues are wounded.

Increased disease severity caused by crown wounding may be due to the location and function of crown tissue in ABG plants. Environmental conditions are probably more favorable for anthracnose disease development near the crown due to the humid and shaded microenvironment produced by the upper turf canopy (Smiley et al., 2005). Additionally, more inoculum may be present near the crown due to the persistence of *C. cereale* on decayed plant debris in thatch (Crouch and Beirn, 2009; Settle et al., 2006). Crowns are the major meristematic organ of grass plants. Infestation of crown tissue by *C. cereale* may cause greater reductions in plant vigor than infection of leaf tissue due to the vital role that crown tissue plays in the tiller, stem and root vascular systems of ABG

(Beard, 1973). Upon ingress of ABG crown tissue, *C. cereale* can produce secondary hyphae which enter vascular tissue, cut off nutrient supply and, ultimately, kill the plant (Smith, 1954; Smith et al., 1989).

Recent research has shown that the hemibiotroph *C. graminicola* switched from a biotrophic phase to a necrotrophic phase when plant defense responses were synthesizing reactive oxygen species (ROS) and abscisic acid (ABA) at peak levels in maize (*Zea mays* L.) (Vargas et al., 2012). Mechanical wounding causes plant responses similar to pathogen invasion, including the upregulation of ROS and ABA synthesis (Bostock and Stermer, 1989). Therefore, plant responses to wounding caused by deep VC may trigger *C. cereale* to switch from a nonlethal, biotrophic relationship to a destructive necrotrophic phase within the ABG plant. Transciptomic, histological and biochemical studies are needed to test this hypothesis.

Shallow VC in the current study was less likely to wound crowns and did not increase anthracnose severity similar to the findings of Inguagiato et al. (2008). Surprisingly, shallow VC reduced ($p \leq 0.1$) disease severity on 5 of 32 disease assessments during the current study. The removal of canopy biomass by shallow VC may have increased airflow and decreased wetness and humidity in the turf canopy ultimately causing conditions to be less conducive for disease development. Shallow VC may also have stimulated new shoot growth (Schery, 1966), which possibly improved plant vigor and made ABG less susceptible to *C. cereale*. Furthermore, the healing of wounds caused by shallow VC may have increased ABG resistance to infection by *C. cereale*. Wound healing in maize and chili pepper (*Capsicum annuum* cv. Nokkwang) provided resistance to infection by *C. graminicola* and *C. acutatum*, respectively; disease severity of wounded plants was not increased when inoculation occurred immediately after re-wounding (Kim, 2008; Muimba-Kankolongo and Bergstrom, 1990). Wound healing in maize is thought to involve the synthesis of defense chemicals and a heavily lignified papillum that hinder ingress by *C. graminicola* (Bergstrom and Nicholson, 1999; Mims and Vaillancourt, 2002). Similar responses confer host resistance to fungal invasion in several other pathosystems (Bostock and Stermer, 1989; Lipetz, 1970).

Vertical cutting produced contrasting results among the current and previous studies, which was not unexpected due to differences in methodology. Our results and those reported by Inguagiato et al. (2008) indicated that shallow VC to a depth that was not likely to injure crowns usually did not enhance anthracnose disease severity; whereas, Uddin et al. (2008) reported that VC to a depth of 3.3 mm increased disease severity even when the height of cut was 4.3 mm and crowns were less likely to be injured. Such increases in the severity of anthracnose may be attributed to the greater frequency (every 7 d) of VC used by Uddin et al. (2008) compared to the single application of VC made by the current authors and biweekly VC by Inguagiato et al. (2008). Additionally, the blade width and blade spacing on the VC equipment used by Uddin et al. (2008) caused 16% of the turf surface area to be affected by VC; whereas, the VC equipment used in the current study and in the study conducted by Inguagiato et al. (2008) affected 4 and 8% of the turf surface, respectively. Increased VC frequency and increased turf area affected by VC probably resulted in more extensive defoliation of plants, which may have increased stress and predisposed plants to anthracnose. Maize anthracnose severity was increased when plants were defoliated (Dodd, 1980; Mortimore and Ward, 1964), and low mowing (i.e., increased defoliation) of ABG can also increase disease severity (Backman et al., 2002; Inguagiato et al., 2009). Moreover, the shallow VC (3.3 mm deep) treatment used by Uddin et al. (2008) was applied to heights of cut (2.0 and 3.0 mm) that were less than the depth of VC, probably wounding crowns in addition to leaves and sheaths.

Wounding cannot make plants more susceptible to disease unless a virulent pathogen and conducive environmental conditions are present (Agrios, 2005). Plots in the study of Uddin et al. (2008) were inoculated with *C. cereale* only hours after VC treatments (Michael Soika, personal communication) and VC increased disease severity on 100% of rating dates. However, on uninoculated turf in the current study or when inoculation was delayed 7 d after VC treatments (Inguagiato et al., 2008), disease severity was increased by VC on only 6 and 8% of rating dates, respectively. In the greenhouse, anthracnose basal rot was increased when wounded crowns of ABG tillers were inoculated with *C. cereale* (reported as *C. graminicola*) up to 12 h after wounding (Hoyland and Landschoot, 1994). Similarly, inoculating potato (*Solanum tuberosum* L.) plants on the same day of wounding significantly increased infection by *C. coccodes* (Wallr.) S. J. Hughes (causal agent of black dot of potato); however, delaying inoculation by 3 d resulted in similar levels of disease in wounded and unwounded tissue (Johnson and Miliczky, 1993). When inoculation of wounded of maize stalks with *C. graminicola* was delayed by as little as 1 to 2 h, wounded tissue was almost as tolerant of anthracnose stalk rot as unwounded tissue (Muimba-Kankolongo and Bergstrom, 1990). Therefore, a lack or low level of inoculum at the time of VC or shortly thereafter in the current study may explain why crown wounding caused by deep VC did not consistently increase disease severity.

