INFLUENCE OF NUTRIENT MANAGEMENT AND SOIL pH ON ANTHRACNOSE SEVERITY OF ANNUAL BLUEGRASS PUTTING GREEN TURF

By

CHARLES J. SCHMID

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James A. Murphy and Bruce B. Clarke

And approved by

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ABSTRACT OF THE DISSERTATION

Influence of Nutrient Management and Soil pH on Anthracnose Severity of Annual Bluegrass Putting Green Turf

By CHARLES J. SCHMID

Dissertation Directors:

James A. Murphy and Bruce B. Clarke

Anthracnose (*Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman) is a fungal disease of annual bluegrass [*Poa annua* L. f. reptans (Hausskn) T. Koyama; ABG] turf, which can be intensified when abiotic conditions weaken turfgrass plants. Five field trials conducted from 2009 to 2015 evaluated the effects of N program, soluble N rate, N source, K source and rate, and soil pH on anthracnose severity of ABG maintained as putting green turf. Soluble N rate applied during mid-season had the greatest influence on anthracnose severity. Granular N rate and season in which the majority of granular N was applied also influenced disease severity but to a lesser extent. Soluble N applied at 73 kg N ha^{-1} yr^{-1} in combination with moderate rates (147 or 220 kg N ha^{-1} yr^{-1}) of granular N applied during the spring resulted in the greatest reduction in disease severity. Further analysis of the influence of soluble N rate on anthracnose severity found that higher rates (14.6 to 24.4 kg N ha^{-1} wk^{-1}) of soluble N can be applied from late-spring through early-summer to reduce disease severity, but as the summer progresses moderate (9.8 kg N ha^{-1} wk^{-1}) to low (4.9 kg N ha^{-1} wk^{-1}) rates of soluble N should be applied to avoid excessive rates of N increasing disease severity.

Playability (i.e. ball roll distance) of ABG turf was reduced by rates of soluble N applied at ≥ 14.6 kg ha^{-1} wk^{-1} compared to N applied at 4.9 kg ha^{-1} wk^{-1}. Basic N sources (potassium nitrate and calcium nitrate) applied at 4.9 kg N ha^{-1} every 7-d reduced disease severity compared acidic N sources (ammonium nitrate and ammonium sulfate) applied at the same rate and frequency; however, when N was applied at 4.9 kg ha^{-1} every 14-d, disease severity was greater and few differences were seen among N sources. Potassium (K) fertilization reduced anthracnose severity regardless of K rate or K source. Critical soil K and leaf K concentration values affecting anthracnose severity were calculated to range from 43 to 70 mg kg^{-1} (Mehlich 3) and 19.3 to 23.1 g kg^{-1}, respectively, using nonlinear regression models (Cate-Nelson, linear plateau, and quadratic plateau). Plots with moderately acidic soil (pH < 5.5) and deficiencies in extractable soil Ca increased disease severity compared to plots with neutral (to slightly acidic) soil pH and adequate soil Ca. Optimum soil pH for reducing anthracnose severity and maintaining acceptable turfgrass quality of ABG putting green turf was between pH 6.0 and 6.5 and critical soil Ca concentrations ranged from 392 to 825 mg kg^{-1}. It is not clear whether acidic soil conditions and/or deficiencies in extractable Ca caused increased anthracnose severity and a reduction in turfgrass performance. Taken together, these studies clearly indicate that best management practices that include proper plant nutrition and possibly modification of soil pH are effective at reducing anthracnose severity and should be incorporated into an integrated disease control program.

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ANTHRACNOSE OF TURFGRASS

Anthracnose, caused by *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman (Crouch et al., 2006), is a destructive fungal disease that infects turfgrasses weakened by abiotic stresses induced by environmental factors or management practices (Smiley et al., 2005). The disease can be found on almost all cool-season turfgrass species throughout the world, but is particularly damaging on annual bluegrass (ABG) [*Poa annua* L. f. reptans (Hausskn) T. Koyama] turf (Smiley et al., 2005). Symptoms of anthracnose can appear as a foliar blight or basal rot; first appearing as a yellow or reddish brown discoloration of the foliage, and coalescing to form large areas of thinned turf as the disease progresses. A diagnostic feature of the disease is the distinctive fruiting bodies, called acervuli, produced *C. cereale*, which have hair-like setae protruding from them. Anthracnose can occur at almost any time throughout the year, but is generally more prevalent in the summer during periods of high-temperature stress. Several studies have shown that infection of ABG turf is intensified at high temperatures ($\geq$ 30 °C) and extended periods of leaf wetness (Danneberger et al., 1983; Danneberger et al., 1984; Vargas et al., 1993).

In 1909, Selby and Manns were the first to report anthracnose on Kentucky bluegrass (*Poa pratensis* L.; KBG) in Ohio. Twenty years later, Sprauge and Evaul (1930) identified this disease on ABG putting green turf in New Jersey, noting that significant

damage during the summer of 1928 on golf courses throughout the state was associated with unusually heavy rainfall and high temperatures. The disease was not reported again as a major problem of ABG putting greens in the U.S. for almost 40 years until several outbreaks occurred in Midwest and East Coast during mid-1960s to 1980s (Alexander, 1969; Vargus and Detweiler, 1985). These outbreaks prompted several studies investigating the pathogenicity and management of this disease (Danneberger et al., 1983; Danneberger et al. 1984; Jackson and Herting, 1985; Vargas and Detweiler, 1985). Over the past twenty years, there has been another resurgence of anthracnose on golf course putting greens, this time attributed to stressful management practices implemented to increase ball roll (e.g., low nitrogen rates, soil water, and mowing height) (Inguagiato et al., 2008; Vermeulen, 2003; Wong and Midland, 2004).

A considerable amount of research has been conducted and published on the impact of cultural management practices on anthracnose disease. These studies have investigated the effects of nitrogen fertility (Danneberger et al. 1983; Inguagiato et al., 2008; Roberts et al., 2010), sand topdressing (Hempfling et al., 2015; Inguagiato et al. 2012; Inguagiato et al., 2013; Roberts and Murphy, 2014), mowing practices (Inguagiato et al., 2009b), irrigation quantity (Danneberger et al., 1984; Roberts et al., 2011), plant growth regulators (Inguagiato et al., 2008; Inguagiato et al., 2009a; Inguagiato et al., 2010), lightweight rolling (Inguagiato et al., 2009b; Roberts et al., 2012), and verticutting (Inguagiato et al., 2008) on the severity of anthracnose on ABG putting green turf.

Nitrogen fertilization is one of the most important management factors that influences anthracnose severity of ABG turf. Several field studies have reported that

inadequate or excessive N fertilization can enhance the severity of this disease (Danneberger et al. 1983; Inguagiato et al., 2008; Roberts et al., 2010); a detailed review of this literature is presented in the following section (Nitrogen). Mowing (height and frequency) is another management practice that greatly influences anthracnose. Low mowing heights (2.8 mm) have been shown to increase disease severity; whereas, more frequent mowing (double cutting) had little effect on this disease (Inguagiato et al., 2009). Similarly, lightweight rolling did not influence the severity of anthracnose (Inguagiato et al., 2009; Roberts et al., 2012); contrary to the assumption that rolling would increase plant stress and disease susceptibility. Sand topdressing was another management practice that was thought to increase susceptibility to anthracnose. However, several studies have conclusively shown that aggressive sand topdressing programs (frequent, moderate-rate topdressing) actually reduces disease severity; regardless of incorporation method, sand shape, or foot traffic (Hempfling et al., 2015; Inguagiato et al., 2012; Roberts and Murphy, 2014). Additionally, research has shown that improper irrigation quantity, either drought stress (Danneberger et al., 1984; Roberts et al., 2011) or overwatering (Roberts et al., 2011), can exacerbate disease severity. Other management practices such as verticutting and application of plant growth regulators (ethephon, mefluidide, and trinexapac-ethyl) have been reported to either have no effect or slightly reduce the severity of anthracnose (Inguagiato et al., 2008; Inguagiato et al., 2009a; Inguagiato et al., 2010) on ABG putting green turf.

NITROGEN

Of the thirteen mineral nutrients that plants require for growth, nitrogen is required in the greatest quantity. Nitrogen is vital to plants because it is found in numerous compounds including chlorophyll, amino acids, proteins, nucleic acids, and enzymes (Beard, 1973; Carrow et al., 2001). Nitrogen is also found in compounds that serve as osmoregulants such as glycine, betaine and proline, which help plants adjust to stresses such as extremes in temperature and moisture (Carrow et al., 2001).

The primary forms of N that are available to plants are nitrate, ammonium, and urea; which can be taken up the roots or absorbed by leaves. Nitrogen uptake by roots is typically in the form of nitrate or ammonium and, under well-aerated conditions, the latter predominates. Once inside the plant, nitrate is reduced to ammonia or ammonium, which is quickly assimilated into amino acids (Carrow et al., 2001).

Nitrogen Fate Applied to Turfgrass

Plant uptake

Nitrogen uptake by roots (and removal in clippings) accounts for a significant amount of N applied to turfgrass. Initial work investigating N uptake by turfgrass roots focused on recovery of N from KBG clippings. Comprehensive research conducted by Hummel and Waddington (1981) examined the effect of various nitrogen sources on the recovery of N in KBG clippings. They found that between 46 to 52% of N was recovered from soluble N forms and sulfur coated urea (SCU), whereas, N recovery was much lower (15 to 29%) from less soluble sources such as ureaform, organiform, and sewage

sludge. These results were further confirmed by Hummel and Waddington (1984) while investigating the influence of N application rate and timing of different SCU materials on clipping yield and N uptake. They found the greatest recovery of N in clippings (49 to 59% of N applied) from a soluble N form (ammonium nitrate). There also appeared to be a linear response between N recovery and 7-d dissolution rate of SCU, with the greatest dissolution rate having the greatest N recovery. Starr and DeRoo (1981) found slightly lower N recovery in clippings from a KBG and red fescue (*Festuca rubra* L.) mixture. They also found that returning clippings increased turfgrass yield by 33%, compared to treatments that removed clippings. Interestingly, in the third year of this study ^{15}N labeled fertilizer was used to distinguish between N from fertilizer and organic N sources made available through mineralization. Until this point turfgrass researchers had not accounted for turnover of organic N sources through mineralization or atmospheric deposition of N when investigating N recovery.

Several recent field studies investigating N uptake in turfgrass have been carried out using ^{15}N labeled fertilizers in lysimeters. Miltner et al. (1996) found that approximately 35% of ^{15}N urea was recovered in KBG clippings over a 2-yr period. They also found that approximately 20% of labeled urea was found in the thatch and also in the soil after 2-yr. Engelsjord et al. (2004) investigated ^{15}N labeled fertilizer fate in both KBG and perennial ryegrass (*Lolium perenne* L.). In this trial, KBG recovery of ^{15}N from shoot tissue, thatch, and soil were 47, 20, 9%, respectively; whereas, the corresponding values for perennial ryegrass were 43, 10, 14% after one year of N treatments. Horgan et al. (2002b) found slightly lower N recovery values for KBG and also found season

variation in N recovery, with between 27 and 32% ^{15}N labeled KNO_3 recovered from the turfgrass plant during the spring and 20 – 22% recovered during the summer.

Studies have also been conducted to determine the influence of turfgrass species and cultivar on N recovery in clippings. Liu and Hull (2006) found differences in clipping yield and N recovery among three cool-season turfgrass species (KBG, Tall Fescue [*Schedonorus arundinaceae* (Schreb.) Dumort.], and perennial ryegrass). Of the three species, KBG and tall fescue had the greatest N recovery over the entire season; with these species increasing N recovery by >30% compared to perennial ryegrass. Similarly, Walker et al. (2007) found that tall fescue and KBG had greater dry matter yields compared to perennial ryegrass, but leaf tissue N was decreased in both species. However, significantly greater clipping yields in tall fescue and KBG resulted in greater N recovery for these two species compared to perennial ryegrass. Liu and Hull (2006) also investigated the effect of turfgrass cultivar (within three cool-season species) on N recovery and consistently found significant differences between KBG cultivars; whereas, few differences were seen in N recovery between both tall fescue and perennial ryegrass cultivars.

Volatilization

One of the potential losses of ammonia (NH_3) in turfgrass systems is through volatilization, which is the gaseous loss of N to the atmosphere. The process of ammonia volatilization from urea fertilizer can be described using the following reactions (Titko et al., 1987);

$$[1] \quad CO(NH_2)_2 + H^+ + 2H_2O + \text{urease} \rightarrow 2NH_4^+ + HCO_3^-$$

$$[2] \quad HCO_3^- + H^+ \rightleftharpoons CO_2(g) + H_2O$$

$$[3] \quad NH_4^+ + OH^- \rightleftharpoons NH_4OH \rightleftharpoons NH_3(g) + H_2O$$

In this process, urea undergoes enzymatic hydrolysis to form ammonium which is then decomposed to form ammonia. Nitrogen fertilizer sources including urea, isobutylidene (IBDU), sulfur-coated urea and ureaformaldehyde are prone to ammonia volatilization (Volk, 1959; Nelson et al., 1980; Torello et al., 1983; Titko et al., 1987; Knight et al., 2007). Initial work by Volk (1959) demonstrated that ammonia volatilization was the greatest on bare soils, with as much as 59% of N lost to the atmosphere. He also found that ammonia volatilization was greater for crystalline urea compared to pelleted urea; however, both had significant ammonia losses (average 7-d N loss of 29 and 21%, respectively). Several studies have also shown that use of slow-release fertilizers can significantly reduce ammonia volatilization in turfgrass (Nelson et al., 1980; Torello et al., 1983; Knight et al., 2007). For example, Knight et al. (2007) found that N loss from polymer-coated urea and methylene urea was significantly less than urea. Torello et al., (1983) also found that ammonia volatilization was decreased when sulfur-coated urea was applied, compared to prilled urea at the same rate.

Soil and environmental conditions can also have an effect on ammonia volatilization. Clay et al. (1990) found that volatilization was dependent on temperature, soil moisture, and soil pH, with the greatest volatility occurring when temperature and pH are increased, and soil moisture is decreased. Similarly, Titko et al. (1987) found increasing air temperature from 10 to 22°C resulted in a significant

increase in ammonia volatilization. Several studies have also shown that volatilization losses can be significantly reduced when irrigation is applied after urea applications (Titko et al., 1987; Bowman et al., 1987). Titko et al. (1987) reported a 96 and 66% decrease in ammonia losses from granular urea and dissolved urea, respectively, when irrigation was applied after treatment. Additionally, Bowman et al. (1987) reported volatilization losses of N as great as 36% of total N applied when no supplemental irrigation was administered; however, when as little as 1.0 cm of irrigation was applied, N losses were reduced to < 8%.

Immobilization

Immobilization of N in soils occurs when inorganic nitrate is assimilated into organic biomass (plant-unavailable form) by soil microorganisms (Frank and Guertal, 2013a). A substantial amount of N can be incorporated into microbial biomass (immobilized) rapidly following a fertilizer application (Bristow et al., 1987; Bowman et al., 1989; Engelsjord et al., 2004). Bowman et al. (1989) observed a rapid depletion of inorganic N in the time period between 30-min to 4-hr after application, which they attributed to biological immobilization. Bristow et al. (1987) found 37% of ^{15}N fertilizer was incorporated into microbial biomass two days after application, 32% of which was in the 0-5 cm soil layer. Similarly, Engelsjord et al. (2004) observed up to 38% ^{15}N labeled fertilizer was immobilized two days after application to KBG turf.

Several studies have shown that an appreciable amount of N can be immobilized in the thatch (Starr and DeRoo, 1981; Miltner et al., 1996; Engelsjord et al.,

2004). Miltner et al., (1996) found that 31% of spring applied ^{15}N fertilizer was recovered in the thatch 18-d after treatment to KBG turf. Engelsjord et al. (2004) reported 28 and 38% of ^{15}N labeled fertilizer immobilized in the thatch of perennial ryegrass and KBG, respectively. Differences in N immobilization between the two species in this study were attributed to discrepancies in organic matter content of the thatch; KBG turf had greater organic matter content (8%) compared to perennial ryegrass turf (2%). Although studies have shown a significant amount of N can be immobilized rapidly in soils, mineralization of organic N will become available to plants in the long term (Miltner et al., 1996).

Denitrification

The term denitrification refers to the gaseous loss of N in the form of nitrous oxide (N_20), nitric oxide (NO), or N_2 gas (Carrow et al., 2001). This process involves the reduction of nitrate to form one of the previously mentioned gases and can be described using the following reaction:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N2$$

Denitrification is facilitated by several groups of soil bacteria (i.e. *Bacillus* and *Pseudomonas*), which are mostly anaerobic; however, a few can function under aerobic conditions (Carrow et al., 2001; Wang and Skipper, 2004). Several factors have been shown to influence denitrification including: 1) presence of decomposable organic matter, 2) soil moisture and oxygen content, 3) soil temperature, 4) soil pH, 5) plant growth, and 6) nitrate level (Carrow et al., 2001).

Initial work by Mancino and Torello (1986) identified that soil type and irrigation treatment influenced denitrifier populations, but nitrogen rate did not. In this study, a silt soil type had greater denitrifier populations compared to silt loam soil, which was attributed to the greater water-holding capacity and greater organic matter content of the silt soil. It was also determined that denitrification was greater under irrigated conditions compared to non-irrigated. Later work by Mancino et al. (1988) found that denitrification losses were correlated with soil texture, percent soil saturation, and temperature. When soils were < 75% saturation, denitrification losses did not exceed 0.4% of total N applied; however, when soils were saturated, N losses were as much as 5.4% of N applied (incubated at 22°C) (Mancino et al. 1988). They also found a positive linear relationship between denitrification and soil temperature between 22 and 30°C, but denitrification did not increase above 30°C. Greatest N loss (92.6% of N applied) was observed in a saturated silt soil incubated at 30°C. Less dramatic losses of N were observed by Horgan et al. (2002a) using direct measurement of denitrification with ^{15}N labeled fertilizer. They observed large fluxes in N_2 and N_2O following heavy rainfall events, with maximum N losses of 7.3 and 3.9%, respectively.

A significant precipitation event following a fertilizer application (within 3-d) has also been shown to increase N_2O losses from perennial ryegrass (Bremer, 2006). Bremer (2006) also observed a rate response with respect to N_2O losses, with high rate urea applications (250 kg N ha^{-1} yr^{-1}) increasing N_2O emissions by 63% compared to a lower rate (50 kg N ha^{-1} yr^{-1}), regardless of N sources (urea vs. ammonium sulfate), which is in contrast to previous results investigating effect of N rate on N_2O emissions.

Bijoor et al. (2008) also observed increased N_2O fluxes due to high rate fertilizer applications (two rating dates). In general, it appears that large fluxes in N due to denitrification are only a major concern when soils are saturated, thus fertilizer application should not be made to soils that are saturated or when heavy rain is imminent because of the increased potential for denitrification and leaching.

Leaching

Nitrogen leaching can be defined as movement of nitrate anions by water deeper into the soil profile and possibly into the groundwater (Frank and Guertal, 2013a). Nitrogen leaching is important because: 1) high concentrations of nitrate in the groundwater can cause health issues for pregnant women and infants and 2) loss of nitrate though leaching can be substantial (especially in sandy soils) and thus economically and environmentally deleterious.

To date, many studies have been conducted to investigate N leaching in turfgrass systems. Specifically in cool-season turfgrasses, N leaching has been studied in KBG (Rieke and Ellis, 1973; Nelson et al., 1980; Geron et al., 1993; Milner et al., 1996; Petrovic, 2004; Frank et al., 2006), blends of KBG and tall fescue (Goss et al., 1990), and KBG and red fescue (Starr and DeRoo, 1981; Morton et al., 1988; Mangiafico and Guillard, 2006). Initial work by Rieke and Ellis (1974) identified several conditions in which nitrate leaching was the greatest: when annual N rates are high (290 kg N ha^{-1}); infrequent, high rate application of soluble N; high rainfall or irrigation rates; and in sandy soils. Frank et al. (2006) also found a greater concentration (5 kg N ha^{-1} at 637-

DAT) of ^{15}N labeled urea in leachate of KBG turf fertilized at a high rate (245 kg N ha^{-1}), confirming that fertilizer rate can influence N leaching, with greater N rates resulting in greater N loss. Several investigations have shown that N leaching can be reduced with the use of slow-release fertilizers (Nelson et al. 1980; Snyder et al. 1984; Shuman et al., 2006). Other studies have found that correct fertilizer rate and application timing can significantly reduce N leaching. Miltner et al. (1996) found that only 0.23% of ^{15}N labeled urea was recovered from leachate over a 2-yr period when N was applied at 196 kg N ha^{-1} yr^{-1}. Similar findings were reported by Engelsjord et al. (2004) in which they found very little ^{15}N labeled fertilizer at the 20 – 40 cm depth within one year when N was applied over six application at rate of 49 kg N ha^{-1}.

In sandy soils, N leaching can be substantial because of high saturated or near-saturated water conductivity rates of the soil. Because of this, sand-base putting greens are particularly prone to nitrate leaching. A considerable amount of literature has been published on nitrate leaching in golf greens (Brown et al. 1977; Mitchell et al. 1978; Brown et al. 1982; Mancino and Troll, 1990; Bigelow et al. 2001; Johnston et al. 2001). Brown et al. (1977) investigated how irrigation and N rate affected N leaching. In initial research, they found that N leaching was minimized when irrigation was applied near or at the evapotranspiration rate. They also found that N leaching was highest during winter which they attributed to high volumes of precipitation and limited turfgrass growth during this time. Johnston et al. (2001) found similar results, with greatest N leaching in the late fall and early spring when precipitation was high and turfgrass growth rate was low. While investigating soil mixtures and irrigation method, Mitchell

et al. (1978) found that nitrate leaching was the greatest in soil mixtures that had high permeability and that leaching was increased by subsurface irrigation. More recent research on rootzone amendments by Bigelow et al. (2001) has shown that soil amendments can significantly reduce ammonium leaching compared to non-amended sand, with ammonium leaching inversely related to the CEC of the amendment. However, none of the amendments studied effectively decreased nitrate leaching. In general, it appears N leaching is only a major concern during periods of heavy precipitation or when poor irrigation management is employed.