Anthracnose epidemics on maize and turf are commonly associated with periods of high temperature, high humidity and prolonged leaf wetness; spore formation and transport is also enhanced during wet conditions (Bergstrom and Nicholson, 1999; Danneberger et al., 1984; Vargas et al., 1992). Vertical cutting in the current study was performed when the turf canopy was dry, as commonly practiced (Beard, 2002). Thus, the timing of VC treatments during our study probably occurred when environmental conditions were not extremely conducive for infection by *C. cereale.*

In summary, our findings that deep VC slightly increased disease severity on few rating dates and shallow VC, which wounded mostly leaves, produced subtle reductions in disease severity suggest that VC depth may be a factor that influences anthracnose disease development. It is plausible that environmental conditions controlling disease development and the abundance of viable *C. cereale* inoculum at the time of VC may be determining factors in the likelihood for deep VC to increase disease severity. Therefore, VC should not be performed at depths that injure crowns when disease pressure is high. Moreover, timing of deep VC should coincide with periods of low temperature, low humidity and adequate sunlight whenever possible to avoid the risk of increasing disease severity. Shallow VC appears to not exacerbate anthracnose disease probably because it causes less stress to ABG and less exposure to inoculum and microenvironments favorable for infection by *C. cereale*.

REFERENCES

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

Backman, P., G. Stahnke, and E. Miltner. 2002. Anthracnose update: Cultural practices affect spread of disease in northwest. Turfgrass Trends 11:T1-T2, T4.

Beard, J.B. 1973. Turfgrass: Science and culture. Prentice Hall, Englewood Cliffs, NJ.

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

Beard, J.B., and H.J. Beard. 2005. Beard's turfgrass encyclopedia for golf courses, grounds, lawns, sports fields. Michigan State Univ. Press, East Lansing, MI.

Bergstrom, G.C., and R.L. Nicholson. 1999. The biology of corn anthracnose: knowledge to exploit for improved management. Plant Dis. 83(7):596-608.

Bostock, R.M., and B.A. Stermer. 1989. Perspectives on Wound Healing in Resistance to Pathogens. Annu. Rev. Phytopathol. 27(1):343-371. DOI: doi:10.1146/annurev.py.27.090189.002015.

Bruehl, G.W., and J.G. Dickson. 1950. Anthracnose of cereals and grasses. USDA Tech. Bull. 1005:1-37.

Burpee, L.L., and L.G. Goulty. 1984. Influence of cultivation practices and fungicides on the development of anthracnose in a golf course fairway. Univ. of Guelph Turfgrass Res. Rep.:8-10.

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(3):524-530. DOI: 10.2134/agronj1987.00021962007900030025x.

Christians, N. 2011. Fundamentals of turfgrass management. John Wiley & Sons, Inc., Hoboken, NJ.

Crouch, J.A., and L.A. Beirn. 2009. Anthracnose of cereals and grasses. Fungal Diversity 39:19.

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(1):46-60. DOI: 10.1094/PHYTO-96-0046.

Danneberger, T., J. Vargas Jr, and A. Jones. 1984. A model for weather-based forecasting of anthracnose on annual bluegrass. Phytopathology 74(4):448-451.

Dodd, J.L. 1980. Grain sink size and predisposition of *Zea mays* to stalk rot. Phytopathology 70:534-535.

Gaussoin, R.E., W.L. Berndt, C.A. Dockrell, and R.A. Drijber. 2013. Characterization, development, and management of organic matter in turfgrass systems, In: J. C. Stier, Horgan, Brian P., Bonos, Stacy A., and Schmitt, Gail K. (Ed.), Turfgrass: Biology, Use, and Management, ASA, CSSA, & SSSA Inc., Madison, WI. pp. 1328.

Halisky, P.M., R.F. Myers, and R.E. Wagner. 1981. Relationship of thatch to nematodes, dollar spot and fungicides in Kentucky bluegrass turf. Proc. Int. Turf. Res. Conf. 4:415-420.

Hoyland, B.F., and P.J. Landschoot. 1994. Wound predisposition of *Poa annua* to anthracnose basal rot. ASA-CSSA-SSSA Annu. Meet., Seattle, WA, Agron. Abstr. 86:183.

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(4):1595-1607. DOI: 10.2135/cropsci2007.06.0343.

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(4):1454-1462. DOI: 10.2135/cropsci2008.07.0435.

Johnson, D.A., and E.R. Miliczky. 1993. Effects of wounding and wetting duration on infection of potato foliage by *Colletotrichum coccodes*. Plant Dis. 77(1):13-17.

Kim, Y.H. 2008. Effect of delayed inoculation after wounding on the development of anthracnose disease caused by *Colletotrichum acutatum* on chili pepper fruit. The Plant Pathol. J. 24(4):392-399.

Landreth, J., D. Karcher, and M. Richardson. 2008. Cultivating to manage organic matter in sand-based putting greens: University of Arkansas researchers provide important insight for managing organic buildup on putting greens. U.S. Golf Assoc. Green Section Record 46(1):16-19.

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

Lipetz, J. 1970. Wound healing in higher plants. Int. Rev. Cytol 27(1):1-28.

Lockyer, J. 2009. Successful fine turf organic matter management. Int. Turfgrass Bull. 244:9-11.

Mims, C.W., and L.J. Vaillancourt. 2002. Ultrastructural characterization of infection and colonization of maize leaves by *Colletotrichum graminicola*, and by a *C. graminicola* pathogenicity mutant. Phytopathology 92(7):803-812.

Moore, D. 2005. The supa greens maintenance cassette system. Int. Turfgrass Bull. 228:21, 23.

Mortimore, C.G., and G.M. Ward. 1964. Root and stalk rot of corn in southwestern Ontario: III. sugar levels as a measure of plant vigor and resistance. Can. J. Plant Sci. 44:451-457.

Muimba-Kankolongo, A., and G.C. Bergstrom. 1990. Transitory wound predisposition of maize to Anthracnose stalk rot. Can. J. Plant Pathol. 12(1):1-10.

Orshinsky, A.M., M.J. Boehm, and G.J. Boland. 2012. Plant wounding and *Ophiostoma mitovirus 3a* (OMV3a) influence infection of creeping bentgrass by *Sclerotinia homoeocarpa*. Can. J. Plant Pathol. 34:493.