Nitrogen Effect on Turfgrasses

Nitrogen is one of the most important components of turfgrass nutrition because of the relatively large quantity of N required for turfgrass growth (compared to all other macro- and micronutrients). The amount of N typically found in turfgrass tissue ranges from 2 to 6% compared to P and K which are <1 and <3%, respectively (Beard, 1973; Carrow et al., 2001). Nitrogen plays a key role in influencing numerous plant responses such as: color, shoot growth, shoot density, root growth, rhizome and stolon growth, carbohydrate reserves, stress tolerance, thatch accumulation, and recuperative potential (Beard, 1973; Carrow et al., 2001).

In turfgrass systems, N is typically applied to match turfgrass growth. For cool-season turfgrass, this means that the majority of N is applied in the late spring and early fall when growth rate is the greatest. Nitrogen application during this time period is important for recovery from injury and enhances turf density, as well as to promote root

growth prior to summer stress. Low-rate soluble applications of N are also required during the summer months on high value turf areas, such as putting greens, to maintain acceptable quality. As temperature decrease in early fall, turfgrass growth rate increases, and N fertilization is essential for recovery from summer stresses (heat, pests, and drought). Nitrogen requirement during late fall is significantly reduced due to decreased turfgrass growth rate and limited N uptake. It is also thought that late fall application of N to ABG can cause increased seed production the following spring (Carrow et al., 2001).

Annual bluegrass growth

Since ABG is generally considered a weed, limited field research has investigated its N requirements in a monostand; most research has been conducted on a polystand of bentgrass and ABG (Dest and Guillard, 1987; Gaussoin and Branham, 1989; Lawson, 2000; Schlossberg and Schmidt, 2007). Previous research investigating the effect of N on bentgrass-ABG community structure has shown that bentgrass populations increased when N was withheld for 3-yrs, suggesting ABG has a greater N requirement than bentgrasses (Dest and Guillard, 1987). Research also has proven that N timing and rate can influence ABG growth. Dest and Allinson (1981) found that frequent, low-rate N application (12 kg N ha^{-1}) consistently provided acceptable turfgrass quality regardless of P rate. They also recommended that N application > 12 kg N ha^{-1} should not be made to ABG from late June through July. Gaussoin and Branham (1989) noted that N fertility only affected ABG population in 1 out of 3 years,

with plots receiving 98 kg N ha^{-1} yr^{-1} having significantly less ABG than plots receiving 293 kg N ha^{-1} yr^{-1}.

Several studies have investigated the effect of nitrogen form (nitrate vs. ammonium) on ABG growth. Eggens and Wright (1985) determined that ABG favors nitrate-N over ammonium, with maximum growth (shoot, root and tiller numbers) occurring at 75% nitrate-N and 25% ammonium-N. Later work by Eggens et al. (1987) confirmed these results and suggested that low soil pH due to increasing ammonium-N concentration inhibited ABG growth. Lawson (2000) observed that fertilization with ammonium nitrate significantly increased ABG populations in a red fescue (*Festuca rubra* L.)/colonial bentgrass (*Agrostis capillaries* L.) mixture compared to ammonium sulfate. He also concluded that differences between N sources were likely due to their differential effects on soil pH.

Turfgrass Diseases

Nitrogen rate has been shown to influence disease severity in turfgrass. Excessive levels of N have been shown to increase severity of grey leaf spot (*Pyricularia grisea* [Cooke) Sacc.) (Freeman. 1964; Williams et al., 2001), brown patch (*Rhizoctonia solani* Kuhn) (Bloom and Couch, 1960; Burpee, 1995; Ebdon, 2005), leaf spot (*Bipolaris* spp.) (Cheesman et al., 1965; Funk, 1967; Funk et al., 1966; Halisky et al., 1966), typhula blight (*Typhula incarnate* Fr.) (Ebdon, 2005), Pythium (*Pythium* spp.) (Freeman, 1974), and Microdochium patch (*Microdochium nirvale* [Fr.] Samuels & I.C. Hallett) (Goss and Gould, 1968; Madison et al., 1960; Raike et al., 1997). High N rates can cause an

imbalance in other nutrients such as phosphorus (P) and potassium (K), which could lead to increased disease severity. In contrast, high levels of N can reduce severity of dollar spot (*Sclerotinia homoeocarpa* F.T. Bennet) (Cook et al., 1964; Davis and Dernoeden, 2002; DeFrance, 1938; Golembiewski and Danneberger, 1998; Landschoot and McNitt, 1997; Markland et al. 1969; Ryan et al., 2011; Smith, 1955; Smith, 1956a; Teuton et al., 2007; William et al., 1996), anthracnose (*Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman) (Inguagiato et al., 2008; Roberts et al., 2010; Uddin et al., 2009), red thread (*Laetisaria fuciformis* [McAlpine] Burdsall) (Cahill et al., 1983; Gould and Goss, 1967; Muse and Couch, 1964; Raikes et al., 1997; Smith, 1954; Tredway et al., 2001; Woolhouse, 1986), rust (*Puccinia* spp.) (Couch, 1995; Roberts, 1963), and bentgrass dead spot (*Ophiosphaerella Agrostis* Dernoeden, M.P.S. Câmara, N.R. O'Neill, van Berkum et M.E. Palm) (Kaminski and Dernoeden, 2005). Couch and Bloom (1960) suggest that the benefit of high N fertilization is a result of rapid plant recovery (growth) from disease, rather than enhancing a plant's resistance to infection.

Nitrogen form can also affect turfgrass disease severity by modifying soil pH. Nitrogen forms such as ammonium sulfate, ammonium nitrate, and urea can acidify soils, especially those that are weakly buffered. Other sources like potassium nitrate and calcium nitrate can increase soil pH (more alkaline). Disease such as Microdochium patch, take-all patch (*Gaeumannomyces graminis* var. *graminis* [Sacc.] Arx & D.L. Olivier), and summer patch (*Magnaporthe poae* Landschoot & Jackson) have been shown to be strongly affected by N source and soil pH (Davis and Dernoeden, 1991; Hill et al., 2001; Jackson, 1958; Robinson, 1980; Thompson et al., 1993; Thompson et al.,

1995). The effect of nitrogen form on soil pH and turfgrass disease severity is discussed further in the soil acidity section.

Nitrogen fertilization rate and timing have been shown to affect anthracnose severity in turfgrass. Initial work on the effect of nitrogen rate and time on anthracnose severity was done by Danneberger et al. (1983). They found that moderate rates of N (146 kg N ha^{-1}) had less disease incidence than higher N rate (292 kg N ha^{-1}) on ABG turf maintained at 1.3 cm (fairway height). They also found that moderate rates of N in combination with fungicides provided the greatest reduction in anthracnose severity. Data from this trial also suggested that spring applications of N increased disease incidence compared to summer applications. Several recent studies have investigated the effect of low rate soluble application of N on anthracnose severity of ABG putting green turf and have reported contradictory results with regard to N rate and timing. Inguagiato et al. (2008) found that ammonium nitrate application at 4.9 kg ha^{-1} every 7-d from May through September reduced disease severity compared to the same rate every 28-d. Similarly, Roberts et al. (2010) found that 4.9 kg ha^{-1} wk^{-1} or 9.8 kg ha^{-1} 2-wk^{-1} provided the greatest reduction in disease severity compared to lower rates. They also found that initiating N fertilization before symptoms of the disease are evident (mid-May) was more effective at controlling the disease than initiating N fertilization during disease onset (mid-June). Together these studies indicate that both inadequate and excessive amounts of N can increase anthracnose severity; however, it is unclear exactly what annual rate of N (between 146 and 292 kg N ha^{-1} yr^{-1}) is excessive.

POTASSIUM

Potassium (K) is an important nutrient for turfgrass growth and is required in relatively large quantities, second only to N (Frank and Guertal, 2013b). Potassium ions are taken up from the soil solution by plant roots, and once inside are highly mobile but also highly regulated by K-channels (Carrow et al., 2001; Frank and Guertal, 2013b), which facilitate diffusion of K ions across cell membranes (Hedrich et al., 2011). Unlike all other plant essential nutrients, K is not a constituent of any plant compound (Carrow et al., 2001). However, K has many important functions in plants including: activation of enzymes, water regulation (osmoregulation), energy regulation, translocation of sugars (sucrose), and protein synthesis (Carrow et al., 2001; Frank and Guertal, 2013b; Jackson and Volk, 1968; Liebhardt, 1968; Wilson and Evans, 1968).

Potassium Fate in Turfgrass

Plant uptake

Potassium uptake by plants has been studied for almost a century (Bartholomew and Janssen, 1929); however, our understanding of the role of K nutrition in turfgrass is not fully understood. Initial work by Bartholomew and Janssen (1929), investigated the effect of K rate on tissues K content and yield of agronomic crops in field and greenhouse studies. Several important findings came out of this initial work including the concept of luxury consumption of K in plants, which is when a plant takes up more K than is required for growth. Bartholomew and Janssen (1929) also observed

that plants could absorb a considerable amount of K early in the growing season and that K could be translocated throughout the plant as it matures.

In contrast to earlier research, more recent K studies in turfgrass have failed to demonstrate a correlation between plant tissue K content and clipping yield, turf quality, or soil test K (Ebdon et al., 1999; Fitzpatrick and Guillard, 2004; Sartain, 2002; Webster and Ebdon, 2005). Ebdon et al., (1999) reported that K applied alone had no effect on KBG growth, but interaction with N and P resulted in a varied growth response. Fitzpatrick and Guillard (2004) compared rates of K (0 to 243 kg N ha^{-1} yr^{-1}) across varying N rates and found no positive effect of K fertilization on clipping yield and KBG quality even though soil test K levels were low. Interestingly, K content in the clippings was maximized when moderate rates of K (82 to 161 kg N ha^{-1} yr^{-1}) were applied compared to higher and lower rates. Webster and Ebdon (2005) observed a linear relationship between K rate (49 to 441 kg N ha^{-1} yr^{-1}) and both tissue K concentration of perennial ryegrass and soil exchangeable K, but tissue K and soil K were not correlated. Johnson et al., (2003) reported a weak relationship between K fertilization rate and tissue K concentration in creeping bentgrass (*Agrostis stolonifera* L.).

Several studies have failed to show a correlation between soil exchangeable K and tissue K concentration in cool-season turfgrasses (Dest and Guillard, 2001; Fitzpatrick and Guillard, 2004; Johnson et al., 2003; Webster and Ebdon, 2005; Woods et al., 2006). Woods et al. (2006) observed no correlation between tissue K concentration and soil K following an application of K at rates ranging from 10 to 60 kg K ha^{-1} every 14-

d^{-1} even when soil K was extracted using various methods (1 *M* NH_4OAC, Mehlich 3, Morgan, 0.01 *M* SrCl2, and 1:5 H2O). They speculated that the lack of correlation was due to nonexchangeable K being released into exchangeable and soluble forms.

Interaction with other nutrients

Interactions between K and other plant nutrients, including macronutrients (N and P) and base cations (Ca^{2+} and Mg^{2+}), can influence the uptake of K. Interactions with calcium (Ca) and magnesium (Mg) are particularly important because they can inhibit the uptake of K (Carrow et al., 2001). Stanford et al. (1942) were the first to observe that Ca and Mg could influence the uptake of K in corn (*Zea mays* L.), and that K applications could suppress the uptake of Ca and Mg in "high-lime" (calcareous) soils. In turfgrass, several studies have investigated the interaction between K, Ca, and Mg (Cripps et al., 1989; Miller, 1999; Sartain, 1993; Waddington et al., 1972; Woods et al., 2006). Sartain (1993) demonstrated that K and Mg applications (200 kg ha^{-1} 60-d^{-1} each) could reduce soil Ca to levels below that of the untreated check. Cripps et al. (1989) found that K fertilizations increased K concentration in the leaf tissue of bermudagrass [*Cynodon dactylon* (L.) Pers.], but decreased plant Ca and Mg concentrations. Miller (1999) also observed that excessive soil K can reduce Ca and Mg in both the soil and tissue of bermudagrass. Potassium fertilization of creeping bentgrass has also been shown to decrease Ca and Mg in both the soil and plant tissue; however, these changes were not considered detrimental to turf growth (Waddington et al., 1972). Conversely, research has suggested that calcareous, sand-based putting greens with high levels of Ca, may repress K uptake of creeping bentgrass (Woods et al., 2006).

Research has also focused on the interaction between N and K, as well as the interaction between P and K. Early work by Christians et al. (1979) found an interaction between N and K fertilization on creeping bentgrass turf, reporting that reduced levels of N were required to attain maximum turf quality as the rate of K was increased. Trenholm et al. (1998) also observed an interaction between N and K with respect to shoot and root growth, maximizing both parameters when N and K were applied at 9.8 and 4.9 kg ha^{-1} mo^{-1}, respectively. Interactions between N and K also appear to influence stress tolerance of turfgrass (Ebdon et al. 1999; Websters and Ebdon, 2005), which will be discussed in the following section. In addition to N, the literature has also shown that K can interact with P (Fry et al., 1989; Waddington et al., 1978). Waddington et al. (1978) reported that ABG populations were influenced by a P and K interaction, with the greatest ABG population observed at the highest rates of P and K (195 kg P ha^{-1} and 152 kg K ha^{-1}). Fry et al. (1989) also observed a weak interaction (1 out of 5 years) between P and K; K applied at 8 kg K ha^{-1} mo^{-1} slightly improved creeping bentgrass quality at increasing P rates compared to non-K treated plots.

Runoff and leaching

Studies investigating the loss of K from turfgrass systems are somewhat limited, especially those using a lysimeter; however, several have reported that K can be lost via leaching and runoff. High sand content putting greens have been shown to be particularly susceptible to leaching of exchangeable K (Johnson et al., 2003; Lodge and Lawson, 1993; Sheard et al., 1985). High rainfall rates, high irrigation rates, and/or appreciable amounts of Na, Ca, or Mg in the soil solution can exacerbate leaching of K

(Carrow et al., 2001). Sheard et al. (1985) measured the loss of K from two sand types (alkaline and acid sand) using lysimeters and found that 34% of applied K was leached in the acid sand compared to only 17 % in the alkaline sands. While investigating rootzone construction and irrigation rates, Lodge and Lawson (1993) observed a decrease in soil K content as irrigation rates increased, speculating that the decrease was a result of leaching. Johnson et al. (2003) measured extractable K at various depths (0 to 7.5, 7.5 to 15, 15 to 22.5, and 22.5 to 30 cm depths) in creeping bentgrass turf grown on a sand-based rootzone, and found downward K movement through the soil profile indicative of leaching, but did not directly measure leachate exiting the root zone.

Only one study in a turfgrass system has investigated the loss of K though storm water runoff (Kelling and Peterson, 1975). In this study, K concentrations in runoff were measured following a simulated rainfall event (18 cm of rain over 90 min) applied to nine home lawns following applications of K at rates between 41 and 186 kg K ha^{-1}. Results from this trial indicate that runoff of K was relatively high (maximum of 23 mg L^{-1}, or 10% of K applied) when soil infiltration rates were low (< 3 cm hr^{-1}).

Soil Tests for Potassium

Soil tests for K have been commonly used for years to estimate fertilizer requirements for crops. Rapid chemical extractions that measure soil K usually extract both exchangeable K and soil solution K as an index for K availability (Frank and Guertal, 2013b; Haby et al., 1990). Numerous K extraction methods have been used in the United States and Canada to estimate K availability in soils, including the ammonium

acetate, Baker, Bray, Mehlich I, Kelowna, Mechlich III, Mississippi, Morgan, modified Morgan, Olsen, Soltanpour, and Texas methods (Haby et al., 1990). Of the extraction methods, the 1 *M* ammonium acetate (NH_4OAc) extraction method (Knudsen et al., 1982) is most commonly used for K (Carrow et al., 2001; Haby et al., 1990). Neutral 1 *M* ammonium acetate is considered a "universal" extractant because it can remove several elements from soil in one extraction (Haby et al., 1990). The Mehlich III method (Mehlich, 1984) is another "universal" extractant that was developed for neutral to acidic soils (non-calcareous). This soil test extractant utilizes a weak acid which removes approximately 20% more K than 1 *M* ammonium acetate method, due to the partial removal of the nonexchangeable K fraction, but the two methods are highly correlated to each other (Carrow et al., 2001; Haby et al., 1990). Woods et al. (2006) compared three commonly used K extraction methods (NH_4OAc, Mehlich III, Morgan) and found that while each differed in extractable K, all extractants were able to detect changes in soil K as a result of fertilizer treatments.

Potassium Effect on Turfgrass

Stress tolerance

The role of K in stress tolerance of turfgrasses has been well documented in the literature, affecting drought, heat, wear, and cold tolerance. Potassium applications have been shown to reduce drought stress (Carroll and Petrovic, 1991a; Ebdon et al., 1999; Waddington et al., 1978). Waddington et al., (1978) observed less severe wilting when K was applied to a creeping bentgrass putting green (maintained at 5 mm). Carroll

and Petrovic (1991a) found a varied response to K at different N application rates applied to KBG turf; when low rates of N (35 kg N ha^{-1}) were applied K applications increased leaf turgor pressure and leaf tissue solute levels. However, when N was applied at a high rate (175 kg N ha^{-1}), excessive top (leaf) growth reduced tissue solute levels, thus counteracting the beneficial effects of K applications. Similarly, at moderate rates of N and P (147 kg N ha^{-1} yr^{-1} and 21.5 kg P ha^{-1} yr^{-1}), increasing rates of K minimized water use of KBG; whereas, at higher rates of N and P (294 kg N ha^{-1} yr^{-1} and 43 kg P ha^{-1} yr^{-1}) water use was increased as K rate increased (Ebdon et al. 1999). Moreover, Schmidt and Breuninger (1981) observed faster recovery for drought stress when K was applied, regardless of N and P fertilization. In contrast, Dipaola and Engel (1976) observed no improvement in desiccation resistance or changes in final root weights of creeping bentgrass from applications of K.

Potassium nutrition has also been associated with heat tolerance in turfgrass (Jiang and Huang, 2001; Pellett and Roberts, 1963; Shen et al., 2009). Pellett and Roberts (1963) reported that high N in combination with high K rates applied to KBG improved heat resistance compared to high N with low K rates. Jiang and Huang (2001) observed that K ion concentrations in cell sap of drought-preconditioned KBG plants were greater than non-precondition plants, resulting in greater turf quality throughout the entire heat stress period. In a study comparing the heat tolerance of KBG to bermudagrass, Shen et al. (2009) found that heat stress reduced the K concentration of KBG, whereas, K concentration in bermudagrass was not influenced by heat stress.

Numerous studies have investigated the effect of K fertilization on wear tolerance of turfgrass (Carroll and Petrovic, 1991b; Carrow et al., 1987; Hawes and Decker, 1977; Hoffman et al., 2010a, 2010b; Shearman and Beard, 1975; Trenholm et al., 2001); however, mixed results have been observed. Shearman and Beard (1975) were the first to report the association between K fertilization and wear tolerance. They reported that K applied at 270 to 360 kg K ha^{-1} yr^{-1} improved wear tolerance significantly, as well as, load bearing capacity and leaf tensile strength of creeping bentgrass compared to lower rates of K. In a recent study, Hoffman et al. (2010a) reported K applications improved recovery from differential slip wear treatments when measured 2-wk after application; however, a reduction in wear tolerance with increasing K rate was observed when a grooming brush was applied to perennial ryegrass. Other studies have failed to show a correlation between K and wear tolerance (Carroll and Petrovic, 1991b; Carrow et al., 1987; Hawes and Decker, 1977; Hoffman et al., 2010b; Trenholm et al., 2001). Failure to produce any improvement in wear tolerance from K applications in these studies was most likely due to elevated soil test K levels prior to treatment applications.

Many studies have evaluated the influence of K fertilization on cold tolerance and winterkill in warm-season grasses (Adams and Twersky, 1960; Belesky and Wilkinson, 1983; Gilbert and Davis, 1971; Juska and Murray, 1974; Keisling et al., 1979; Miller and Dickens, 1996a, 1996b; Reeves et al., 1970). In contrast, the number of studies that have investigated the effect of K fertilization on cold tolerance and winterkill in cool-season grasses is limited (Razmjoo and Kaneko, 1993; Schmid et al.,

2016; Webster and Ebdon, 2005). Webster and Ebdon (2005) reported that cold hardiness (whole plant survival and electrolyte leakage) of perennial ryegrass was maximized when K was applied between 245 and 441 kg K ha^{-1} yr^{-1} in combination with moderate rates of N (49 to 147 kg N ha^{-1} yr^{-1}); whereas increased freeze damage was observed when high rates of N (343 to 441 kg N ha^{-1} yr^{-1}) were applied with similar rates of K. Razmjoo and Kaneko (1993) also showed that K influenced winter hardiness of perennial ryegrass, with increasing K rate up to 350 kg K ha^{-1}, reducing electrolyte leakage; no additional benefits were seen from increasing K rate above this point. Observations of winter injury on ABG putting green turf in NJ indicated that K fertilization, regardless of rate or source, reduced winter injury compared to the untreated control (Schmid et al., 2016). Additionally, when plants from this study were taken to a growth chamber, the lethal temperature (LT_{50}; temperature at which 50% of plants are killed) was decreased in plants that received K fertilization compared to plants that received no K fertilization; meaning K fertilized plants could withstand colder temperatures.