Roberts, J.A., J.C. Inguagiato, B.B. Clarke, and J.A. Murphy. 2011. Irrigation Quantity Effects on Anthracnose Disease of Annual Bluegrass. Crop Sci. 51(3):1244-1252. DOI: 10.2135/cropsci2010.07.0444.

Schery, R.W. 1966. Remarkable Kentucky bluegrass. Southern California Turfgrass Culture. 8:30-31.

Settle, D.M., A.D. Martinez-Espinoza, and L.L. Burpee. 2006. Anthracnose of Turfgrass. The Plant Health Instructor [Online]:[1-6]. DOI: DOI:10.1094/PHI-I-2006-1205-01.

Smiley, R.W., P.H. Dernoeden, and B.B. Clarke. 2005. Compendium of turfgrass diseases. APS press, St. Paul, MN.

Smith, J.D. 1954. A disease of *Poa annua*. J. Sports Turf Res. Inst. 8:344-353.

Smith, J.D., N. Jackson, and A.R. Woolhouse. 1989. Fungal diseases of amenity turf grasses. E. & FN Spon, New York, NY.

Tisserat, N.A., and J. Fry. 1997. Cultural practices to reduce spring dead spot (*Ophiosphaerella herpotricha*) severity in *Cynodon dactylon*. Int. Turf. Soc. Res. J. 8:931-936.

Towers, G., K. Green, E. Weibel, P. Majumdar, and B.B. Clarke. 2003. Evaluation of fungicides for the control of anthracnose basal rot on annual bluegrass. Fungicide and Nematicide Tests 58:T017.

Turgeon, A.J. 2011. Turfgrass Management, Prentice Hall, 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.

Unruh, J.B., S.D. Davis, P.F. Colbaugh, B.J. Brecke, and D.O. Stephenson. 2005. Impact of various chemical and nutrient inputs and cultural treatments on 'Tifeagle bermudagrass (*Cynodon dactylon* x *C. transvaalensis*). Int. Turfgrass Soc. Res. J. 10(1):455-461.

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

Vargas, J.M., T.K. Danneberger, and A.L. Jones. 1992. Effects of temperature, leaf wetness duration and inoculum concentration on infection of annual bluegrass by

Colletotrichum graminicola. International Turfgrass Society Research Journal 7:324-328.

Vargas, W.A., J.M.S. Martín, G.E. Rech, L.P. Rivera, E.P. Benito, J.M. Díaz-Mínguez, M.R. Thon, and S.A. Sukno. 2012. Plant defense mechanisms are activated during biotrophic and necrotrophic development of *Colletotricum graminicola* in maize. Plant physiology 158(3):1342-1358.

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(3):368-377.

Table 5.1. Anthracnose severity response to depth of vertical cutting on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010: Trial run 1.

Vertical Cutting Depth‡	23 July	25 July	28 July	31 July	3 Aug.	7 Aug.	11 Aug.	14 Aug.	20 Aug.	31 Aug.
mm	---------- percent turf area infested ----------									
No Vertical Cutting	5.7	7.3	8.0	20.7	25.0	33.3	42.0	47.7	50.7	58.0
1.3	6.7	7.3	7.0	20.0	23.0	30.0	37.0	43.3	45.7	57.7
7.6	6.7	7.3	8.0	24.3	27.0	35.0	41.3	46.3	49.3	57.0
$LSD_{0.05}$	2.5	2.8	2.5	3.0	4.0	3.9	4.7	7.1	6.1	6.2
Source of Variation	---------- $P > F$ ----------									
Treatment	NS§	NS	NS	*	NS	*	0.08†	NS	NS	NS
CV, %	41.9	40.1	34.6	14.6	17.1	12.8	12.5	16.4	13.3	11.4

*Significant at the 0.05 probability level.

†Probability level ≤ 0.1.

‡Vertical cutting was applied once on 23 July 2010 using blades that were 1.5 mm thick and spaced 40 mm apart.

§NS, not significant.

Figure 5.1. Anthracnose severity response to depth of vertical cutting on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010. Vertical cutting was applied once on 23 July 2010 using blades that were 1.5 mm thick and spaced 40 mm apart. Error bar indicates Fisher's protected LSD at $\alpha = 0.05$ for treatment comparison on a specific rating date; no error bar indicates a non-significant F test: Trial run 1.

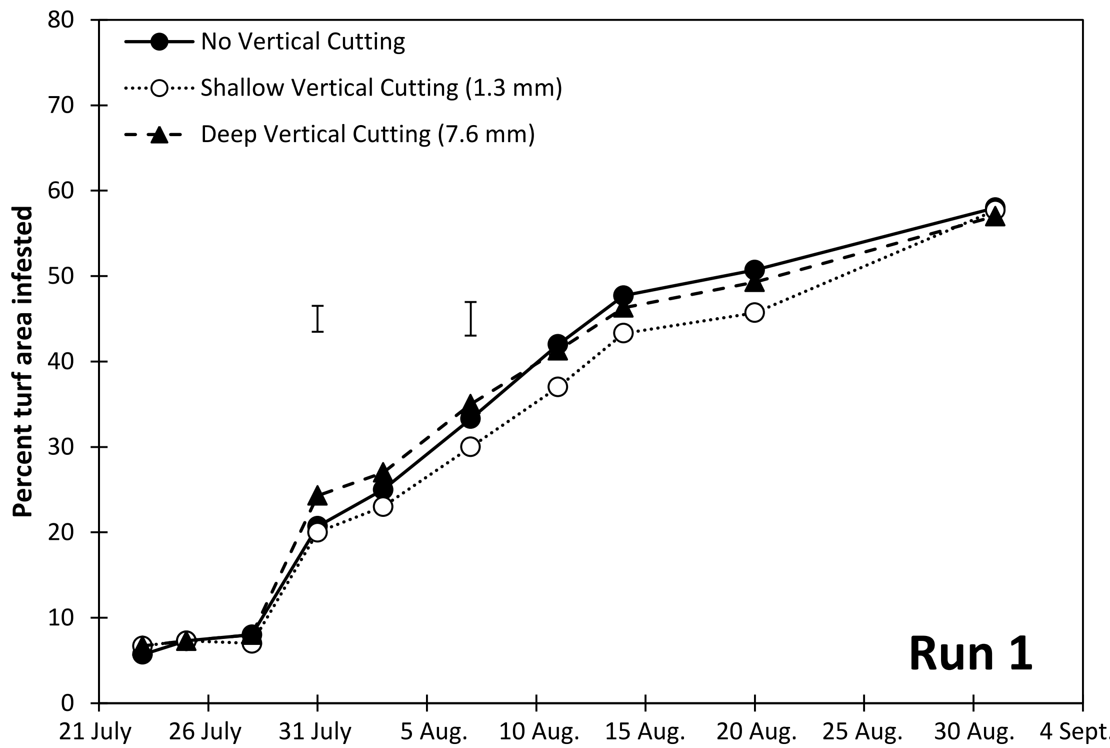


Table 5.2. Anthracnose severity response to depth of vertical cutting on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2011: Trial run 2.