Diseases

Contrary to N fertilization, much less information is available regarding the relationship between K applications and disease incidence of turfgrasses, and much of the literature is contradictory. It has been suggested that several diseases of cool-season grasses are influenced by K, including: dollar spot, brown patch, red thread, take-all patch, Microdochium patch, and Typhula blight (Goss, 1969; Goss and Gould, 1967; Markland et al., 1969; Moody, 2011; Waddington et al., 1978; Webster and Ebdon,

2005; Woods et al., 2006). While investigating the effect of N sources (Miloganite, Agrinite, and sodium nitrate) on creeping bentgrass turf, Markland et al. (1969) noted a correlation (r = 0.826) between dollar spot incidence and tissue K content, with increasing K content (from 25 to 32.5 g kg^{-1}) resulting in reduced dollar spot incidence. This result was surprising since K was applied uniformly (at 49 kg K ha^{-1} yr^{-1}) to the all treatments. The authors attributed increasing tissue K content to high N rate (488 kg N ha^{-1} yr^{-1}) increasing uptake of K, thus the decrease in disease incidence is most likely a response to N rate. Other studies have failed to demonstrate a relationship between K fertilization and dollar spot incidence when soil K was either deficient (Waddington et al., 1978) or within a moderate range (50 to 125 mg kg^{-1}) (Woods et al., 2006). Interestingly, Waddington et al. (1978) did, however, observe an increase in brown patch severity when K applications were made to soils with deficient K content compared to the untreated check. Goss (1969) reported that K fertilization influenced both red thread and take-all patch, with K applications resulting in reduced incidence of both diseases, but no soil test data was reported. Goss and Gould (1967) also found that K fertilization to soils with "sufficiently high" soil K (167 to 560 kg ha^{-1}, Morgan extract method) reduced take-all patch in colonial bentgrass. In contrast, Cahill (1983) observed that increasing N rate (up to 219 kg N ha^{-1}) decreased red thread severity regardless of K rate; however, an interaction between N and K indicated that a moderate rate of N (194 kg N ha^{-1}) in combination with a moderate rate K (135 kg K ha^{-1}) reduced disease severity compared to no K and higher rates of K (0 and 270 kg ha^{-1} K)

applied at the same rate of N. No soil test data was reported in this study either, so it is unclear whether the soil was deficient in K prior to treatment applications.

Several studies have shown a reduction in Microdochium patch on colonial bentgrass when K is applied with moderate levels of N (292 kg N ha^{-1}), but K fertilization had little effect on disease severity at higher rates of N (Brauen et al., 1975; Goss, 1969; Goss and Gould, 1968). Interestingly, Goss and Gould (1968) observed an interaction between P and K, where increasing K rates resulted in increased Microdochium patch in the absence of P. This is further confounded by the fact that neither P nor K were deficient in the soil prior to treatment applications. Moody (2011) reported no correlation between tissue K content and Microdochium patch. Other studies have shown that K can influence Typhula blight (*T. incarnata*) (Moody, 2011; Webster and Ebdon, 2005; Woods et al., 2006). Moody (2011) and Woods et al. (2005) both observed increased disease severity when extremely high rates of soluble K (> 20 kg ha^{-1} 10-d^{-1} or 30 kg ha^{-1} 14-d^{-1}) were applied in combination with moderate levels of N (~ 4.9 kg N ha^{-1} 7-d^{-1}) to calcareous sand which exhibited low or medium levels of soil K. Under sufficient soil K conditions (134 to 232 mg kg^{-1}, Morgan extraction method), Webster and Ebdon (2005) reported an increase in Typhula blight (*T. incarnata*) only when K fertilization was applied in combination with high rates of N (343 to 441 kg N ha^{-1} yr^{-1}). To date, no studies have investigated the effect of K fertilization on anthracnose disease of ABG turf.

After a review of the literature, no clear patterns emerge as to the effect of K fertilization on disease severity of cool-season turfgrasses. Lack of soil test data and lack

of uniformity in soil test methods make it difficult to compare between studies. Also interactions between K and other macronutrients (N and P) appear to be important, influencing disease responses and making it difficult to determine the effect of K fertilization. However, several patterns have emerged from previous research investigating the effect of K on cool-season turf diseases including: 1) nutrient imbalances in the soil and/or plant tissue can increase susceptibility to diseases, and 2) exceptionally high rates of nutrients (N, P, and K) can also increase disease severity.

SOIL ACIDITY

Soil reaction is the degree of acidity or alkalinity and can be expressed as pH [= -log (H+)] (Sparks, 2003). Soils with a pH < 7 are considered acidic, while those with a pH > 7 are considered alkaline. Since pH is measured on a logarithmic scale, a soil pH of 6 has a 10-fold increase in H+ activity compared to a soil pH of 7 and a 100-fold increase compared to a soil pH of 8.

For more than a half century, there was a great debate over the cause of soil acidity. The study of soil acidity has even been aptly described as a 'merry-go-round' because of terminology changes, more precise analytical equipment, and improvements in our understanding of soils (Jenny, 1961)

Materials and Reactions Responsible for Soil Acidity

The acidity of a soil is largely determined by the composition of the soil and the ion exchange and hydrolysis reaction associated with various soil components (Thomas and Hargrove, 1984). Most of the total acidity in soil comes from H^+ and Al^{+3} on soil colloids. At pH < 5.0, exchangeable Al^{+3} is the primary source of H^+ and thus acidity in soils (Carrow et al., 2001). Under these conditions (pH < 5), exchangeable Al^{+3} that is associated with cation exchange sites (CEC) of clay particles and organic matter becomes hydrolyzed and releases H^+ ions (and $Al(OH)^{+2}$) into the soil solution. Previous research by Brown and Hutchinson (1979) reported that exchangeable Al^{+3} in a Caribou loam decreased as soil pH was increased from 4.0 to 5.5 confirming the effect of Al^{+3} at low pH. In sand based rootzones, little to no clay is present, so Al^{+3} toxicity is not a

major concern. Exchangeable H^+ is another source of acidity that is also present on CEC sites at low soil pH (<5.0) (Carrow et al., 2001). At low pH, an appreciable amount of H^+ is tightly bound to clay structures and organic matter and is considered bound H^+. The impact of bound H^+ on soil pH is relatively minimal since only small quantities are released in to soil solution.

In moderately acidic conditions (pH 5 – 6.5) hydroxyl-Al ($Al(OH)^{+2}$ and $Al(OH)_2^+$) on CEC sites and in the soil solution become hydrolyzed and produce H^+ ions. An additional source of H^+ in soils is associated with hydroxyl-Al movement into clay interlayers, where H+ is released from interlayers as soil pH increases (Carrow et al., 2001). Several studies have documented the role of hydroxyl-Al association clay interlayers in moderately acidic conditions (Coleman and Thomas, 1964; Schwertmann and Jackson, 1964; Volk and Jackson, 1964).

The total acidity of a soil can be divided into three distinct classes: active acidity, salt-replaceable acidity, and residual acidity (Carrow et al., 2001). Active acidity is what is typically measured when testing soil pH and is a measure of H^+ in the soil solution. Salt-replaceable acidity is all of the H^+, Al^{+3}, and hydroxyl-Al cations associated with CEC sites on clay particles and organic matter that can be replaced by other cations. Finally, residual acidity is any bound or interlayer H^+ and Al^{+3} that cannot be easily replaced by other cations. When appreciable amounts of clay and organic matter content are found in a soil, salt-replaceable and residual acidity often account for much

more of the total acidity than active acidity. The combination of salt-replacement and residual acidity has been termed potential acidity.

In addition to the source of acidity mentioned above, soluble acids such as those formed by fertilizers can have a strong influence on soil pH. Although the influence of these soluble acids can be transient, the effect on acidity of soils with little buffer capacity can be significant (Thomas and Hargrove, 1984). This is especially true for fertilizers that contain ammonium (NH_4^+). During nitrification of NH_4^+ to NO_2^-, high concentrations of HNO_3 and H_2SO_4 can be produced in the soil (Thomas and Hargrove, 1984). Blevins et al. (1977) showed that this effect is more pronounced under no-tillage systems, with non-tilled soils resulting in greater decreases in soil pH from ammonium nitrate applications than conventional tillage; however, no explanation was given for the difference in soil pH. These results suggest that golf course putting greens (sand based) can be especially susceptible to dramatic changes in soil pH due to acidifying fertilizers. Of the nitrogen forms commonly used in turfgrass systems, sulfur-coated urea and ammonium sulfate have the highest equivalent acidity, followed by urea, ammonium nitrate and IBDU (Carrow et al. 2001). Other N forms such as potassium nitrate, sodium nitrate, and calcium nitrate are basic and can cause a modest increase in soil pH, especially in poorly buffered soils.

Measurement of Soil pH

Soil pH is the most commonly measured soil characteristic. The measurement of pH in soil is usually determined in a 1:1 soil-to-water mixture (Mclean, 1982);

however, others have suggested the use of $CaCl_2$ solution to minimize the suspension effect and variability due to salt content (Schofield and Taylor, 1955). Soil pH measurements in North America are also taken using the saturated paste method or a 1:2 soil/water suspension (Miller and Kissel, 2010). A recent survey of laboratories enrolled in the North American Proficiency Testing (NAPT) Program by Miller and Kissel (2010) showed that approximately 55% of laboratories performed soil pH measurements using 1:1 soil/water suspension.

Studies of pH measurements in a soil/water suspension using a glass electrode have been well documented. Keaton (1938) and Davis (1943) have both shown that decreasing the soil/water ratio will increase pH. Keaton showed that 1:10 soil/water solutions had pH values between 0.35 to 0.40 pH units higher than pH measured with a 1:1 soil/water ratio. Davis demonstrated that as soil moisture content decreased (increasing soil/water ratio), initial pH readings of the solution decreased. A survey by Miller and Kissel (2010) of soil testing laboratories found that soil pH measurements using saturated paste method were 0.16 pH units lower than 1:1 soil/water solution.

The suspension effect is one of the more controversial aspects of soil pH measurement and is defined as a reduction in pH due to electrodes in contact with a soil suspension rather than a supernatant solution above the suspension (Coleman et al., 1951; Thomas, 1996). It is commonly accepted that this phenomenon is real; however, there is debate over the interpretation of what is occurring. There are two basic theories (interpretations) as to what is causing the suspension effect in soils. The first argues that H^+ near the clay surface dissociates enough to affect pH when the electrode

is near the clay particle surface (Marshall, 1964). The second theory suggests that the suspension effect is primarily caused by the electrical charge of soil, affecting mobility of K+ and Cl- and creating a salt bridge when in contact with a soil suspension or sediment (Coleman et al. 1951). The latter theory was confirmed by Olsen and Robbins (1971) and is generally accepted as the true cause of the suspension effect.

Salt content in the soil solution can be a major factor influencing soil pH measurements. Soluble salt accumulation in the soil is associated with natural salt sources, fertilizers, soil amendments, and crop residue incorporation (Miller and Kissel, 2010) and, in general, have a tendency to lower pH values as the concentration of salt (electrical conductivity; EC) increases (Thomas, 1996). The effect of salt on pH has been demonstrated in the literature by comparing pH values obtain using 1:1 soil/water solution and those obtained using 1:1 $CaCl_2$ solution (Miller and Kissel, 2010; Schofield and Taylor, 1995; Sumner, 1994). It has been hypothesized that the reduction in pH is due to the exchange of Ca^{2+} with H^{+} and Al^{3+} on soil surface (Miller and Kissel, 2010). Season variations in weather conditions (wet vs. dry) can also cause differences in salt content, making it difficult to compare pH values from different times in a year. Data from Shuman et al. (1983) demonstrated the seasonal effect on soil pH, where they found that soil pH (measured in water) for all treatments (lime, acid, and control) generally decreased during the summer months and increased during the winter. Kissel et al. (2009) showed the effect of wet and dry weather on soil pH measured in 1:1 soil/water solution. In wet winters (Nov. – March), soluble salts in the soil profile were diluted which resulted in higher pH values compared to dry winters. In studies

investigating the effect of N source on soil acidity Pierre et al. (1970) found substantial differences in soil pH (as much as 0.93 pH units) between leached and non-leached soils, with leached soils having higher soil pH values. Salt concentrations in the soil solution is one of the most important factors affecting the measurement of soil pH. Increases in salt concentrations in the soil solution can interact with the glass electrode measuring soil pH and cause dramatic a decrease in soil pH (0.5 pH units) (Sumner, 1994). For these reasons, soil pH should be measured at the same time of the year each season to limit the effect of seasonal variation.

Neutralizing Soil Acidity

Mechanism and products

The reaction in which $CaCO_3$ neutralizes soil acidity is complex and the rate of neutralization, as well as the final reaction products, is not understood completely. However, the effect of limestone on soil pH has been studied extensively and has been summarized by Coleman et al. (1959).

The reaction for dissolution and hydrolysis of $CaCO_3$ in water is as follows:

$$CaCO_3 + H_20 \rightarrow Ca^{2+} + HCO_3^- + OH^-$$

Thomas and Hargrove (1984) generalized the overall reaction of limestone with an acid soil as:

$$2Al\text{-soil} + 3CaCO_3 + 3H_2O \rightarrow 3Ca\text{-soil} + 2Al(OH)_3 + 3CO_2$$

Exchangeable Ca^{2+} and Mg^{+}, hydroxyl-Al ($Al(OH)_3$), and hydroxyl-Fe ($Fe(OH)_3$) are the final products of lime reaction in acid soils.

Factors affecting the rate of change

The reaction rate of $CaCO_3$ in soils varies greatly depending on the source of liming material. Typical agricultural lime comes from ground limestone and is found in two forms, calcitic or dolomitic limestone. Calcitic limestone is largely $CaCO_3$ with minimal amounts of Mg, whereas, dolomitic limestone contains an appreciable amount of Mg (Beard, 1973). Dolomitic limestone is also harder and more resistant to acids, which causes it to react at a much slower rate than calcitic limestone (Thomas and Hargrove, 1984). Hydroxides (e.g. hydrated lime) and oxides (e.g. quicklime) of calcium and magnesium are additional lime materials that are used less commonly on turfgrasses. Compared to carbonate sources (calcitic and dolomitic limestone), these lime materials react much more rapidly in soils because of their high water solubility (Beard, 1973). These hydroxides and oxides are caustic and can cause significant injury ("burn") to turfgrass, which is why these materials are usually applied to bare soil and incorporated prior to turfgrass establishment.

Particle size of the liming material also affects the reaction rate in soil because of the low solubility of carbonate limestone sources. Smaller particle size means more surface area for the soil solution to come into contact with and more disassociation to occur. In research conducted to determine the effect of limestone source and particle size, Meyer and Volk (1952) found that courser lime particles (4 - 20-mesh sieve) had

little effect on soil acidity, medium size lime particles (20 - 60 mesh sieve) took up to 18 months to fully react (neutralize acidity) and finer particles (> 100 mesh sieve) reacted soon after application. They also found that calcitic limestone was slightly more effective than dolomitic limestone at neutralizing soil acidity. Meyer and Volk (1952) recommended that limestone should be fine enough to pass through a 40-mesh sieve so it will be effective within a year of application.

Soil mixing also affects the rate of reaction for $CaCO_3$. In general, neutralization rates increase with incorporation/mixing with the soil (Thomas and Hargrove, 1984). Unlike agricultural systems, turfgrass soils are not routinely cultivated (thoroughly mix) and thus results in relatively slow neutralization rates. Environmental factors such as temperature and moisture affect limestone neutralization rates in soils, since it is strongly dependent on the dissolution rate of the liming material. The neutralization rate tends to increase under moist, warm conditions because it increases the rate of dissolution and hydrolysis of $CaCO_3$.

Gypsum effect on soil pH

Gypsum ($CaSO_4*2H_2O$) is a relatively common mineral that is principally used as a Ca source or soil conditioner on sodic soils (Shainberg et al., 1989). A sodic soil contains high levels of exchangeable Na^+ that adversely effects growth and soil structure (Carrow and Duncan, 1998). Gypsum is generally considered to have no effect on soil pH; however, several studies have shown under field and laboratory conditions, gypsum applications can slightly increase soil pH (Farina and Channon, 1988; Hue et al., 1985;

Richey et al., 1980; Shainberg et al., 1989). Others have found that gypsum has little to no effect on soil pH (Pavan et al., 1982, 1984). When a pH change is observed, the magnitude of the change is usually small (0.2-0.3 pH units) and only detectable when pH is measured in water (Shainberg et al. 1989). In theory, the pH change caused by gypsum is a result of Ca^{+2} replacing H^{+} and Al^{+3} (hydrolysis) and SO_4^{-2} replacing OH^{-}. The latter reaction is important because OH^{-} replaced by SO_4^{-2} neutralizes H^{+} released through hydrolysis of Al^{+3} (Chang and Thomas, 1963). The small rise in soil pH is more likely to occur on highly weathered soils or soils with low CEC and exchangeable acidity (Shainberg et al., 1989), such as sand rootzones in golf course putting greens.

Soil pH and Turfgrass

pH effect on turf growth

The effect of soil pH on turfgrass growth varies depending on species; however, most turfgrasses are adapted to moderately acid soil conditions (pH 6 – 7; Beard, 1973). A list of optimum pH ranges for cool-season turfgrass species are listed in Table 1. In general, bluegrass [Kentucky, rough (*Poa trivialis* L.), and ABG] and ryegrass [perennial and Italian (*Lolium perenne* L. subsp. *multiflorum* (Lam.) Husnot)] species tend to favor slightly more basic conditions compared to bentgrasses [creeping, colonial, and velvet (*Agrostis canina* L.)] and fescue [Chewing's (*Festuca rubra* L. subs. *fallax* (Thuill.) Nyman), red, and sheep (*Festuca ovina* L.)] species.

The effect of soil acidity on turfgrass growth has been a subject of interest for many years. At the turn of the century, Wheeler and Tillinghas (1900) observed that

lime additions to “excessively acid” soils increased pasture grass [tall oat grass (*Arrhenatherum album* (Vahl) Clayton), smooth brome (*Bromus inermis* Leyss.), KBG, and orchardgrass (*Dactylis glomerata* L.)] yield by two to three times compared to non-limed plots. In the mid- to late-1920’s, soil acidity was a prominent topic of greenskeepers as evident by the many articles published in the *Bulletin of the U.S. Golf Assoc. Green Section.*; eight articles were published from 1925 to 1928 on soil acidity effect on turfgrass growth and weed populations (MacGregor, 1928; Noer, 1928; Noer, 1928a; Noer, 1928b; Noer, 1928c; Oakley, 1925; USGA staff, 1927; Valentine, 1928) During this time, many greenskeepers thought that “sour soils” (acidic soils) were causing putting greens to perform poorly (Oakley, 1925). However, Oakley (1925) argued that maintaining soil acidic conditions helped control weeds such as white clover (*Trifolium repens* L.) and crabgrass (*Digitaria* spp.). This was towards the end of the “acid era” of turfgrass management in which ammonium sulfate was used excessively to control weeds and clover. During the summer of 1928, hot, humid conditions caused significant loss of turf on putting greens throughout the Northern U.S., which was attributed to severely acid soils as well as several turfgrass pathogens found in association with the damaged turf (Engel, 1982; Sprauge and Evaul, 1930). This event signaled the end of the “acid era” of turfgrass management and a shift in research towards investigating the effect of acidity on turfgrasses.

The first comprehensive study of soil pH effects on bentgrasses was conducted by Reid (1932). In these experiments she looked at shoot and root growth response of three bentgrass species (creeping, velvet, and colonial) to lime and acid treatments on

two soil types and a range of environmental conditions. Reid found that creeping and colonial bentgrass could grow between pH 4.5 and 8.3 and that velvet bentgrass was less tolerant of higher soil pH. She concluded that lack of growth in acidic soils was a result of both nutrient deficiency (P) and toxicity (Al and Fe) and that bentgrasses are less acid tolerant during mid-summer compared to other times of the year. Around this time Monteith (1932) also summarized data from the Arlington, VA fertility trials and concluded that bentgrasses thrived in slightly acidic soil conditions.

Compared to the bentgrasses, ABG turf is less tolerant of acidic soils. Initial observations on the effect of soil pH on ABG growth were made in the late 1920's. Sprauge and Evaul (1930) were one of the first to conduct experiments on the effect of soil pH on ABG populations in bentgrass turf. In a fertilizer experiment on ABG/bentgrass putting greens, the authors observed that strongly acidic soils (< 5.4) reduced the growth of ABG. Sprauge and Evaul (1930) also conducted greenhouse experiments to better understand the relationship between ABG growth and soil pH. In this study they found that ABG had very little growth and eventually died at soil pH above 7.0 and below 4.0; optimum growth was observed at pH 6.1. Sprague and Burton (1937) also conducted greenhouse experiments investigating the effect of lime and fertilizer treatments on the growth of ABG. They found that increasing soil pH from 5.3 to 6.3 with lime produced an increase in ABG growth regardless of fertilizer treatment. Ferguson (1936) observed that ABG was not present in areas of a research putting green receiving regular topdressing amended with ammonium sulfate and iron sulfate, which had a pH of 4.23. In contrast, other areas of the putting green that received sodium

nitrate fertilization had a pH of 6.97 and the sward population was 7% ABG. Ferguson (1936) also studied the effect of acidity on germination of ABG seed and found that no germination occurred at pH 3.58, but 66% of ABG seed germinated at pH 5.20. This led Ferguson to speculate that the correlation between soil pH and ABG abundance was not due to toxicity of mature plants, but rather the failure of ABG seeds to establish at low soil pH.

Several studies have also reported sulfur applications reducing ABG populations in mixed turf stands (Goss, 1974, Kato et al., 2000). Goss (1974) found that sulfur applied at 168 kg ha^{-1} reduced ABG populations in a colonial bentgrass/ABG mixture, regardless of N, P, and K treatments. Analysis of soil pH in the surface 2.5 cm showed that sulfur applications decreased pH by 0.6 compared to non-sulfur plots. More current research by Kato et al. (2000) found a positive correlation between soil pH and ABG populations in a zoysiagrass (*Zoysia japonica* Steud.) /ABG mixture, with ABG population increasing as soil pH increased. The authors also suggested that ABG can be controlled by maintaining the soil pH of the soil surface (0-1 cm) at about 4.7 to inhibit emergence and growth of ABG.

In the published literature, studies have primarily focused on the control of ABG in mixed stands of turfgrass. Few studies have investigated the effect of soil pH on monostands of annual bluegrass. Although some greenhouse studies have identified an optimum pH for ABG monostands, it is unclear how accurately these results compare to field conditions. Thus field research is needed to determine the optimum soil pH for ABG and the effect of alkaline or acidic soil conditions on ABG growth.

Disease response to soil pH

Soil pH can have a significant impact on turfgrass diseases such as Microdochium patch, take-all patch, and summer patch (Couch, 1995). The severity of all three diseases increases as soil pH increases above pH 6.0 to 6.5. Of the turfgrass diseases affected by soil reaction, take-all patch is the most well understood because of its association with economically important crops such as wheat (*Triticum* L.) and oats (*Avena sativa* L.) (causal agent is *G. graminis* var. *tritici* Walker and *G. graminis* var. *avenae* [E.M. Turner] Dennis, respectively) in addition to bentgrass. A considerable amount of literature has been published on the impact of pH on *G. graminis* and it has become a model system for studying root-infecting pathogens and rhizosphere interactions (Cook, 2003). The mechanism behind the suppression of take-all patch at low soil pH have been well described in the literature and have been summarized by Cook (2003). Deficiencies in the Mn^{2+} in the plant can inhibit proper growth and reduce its ability to produce phenolic compounds and lignins, which are known to suppress take-all patch in wheat (Rengel et al., 1993; Rengal et al., 1994). At high soil pH, Mn^{2+} is less available to plants and *G. graminis* has the ability to oxidize Mn^{2+} in the rhizosphere to a form that is unavailable to plants (Mn^{3+} and Mn^{4+}), causing increased disease severity. Conversely, at low soil pH, competition for Mn^{2+} is decreased because the element is more readily available (Figure. 1) and take-all patch is significantly reduced (Rengel et al., 1993; Rengal et al., 1994; Pedler et al. 1996). It has also been reported that reducing soil pH can increase the population of fluorescent pseudomonads in the

rhizosphere, which protect roots from infection by *G. graminis* (Cook, 2003; Haas and Defango, 2005).

Outbreaks of take-all patch (formerly Ophiobolus patch) have been observed in turfgrass stands where limestone or other alkaline materials have been used (Goss and Gould, 1967; Jackson, 1958; Smith, 1956b; Smith et al., 1989). Smith (1956b) was the first to report the association between limestone applications and take-all patch outbreaks on *Agrostis* spp. He also determined that particle size of liming material influenced the severity of take-all patch outbreaks, with finer particles causing more disease than coarser liming materials (Smith et al. 1989). Jackson (1958) also related an increase in take-all patch occurrence to application of calcareous materials which raised the pH at the turf surface above 6.0. While investigating the relationship between soil fertility levels and take-all patch severity, Goss and Gould (1967) reported a weak correlation (r=0.31) between take-all patch and pH levels of the upper 15 cm of soil. Lack of strong correlation in this study was likely due to the relatively low soil pH range (pH 4.0 – 5.6) studied in this trial; take-all patch is a more aggressive disease problem at higher pH (> pH 6.0). Others have studied the relationship between soil pH, Mn^{2+}, and take-all patch on creeping bentgrass. Hill et al. (1999) reported that monthly applications of manganese sulfate ($MnSO_4$) from March through November reduced take-all patch severity by 15% compared to the untreated control. Additional research by Heckman et al. (2003) investigated the effect of rate and timing of $MnSO_4$ applications on take-all patch severity in creeping bentgrass. They found that a single application of $MnSO_4$ (2.25, 4.50, 6.75, or 9.00 kg Mn^{2+} ha^{-1}) in either April or October

effectively reduced disease compared to the untreated control; however, under severe disease pressure, higher rates (6.75 and 9.00 kg Mn^{2+} ha^{-1}) were more effective.

Similar to take-all patch, summer patch severity is exacerbated at soil pH > 6.0. Davis and Dernoeden (1991) were the first to observe that sulfur coated urea (SCU) applications decreased bulk soil pH and summer patch severity of KBG; however, results were inconclusive since disease infestation only occurred during one season. Thompson et al. (1993) also investigated the effect of nitrogen source and soil pH on summer patch severity of KBG. They found that ammonium sources (ammonium sulfate and ammonium chloride) and SCU provided the greatest reduction in soil pH as well as summer patch severity compared to other N sources and no N. They also measured *in vitro* the growth response of five *M. poae* isolates to a range of soil pH (3.4 to 7.2) and found that maximum growth of the pathogen occurred above pH 5.5. Thompson et al. (1995) found that acidifying fertilizers such as ammonium sulfate could reduce summer patch severity up to 75% compared to calcium nitrate applied at the same rate of N. Although acidifying fertilizers can be used to decrease summer patch severity, continued use can eventually cause the soil to become too acidic for adequate turfgrass growth and vigor, particularly on poorly buffered soils. To counter this effect, Hill et al. (2001) investigated the influence of liming practices on the ability of ammonium sulfate for the control of summer patch. They found that limestone applied to maintain acceptable pH levels (pH 6 to 6.5) for turfgrass growth did not reduce the effectiveness of ammonium sulfate for the control of summer patch disease.

Microdochium patch (formerly Fusarium patch) is another fungal disease that is more severe at higher soil pH (Couch, 1995; Smiley et al., 2005). Initial observations of this disease in Great Britain reported incorrectly that it was more prevalent on turf growing on acid soils (Jones, 1937). More recently, several studies have documented that the severity of Microdochium patch is intensified with an application of limestone or other alkaline materials (Lawson, 2000; Robinson, 1980; Smith, 1958b). Smith (1958b) was the first to identify that limestone application to turfgrass (ABG) greatly increased the incidence of Microdochium patch. Robinson (1980) also noted that Microdochium patch was more severe on plots fertilized with calcium ammonium nitrate (mixture of $CaCO_3$ and NH_4NO_3; also known as nitro-limestone) compare to plots fertilized with ammonium sulfate or urea. This result is likely due to the pH increase caused by the calcium ammonium nitrate application.

A relationship between soil reaction and dollar spot of bentgrass has also been suggested, with increased limestone rate (0 vs. 2440 kg $CaCO_3$ ha^{-1}) associated with greater dollar spot incidence on velvet bentgrass (Ledeboer and Skogley, 1967). However, other researchers reported no influence of soil pH or limestone application on dollar spot of KBG or perennial ryegrass (Couch and Bloom, 1960; Turner 1980). No additional research is available to either confirm or refute the observed responses of dollar spot to soil pH.

Spring dead spot (SDS) of bermudagrass is an example of a soil pH responsive disease that affects warm-season grasses. Spring dead spot is a disease that can be caused by three different species of *Ophiosphaerella: O. korrae* (J. Walker & A.M. Sm.)

Shoemaker and Babcock*, O. herpotricha* (Fr.:Fr.) J. Walker*, and O. narmari* (J. Walker & A.M. Sm.) Wetzel, Hulbert, & Tisserat (Tredway et al., 2009b). Initial research by Dernoeden et al. (1991) investigating the effect of cultural management practices on SDS suggested that acidification of soil with NH_4-N reduced severity of the disease over time. In this trial, various N sources ($NaNO_3$, $(NH_4)_2SO_4$, NH_4Cl, and urea) and KCl were applied at two locations and observed for SDS severity on 'Tufcote' bermudagrass caused by *O. korrae*. However, only in the third year, at one location, did NH_4-N [$(NH_4)_2SO_4$ and NH_4Cl] + KCl treatments reduce SDS severity compared to other N sources and the untreated control; SDS severity was positively correlated (r = 0.80) to soil pH. Vincelli et al. (1995) reported that applications of elemental sulfur (337 and 508 kg ha^{-1}) on fairway turf reduced SDS severity (caused by *O. herpotricha*) compared to limestone application (6,640 kg ha^{-1}) and the untreated control. Moreover, Tredway et al. (2009a) found that SDS caused by *O. herpotricha* and *O. korrea* responded differently to N source applications. Spring dead spot caused by *O. herpotricha* was suppressed by the application of $(NH_4)_2SO_4$ and sulfur coated urea compared to $Ca(NO_3)_2$ and $CO(NH_2)_2$. Whereas, $Ca(NO_3)_2$ significantly reduced SDS caused by *O. korrea* compared to $(NH_4)_2SO_4$, urea, and sulfur coated urea, suggesting *O. korrea* may not be responsive to soil pH.

Models for Determining Critical Nutrient Concentrations

Recommendations for fertilization of various turfgrass species are developed from field and greenhouse studies where turf quality and yield responses are measured over a range of fertilizer rates. Typically, these responses are compared to fertilizer rate, soil nutrient concentration, and/or leaf tissue concentration to determine the optimum fertilizer or critical nutrient concentration. Several nonlinear regression models have been commonly used in agricultural systems to determine critical levels, these models include: the Cate-Nelson model (Cate and Nelson, 1971), linear-plateau model (Waugh et al., 1973), and quadratic-plateau model (SAS Institute, 2009). In addition, regression models including quadratic, exponential, and square root have been used to estimate economic optimum rate of fertilization in agriculture. The Cate-Nelson model divides a data set into two categories: high probability of response and low probability of a response. The dividing line between the two categories is the critical level for the independent variable (e.g. fertility rate, soil nutrient concentration, or leaf nutrient concentration) being measured. Linear plateau and quadratic plateau are both segmented polynomial models. The linear plateau model is described with the following equations:

$$Y = a + bX \text{ if } X < C$$

$$Y = P \qquad \text{if } X \geq C$$

where Y is the dependent variable (i.e. yield, quality, or disease severity) and X is the independent variable (i.e. fertilizer rate, soil nutrient concentration, or leaf nutrient concentration); a is the intercept, b is the linear coefficient, C is the critical value

(intersect of the linear response and the plateau line), and *P* is the plateau yield (dependent variable); *a*, *b, C,* and *P* are constants obtained by model fitting (Waugh et al., 1973). The quadratic plateau model is described with the following equations:

$$Y = a + bX + cX^2 \text{ if } X < C$$

$$Y = P \qquad \text{if } X \geq C$$

where *Y* is the dependent variable (i.e. yield, quality, or disease severity) and *X* is the independent variable (i.e. fertilizer rate, soil nutrient concentration, or leaf nutrient concentration); *a* is the intercept, *b* is the linear coefficient, *c* is the quadratic coefficient, *C* is the critical value (intersect of the linear response and the plateau line), and *P* is the plateau yield (dependent variable); *a*, *b, c, C,* and *P* are constants obtained by model fitting (SAS Institute, 2009).

Several agricultural studies have compared the efficacy of various models for determining critical soil nutrient concentration and fertilization rates (Cerrato and Blackmer, 1990; Mallarino and Blackmer, 1992; Willcutts et al., 1998). Cerrato and Blackmer (1990) compared several models (linear plateau, quadratic plateau, quadratic, exponential, and square root) for their ability to describe a corn yield response to nitrogen fertilizer rate. They found that all models seemed to fit yield data equally well based on the R^2 statistic; however, the quadratic, exponential, and square root models tended to overestimate economic optimum rates of fertilization. The quadratic plateau model provided the most accurate description of the yield response to N fertilizer rate. Mallarino and Blackmer (1992) compared methods for determining critical soil test phosphorus concentrations for maximizing corn yields and found that fertilization

recommendations based on the Cate-Nelson model provided the greatest net economic return, followed by the linear-plateau model.

Several turfgrass studies have adapted these yield models to provide fertilizer recommendations to maximize turf growth (yield) (Collins and Allinson, 2004; Guillard and Dest, 2003; Mangiafico and Guillard, 2007; Petrovic et al., 2005), turf quality (Guillard and Dest, 2003; Kreuser et al., 2012; Petrovic et al., 2005), chlorophyll concentration (Mangiafico and Guillard, 2005; Mangiafico and Guillard, 2007), and normalized difference vegetative index (Guillard et al., 2016). However, no previous study has attempted to compare the efficacy of the various models in turfgrass systems. Moreover, no previous study has attempted to relate soil or leaf tissue nutrient concentrations to disease severity in agricultural crops or turfgrass systems using nonlinear regression models.

SUMMARY

It has been shown that N fertilization has a significant impact on anthracnose severity of ABG turf (Danneberger et al., 1983; Inguagiato et al., 2008; Roberts et al., 2010); however, questions still remain as to the effect of granular N rate, season in which granular N is applied, soluble N rate, and N source on the severity of this disease. This dissertation describes five field trials, three of which were initiated to investigate the effect of N fertilization [N programming (chapter 1), soluble N rate (chapter 2), and soluble N source (chapter 3)] on anthracnose severity of ABG putting green turf. In addition, K fertilization has been shown to improve the stress tolerance of turfgrass (Carrow et al., 2001), and since anthracnose is a disease that is known to infect weakened (stressed) plants (Smiley et al., 2005), it is conceivable that K fertilization could reduce the incidence of anthracnose disease. To test this hypothesis, a fourth field study was initiated to investigate the effect of K rate and source on disease severity (chapter 4). Finally, soil pH has been shown to influence the growth and overall quality of ABG turf (Ferguson, 1936; Sprague and Burton, 1937; Sprauge and Evaul, 1930), but the exact level at which soil pH becomes detrimental to turf is not clearly defined. Low soil pH (< 5) can weaken turf and inhibit growth of ABG plants, possibly increasing susceptibility to infection from anthracnose. Thus, a fifth field study was initiated to determine the response of ABG turf and its susceptibility to anthracnose disease over a broad range of soil pH (chapter 5).

Figures and tables

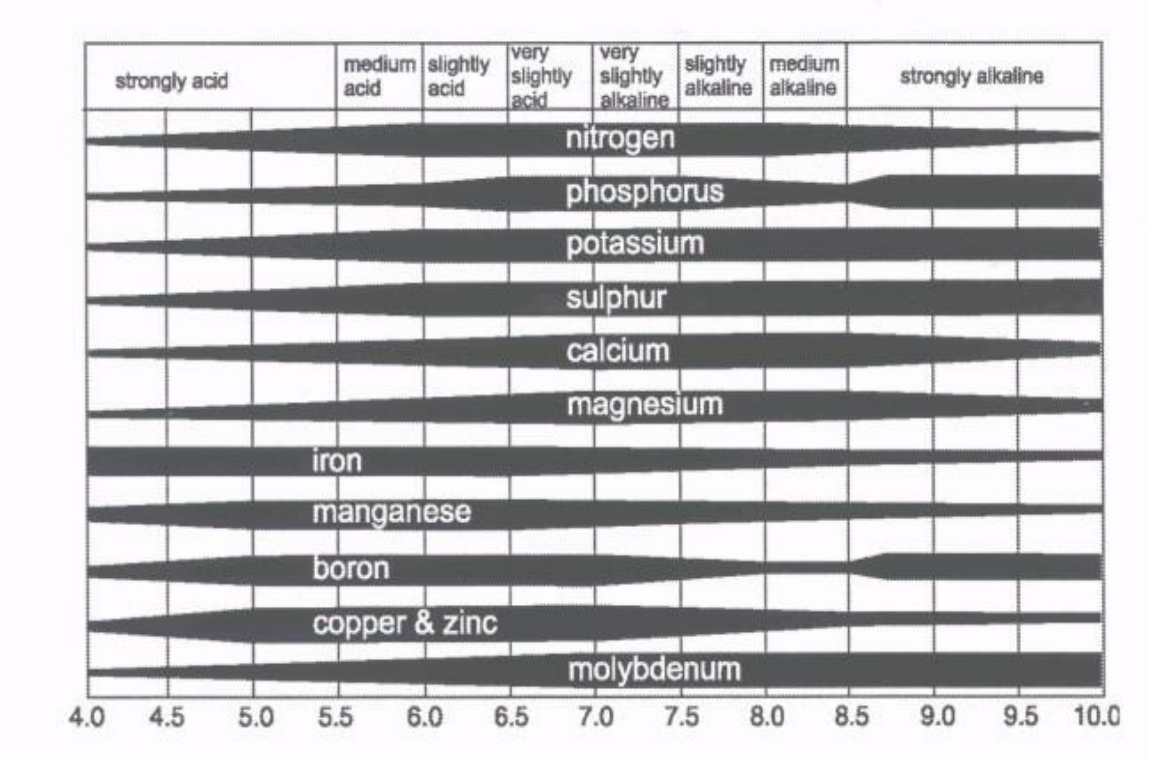

Figure 1. Influence of soil pH on nutrient availability. A wider band width implies greater availability for plant uptake (after Truog, 1947).

Table 1. Optimum soil pH range for 14 cool-season turfgrass species (adapted from Beard, 1973).

Optimum soil pH range	Turfgrass species
7.0 - 6.0	Kentucky bluegrass
	Rough bluegrass
	Perennial ryegrass
	Italian ryegrass
6.5 - 5.5	Annual bluegrass
	Tall fescue
	Canada bluegrass
	Creeping bentgrass
	Colonial bentgrass
	Red fescue
	Chewing fescue
6.0 - 5.0	Velvet bentgrass
	Redtop
5.5 - 4.5	Sheep fescue

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CHAPTER 1. The Effect of Nitrogen Programming on Anthracnose Severity of Annual Bluegrass Turf

Abstract. Nitrogen fertilization affects the development of anthracnose disease (caused by *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, & Hillman) of annual bluegrass (ABG) [*Poa annua* L. f. reptans (Hausskn) T. Koyama] putting green turf; however, a more comprehensive understanding of N management throughout the growing season is needed. This 2-yr field study evaluated the effects of rate of granular N fertilization (73, 147, or 220 kg N ha^{-1} yr^{-1}), season (spring or autumn) in which the majority of granular N fertilization was applied, and soluble N rate (0, 18, 37, or 73 kg N ha^{-1} yr^{-1}) applied mid-season on anthracnose severity, quality and color of ABG turf mowed at 3.4 mm. Soluble N rate applied from May through August had the greatest influence on area under the disease progress curve (AUDPC; anthracnose severity over time). Soluble N applied at 73 kg N ha^{-1} yr^{-1} reduced AUDPC by 41 to 22% in 2009 and 2010, respectively compared to no soluble N. Granular N rate also had a significant impact on AUDPC, with granular N applied at 220 kg N ha^{-1} yr^{-1} resulting in the greatest reduction in anthracnose severity compared to lower rates (73 and 147 kg N ha^{-1} yr^{-1}). The season main effect and granular N rate x season interaction had significant but smaller effects on AUDPC. In general, granular N rate had less of an effect on disease severity when applied in the autumn compared to spring. Additionally, moderate rates of granular N (147 kg N ha^{-1} yr^{-1}) applied in the spring were more effective at reducing disease severity than higher granular N rates (220 kg N ha^{-1} yr^{-1}) applied in the autumn.

Treatments that provided the greatest reduction in disease severity also maintained an acceptable turf quality and color rating ($\geq$ 5.0) on a majority of observation dates in 2008, 2009, and 2010. Taken together, these results suggest that N programs which emphasized fertilization in the spring and summer and provided adequate N were the most effective at reducing anthracnose severity.

INTRODUCTION

Anthracnose, caused by *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, & Hillman (Crouch et al., 2006), is a destructive turfgrass disease with numerous turfgrass hosts including *Cyndon, Eremochloa, Festuca, Lolium and Poa* spp. but is especially damaging on *Poa annua* L. f. reptans (Hausskn) T. Koyama (annual bluegrass; ABG) and *Agrostis* spp. (Smiley et al., 2005). Appearance of this disease on ABG putting green turf can occur throughout the entire growing seasons but is most destructive during the summer when stressful environmental conditions (high heat and humidity) promote infection (Smiley et al., 2005). A prediction model used to forecast anthracnose infection in ABG turf demonstrates that temperature and hours of leaf wetness are the most important factors influencing disease development; increasing both variables results in increased disease severity (Danneberger et al., 1984). Improper cultural management practices such as low mowing height and low nitrogen fertility have also been shown to exacerbate this disease (Inguagiato et al. 2008, Inguagiato et al. 2009). Poor management practices in combination with environmental conditions favorable for the disease can result in significant loss of putting green turf.

Nitrogen fertilization on putting green turf is typically applied at very low rates (spoon-feeding) during the summer months (June through September) in an effort to maintain high green speed (ball roll distance) and prevent surges in vertical growth (Beard, 1973; Carrow et al., 2001; Vargas and Turgeon, 2004). Recommended N rates for ABG putting green turf during this period of time ranges from 98 to 146 kg N ha^{-1}, with an additional 49 to 73 kg N ha^{-1} applied during the spring and fall (Vargas and

Turgeon, 2004). A number of researchers have reported that soluble N rates during the summer months can influence anthracnose severity of ABG putting green turf (Inguagiato et al., 2008; Roberts et al., 2010). Initial work by Inguagiato et al. (2008), found that low rate (4.9 kg N ha^{-1}) soluble applications of ammonium nitrate applied every 7-d reduced anthracnose severity compared to the same rate applied every 28-d. Similar results were found by Roberts et al. (2010) who showed that N rates of 4.9 kg N ha^{-1} wk^{-1} and 9.8 kg N ha^{-1} 2 wk^{-1} provided the greatest reduction in disease severity compared to lower rates. Additionally, Roberts et al. (2010) found that initiating a soluble N program in May, prior to symptom expression reduced anthracnose severity compared to soluble N initiated in June at the onset of disease.