Vertical Cutting Depth‡	6 July	7 July	8 July	10 July	12 July	14 July	16 July	18 July	20 July	22 July	24 July	27 July	1 Aug.
mm	-- percent turf area infested --												
No Vertical Cutting	5.0	7.0	8.3	11.0	12.7	21.3	28.0	26.0	25.3	37.3	46.7	54.0	71.0
1.3	6.0	4.7	4.7	9.3	11.7	15.7	22.7	25.7	26.7	36.0	46.0	52.0	66.3
7.6	6.0	5.0	7.3	10.0	11.0	18.3	28.0	25.0	23.7	32.7	42.7	55.3	71.3
$LSD_{0.05}$	3.7	3.7	3.4	3.4	3.9	5.6	5.9	6.4	8.6	7.6	8.9	9.7	10.2
Source of Variation	-- P > F --												
Treatment	NS§	NS	0.09†	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV, %	69.9	70.0	53.0	35.9	35.3	32.1	24.0	26.7	36.5	22.8	21.1	19.1	15.6

†Probability level ≤ 0.1.
‡Vertical cutting was applied once on 6 July 2011 using blades that were 1.5 mm thick and spaced 40 mm apart.
§NS, not significant.

Figure 5.2. Anthracnose severity response to depth of vertical cutting on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2011. Vertical cutting was applied once on 6 July 2011 using blades that were 1.5 mm thick and spaced 40 mm apart. No error bar indicates a non-significant F test: Trial run 2.

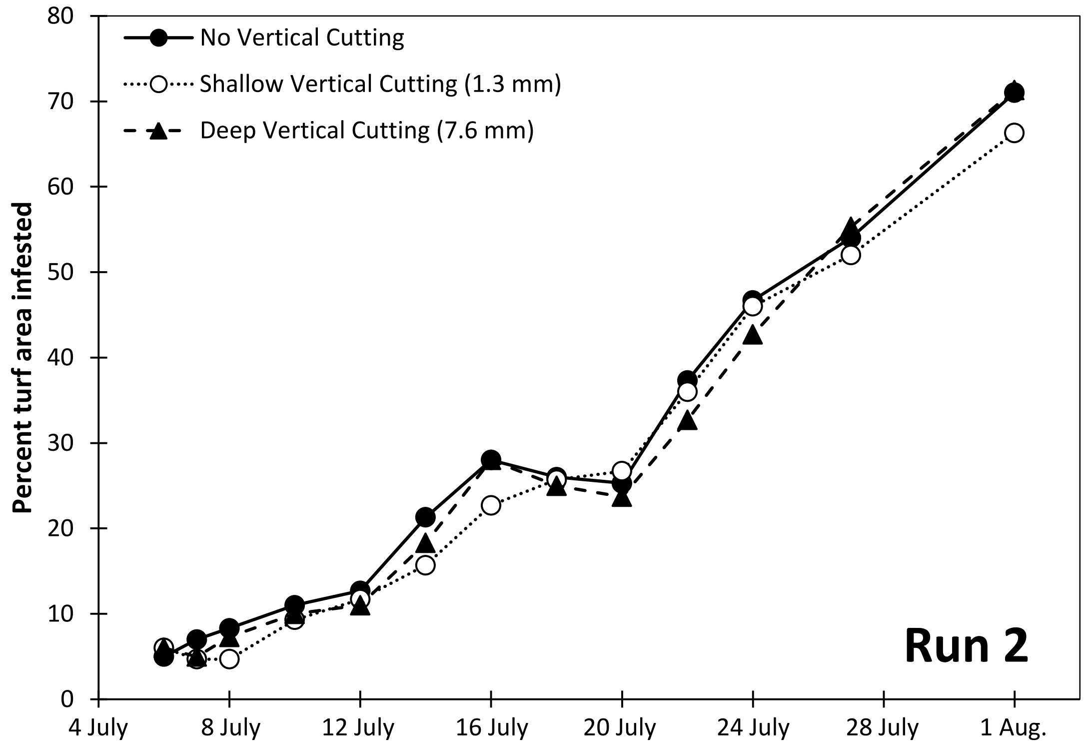


Table 5.3. Anthracnose severity response to depth of vertical cutting on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2011: Trial run 3.

Vertical Cutting Depth‡	4 Aug.	6 Aug.	8 Aug.	11 Aug.	15 Aug.	17 Aug.	19 Aug.	25 Aug.	2 Sept.
mm	-- percent turf area infested --								
No Vertical Cutting	31.3	30.3	32.3	30.7	30.7	30.0	28.7	34.3	26.3
1.3	23.3	26.0	27.0	25.7	24.3	23.3	21.3	27.3	23.0
7.6	27.3	29.0	31.7	27.3	26.3	25.3	24.0	34.0	25.3
$LSD_{0.05}$	7.0	5.4	6.8	6.4	5.7	5.5	7.0	7.5	3.9
Source of Variation	-- $P > F$ --								
Treatment	0.08†	NS§	NS	NS	0.09	0.06	NS	NS	NS
CV, %	27.2	20.1	23.9	24.5	22.5	22.3	30.2	25.2	16.7

†Probability level ≤ 0.1.

‡Vertical cutting was applied once on 3 Aug. 2011 using blades that were 1.5 mm thick and spaced 40 mm apart.