Granular (solid applications) N fertilizers are commonly used as a part of a N program, supplementing soluble N applications during periods of high nutrient demand (i.e. spring and early fall). But, increased marketing of foliar (liquid) fertilization has been encouraging superintendents to reduce and possibly eliminate higher rate granular-N fertilization. Limited research is available as to the effect of granular N fertilization on anthracnose severity of annual bluegrass putting green turf. Danneberger et al. (1983) investigated the effect of granular N carriers on anthracnose severity on annual bluegrass maintained at fairway height (1.3 cm) and found moderate rates of granular N (146 kg N ha^{-1} yr^{-1}) reduced disease severity compared to higher and lower rates of N (292 and 0 kg N ha^{-1} yr^{-1}), regardless of N source (Urea, IBDU, sulfur coated urea). However, previous research has not clearly defined the possible role of late- or early-season higher N rate granular fertilization on anthracnose of annual

bluegrass putting green turf. Nor has the influence of the timing of granular-N fertilization on the frequency of low rate soluble-N fertilization during the growing season been defined. The objective of this field study was to evaluate the effect of autumn or spring granular N fertilization on anthracnose severity and to determine whether the disease response to frequent low rate soluble-N fertilization during summer is influenced by autumn- or spring granular-N fertilization.

MATERIALS AND METHODS

Site Description and Maintenance

A 2-year field study was initiated in 2008 on ABG turf grown on a Nixon sandy loam (fine-loamy, mixed, semiactive, mesic Typic Hapludults) with a 5 cm sand topdressing layer in North Brunswick, NJ. The study location was a monostand of ABG turf that was established in 2007 using seed indigenous to the site. Plot area was mown seven times wk^{-1} using a walk-behind greens mower (model 1000; Toro Company, Bloomington, MN) equipped with a narrow wiehle front roller (model 99-6241; Toro Company, Bloomington, MN) and bench set at 3.4 mm. Sand topdressing was applied at a rate of 0.15 L m^{-2} every 14-d from May through October each year and brushed in with a coco mat. Irrigation was applied to achieve moderately dry conditions typical of golf courses in the Northeast US using a combination of overhead irrigation and syringing with a handheld hose equipped with a fan nozzle. Phosphorus and potassium were applied based on soil test results; P was applied at 21.3 kg P ha^{-1} yr^{-1} in both years and K was applied at 26.5 and 0 kg K ha^{-1} yr^{-1} in 2009 and 2010, respectively.

Plant growth regulator 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 to 10 Nov. 2009 and from 19 March to 2 Oct. 2010. Ethephon [(2-chloroethyl) phosphonic acid] was applied at a rate of 3.76 kg a.i. ha^{-1} on 25 March, 13 April, and 28 April 2009 and on 19 March, 2 April, and 23 April 2010 to suppress ABG seedhead development. Anthracnose was arrested with fungicides after summer soluble N treatments were suspended at the end of 2009 to allow plots to recover

during the fall and winter. Chlorothalonil (2,4,5,6-tetrachloroisophthalonitrile) was applied at 10.6 and 12.7 kg a.i. ha^{-1} on 3 September and 24 Sep 2009, respectively. Chlorothalonil and Iprodione [3-(3,5-Dichlorophenyl)-N-isopropyl-2,4-dioxoimidazolidine-1-carboxamide] were applied at 12.7 and 3.1 kg a.i. ha^{-1}, respectively on 30 October and 11 Nov 2009. Fungicides that were shown to be ineffective at controlling anthracnose (Towers et al., 2003) on the site were used to control dollar spot (*Sclerotinia homoeocarpa* F.T. Bennet), brown patch (*Rhizoctonia solani* Kühn), summer patch (*Magnaporthiopsis poae* [Landsch. & N. Jacks.] J. Luo & N. Zhang; reported as *Magnaporthe poae* Landschoot and Jackson), and waitea patch (*Waitea circinata* var. *circinata*). A rotational program of boscalid [3-pyridinecarboxamide 2-chloro-N-(4'-chloro[1,1'-biphenyl]-2-yl)] and vinclozolin [3-(3, 5-dichlorophenyl)-5-ethenyl-5-methyl-2, 4-oxazolidinedione] was used to control dollar spot, whereas brown patch, summer patch, and waitea patch were controlled with a rotation of flutalonil [N-(3-[1-methylethoxy] phenyl)-2-(trifluoromethyl)benzamide] and azoxystrobin [methyl (E)-2-{2-[6-(2-cyanophenoxy)pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate]. Algae was suppressed using mancozeb (ethylene bisdithiocarbamate) at rates ranging from 9.2 to 15.3 kg a.i. ha^{-1} on 7 July and 1 Aug 2009, and on 5 June, 11 June, 27 June, 15 July, 20 July, 28 July, and 28 Aug 2010. Insect pests [annual bluegrass weevil (*Listronotus maculicollis* Dietz) and black cutworm (*Agrotis ipsilon* Hufnagel)] 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] at 0.25 kg a.i. ha^{-1} on 14 June 2009, with bifenthrin [2-Methyl-3-phenylphenyl)methyl (1S,3S)-3-

[(Z)-2-chloro-3,3,3-trifluoroprop-1-enyl]- 2,2-dimethylcyclopropane-1-carboxylate] at 0.08 kg a.i. ha^{-1} on 9 September and 8 Oct 2009, and with chlorantraniliprole [3-broom-N-[4-chloor-2-methyl-6-(methylcarbamoyl)fenyl]-1-(3-chloor-2-pyridine-2-yl)-1H-pyrazool-5-carboxamide] at 0.18 kg a.i ha^{-1} on 30 Apr. 2010.

Treatment Design

The trial used a 3 x 2 x 4 factorial arrangement in a randomized complete block design with three replications. The plot size for the study was 1.5 x 2.4 m and treatments were applied to the same location each year. The first factor was the annual granular N fertilization rate: 73, 146 and 220 kg ha^{-1} (1.5, 3.0 and 4.5 lbs 1000-ft^{-2}). The second factor was the season of granular fertilization (autumn and spring) in which two-thirds of the annual rate of granular N was applied. Table 1 summarizes the distribution of granular-N rate over time for each of the treatment combinations for these first two factors. Granular N treatments were applied with a 1.5 m drop spreader (model 6505; Gandy Company) as a split application in autumn on 8 Sep and 21 Oct 2008 and 9 Sep and 12 Oct 2009, and in the spring on 29 Mar and 3 May 2009 and 27 Mar and 1 May 2010. Granular N source for the study was isobutylidenediurea (IBDU), with 87% water insoluble N and a size guide number of 80 (Par Ex IBDU; Lebanon Seaboard Corp., Lebanon, PA). The third factor was the soluble-N fertilization rate during the mid-season: 0, 18, 37, and 73 kg N ha^{-1} yr^{-1}. These N rates were achieved by applying 0 or 4.6 kg ha^{-1} (0 or 0.093 lb 1000-ft^{-2}) as a urea solution every 1, 2 or 4 wk a over 16 week period from 18 May to 24 Aug. 2009 and from 24 May to 2 Sept. 2010. A gas powered backpack sprayer (model SHR – 210; Echo Inc., Lake Zurich, IL) with a five nozzle boom

equipped with 0.3 MPa constant flow valves (model 11-16SY; G.A.T.E. LLC, Sebastian, FL) and extended range flat spray tips (model XR8003; TeeJet® Technologies, Springfield, IL) was used to apply the urea solution. Water (< 0.25 cm) was applied to each plot using a handheld hose equipped with a fan nozzle immediately following N applications to prevent foliar injury ("burn").

Thus, the range of annual N applied over all treatment combinations was 73 to 293 kg ha^{-1} (1.5 to 6.0 lbs 1000-ft^2).

Data Collection and Analysis

Anthracnose severity (percentage of turf area infested) was assessed routinely from 11 June through 26 August 2009 and from 21 May through 12 September 2010 using the line intercept-grid count method described by Inguagiato et al. (2008) that produced 273 observations over 1.4 m^2 plots. Area under disease progress curve (AUDPC), which is a quantitative assessment of disease severity over time, was calculated using sequential disease data (within each year) according to the equation:

$$\mathrm{AUDPC} = \sum_{i=1}^{n} [\frac{(X_i + X_{i+1})}{2}(t_i + t_{i+1})]$$

in which X_i is the anthracnose disease severity at the ith observation, t is the time (days) at the ith observation, and n is the total number of observations (Madden et al., 2007).

Turfgrass quality and color were visually rated periodically from autumn 2008 through autumn 2010. Turfgrass quality used a 1 to 9 scale (9 = best, 5 = minimum acceptable, 1= dormant or dead turf) and took into account turf density, uniformity and

evenness (playability), and overall appearance similar to methods described by Skogley and Sawyer (1992). Turfgrass color was evaluated in a separate rating using a 1 to 9 scale (9 = optimal [darkest] green, 5 = minimum acceptable green-yellow, 4 to 2 = increasing unacceptable chlorosis, 1= complete chlorosis). Turf quality and color data were combined within each season in each year. Ratings made between 1 September and 5 December were combined for autumn; ratings from 24 March through 19 May were combined for spring; and ratings from 20 May through 31 August were combined for summer.

All analyses were carried out using the Statistical Analysis System (SAS) software package (v. 9.4; SAS Institute) and data were subjected to analysis of variance using the generalized linear model (GLM) procedure for a randomized complete block design. Statistically significant main effects and interaction means were separated using Fisher's protected least significant difference test at the 0.05 probability level employing the equation described by Dowdy et al. (2004). Orthogonal contrasts were used to determine the response (linear and quadratic) of dependent variables (anthracnose severity, turf quality, and turf color) to the three levels of granular N. Similarly for soluble N, orthogonal contrasts were used to test for linear, quadratic and cubic responses to the four levels of soluble N. The amount of variation attributed to each treatment factor (season, granular N rate, and soluble N rate) was determined by comparing the sum of squares for each factor with the total sum of squares.

RESULTS AND DISCUSSION

Anthracnose Severity

Anthracnose infection occurred naturally in both 2009 and 2010. Symptoms of the disease began to appear in early June 2009 and continued to gradually increase in severity until late August 2009 (25 – 39% by 26 August) when disease infestation was halted with fungicide applications to ensure a full recovery from damage by the following spring (Table 2). Anthracnose disease developed earlier in 2010 (mid-May) and increased sharply to a moderate levels (44 – 53%) by 21 June 2010, at which point disease severity only slightly increased until 12 Sept. 2010 (Table 3).

Over the 2-yr trial, the main factors accounted for the majority of variation in the statistical model (Tables 2 & 3), but significant interactions did occur between granular N rate and season, as well as between granular N rate and soluble N rate. These interactions provide insight into subtle nuances in the main effects and, because of this, are presented along with the main effects. Moreover, the disease severity response was relatively consistent throughout each season, thus, AUDPC data was used to describe general trends for each season, while individual disease assessments was used to describe any deviations within each season.

Granular N Rate

The granular N main effect influenced AUDPC in both years, accounting for 16 and 35 % of variation in the statistical model in 2009 and 2010, respectively (Tables 2 and 3). A negative linear response was exhibited between granular N rate and AUDPC in 2009 and 2010 (Tables 2 and 3). Granular N applied at 220 kg N ha^{-1} yr^{-1} provided the

greatest reduction in disease severity, reducing AUDPC by 30 and 19% in 2009 and 2010, respectively, compared to granular N applied at 73 kg N ha^{-1} yr^{-1}. The 147 kg N ha^{-1} yr^{-1} granular N treatment was not as effective at suppressing anthracnose severity (reducing AUDPC) as the higher granular N rate (220 kg N ha^{-1} yr^{-1}); however, it was more effective than granular N applied at 73 kg N ha^{-1} yr^{-1} in both years (Tables 2 and 3). Interestingly, anthracnose severity exhibited a delayed response to granular N rate, not influencing the severity of disease until 28 July 2009, but was significant on all subsequent observations in 2009 and 2010. This delayed response from IBDU applications was not unexpected since previous research has shown that the initial response from surface applications of IBDU can be delayed due to its low solubility and poor contact with moisture-containing substrates (i.e. soil) (Hummel and Waddington, 1981; Moberg et al., 1970; Volk and Horn, 1975; Wilkinson, 1977). The release of N from IBDU (conversion to NH_3) is influenced by temperature, moisture, particle size, and soil pH (Turner and Hummel, 1992), but is independent of microbial activity unlike other slow-release N sources (e.g. ureaform) (Lunt and Clarke, 1969). Previous research has shown that moderate rates (146 kg N ha^{-1} yr^{-1}) of IBDU applied to ABG turf maintained at 1.3 cm decreased anthracnose severity compared to higher rates (292 kg N ha^{-1} yr^{-1}) and no N (Danneberger et al., 1983). However, the findings of the current study indicate that high rates of granular N (IBDU; 220 kg N ha^{-1} yr^{-1} with as much as 147 kg N ha^{-1} in the spring) can be applied without concern of increasing disease severity. A possible explanation for this discrepancy between the two studies might be differences in cultural management practices (i.e. mowing height and mowing frequency) on greens

vs. fairways, which may have resulted in an increased N requirement in the current (greens) study due to lower mowing height and more frequent mowing (7-d wk^{-1}).

Season

Season (autumn vs. spring) had a smaller effect on AUDPC in 2009 and 2010 compared to the granular N rate factor; only accounting for 9 and 6% of variation in the statistical model, respectively (Table 2 and 3). Granular N fertilizer applied mostly in spring decreased AUDPC by 20 and 6% compared to autumn fertilization in 2009 and 2010, respectively (Tables 2 and 3). Initially from 11 June to 3 July 2009, season of granular fertilization accounted for the most variation in disease severity (16 – 19%; Table 2) compared to all other factors and interactions; however, from 28 July 2009 through the end of the study, the effect of season on disease severity diminished compared to other treatment factors. Historically, moderate N fertilization rates (49 to 146 kg N ha^{-1}) have been recommended for cool-season turfgrasses in autumn because of their effect on enhancing winter color and turf quality (Bigelow et al., 2007; Grossi et al., 2005; Miltner et al., 2004; Powell et al., 1967a), spring color and turf quality (Bigelow et al., 2007; Miltner et al., 2004; Wehner and Haley, 1993), root growth (Moore et al., 1996; Powell et al. 1967b), and on cold tolerance (Webster and Ebdon, 2005). However, limited information is available as to the effect of autumn fertilization specifically on ABG quality, color, or anthracnose severity. Danneberger et al. (1983) investigated the impact of starting a N fertilization program in the spring vs. summer on anthracnose severity and found that initiating N applications in the summer decreased anthracnose severity compared to a spring program, but their study did not examine the effect of

autumn fertilization on disease. The current study is the first to report that spring granular N fertilization reduced anthracnose severity compared to the same N rates applied in autumn.

The interaction between granular N rate and season had an effect on AUDPC in 2009, but not in 2010 (Table 2 and 3). This interaction indicated that greater disease suppression occurred when the majority of granular N applied at 147 and/or 220 kg N ha^{-1} yr^{-1} was applied during spring compared to autumn (Figure 1). These results indicate that lower rates of granular N can be used to reduce anthracnose damage when the application is made at the appropriate time (spring). This interaction occurred on 5 of 12 disease rating dates during 2009 and 2010, and are listed in Table A.1.

Soluble N Rate

The main effect of soluble N rate had the greatest impact on AUDPC in 2009 and 2010, accounting for 28 and 43% of variation in the model, respectively (Table 2 and 3). A negative linear response was observed between AUDPC and soluble N rate during 2009 and 2010, with soluble N applied at 73 kg N ha^{-1} yr^{-1} decreasing AUDPC by 41 and 22%, respectively, compared to no soluble N (Table 2 and 3). Lower rates of soluble N (18 and 37 kg N ha^{-1} yr^{-1}) were less effective at reducing anthracnose severity compared to higher rates (73 kg N ha^{-1} yr^{-1}), but were still more effective than the no soluble N treatment (Table 2 and 3). During both years, the only two dates when soluble N rate did not affect disease severity were 11 June 2009 and 21 May 2010, which was not surprising since soluble N treatments had just been initiated or it was prior to treatment initiation (Tables 2 and 3). Moreover, the effect of soluble N rate became more

apparent as the season progressed and disease severity increased, accounting for the majority (18 to 48%) of variation in the statistical model during late summer (July through early September) in both years. These results are in agreement with those obtained by Inguagiato et al. (2008), who found that soluble N applied at 4.9 kg N ha^{-1} every 7-d during the summer (May through September) was most effective at reducing disease severity compared to the same rate applied every 28-d. This N rate and frequency (4.9 kg N ha^{-1} every 7-d) was similar to the highest soluble N rate (73 kg N ha^{-1} yr^{-1}) applied in the current study, which was applied at 4.6 kg N ha^{-1} every 7-d. Roberts et al. (2010) also observed a similar response, with N applied at 58.8 kg N ha^{-1} total (4.9 kg N ha^{-1} wk^{-1} or 9.8 kg N ha^{-1} 2-wk^{-1}) providing the greatest reduction in anthracnose severity compared to lower rates.

The interaction between soluble N rate and granular N rate had no effect on AUDPC in either year, but did influence anthracnose severity on two observation dates (28 July and 12 August) in 2009 (Table 2), indicating that at lower rates of soluble N, disease severity was more responsive to granular N rate (Table 4). In contrast, at the highest rate of soluble N, there was no disease severity response to granular N rate on either date. Interestingly, disease severity was decreased by 11 and 12% on 28 July and 12 Aug 2009, respectively, when N was evenly split between granular N and soluble N (146 kg N ha^{-1} yr^{-1} total) compared to the same rate applied only as granular N (Table 4). Together these results indicate that lower rates of granular N can be applied in combination with higher rates of soluble N to reduce anthracnose severity.

Turf Quality

Granular N rate, season, and soluble N rate greatly influenced mean ABG quality during most of the study (Table 5). Interactions including season x granular N rate and granular N rate x soluble N rate occurred periodically through 2009 and 2010, and provided additional insight into the main effects on ABG turf quality. Because of this, interaction data will be presented with the main effects. A season x soluble N rate interaction occurred during the summer of 2009, but was not meaningful and thus will not be discussed (Table A.2).

Granular N Rate

Granular N rate had the greatest influence on turf quality during spring 2009, autumn 2009 and spring 2010, accounting for 79, 62, and 72% of variation in the statistical model, respectively (Table 5). A positive linear relationship was observed between granular N rate and mean turf quality during all seasons of the study (Table 5). Granular N applied at 220 kg N ha^{-1} yr^{-1} maintained acceptable turf quality ($\geq$ 5.0) on all observation dates in 2008, 2009, and 2010; whereas, application rates of 147 and 73 kg N ha^{-1} yr^{-1} only had acceptable turf quality ratings on 67 and 58% of dates, respectively (24 total observations; Tables A.3, A.4, and A.5).

Season

Season had much less of an influence on turf quality compared to other main effects; however, during the autumn of 2008, the main effect of season had the greatest influence on turf quality, accounting for 32% of the variation in the statistical model (Table 5). Applying the majority of granular N in autumn improved turf quality during the autumn of 2008, the autumn of 2009, and the spring of 2010; whereas, spring

granular fertilization improved mean turf quality during the summer of 2009 and 2010 (Table 5). No difference in mean turf quality was observed between seasons during the spring of 2009. Much of the available literature on the effect of spring and autumn granular fertilization has not focused on ABG turf. However, previous studies have shown that autumn N applications to other cool-season turfgrasses [Kentucky bluegrass (*Poa pratensis* L.); Perennial ryegrass (*Lolium perenne* L.); Tall fescue (*Festuca arundinacea* Schreb.)] can improve winter turf quality (Bigelow et al., 2007; Dernoeden et al., 1993; Grossi et al., 2005; Miltner et al., 2004) and spring turf quality (Bigelow et al., 2007; Miltner et al., 2004). Moreover, spring applications of N have been shown to encourage ABG growth and encroachment in mixed stands (Engel, 1977; Rieke and Bay, 1976).

Interactions between granular N rate and season occurred during autumn of 2009 and during the summer of 2010 (Table 5), with season having no effect on mean turf quality at the lowest rate of granular N (73 kg N ha^{-1} yr^{-1}), whereas, at higher rates of granular N (220 and 147 kg N ha^{-1} yr^{-1}) season resulted in better turf quality depending on the season of application (Table 6). Better quality was observed in autumn 2009 when the greater N rates were applied in autumn, while better quality was observed in summer 2010 when greater N rates were applied in spring.

Soluble N Rate

Soluble N rate had the greatest impact on turf quality during the summer of 2009 and 2010, accounting for 42 and 58% of the variation in the statistical model. Similar to granular N rate, soluble N rate exhibited a positive linear relationship with turf

quality, improving turf quality during the summer and autumn of 2009 and during the spring and summer of 2010 (Table 5). Summer soluble N applied at 73 and 37 kg N ha^{-1} yr^{-1} maintained acceptable turf quality ratings ($\geq$ 5.0) on 92 and 75% of dates, respectively, in 2008, 2009, and 2010 (24 total observations; Table A.3, A.4, and A.5). In contrast, soluble N applied at 0 or 18 kg N ha^{-1} yr^{-1} only maintained acceptable quality ratings on 54 and 58% of dates, respectively. Inguagiato et al. (2008) also observed a similar increase in turf quality ratings during the summer as a result of increased soluble N rate.

Turf quality was also influenced by the granular N rate x soluble N rate interaction during the summer of 2009 (Table 5), where mean turf quality was less responsive to soluble N rate at the highest rate of granular N (220 kg N ha^{-1} yr^{-1}) compared to lower granular N rates (Table 7). Additionally, granular N applied at 147 kg N ha^{-1} yr^{-1} in combination with the highest soluble N rate (73 kg N ha^{-1} yr^{-1}) maintained as high of a mean turf quality rating during the summer of 2009 as granular N applied at 220 kg N ha^{-1} yr^{-1} and soluble N applied at 73 kg N ha^{-1} yr^{-1} (Table 7), indicating that granular N rate can be reduced while still maintaining excellent turf quality.

Turf Color

The response of ABG color to the main factors (season, granular N rate, and soluble N rate) was similar to the response of turf quality, and accounted for the majority of variation in 2008, 2009, and 2010 (Table 8). Interactions including granular N rate x season, which occurred frequently 2008, 2009 and 2010, and granular N rate x soluble N rate, which was observed in summer 2009, provided additional insight into the

effect of N programming on ABG color and will be presented with the main effects. During the spring of 2009, a season x soluble N rate interaction occurred prior to the initiation of soluble N treatments (Table 8), but did not have a meaningful effect on turf color and thus will not be discussed.

Granular N Rate

Granular N rate had the greatest impact on turf color during the autumn of 2008 and 2009 and during the spring of 2009 and 2010, accounting for 45, 60, 94, and 83% of variation in the statistical model, respectively (Table 8). However, granular N rate influenced ABG color throughout of the study (Table 8), exhibiting a positive linear relationship to granular N rate. Granular N applied at 220 kg N ha^{-1} yr^{-1} produced the highest turf color rating throughout the trial period, maintaining acceptable turf color ($\geq$ 5.0) on 91% of dates; whereas granular N applied at 147 and 73 kg N ha^{-1} yr^{-1} had acceptable turf color on 74 and 39% of dates, respectively (23 total observations; Table A.6, A.7, and A.8). These results are not surprising since nitrogen rate has a major influence on turf color (Carrow et al., 2001).

Season

Compared with other main effects, season had much less of an impact on turf color; however, season did influence mean ABG color during all seasons except for spring of 2009 and 2010 (Table 8). Lack of turf color differences during the spring may be explained by the fact that the color response to autumn granular treatments occurred during the autumn and winter; whereas, spring granular treatments had just been applied when the spring color ratings were taken. Thus, a similar quantity of N

was available to ABG plants during the spring because of the timing/release characteristics of the granular N applications. During the autumn of 2008 and 2009, plots with the majority of granular N applied during the autumn had darker green turf color ratings compared to the spring treatments. In contrast, plots in which the majority of granular N was applied in the spring maintained darker green turf color during the summer of 2009 and 2010, compared to autumn treatments. These results were not surprising since the release of N from IBDU is not dependent on microbial degradation (Lunt and Clarke, 1969), thus autumn applications of IBDU will supply N throughout the autumn and winter; whereas, spring applications will supply N during the spring and summer as long as moisture is present.

The granular N rate x season interaction influenced turf color throughout the study except spring of 2010 (Table 8). In general, mean turf color ratings in the autumn were more responsive to granular N rate when applications were made in the autumn; whereas, mean color ratings in the summer were more responsive to spring granular N rates (Table 9).

Soluble N Rate

Not surprisingly, soluble N rate applied during mid-season had the greatest influence on turf color during the summer of 2009 and 2010, accounting for 45 and 54% of variation in the statistical model, respectively (Table 8). Similar to the granular N rate, there was a positive linear color response to soluble N rate during the summer and autumn of 2009 and the spring and summer of 2010 (Table 8). Soluble N applied at 73 or 37 kg N ha^{-1} yr^{-1} maintained acceptable turf color ratings ($\geq$ 5.0) on 78% of

observation dates during the study (23 total observations; Table A.6, A.7, and A.8). As expected, when no soluble N was applied, turf quality was only above an acceptable color level on 43% of dates. These responses highlight the strong role that light, frequent applications of soluble N have in maintaining acceptable turf color, especially during the summer. Turf color response to soluble N rate depended on the granular N rate during the summer of 2009 (Table 8), and indicated that turf color was more responsive to soluble N rate at lower rates of granular N (73 and 147 kg N ha^{-1} yr^{-1}) compared to 220 kg N ha^{-1} yr^{-1} (Table 10). However, acceptable turf color was not achieved at the lower rates of soluble N when the granular N rate was also low.

CONCLUSIONS

The goal of this study was to develop a better understanding of the effect of N timing and N rate on anthracnose severity of ABG turf. Of all the factors, soluble N rate had the greatest influence on disease severity, underscoring the importance of N fertilization during mid-season, as well as, the benefits of increasing soluble N rate for reducing anthracnose severity. Moderate rates of soluble N (73 kg N ha^{-1} yr^{-1}) applied from May through August maintained acceptable ABG quality and color, as well as limiting anthracnose severity. Granular N rate also had a significant influence on anthracnose severity, with increasing the rate (to 220 kg N ha^{-1} yr^{-1}) resulting in the greatest reduction in the severity of disease. Season of granular N fertilization had a lesser but significant effect on disease severity. Nitrogen fertilization in the autumn has long been recognized as an important management practice for cool-season turfgrasses; however, this study clearly indicates that spring fertilization is more effective at reducing anthracnose severity than autumn fertilization. Collectively, these findings illustrate the importance N rate and timing of N fertilization on anthracnose severity. Thus, N programs for ABG putting green turf should be implemented to avoid N deficiencies leading into and during the growing season that would likely result in greater anthracnose severity.

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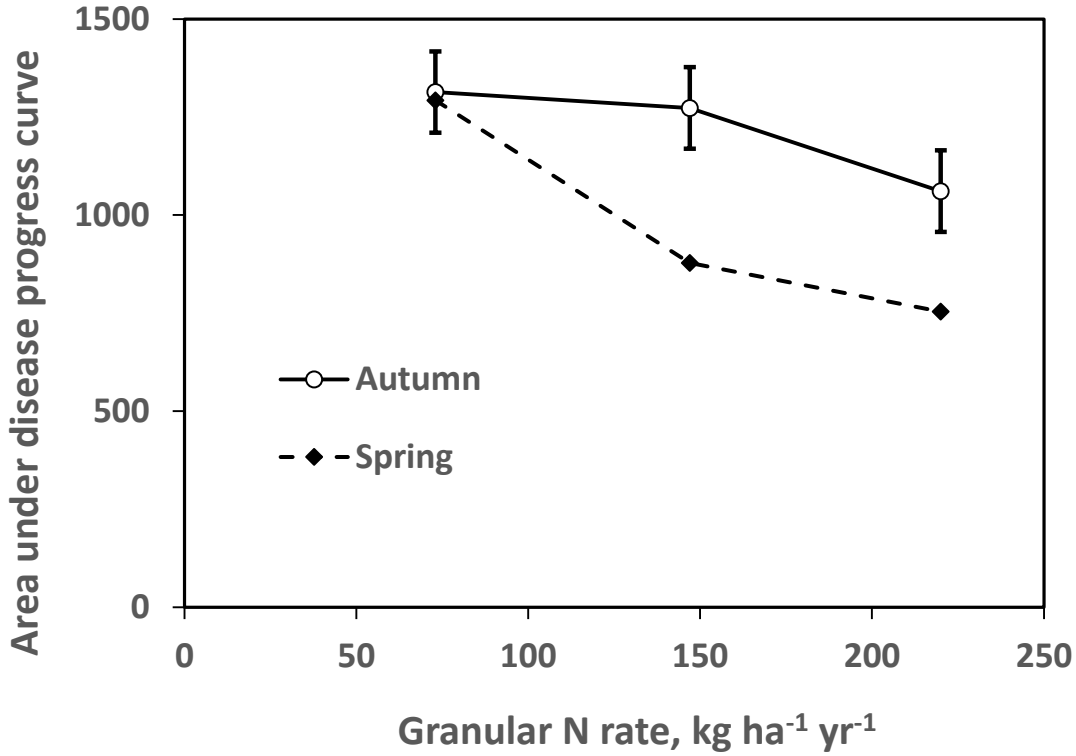

Figure 1. Area under the disease progress curve response to granular N rate and season of granular fertilization on annual bluegrass turf mowed at 3.4 mm in North Brunswick, NJ during 2009. Error bars represent Fisher's protected least significant difference values at 0.05 probability.

Table 1. Summary of treatment combinations (1st and 2nd factors) for granular-N fertilization applied during Autumn 2008-09 and spring 2009-10 to annual bluegrass putting green turf mowed at 3.4 mm in North Brunswick, NJ

Primary Season of Fertilization	Granular N Rate by month†				Annual N
	Sep	Oct	Mar	May	
	---------- kg ha^{-1}----------				
None	0	0	0	0	0
Spring	24	0	24	24	73
Autumn	24	24	24	0	73
Spring	24	24	49	49	146
Autumn	49	49	24	24	146
Spring	37	37	73	73	220
Autumn	73	73	37	37	220

† Granular N treatments were applied in the spring on 29 Mar and 3 May 2009 and on 27 Mar and 1 May 2010; autumn treatments were applied on 8 Sep and 21 Oct 2008 and on 9 Sep and 12 Oct 2009.

Table 2. Analysis of variance of the anthracnose severity response to granular-N rate, season of granular fertilization, and soluble-N rate applied during mid-season to annual bluegrass turf in North Brunswick, NJ, during 2009.

Main effects	Turf area infested							AUDPC[†]
	11-Jun	23-Jun	3-Jul	13-Jul	28-Jul	12-Aug	26-Aug	
	%							
Granular N Rate								
73 kg N ha^{-1} yr^{-1}	3.3	5.8	7.0	10.3	19.4	33.4	34.9	1303
147 kg N ha^{-1} yr^{-1}	2.7	4.6	5.8	8.8	15.0	27.3	31.3	1076
220 kg N ha^{-1} yr^{-1}	2.3	4.6	5.6	7.6	9.1	25.0	27.6	907
$LSD_{0.05}$	NS	NS	NS	NS	2.6	3.4	3.3	147
Season								
Autumn	3.6	6.0	7.5	11.0	16.8	30.2	32.3	1216
Spring	2.0	4.0	4.7	6.9	12.2	26.9	30.3	975
Soluble N Rate								
0 kg N ha^{-1} yr^{-1}	3.3	6.1	7.2	11.9	21.3	34.7	39.0	1405
18 kg N ha^{-1} yr^{-1}	3.3	4.7	6.8	9.3	15.4	28.3	31.8	1119
37 kg N ha^{-1} yr^{-1}	2.4	5.2	5.9	8.6	13.3	27.3	29.2	1039
73 kg N ha^{-1} yr^{-1}	2.1	3.9	4.6	5.9	8.1	23.9	25.1	819
$LSD_{0.05}$	NS	1.4	1.8	2.8	3.0	4.0	3.8	170
Source of variation	ANOVA							
Granular N Rate (GNR)	NS	NS	NS	NS	***(25%)	***(16%)	***(13%)	***(16%)
Linear	NS	NS	NS	*	***	***	***	***
Quadratic	NS	NS	NS	NS	NS	NS	NS	NS
Season (S)	***(16%)[‡]	***(17%)	***(19%)	***(17%)	***(7%)	*(3%)	NS	***(9%)
GNR x S	NS	*(7%)	*(7%)	NS	*(4%)	*(4%)	NS	*(4%)
Soluble N Rate (SNR)	NS	*(11%)	*(10%)	**(18%)	***(32%)	***(19%)	***(37%)	***(28%)
Linear	*	**	**	***	***	***	***	***
Quadratic	NS	NS	NS	NS	NS	NS	*	NS
Cubic	NS	NS	NS	NS	NS	NS	NS	NS
GNR x SNR	NS	NS	NS	NS	*(6%)	**(14%)	NS	NS
S x SNR	NS	NS	NS	NS	NS	NS	NS	NS
GNR x S x SNR	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	63.7	42.5	43.8	46.6	30.4	20.8	18.0	23.1

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively; NS, not significant.

[†] AUDPC, area under disease progress curve

[‡] Percent variation is shown in parentheses for significant factors within the factorial analysis.

Table 3. Analysis of variance of the anthracnose severity response to granular-N rate, season of granular fertilization, and soluble N rate on annual bluegrass turf in North Brunswick, NJ, during 2010.

Main effects	Turf area infested					AUDPC[†]
	21-May	3-Jun	21-Jun	21-Jul	12-Sep	
	---------- % ----------					
Granular N Rate (GN)						
73 kg N ha^{-1} yr^{-1}	13.6	19.6	52.9	60.0	60.9	5766
147 kg N ha^{-1} yr^{-1}	11.2	17.9	48.0	55.9	56.0	5308
220 kg N ha^{-1} yr^{-1}	5.3	14.5	45.7	48.5	50.4	4702
$LSD_{0.05}$	1.0	1.5	2.6	2.7	3.2	170
Season (S)						
Autumn	10.5	18.3	51.1	56.2	57.4	5431
Spring	9.7	16.4	46.6	53.4	54.2	5086
Soluble N Rate (SN)						
0 kg N ha^{-1} yr^{-1}	10.7	18.1	53.4	60.2	62.4	5785
18 kg N ha^{-1} yr^{-1}	10.2	17.2	50.5	57.7	60.3	5539
37 kg N ha^{-1} yr^{-1}	10.2	18.3	47.7	54.5	54.9	5211
73 kg N ha^{-1} yr^{-1}	9.2	15.7	43.8	46.8	45.4	4499
$LSD_{0.05}$	NS	1.7	3.0	3.2	3.7	195
Source of variation	ANOVA					
Granular N Rate (GNR)	***(71%)[‡]	***(33%)	***(20%)	***(33%)	***(21%)	***(35%)
Linear	***	***	***	***	***	***
Quadratic	***	NS	NS	NS	NS	NS
Season (S)	NS	**(7%)	***(11%)	*(3%)	*(3%)	***(6%)
GNR x S	*(2%)	NS	NS	NS	NS	NS
Soluble N Rate (SNR)	NS	*(8%)	***(28%)	***(37%)	***(48%)	***(43%)
Linear	*	**	***	***	***	***
Quadratic	NS	NS	NS	NS	NS	NS
Cubic	NS	NS	NS	NS	NS	NS
GNR x SNR	NS	NS	NS	NS	NS	NS
S x SNR	NS	*(6%)	NS	NS	NS	NS
GNR x S x SNR	*(4%)	NS	NS	NS	NS	NS
CV (%)	17.8	14.6	9.2	8.6	9.9	5.5

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively; NS, not significant.

[†] AUDPC, area under disease progress curve

[‡] Percent variation is shown in parentheses for significant factors within the factorial analysis.

Table 4. Anthracnose severity response to the interaction of granular N rate and soluble N rate on annual bluegrass turf in North Brunswick, NJ, during 2009.

Soluble N Rate	28-Jul			12-Aug		
	Granular N Rate, kg N ha^{-1} yr^{-1}					
	73	**147**	**220**	**73**	**147**	**220**
kg N ha^{-1} yr^{-1}	---------- % ----------					
0	29.1a[†]A[‡]	21.4aB	13.6aC	43.8aA	33.7aB	26.6aC
18	22.1bA	16.1bB	8.1bC	34.8bA	27.2abB	22.9aB
37	16.4cA	15.0bA	8.4bB	33.3bA	24.9bB	23.9aB
73	10.0dA	7.8cA	6.4bA	21.9cA	23.3bA	26.5aA

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

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

Table 5. Analysis of variance of seasonal turf quality of annual bluegrass as influenced by season of granular fertilization, granular N rate, and soluble N rate in North Brunswick, NJ, during 2008, 2009, and 2010.

Main effects	Turf Quality†					
	2008	2009			2010	
	Autumn‡	Spring	Summer	Autumn	Spring	Summer
	1 - 9 scale					
Granular N Rate						
73 kg N ha^{-1} yr^{-1}	8.0	5.5	5.9	3.2	3.2	4.5
147 kg N ha^{-1} yr^{-1}	8.3	6.4	7.3	4.3	4.3	5.3
220 kg N ha^{-1} yr^{-1}	8.5	7.2	8.1	5.7	5.9	6.2
$LSD_{0.05}$	0.2	0.2	0.2	0.3	0.3	0.3
Season						
Autumn	8.5	6.4	6.8	4.7	4.6	4.9
Spring	8.1	6.3	7.4	4.1	4.3	5.7
Soluble N Rate						
0 kg N ha^{-1} yr^{-1}	8.3	6.4	5.8	3.7	4.0	4.1
18 kg N ha^{-1} yr^{-1}	8.3	6.3	6.8	4.2	4.4	4.7
37 kg N ha^{-1} yr^{-1}	8.3	6.3	7.5	4.6	4.6	5.5
73 kg N ha^{-1} yr^{-1}	8.3	6.4	8.3	5.1	4.9	7.0
$LSD_{0.05}$	---	---	0.3	0.4	0.3	0.3
Source of variation	ANOVA					
Granular N Rate (GNR)	***(22%)§	***(79%)	***(38%)	***(62%)	***(72%)	***(25%)
Linear	***	***	***	***	***	***
Quadratic	NS	NS	*	NS	*	NS
Season (S)	***(32%)	NS	***(6%)	***(5%)	*(2%)	***(8%)
GNR x S	NS	NS	NS	*(2%)	NS	*(1%)
Soluble N Rate (SNR)	NS	NS	***(42%)	***(16%)	***(7%)	***(58%)
Linear	NS	NS	***	***	***	***
Quadratic	NS	NS	***	NS	NS	NS
Cubic	NS	NS	NS	NS	NS	NS
GNR x SNR	NS	NS	***(7%)	NS	NS	NS
S x SNR	NS	NS	**(1%)	NS	NS	NS
GNR x S x SNR	NS	NS	NS	NS	NS	NS
CV (%)	3.6	5.1	5.6	12.5	11.4	8.1

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively; NS, not significant.

† Turf quality was rated on a 1 to 9 scale, with 9 = best quality and 5 = minimally acceptable quality.

‡ Analysis of variance for each season includes all quality ratings collected from 1 September to 5 December for autumn; 24 March to 19 May for spring; and 20 May to 31 August for summer.

§ Percent variation is shown in parentheses for significant factors within the factorial analysis.

Table 6. Mean turf quality ratings of annual bluegrass turf as influenced by granular N rate and season of granular N fertilization interaction in North Brunswick, NJ, during autumn 2009 (1 September to 5 December) and summer 2010 (20 May to 31 August).

Granular N Rate	Autumn 2009		Summer 2010	
	Season			
	Autumn	Spring	Autumn	Spring
kg N ha^{-1} yr^{-1}	---------- 1 to 9 scale[†] ----------			
73	3.3c[‡]A[§]	3.1cA	4.2cA	4.7cA
147	4.5bA	4.0bB	4.8bB	5.8bA
220	6.3aA	5.2aB	5.7aB	6.7aA

[†] Turf quality was rated on a 1 to 9 scale, with 9 = best quality and 5 = minimally acceptable quality.

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

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

Table 7. Mean turf quality ratings of annual bluegrass turf as influenced by granular N rate and soluble N rate interaction in North Brunswick, NJ, from 20 May to 31 August 2009 (summer).

	Turf Quality[†]		
Soluble N	**Granular N rate, kg N ha^{-1} yr^{-1}**		
Rate	**73**	**147**	**220**
kg N ha^{-1} yr^{-1}	---------- 1 to 9 scale ----------		
0	4.0d[‡]C[§]	5.9dB	7.3cA
18	5.4cC	7.0cB	8.1bA
37	6.5bC	7.6bB	8.4abA
73	7.8aB	8.6aA	8.6aA

[†] Turf quality was rated on a 1 to 9 scale, with 9 = best quality and 5 = minimally acceptable quality.

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

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

Table 8. Analysis of variance of seasonal turf color of annual bluegrass as influenced by granular N rate, season of granular fertilization, and soluble N rate in North Brunswick, NJ, during 2008, 2009, and 2010.

Main effects	Turf Color†					
	2008	2009			2010	
	Autumn‡	Spring	Summer	Autumn	Spring	Summer
	1 - 9 scale					
Granular N Rate						
73 kg N ha^{-1} yr^{-1}	5.9	4.1	5.1	3.5	2.9	4.8
147 kg N ha^{-1} yr^{-1}	6.9	5.4	6.2	4.8	4.2	5.6
220 kg N ha^{-1} yr^{-1}	7.6	6.9	7.3	6.2	5.4	6.4
$LSD_{0.05}$	0.2	0.2	0.2	0.3	0.3	0.2
Season						
Autumn	7.4	5.5	5.7	5.3	4.2	5.1
Spring	6.2	5.4	6.6	4.3	4.2	6.1
Soluble N Rate						
0 kg N ha^{-1} yr^{-1}	6.8	5.4	4.9	4.4	4.0	4.7
18 kg N ha^{-1} yr^{-1}	6.8	5.5	5.9	4.5	4.1	4.9
37 kg N ha^{-1} yr^{-1}	6.7	5.4	6.4	5.0	4.2	5.7
73 kg N ha^{-1} yr^{-1}	6.8	5.5	7.6	5.4	4.5	7.2
$LSD_{0.05}$	---	---	0.3	0.4	0.3	0.3
Source of variation	ANOVA					
Granular N Rate (GNR)	***(45%)	***(94%)	***(34%)	***(60%)	***(83%)	***(23%)
Linear	***	***	***	***	***	***
Quadratic	NS	NS	NS	NS	NS	NS
Season (S)	***(35%)§	NS	***(9%)	***(14%)	NS	***(12%)
GNR x S	***(10%)	**(1%)	**(2%)	***(6%)	NS	*(1%)
Soluble N Rate (SNR)	NS	NS	***(45%)	***(8%)	*(3%)	***(54%)
Linear	NS	NS	***	***	**	***
Quadratic	NS	NS	NS	NS	NS	**
Cubic	NS	NS	NS	NS	NS	NS
GNR x SNR	NS	NS	**(2%)	NS	NS	NS
S x SNR	NS	*(1%)	NS	NS	NS	NS
GNR x S x SNR	NS	NS	NS	NS	NS	NS
CV (%)	5.0	4.8	6.9	10.9	11.1	7.0

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively; NS, not significant.

† Turf color was rated on a 1 to 9 scale, with 9 = darkest green color and 5 = minimally acceptable color.