§NS, not significant.

Figure 5.3. Anthracnose severity response to depth of vertical cutting on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2011. Vertical cutting was applied once on 3 Aug. 2011 using blades that were 1.5 mm thick and spaced 40 mm apart. No error bar indicates a non-significant F test: Trial run 3.

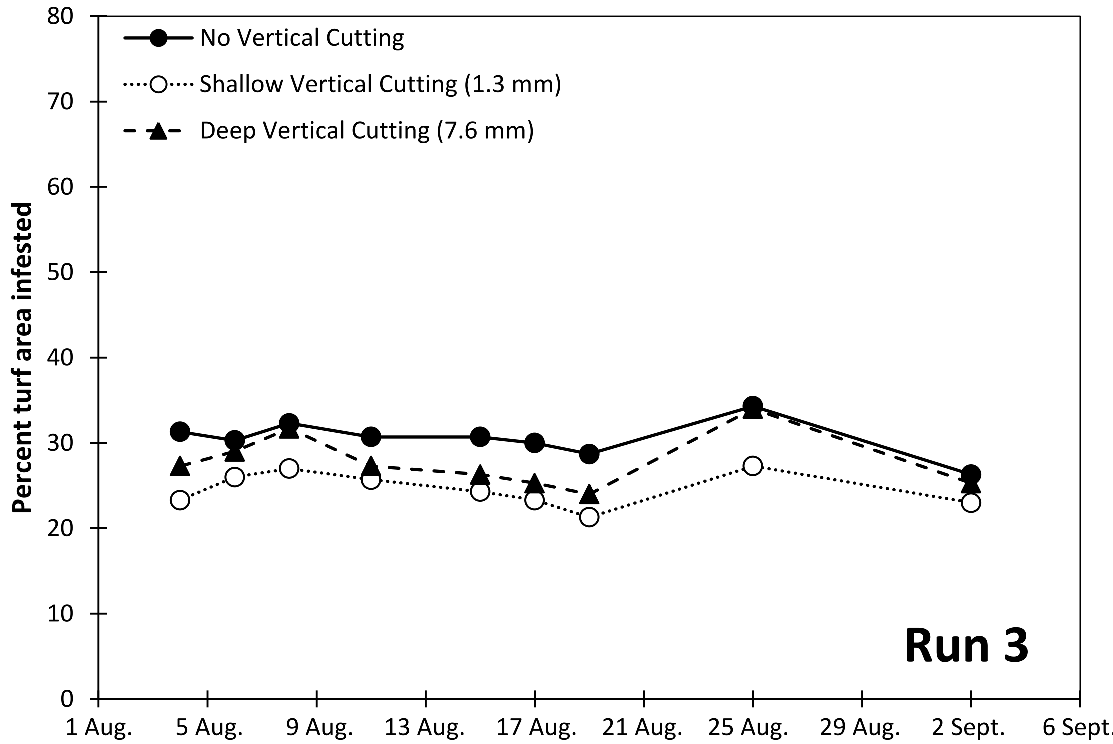


Table 5.4. Turf quality response to depth of vertical cutting on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2011: Trial run 2.

Vertical Cutting Depth†	6 July	7 July	8 July	10 July	12 July	14 July	16 July	18 July	20 July	22 July	24 July	27 July	1 Aug.
mm	1-9 scale‡												
No Vertical Cutting	7.4	7.7	7.7	7.7	7.9	7.9	8.2	8.0	7.7	7.5	7.2	7.5	6.9
1.3	6.7	7.3	7.4	7.4	7.7	8.0	8.2	8.0	7.9	7.6	7.3	7.5	6.7
7.6	4.6	4.5	4.9	5.0	5.2	5.4	5.5	5.7	6.9	6.9	6.8	7.0	6.4
$LSD_{0.05}$	0.7	0.6	0.5	0.6	0.5	0.6	0.5	0.5	0.5	0.4	0.5	0.4	0.4
Source of Variation	$P > F$												
Treatment	***	***	***	***	***	***	***	***	**	**	NS§	*	NS
CV, %	11.3	9.7	8.7	8.8	7.2	9.4	7.7	7.6	7.6	5.8	7.6	5.9	7.2

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

***Significant at the 0.001 probability level.

†Vertical cutting was applied once on 6 July 2011 using blades that were 1.5 mm thick and spaced 40 mm apart.

‡Nine (9) represents the best turf characteristic and 6 represents the minimally acceptable rating.

§NS, not significant.

Table 5.5. Turf quality response to depth of vertical cutting on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2011: Trial run 3.

Vertical Cutting Depth‡	4 Aug.	6 Aug.	8 Aug.	11 Aug.	15 Aug.	17 Aug.	19 Aug.	25 Aug.	2 Sept.
mm	1-9 scale§								
No Vertical Cutting	7.7	7.8	7.7	7.6	7.3	7.1	6.7	6.1	6.1
1.3	6.9	7.2	7.4	7.3	7.2	6.9	6.7	6.1	6.0
7.6	4.0	5.3	6.2	7.0	6.9	6.9	6.6	5.7	5.6
$LSD_{0.05}$	0.6	0.5	0.5	0.5	0.4	0.5	0.6	0.3	0.5
Source of Variation	$P > F$								
Treatment	***	***	***	0.09†	0.06	NS¶	NS	*	0.06
CV, %	9.6	7.8	6.8	7.1	5.7	7.2	9.5	5.8	8.4

*Significant at the 0.05 probability level.
***Significant at the 0.001 probability level.
†Probability level ≤ 0.1.
‡Vertical cutting was applied once on 3 Aug. 2011 using blades that were 1.5 mm thick and spaced 40 mm apart.
§Nine (9) represents the best turf characteristic and 6 represents the minimally acceptable rating.
¶NS, not significant.

APPENDIX

Table A.1. Anthracnose severity response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009.