‡ Analysis of variance for each season includes all color ratings collected from 1 September to 5 December for autumn; 24 March to 19 May for spring; and 20 May to 31 August for summer.

§ Percent variation is shown in parentheses for significant factors within the factorial analysis.

Table 9. Mean turf color ratings of annual bluegrass turf as influenced by granular N rate and season of granular N fertilization interaction in North Brunswick, NJ, during 2008, 2009, and 2010.

Season	Granular N Rate	Turf Color†				
		2008	2009			2010
		Autumn‡	Spring	Summer	Autumn	Summer
	kg N ha^{-1} yr^{-1}	1 - 9 scale				
Autumn	73	6.1cA§	4.3cA	5.0cB	3.5cA	4.5cB
	147	7.5bA	5.3bA	5.7bA	5.5bA	5.1bB
	220	8.5aA	6.9aA	6.6aB	7.0aA	5.8aB
Spring	73	5.8cB	4.0cB	5.3cA	3.4cA	5.1cA
	147	6.2bB	5.5bB	6.7bA	4.1bB	6.2bA
	220	6.6aB	6.8aA	7.9aA	5.3aB	7.0aA

† Turf color was rated on a 1 to 9 scale, with 9 = darkest green color and 5 = minimally acceptable color.

‡ Analysis of variance for each season includes all color ratings collected from 1 September to 5 December for autumn; 24 March to 19 May for spring; and 20 May to 31 August for summer.

§ Lowercase letter indicated differences between granular N rates within a season; upper case letter indicated differences between seasons within a granular N rate according to Fisher's protected LSD (P = 0.05).

Table 10. Mean turf color ratings of annual bluegrass turf as influenced by granular N rate and soluble N rate interaction in North Brunswick, NJ, from 20 May to 31 August 2009 (summer).

Soluble N	Turf Color[†]		
	Granular N rate, kg N ha^{-1} yr^{-1}		
Rate	73	147	220
kg N ha^{-1} yr^{-1}	---------- 1 to 9 scale ----------		
0	3.5d[‡]C[§]	4.9dB	6.2cA
18	4.6cC	5.8cB	7.2bA
37	5.5bC	6.3bB	7.4bA
73	7.0aC	7.6aB	8.3aA

[†] Turf color was rated on a 1 to 9 scale, with 9 = darkest green and 5 = minimally acceptable green color.

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

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

CHAPTER 2. Soluble Nitrogen Fertilizer Rate Effect on Anthracnose Severity and Playability of Annual Bluegrass Turf

Abstract. Anthracnose, caused by *Colletotrichum cereale*, is a destructive disease of annual bluegrass (ABG) putting green turf that can be exacerbated by inadequate or excessive fertilization. The objectives of this 2-yr field study were to assess the impact of higher rates of soluble-N fertilization on anthracnose severity of ABG turf during the late-spring and summer (late-May through August), and to identify an optimum soluble-N fertilization rate. The study was initiated in a different location each year in North Brunswick, NJ in 2010 on ABG turf maintained at 3.2 mm. N-fertilizer (NH_4NO_3) treatments were applied at 4.9, 9.8, 14.6, 19.5 and 24.4 kg ha^{-1} wk^{-1} from 24 May to 8 Aug. 2010 and 25 May to 11 Aug. 2011 in a RCBD with 4 replications. Regression analysis of disease severity data indicated that a cumulative N application rate of 118 kg N ha^{-1} from late-May through mid-August provided the greatest reduction in anthracnose severity. Higher rates of soluble-N (≥ 14.6 kg N ha^{-1} wk^{-1}) in early-June initially resulted in the greatest reduction in disease severity each year; however, repeated applications from mid- July through August caused disease severity to increase rapidly in both years. Nitrogen applied at 9.8 kg N ha^{-1} wk^{-1} produced turf quality and color above an acceptable level (> 5) throughout both years; whereas turf quality and color were typically below an acceptable level when no N was applied during the same period. Playability (i.e. ball roll distance) was reduced by higher rates of soluble-N (≥ 14.6 kg N ha^{-1} wk^{-1}) compared to N applied at 4.9 kg N ha^{-1} wk^{-1}. It is apparent from

higher rates (14.6 to 24.4 kg N ha^{-1}) of soluble-N can be applied from late-spring through early-summer to reduce disease severity, but as the summer progresses only moderate (9.8 kg N ha^{-1} wk^{-1}) to low (4.9 kg N ha^{-1} wk^{-1}) rates of soluble-N should be applied to suppress anthracnose severity while maintaining acceptable turf quality, color and playability.

INTRODUCTION

Anthracnose is a common fungal disease that can be found on almost all turfgrass species throughout the world (Smiley et al., 2005). The causal agent of anthracnose, *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman (Crouch et al., 2006), is particularly damaging to annual bluegrass (ABG) [*Poa annua* L. f. reptans (Hausskn) T. Koyama] turf. In the field, symptoms of the disease can appear either as a foliar blight or basal rot. Foliar blight is typically present during prolonged periods of high temperature stress and basal rot can occur on close-cut turf throughout the growing season (Smiley et al., 2005).

Anthracnose was first observed on Kentucky bluegrass (*Poa pratensis* L.) in the early 1900's (Selby and Manns, 1909). The disease was later identified on ABG in 1928 by Sprauge and Evaul (1930) when significant damage was observed on golf course putting greens throughout New Jersey during an unusually hot wet summer. The disease did not re-emerge as a consistent problem on ABG putting greens in the U.S. until major outbreaks occurred in the 1960s and 1970s (Alexander, 1969; Vargus, 1975), which prompted several studies further investigating the pathogenicity and control of this disease (Danneberger et al., 1983; Danneberger et al. 1984; Jackson and Herting, 1985; Vargas and Detweiler, 1985). Recently, there has been renewed interest in anthracnose due to severe outbreaks of the disease that occurred in the U.S. and Europe from the late 1990's to early 2000's (Inguagiato et al., 2008; Landschoot and Hoyland, 1995; Mann and Newell, 2005; Wong and Midland, 2004). These outbreaks were attributed to a shift in management practices (e.g. low nitrogen and low mowing

height) to encourage increased ball roll (Inguagiato et al., 2008; Vermeulen, 2003; Wong and Midland, 2004). Since then, multiple studies have reported that cultural management practices (N fertilization, mowing and light weight rolling practices, sand topdressing, irrigation management and the use of plant growth regulators) can influence the severity of anthracnose disease on ABG putting green turf (Hempfling et al., 2015; Inguagiato et al., 2008; Inguagiato et al., 2009; Inguagiato et al., 2012; Roberts and Murphy, 2014; Roberts et al., 2011; Roberts et al., 2012).

Nitrogen fertilization of turfgrass has been shown to either enhance or reduce disease severity depending on the pathogen. Frank and Guertal (2013) summarized the effect of N fertilization on turfgrass diseases, including diseases which are intensified by N [Pythium blight (*Pythium aphanidermatum* [Edson] Fitzpatrick), gray leaf spot (*Pyricularia grisea* [Cooke] Sacc.), brown patch (*Rhizoctonia solani* Kühn), typhula blight (*Typhula incarnate* Fr.) and microdochium patch (*Microdochium nirvale* [Fr.] Samuels & I.C. Hallett)], and diseases which are decreased by N [anthracnose, dollar spot (*Sclerotinia homoeocarpa* F.T. Bennet), red thread, (*Laetisaria fuciformis* [McAlpine] Burdsall), crown rust (*Puccinia coronata* Corda f. sp. *agropyri* Erikss.), bentgrass dead spot (*Ophiosphaerella Agrostis* Dernoeden, M.P.S. Câmara, N.R. O'Neill, van Berkum et M.E. Palm), summer patch (*Magnaporthiopsis poae* [Landsch. & N. Jacks.] J. Luo & N. Zhang) necrotic ring spot (*Ophiosphaerella korrae* Walker and A.M. Smith) and take-all patch (*Gaeumannomyces graminis* [Sacc.] Arx & D. Olivier var. *avenae* [E.M. Turner] Dennis)]. Several studies have documented the effect of N fertilization rate on anthracnose severity of ABG turf. Danneberger et al. (1983) found that a moderate rate

of N (146 kg N ha^{-1} yr^{-1}) had less disease incidence than a higher N rate (292 kg N ha^{-1} yr^{-1}) on ABG turf maintained at fairway height (1.3 cm). Inguagiato et al. (2008) reported that N applied at 4.9 kg ha^{-1} every 7-d from May through September reduced disease severity compared to N applied every 28-d. Similarly, Roberts et al. (2010) found that 4.9 kg ha^{-1} wk^{-1} or 9.8 kg ha^{-1} 2-wk^{-1} provided the greatest reduction in disease severity compared to lower rates. Together these studies indicate that both inadequate and excessive amounts of N can potentially increase anthracnose severity; however, it is unclear what the optimum N rate is for reducing anthracnose severity on ABG putting green turf.

The objective of this study was to assess the impact of higher rates of soluble-N fertilization on anthracnose severity of ABG putting green turf during the growing season (May through August) and to identify an optimum soluble-N fertilization rate.

MATERIALS AND METHODS

Site Description and Maintenance

A 2-yr. field study was initiated in May 2010 at the Rutgers Horticulture Farm No. 2 in North Brunswick, NJ (40°28' N, 74°25' W). Treatments were applied to two separate locations in 2010 and 2011, because of the inability of plots to heal from severe anthracnose damage in 2010. The soil type for both locations was a Nixon sandy loam (fine-loamy, mixed, semiactive, mesic Typic Hapludults) with a sand topdressing layer of 41 and 9 mm in 2010 (location 1) and 2011 (location 2), respectively. The monostands of ABG turf were established in 2001 (location 1) and 2009 (location 2) using methods described by Inguagiato et al. (2008). Plot area was mown 7 times wk^{-1} using a walk-behind greens mower (model 1000; Toro Company, Bloomington, MN) equipped with grooved (wiehle roller, model 99-6241; Toro Company, Bloomington, MN) front roller and bench set at 3.2 mm. Prior to treatment initiation, ammonium nitrate (NH_4NO_3) was applied as a foliar spray at 9.8 kg ha^{-1} on 4 April, 1 May, and 17 May 2010, and urea [$CO(NH_2)_2$] was applied at the same rate on 26 April and 6 May 2011. Phosphorus and potassium were not applied to the plot area during the study period. Plant growth regulator trinexapac-ethyl [4-(cyclopropyl-α-hydroxy-methylene)-3,5-dioxocyclohexanecarboxylic acid ethylester] was applied every 14-d at 0.05 kg a.i. ha^{-1} from 19 March to 2 October 2010 and 22 March to 11 October 2011. Ethephon [(2-chloroethyl) phosphonic acid] was applied at a rate of 3.76 kg a.i. ha^{-1} on 19 March, 2 April, and 23 April 2010 and 22 March, 6 April, and 25 April to suppress ABG seedhead development. Fungicides that were shown to be ineffective at controlling anthracnose

(Towers et al., 2003) were used to control algae and other turf diseases at label rates; dollar spot was controlled with a rotation of boscalid [3-pyridinecarboxamide 2-chloro-N-(4'-chloro[1,1'-biphenyl]-2-yl)] and vinclozolin [3-(3, 5-dichlorophenyl)-5-ethenyl-5-methyl-2, 4-oxazolidinedione], brown patch and summer patch were controlled with a rotation of flutalonil [N-(3-[1-methylethoxy] phenyl)-2-(trifluoromethyl)benzamide] and azoxystrobin [methyl (E)-2-{2-[6-(2-cyanophenoxy)pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate]. Mancozeb (ethylene bisdithiocarbamate) was used to suppress algae at rates ranging from 9.18 to 15.31 kg a.i. ha^{-1} on 5 June, 11 June, 27 June, 15 July, 20 July, 28 July, and 28 Aug 2010. Algae suppression was not required during 2011. Insect pests [annual bluegrass weevil (*Listronotus maculicollis* Dietz) and black cutworm (*Agrotis ipsilon* Hufnagel)] were controlled with chlorantraniliprole [3-broom-N-[4-chloor-2-methyl-6-(methylcarbamoyl)fenyl]-1-(3-chloor-2-pyridine-2-yl)-1H-pyrazool-5-carboxamide] at 0.18 kg a.i ha^{-1} on 30 Apr. 2010 and bifenthrin [2-Methyl-3-phenylphenyl)methyl (1S,3S)-3-[(Z)-2-chloro-3,3,3-trifluoroprop-1-enyl]- 2,2-dimethylcyclopropane-1-carboxylate] at 0.13 and 0.07 kg a.i. ha^{-1} on 22 June and 21 Aug. 2011, respectively.

In 2009, the field area (location 1) was inoculated with *C. cereale* isolate HFIIB obtained from an adjacent field to ensure uniform infection. Inoculum was produced and applied according to methods described by Inguagiato et al. (2008) using a concentration of 40,000 conidia mL^{-1} between 1800 and 2000 h on 3, 4 and 11 July 2009, when the minimum air temperature was ≥21°C and relative humidity ≥90%.

Disease outbreaks occurred naturally in 2010 and 2011; *C. cereale* was re-isolated from symptomatic tissue each year to confirm its presence.

Treatment Design

A randomized complete block design with 6 treatments and four replications was used to assess the study objectives. Plot size was 1.5 x 3.7 m and treatments included ammonium nitrate applied as a foliar spray at 0, 4.9, 9.8, 14.7, 19.6, and 24.5 kg ha^{-1} wk^{-1}, beginning on 24 May 2010 and 25 May 2011 and terminating on 11 August (12 wk) in both years. Treatments were applied with a gas powered backpack sprayer (model SHR – 210; Echo Inc., Lake Zurich, IL) attached to a five nozzle boom equipped with 3.0 bar constant flow valves (model 11-16SY; G.A.T.E. LLC, Sebastian, FL) and air induction flat spray tips (model AI8003VS; TeeJet® Technologies, Springfield, IL). Immediately following N application each plot was lightly irrigated (< 0.25 cm) to prevent foliar injury ("burn").

Data Collection and Analysis

Anthracnose severity was rated approximately every 10-14 days from June to early September 2010 and from June to early August 2011 using the line intercept-grid count method described by Inguagiato et al. (2008) to determine the percentage of turf area infested with anthracnose. A total of 546 observations were made over a 2.8 m^2 of plot area and percent area infested was calculated by the following formula:

$$\text{Percent turf area infested} = (n/546) \times 100$$

Where *n* is the number of intersects observed over symptomatic tissue. Turf color and quality were rated from June to September 2010 and from June to August 2011 using a

1 to 9 scale, with 9 representing the best quality/ darkest green color turf and 5 the minimum acceptable. Soil samples were collected on 1 Sept. 2010 and 15 Aug. 2011 to determine soil pH using the 1:1 soil:water (by volume) extract method (Thomas, 1996), and electrical conductivity using 1:2 soil:water extract method ($EC_{1:2}$; Dellavalle, 1992). Four (1.9 cm diameter) cores per plot were collected to a depth of 17 cm with a soil probe and then mixed and subsampled for analysis. Clippings were collected 39 and 72 days after treatment initiation in 2010 (2 July and 4 August), and 36 and 57 days after treatment initiation in 2011 (30 June and 21 July) from the center 2.1 m^2 of plots using a Toro walk-behind greens mower (model 1000). Total N concentration of leaf tissue was determined using the Kjeldahl method (Bremner, 1996). Ball roll distance (BRD) was measured between 1200 and 1600 h from mid-June through early-July in each year before turf area infested with anthracnose exceeded 50%. A Stimpmeter was used to determine BRD, with three balls released in two opposing directions within each plot (6 ball rolls) to determine average distance (Green Section Staff, 1996).

Data was subjected to analysis of variance to identify significant treatment effects using the generalized linear model (GLM) procedure in Statistical Analysis Software (SAS) package (v. 9.3; SAS Institute). Treatment means were separated using Fisher's protected least significant difference (LSD) test at $p < 0.05$ (Dowdy et al., 2004). Regression analysis models were generated with REG procedure in SAS to determine disease severity response to cumulative N applied at the time of data collection. Disease data on individual observation dates was transformed to a percentage of the highest disease severity on each observation date to normalize the data. All normalized

disease data was combined and compared to cumulative N rated to determine the response of disease severity to N rate over the application period (12 weeks). Leaf N concentrations from clipping samples were plotted against disease severity ratings, and a linear-response plateau (LRP) model was developed for each date using the NLIN procedure in SAS. Frequency distributions of BRDs for each treatment over both years were constructed to determine the effect of soluble-N rate on BRD. Pooled *t* tests ($p < 0.05$; Dowdy et al., 2004) were used to compare each treatment to the 4.9 kg N ha^{-1} wk^{-1} treatment, which represents a typical soluble-N rate used on golf course putting greens in the Northeastern US. An *f*-test was used to determine if the treatment variance being compared were equal.

RESULTS AND DISCUSSION

Anthracnose Severity

The initial infestation of anthracnose developed naturally in early-June 2010 and progressed slowly until 15 July after which disease severity sharply increased up to 71% by 1 September (Table 1). In 2011, anthracnose also developed in early-June and steadily increased through 18 July after which disease severity increased sharply to a maximum of 89% on 9 August (Table 2).

Soluble-N rate affected anthracnose severity on all dates in 2010 (Table 1) and 2011 (Table 2). On the first disease ratings of 2010 (7 June), there was a negative linear relationship between soluble-N rate and disease severity, and a quadratic relationship on all subsequent ratings in 2010 and 2011 (Table 1 and 2). Visualization of regression data highlighted cumulative N rate targets at different time points during the season each year of the study(Fig. 1). Early in the growing season (early June), cumulative soluble-N rates of 40 and 49 kg N ha^{-1} (20 and 24 kg N ha^{-1} wk^{-1}) provided the greatest reduction in disease severity in 2010 and 2011, respectively. By late June to early July each year, cumulative soluble-N rates of 115 and 97 kg N ha^{-1} had the least amount of turf area infested with anthracnose; weekly soluble-N rates between 13 to 18 kg N ha^{-1} were required to achieve these cumulative totals (Supplemental Fig. 1). Finally by mid-August, slightly greater cumulative rates of soluble-N of 118 and 122 kg N ha^{-1} provided the greatest reduction in anthracnose severity (Fig. 1). These cumulative N rates required weekly N applied at 10 to 11 kg N ha^{-1} over a 12 week period each year to reach these N totals. Thus, the data indicates that cumulative N requirements can be

divided into three distinct stages throughout the summer growing season. During late-spring through early-summer (mid-May thought early-June) high rates of soluble-N are required prior to the onset of disease to obtain the greatest disease suppression, with target cumulative N rates up to 49 kg N ha^{-1} by early June. From early June through mid-July moderate rates of soluble N should be applied to reduce disease severity, with a target cumulative N rate of approximately 100 kg N ha^{-1} by mid-July. By late summer (August), low rates of soluble-N should be applied, with a target cumulative N rate of about 120 kg N ha^{-1} by mid- to late-August. One rather interesting finding was that on 15 July 2010, regression analysis indicated that minimum disease severity was obtained with a cumulative soluble-N rate 141 kg N ha^{-1}, which was much higher than predicted values on any other date. It is not completely clear why predicted values were so much higher on this date compared to a similar dates in 2011, but it may be partially related to the delayed onset of disease in 2010 compared to 2011.

Prior studies have noted the importance of frequent, low-rate soluble application of N for the reduction anthracnose severity. Inguagiato et al. (2008) found rates of 4.9 kg N ha^{-1} every 7-d reduced disease severity compared to the same rate applied every 28-d; however, higher rates of N were not evaluated in that study. The benefit of increased N rate is thought to be a result of rapid plant recovery (growth) from disease, rather than a resistance to infection (Couch and Bloom, 1960). It may also be possible that N rate can influence the interaction between the environment and the pathogen; previous research has shown that the number of acervuli on ABG leaf blades was reduced by increasing N levels at moderate temperatures (22°C), but at higher

temperatures (32°C) the number of acervuli was lowest at moderate rates of N (Danneberger et al., 1983).

Another important finding of this study was that frequent (every 7-d), high-rate soluble applications of N can increase anthracnose severity, particularly during late summer when disease severity is the greatest. Previous research has not examined the response of anthracnose severity to a broad range of soluble N rates, specifically at the higher rates on the spectrum. However, Danneberger et al. (1983) did observe an increase in anthracnose severity with increasing N rate an ABG maintained at fairway height; a 1.3- to 2.6-fold increase in disease severity was seen when urea (applied as a granular) was applied at 292 kg N ha^{-1} yr^{-1} compared to 146 kg ha^{-1} yr^{-1}. A possible explanation for why high-rate application of N might increase disease is that they can cause carbohydrate reserves to become depleted by rapid shoot production, limiting root growth and decreasing stress tolerance of the grass, particularly during hot weather when anthracnose severity is typically high (Carrow et al. 2001).

Additionally, regression analysis of normalized disease severity data combined across all observation dates for both years indicated that a cumulative N rate of 118 kg N ha^{-1} during the summer (late-May through mid-August) provided the greatest reduction in disease severity (Fig. 2). These results are consistent with other studies, such as Inguagiato et al. (2008) who found that a cumulative N rate of 107.5 kg to 117.3 N ha^{-1} from May through September decreased anthracnose severity compared to lower rates, and further refines recommendation for N fertilization and suppression of anthracnose.