Main Effect	1 Aug.	6 Aug.	13 Aug.	20 Aug.	28 Aug.	3 Sept.	AUDPC
	------------------------ percent turf area infested ------------------------						
Control	12.8	8.3	25.3	25.9	40.4	30.8	2261.4
Frequency (FREQ)							
Single	12.2	9.9	28.2	29.6	41.4	26.4	2396.9
Biweekly	13.8	8.9	28.2	23.8	37.0	21.8	2152.7
Rate (RATE)‡							
0.075 L m^{-2}	12.9	9.9	30.4	30.8	41.1	28.4	2480.2
0.15 L m^{-2}	13.8	8.7	30.3	26.6	39.2	24.4	2308.8
0.3 L m^{-2}	14.4	10.8	27.8	26.5	38.0	24.1	2272.6
0.6 L m^{-2}	11.1	8.6	24.1	23.3	38.6	19.6	2052.6
Planed *F*-Test	-- $P > F$ --						
Control vs. all topdressing	NS§	NS	NS	NS	NS	***	NS
FREQ	NS	NS	NS	0.06†	**	***	0.09
RATE	NS	NS	0.06	NS	NS	***	NS
Linear	NS	NS	**	0.1	NS	***	*
Quadratic	NS	NS	NS	NS	NS	NS	NS
Lack-of-fit	NS	NS	NS	NS	NS	*	NS
FREQ x RATE	NS	NS	*	NS	NS	NS	NS
CV, %	36.1	34.8	17.7	29.2	9.4	10.9	15.5

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
***Significant at the 0.001 probability level.
†Probability level ≤ 0.1.
‡Sand topdressing applications were initiated on 28 July 2009 for both single and biweekly frequencies. Biweekly applications continued to 24 August 2009.
§NS, not significant.

Table A.2. Anthracnose severity response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010.

Main Effect	28 May	4 June	11 June	21 June	28 June	7 July	15 July	28 July	11 Aug.	AUDPC
	percent turf area infested									
Control	24.8	23.9	16.3	21.7	29.0	35.1	30.5	41.4	60.7	6584
Frequency (FREQ)										
Single	27.2	24.6	24.0	25.3	31.1	34.6	31.6	35.5	49.1	6511
Biweekly	27.1	25.3	25.5	27.8	34.7	38.0	29.7	33.5	44.5	6557
Rate (RATE)[‡]										
0.075 $\mathrm{L\ m^{-2}}$	31.3	26.0	25.0	26.5	33.1	38.4	31.6	40.2	55.4	7051
0.15 $\mathrm{L\ m^{-2}}$	25.5	24.1	21.7	24.4	31.9	34.4	31.3	33.8	45.5	6280
0.3 $\mathrm{L\ m^{-2}}$	28.4	22.8	27.7	26.1	32.2	36.2	28.6	32.6	44.6	6373
0.6 $\mathrm{L\ m^{-2}}$	23.4	27.0	24.6	29.3	34.3	36.4	31.0	31.5	41.8	6433
Planed *F*-Test	$P > F$									
Control vs. all topdressing	NS[§]	NS	*	NS	NS	NS	NS	**	***	NS
FREQ	NS	NS	NS	NS	0.1[†]	NS	NS	NS	*	NS
RATE	NS	NS	NS	NS	NS	NS	NS	**	**	NS
Linear	NS	NS	NS	NS	NS	NS	NS	**	**	NS
Quadratic	NS	NS	NS	NS	NS	NS	NS	*	0.06	NS
Lack-of-fit	NS	NS	NS	NS	NS	NS	NS	NS	0.06	NS
FREQ x RATE	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV, %	34.5	25.1	29.0	21.3	17.9	16.5	15.1	13.0	13.1	15.1

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
***Significant at the 0.001 probability level.
†Probability level ≤ 0.1.
‡Sand topdressing applications were initiated on 24 May 2010 for both single and biweekly frequencies. Biweekly applications continued to 19 July 2010.
§NS, not significant

Table A.3. Anthracnose severity response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009.

	13 Aug. 2009	
	Frequency	
Sand rate†	Single	Biweekly
L m^{-2}	-------------%------------	
0.075	31.7	29.2
0.15	26.5	34.1
0.3	26.9	28.2
0.6	27.6	20.7
Linear	NS§	**
Quadratic	NS	NS
Lack-of-fit	NS	NS

**Significant at the 0.01 probability level.

†Sand topdressing applications were initiated on 28 July 2009 for both single and biweekly frequencies. Biweekly applications continued to 24 August 2009.

§NS, not significant.

Figure A.1. Anthracnose severity response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009. Sand topdressing applications were initiated on 28 July 2009 for both single (dashed trendline) and biweekly (solid trendline) frequencies. Biweekly applications continued to 24 August 2009.

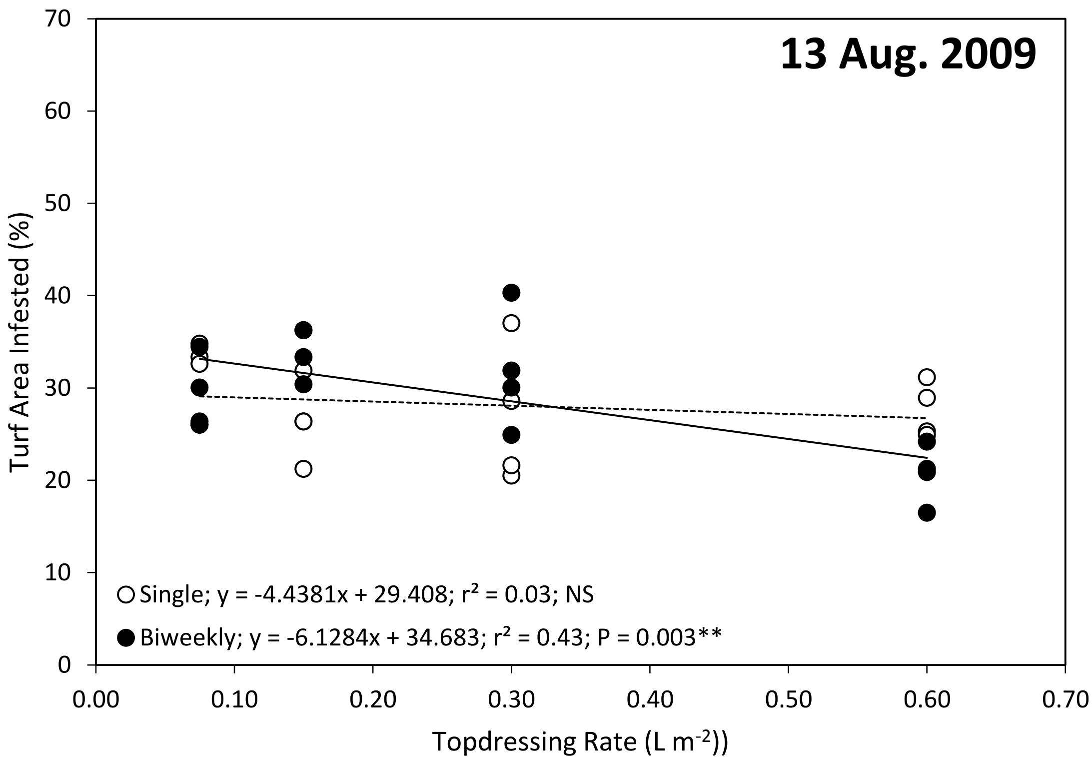


Table A.4. Turf quality response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009.

Main Effect	1 Aug.	7 Aug.	17 Aug.	27 Aug.
	-----------------------1–9 scale†-----------------------			
Control	8.0	8.3	6.3	7.5
Frequency (FREQ)‡				
Single	7.9	7.5	6.6	7.3
Biweekly	7.9	7.6	6.8	7.8
Rate (RATE)				
0.075 L m^{-2}	8.1	7.6	6.6	7.1
0.15 L m^{-2}	8.0	7.8	6.5	7.4
0.3 L m^{-2}	7.9	7.3	6.9	7.7
0.6 L m^{-2}	7.6	7.5	6.9	7.9
Planed *F*-Test	------------------------ $P > F$ ------------------------			
Control vs. all topdressing	NS§	*	NS	NS
FREQ	NS	NS	NS	**
RATE	NS	NS	NS	*
Linear	NS	NS	NS	**
Quadratic	NS	NS	NS	NS
Lack-of-fit	NS	NS	NS	NS
FREQ x RATE	NS	NS	NS	*
CV, %	8.2	7.4	11.1	6.4

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

†Sand topdressing applications were initiated on 28 July 2009 for both single and biweekly frequencies. Biweekly applications continued to 24 August 2009.

‡Nine (9) represents the best turf characteristic and 5 represents the minimally acceptable rating.

§NS, not significant.

Table A.5. Turf quality response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010.

Main Effect	28 May	4 June	11 June	21 June	28 June	7 July	15 July	28 July	11 Aug.
	1–9 scale[‡]								
Control	6.5	5.8	6.8	6.3	5.8	4.8	5.8	3.8	3.0
Frequency (FREQ)[§]									
Single	6.1	6.2	6.3	6.8	5.7	4.9	5.4	4.5	3.9
Biweekly	6.0	6.1	6.2	6.6	5.7	5.1	5.3	4.5	4.5
Rate (RATE)									
0.075 L m^{-2}	6.0	5.9	5.9	6.4	5.5	4.5	5.0	4.0	3.4
0.15 L m^{-2}	6.3	6.0	6.4	6.5	5.5	4.9	5.4	4.5	3.9
0.3 L m^{-2}	5.9	6.3	6.4	6.8	5.8	5.1	5.5	4.6	4.6
0.6 L m^{-2}	6.1	6.4	6.3	7.1	6.0	5.5	5.4	4.9	4.9
Planed *F*-Test	$P > F$								
Control vs. all topdressing	NS[§]	NS	NS	NS	NS	NS	NS	NS	*
FREQ	NS	NS	NS	NS	NS	NS	NS	NS	*
RATE	NS	NS	NS	0.06[†]	NS	NS	NS	NS	**
Linear	NS	NS	NS	**	NS	*	NS	NS	**
Quadratic	NS	NS	NS	NS	NS	NS	NS	NS	NS
Lack-of-fit	NS	NS	NS	NS	NS	NS	NS	NS	NS
FREQ x RATE	NS	NS	NS	NS	NS	NS	*	NS	NS
CV, %	17.6	13.7	13.5	8.2	13.9	16.7	14.9	21.7	21.0

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

†Probability level ≤ 0.1.

‡Nine (9) represents the best turf characteristic and 5 represents the minimally acceptable rating.

§Sand topdressing applications were initiated on 24 May 2010 for both single and biweekly frequencies. Biweekly applications continued to 19 July 2010.

¶NS, not significant.

Table A.6. Turf quality response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009.

	27 Aug. 2009	
	Frequency†	
Rate	Single	Biweekly
L m^{-2}	--------1–9 scale‡-------	
0.075	6.8	7.5
0.15	6.8	8.0
0.3	7.5	8.0
0.6	8.0	7.8
Linear	***	NS§
Quadratic	NS	NS
Lack-of-fit	NS	NS

***Significant at the 0.01 probability level.
†Sand topdressing applications were initiated on 28 July 2009 for both single and biweekly frequencies. Biweekly applications continued to 24 August 2009.
‡Nine (9) represents the best turf characteristic and 5 represents the minimally acceptable rating.
§NS, not significant

Figure A.2. Turf quality response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2009. Sand topdressing applications were initiated on 28 July 2009 for both single (dashed trendline) and biweekly (solid trendline) frequencies. Biweekly applications continued to 24 August 2009. Nine (9) represents the best turf characteristic and 5 represents the minimally acceptable rating.

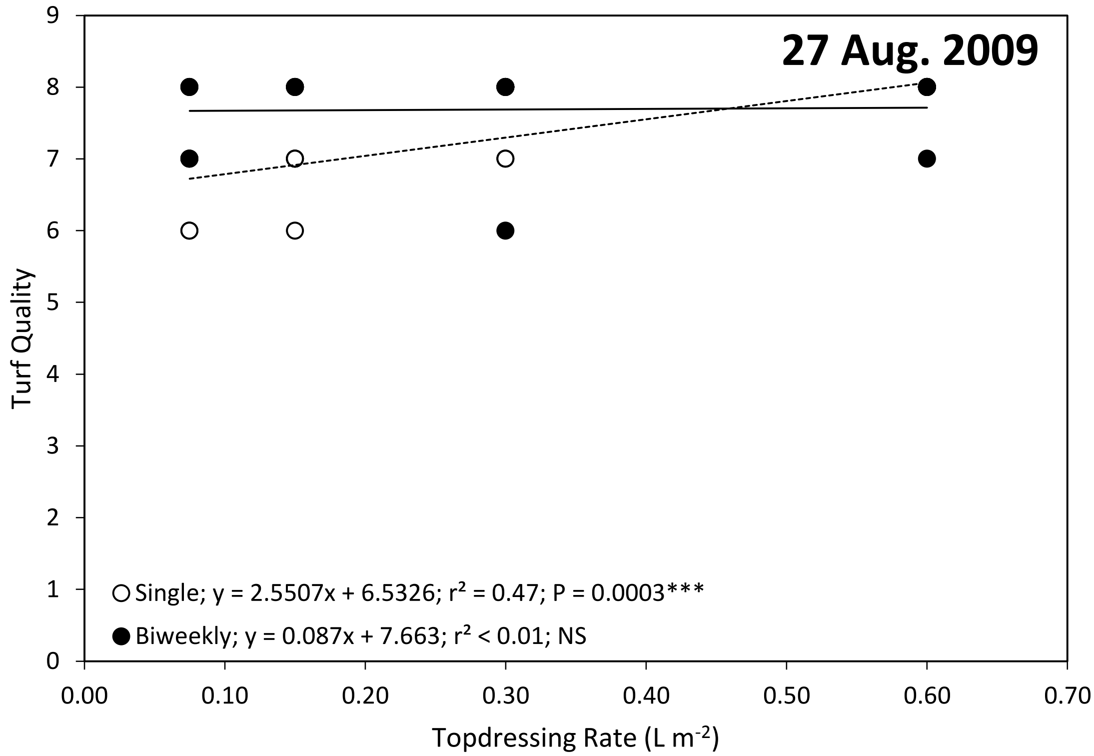


Table A.7. Turf quality response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010.

	15 July 2010	
	Frequency‡	
Rate	Single	Biweekly
L m^{-2}	--------1–9 scale§-------	
0.075	5.0	5.0
0.15	4.8	6.0
0.3	6.0	5.0
0.6	5.8	5.0
Linear	0.08†	NS¶
Quadratic	NS	NS
Lack-of-fit	NS	0.06

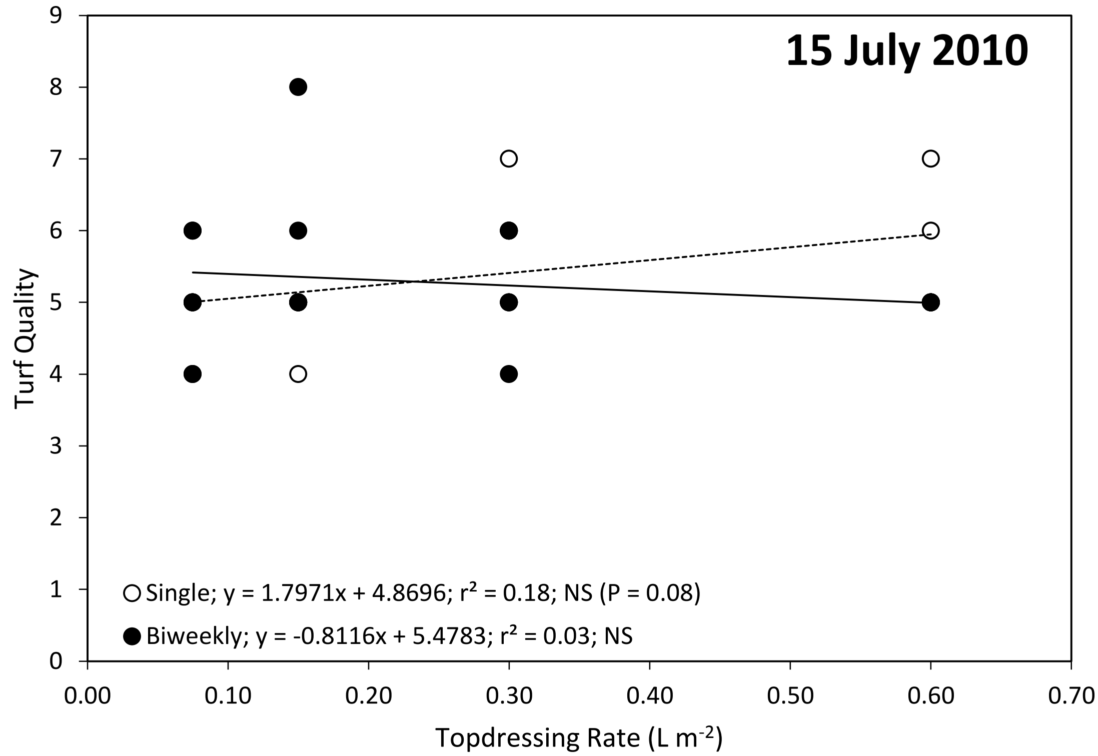
†Probability level ≤ 0.1.

‡Sand topdressing applications were initiated on 24 May 2010 for both single and biweekly frequencies. Biweekly applications continued to 19 July 2010.

§Nine (9) represents the best turf characteristic and 5 represents the minimally acceptable rating.

¶NS, not significant

Figure A.3. Turf quality response to sand topdressing frequency and rate applied during the emergence of disease symptoms on an annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ during 2010. Sand topdressing applications were initiated on 24 May 2010 for both single (dashed trendline) and biweekly (solid trendline) frequencies. Biweekly applications continued to 19 July 2010. Nine (9) represents the best turf characteristic and 5 represents the minimally acceptable rating.



Curriculum Vitae

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Education

B.S. May 2008. Agricultural Sciences and Natural Resources, Spanish (Double Major). Oklahoma State University.

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Occupations

May 2008 to Aug. 2008	Assistant superintendent Oakwood Country Club Enid, OK
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