Turf Quality and Color

Soluble-N rate had an effect on turf quality on all dates in 2010 and 2011 (Table 3). Turf quality exhibited a linear and/or a quadratic relationship to soluble-N rate throughout the study. On 7 June 2010, a linear relationship between soluble-N rate and turf quality was observed and plots fertilized with 19.5 and 24.4 kg N ha^{-1} wk^{-1} initially had better turf quality than lower N rates. However, continued application of 19.5 and 24.4 kg N ha^{-1} wk^{-1} increased disease severity and decreased quality ratings by mid- August 2010. On 3 Sept. 2010, unacceptable quality (< 5) was observed on plots fertilized with 14.6, 19.5, and 24.4 kg N ha^{-1} wk^{-1} which was primarily due to greater disease severity (Table 1). Nitrogen applied at 4.9 and 9.8 kg N ha^{-1} wk^{-1} provided acceptable turf quality throughout the two year study and had the greatest quality rating on the last two rating dates in 2010 (16 August and 3 September). On the first rating of 2011, a quadratic relationship was observed between soluble-N rate and turf quality, with soluble-N rates of 19.5 and 24.4 kg N ha^{-1} wk^{-1} producing the highest quality turf (Table 3). Turf quality of plots fertilized at rates ≥ 14.6 kg N ha^{-1} wk^{-1} remained high through 5 July 2011; however, by 1 August the quality of these plots dropped below an acceptable level, which was primarily due to a significant increase in anthracnose severity (Table 2). Nitrogen applied at 4.9 and 9.8 kg N ha^{-1} wk^{-1} were the only treatments to provide acceptable turf quality throughout 2011.

Soluble-N rate had an effect on turf color on all dates in 2010 and 2011 (Table 4), but was less dramatic than the turf quality response to soluble-N rate (Table 3). A positive linear relationship between soluble-N rate and turf color was observed on 7

June 2010 and on all subsequent ratings in 2010 and 2011 a quadratic relationship was detected. Soluble-N rates of 14.6 to 24.4 kg N ha^{-1} wk^{-1} resulted in color ratings > 8 throughout 2010 (except 14.6 kg N ha^{-1} wk^{-1} treatment on 7 June); whereas, the untreated control (0 kg N ha^{-1} wk^{-1}) resulted in marginally acceptable color (≈ 5) throughout 2010 (Table 4). Nitrogen treatments applied at 4.9 and 9.8 kg N ha^{-1} wk^{-1} had acceptable quality on all rating dates in 2010, with quality scores ranging from 6.1 to 7.4 and 6.9 to 8.3, respectively. On 21 Jun. 2011, N applied at 19.5 and 24.4 kg N ha^{-1} wk^{-1} had the greatest color ratings, and on 5 Jul. 2011 N applied at 14.6, 19.5 and 24.4 kg N ha^{-1} wk^{-1} had the greatest color ratings; however, turf color sharply decrease on 1 August due to the severe anthracnose infestation. Nitrogen applied at 9.8 kg N ha^{-1} wk^{-1} had acceptable color ($\geq$ 5) on all ratings in 2011, whereas, the untreated control had unacceptable color on 2 of 3 ratings in 2011.

Ball Roll Distance

As expected, soluble-N rate had an effect on BRD on all dates (Table 5), with the untreated control consistently having among the greatest ball roll distances throughout both years. A quadratic relationship was observed on 15 June 2010, and 27 June and 5 July 2011; on all other dates in 2010 and 2011 a negative linear relationship between BRD and soluble-N rate was observed (Table 5). Nitrogen applied at 4.9 kg N ha^{-1} wk^{-1} produced a BRD ≥ 2.9 m 60% of the time in 2010 and 2011 (Table 6), which is within or greater than the range of acceptable BRD (2.9 to 3.2 m) for daily play private golf courses in the northeastern United States (Niven, 2008). Limited shoot growth in untreated control (0 kg N ha^{-1} wk^{-1}) plots resulted in BRD ≥ 2.9 m 80% of the time;

however, BRD was not measured in the current study when disease was most severe, thus, as disease severity increases it is likely that ball roll would become more inconsistent. Pooled *t* tests indicated that N rates of 14.6, 19.5, and 24.4 kg N ha^{-1} wk^{-1} decreased mean BRD by 0.17 to 0.24 m compared to N applied at 4.9 kg N ha^{-1} wk^{-1} during the study; whereas mean BRD of the untreated control and 9.8 kg N ha^{-1} wk^{-1} treatment were not statically different from the 4.9 kg N ha^{-1} wk^{-1} treatment (Table 6). Although the mean BRD of the 9.8 kg N ha^{-1} wk^{-1} treatment was not statistically different from the 4.9 kg N ha^{-1} wk^{-1} treatment, it was slightly below the acceptable BRD range (2.8 vs. the acceptable range of 2.9 to 3.2 m; Table 6) and only had BRDs within or above the acceptable BRD range on 50% of the observations dates. Reductions in BRD due to increased N can be compensated for with other management practices such as more frequent mowing and lightweight rolling that can be used to increase BRD without increasing anthracnose severity (Inguagiato et al., 2009; Roberts et al., 2012).

Soil pH and Electrical Conductivity

Soil pH was affected by soluble-N rate in both years, resulting in a quadratic and linear response in 2010 and 2011, respectively (Table 7). Soil pH was decreased from 6.1 (untreated control) to 5.7 (24.4 kg N ha^{-1} wk^{-1} treatment) in 2010, following 12 N application. Initially, no statistical difference in soil pH was observed between N treatments after five N applications of in 2011 (29 June; Table 7); however, after 12 applications a negative linear relationship between soluble-N rate and soil pH was observed, with soil pH ranging from 5.3 (untreated control) to 4.5 (24.4 kg N ha^{-1} wk^{-1} treatment) (Table 7). Annual bluegrass turf is not generally considered to be tolerant of

acidic soils. Sprauge and Evaul (1930) conducted greenhouse experiments to determine the relationship between ABG growth and soil pH and found that ABG produced very little growth and eventually died at soil pH below 4.0; whereas optimum growth was observed at pH 6.1. Sprague and Burton (1937) also found increasing soil pH from 5.3 to 6.3 with limestone increase ABG growth regardless of fertilizer treatment while investigating the effect of lime and fertilizer treatments on ABG growth in greenhouse studies. Moreover, Ferguson (1936) conducted studies on the effect of acidity on germination of ABG seed and found that no germination occurred at pH 3.58, but 66% of ABG seed germinated at pH 5.20; which led him to speculate that the association between soil pH and ABG abundance was not due to toxicity of mature plants but, rather failure of seeds to establish at low soil pH. Thus while it is possible that soil pH has an effect on anthracnose severity of ABG, other factors (e.g. influence of calcium at high pH or nutrient deficiencies or toxicities at pH extremes) may be affecting the disease at various pH levels so, further research is needed to confirm these results.

Electrical conductivity was not affected by soluble-N rate in 2010, but a quadratic relationship was detected on 15 Aug. 2011 (Table 7). Higher rates of soluble-N (19.5 and 24.4 kg N ha^{-1} wk^{-1}) increased $EC_{1:2}$ compared to lower rates; however, the concentration of salt in the soil still remained in the non-saline classification ($EC_{1:2}$ < 0.4 dS m^{-1}) for degree of salinity (Dellavalle, 1992). Unfortunately, it is not possible to make direct comparisons to EC thresholds of ABG turf reported in the literature since reported values were measured using the saturated-paste extract method (EC_e) (Carrow and

Duncan, 1998). However, data from the current study indicates that salinity stress was not caused by any of the nitrogen application rates over the course of a 12 week period

Tissue Nitrogen Content

Critical N concentrations of ABG leaf tissue required to reduce anthracnose severity were determined using the linear plateau model (Figures 3). Significant linear plateau models in 2010 and 2011 indicated that the critical tissue N concentration for reducing anthracnose severity range from 29 to 51 g N kg^{-1} (Fig. 3). Critical N concentration for clippings collected on 2 July 2010 was 51.1 g N kg^{-1}, but when tissue was collected on 4 Aug. 2010 disease severity was so high that there was no correlation between clipping N concentration and anthracnose severity. In 2011, clipping critical N concentration for reducing disease severity was 29 and 31 g N kg^{-1} for tissue collected on 30 June and 21 July, respectively. Further research is needed to identify a more exact critical N value for the reduction of anthracnose severity; however, data from the current study suggests that this value lies somewhere between 30 to 50 g kg^{-1} N. Previous studies have not identified a N sufficiency range for ABG turf, but these values are within or slightly below the N sufficiency range recommended for creeping bentgrass (45 – 60 g N kg^{-1}; *Agrostis stolonifera* L.) (Mills and Jones, 1996).

CONCLUSIONS

As expected, soluble-N rate influenced anthracnose severity throughout both years. A cumulative N rate of 118 kg N ha^{-1} (10 kg N ha^{-1} wk^{-1}) from late-May through mid-August provided the greatest reduction in disease severity; higher or lower cumulative rates of soluble-N resulted in increased anthracnose severity. High soluble-N rates (≥ 14.6 kg N ha^{-1} wk^{-1}) in early June initially decreased anthracnose severity, but repeat (weekly) applications at these rates later in the summer caused disease severity to rapidly increase as the anthracnose epiphytotics progressed each year. It is apparent from the current study that higher rates of soluble-N (≥ 14.6 kg N ha^{-1} wk^{-1}) can be applied during late-spring (late-May), but that moderate to low rates (9.8 to 4.9 kg N ha-1 wk-1) should be applied as the summer progresses to prevent excessive N fertilization and increased disease severity. Soluble-N applied at 9.8 kg N ha^{-1} wk^{-1} to ABG putting green turf provided the most consistent disease suppression, turf quality and color; whereas playability of ABG turf at this rate was similar to plots receiving 4.9 kg N ha^{-1} wk^{-1}. But, increasing soluble-N to rates ≥ 14.6 kg N ha^{-1} wk^{-1} reduced BRD and eventually turf quality and color. Moreover, increased rates of ammonium nitrate applied as a soluble solution significantly decreased soil pH after 12 applications. Soil $EC_{1:2}$ was also influenced by soluble-N rate, with positive linear relationship between N rate and soil $EC_{1:2}$; however, $EC_{1:2}$ values were far below levels that would affect ABG growth. Routine soil testing should be conducted to monitor soil pH and ensure it stays within an acceptable level for ABG growth when applying similar rates of an acidifying N fertilizer. Nonlinear regression analysis between disease severity and tissue N content

indicated a critical concentration for tissue N between 30 and 50 g kg^{-1} N; but further research is needed to determine a more precise critical level.

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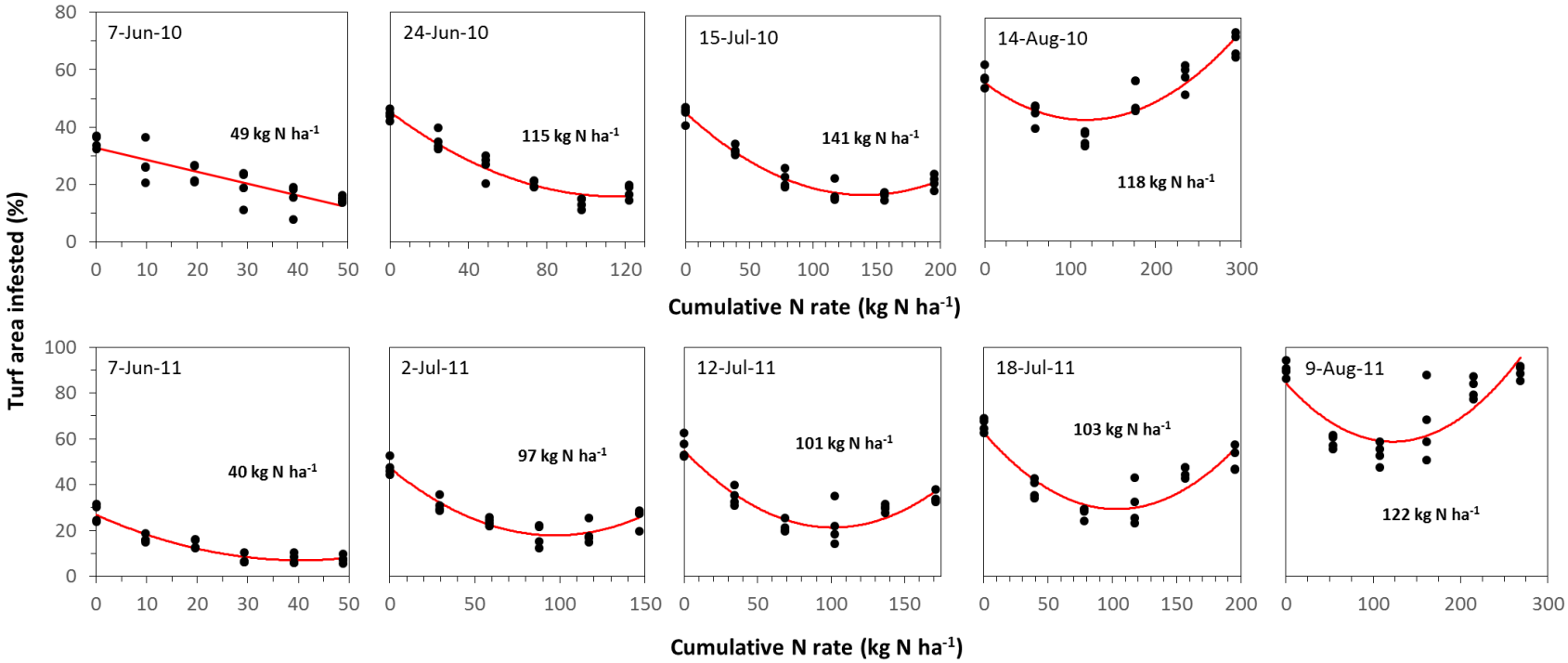

Figure 1. Response (linear or quadratic) of anthracnose severity (turf area infested) of annual bluegrass turf to weekly application rate of ammonium nitrate for each rating date in 2010 (top) and 2011 (bottom); N treatments were applied weekly from 24 May to 11 Aug. 2010 and 25 May to 3 Aug. 2011.

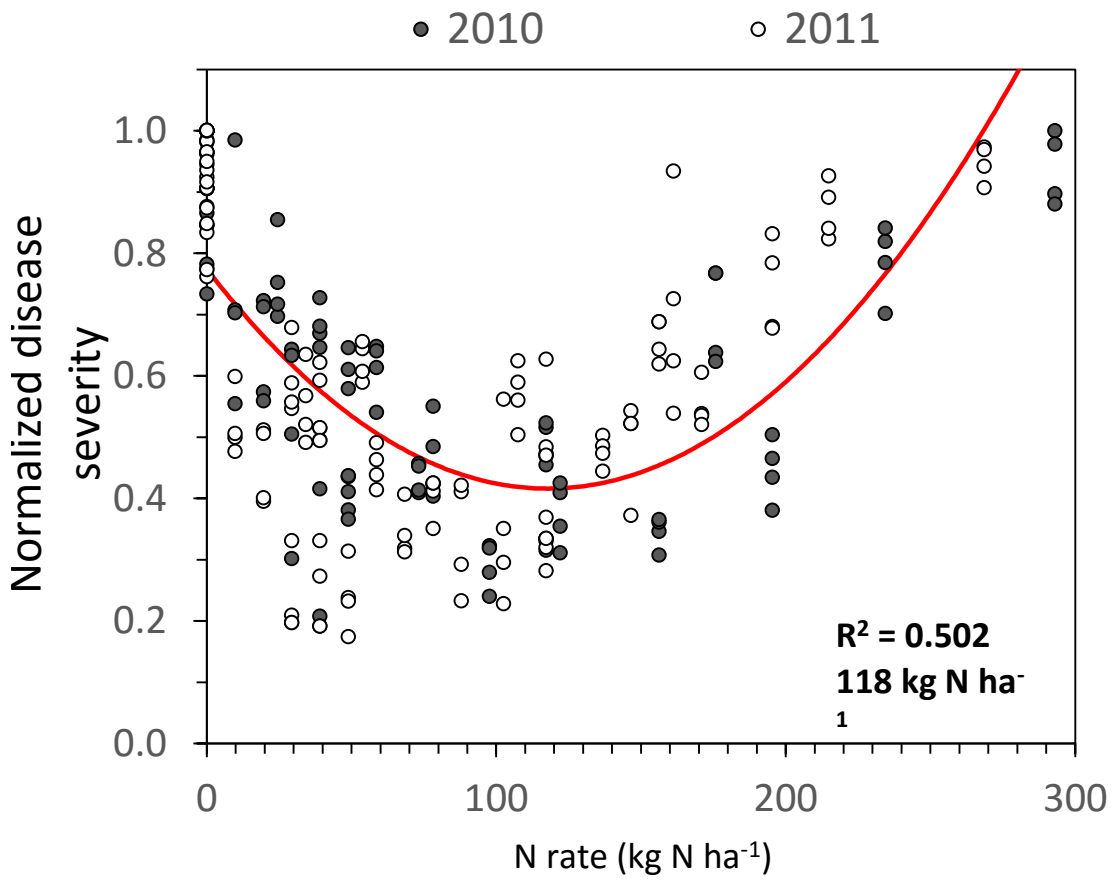

Figure 2. Normalized disease severity response to cumulative soluble-N rate during disease epiphytotics in 2010 (96 observations) and 2011 (120 observations); N treatments were applied from 24 May to 11 Aug. 2010 and 25 May to 3 Aug. 2011.

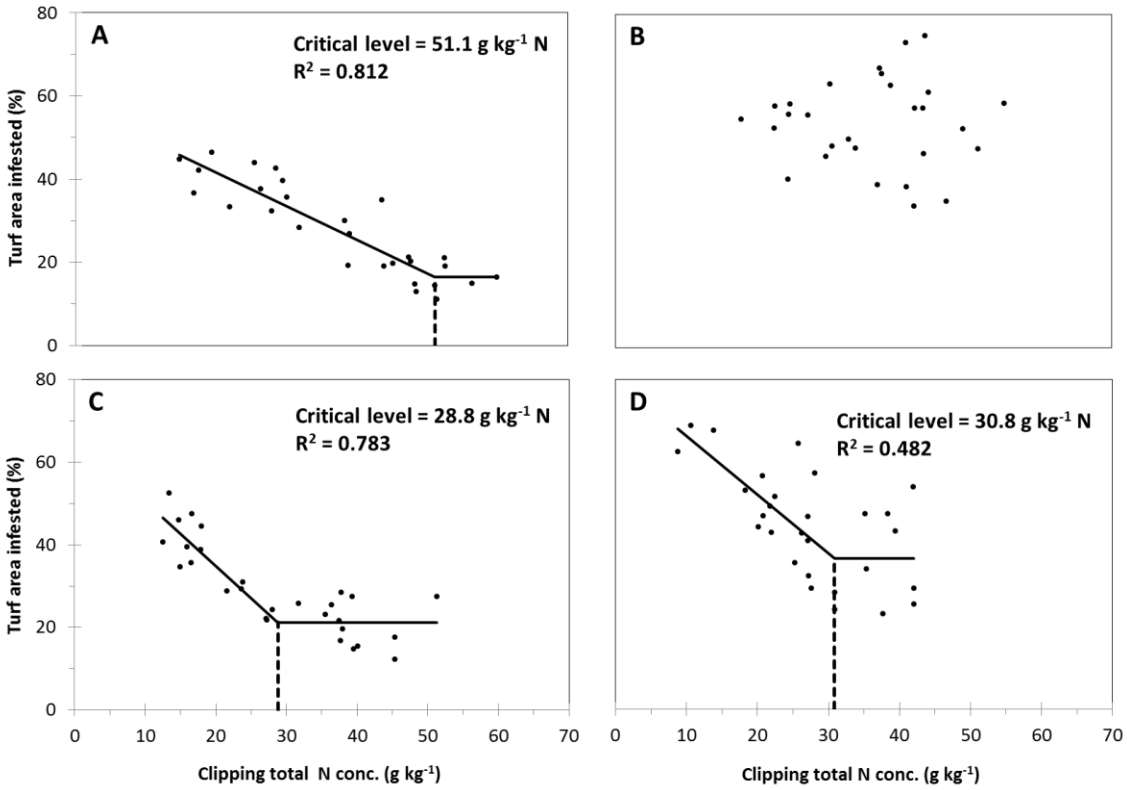

Figure 3. Critical leaf tissue N concentrations as estimated with linear-response plateau model for anthracnose severity of annual bluegrass measured on (A) 24 Jun. 2010, (B) 14 Aug. 2010, (C) 2 July 2011, and (D) 18 July 2011. Turf clippings were collected on (A) 2 Jul. 2010, (B) 4 Aug. 2010, (C) 30 Jun. 2011, and (D) 21 Jul. 2011; total N concentrations were determined using the Kjedahl method. The vertical dotted line to the *x*-axis indicates the critical concentration.

Table 1. Anthracnose severity as affected by nitrogen rate on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ, during 2010.

Nitrogen rate†	Turf area infested				
	7-Jun	24-Jun	15-Jul	14-Aug	1-Sep#
kg N ha^{-1} wk^{-1}	---------- % ----------				
0	34.8	44.4	45.3	58.7	56.5
4.9	27.3	35.1	32.4	45.7	47.1
9.8	23.8	26.4	22.2	36.8	46.9
14.6	19.3	20.1	17.3	52.4	63.0
19.5	15.1	13.5	16.4	58.9	66.4
24.4	14.7	17.4	21.2	70.3	71.1
$LSD_{0.05}$‡	6.0	3.9	4.0	6.9	6.6
Planned F-test§	---------- *p* > F ----------				
Linear	***	***	***	***	***
Quadratic	NS¶	***	***	***	***

***Significant at the 0.001 probability level.

†Ammonium nitrate treatments were applied from 24 May to 11 Aug. 2010.

‡Means separated using Fisher's protected least significant difference test at α= 0.05.

§Orthogonal polynomial contrasts used to determine response curve of the data.

¶NS, not significant.

#Recovery rating taken after N treatments had concluded.

Table 2. Anthracnose severity as affected by nitrogen rate on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ, during 2011.

Nitrogen rate†	Turf area infested				
	7-Jun	2-Jul	12-Jul	18-Jul	9-Aug
kg N ha^{-1} wk^{-1}	%				
0	27.6	47.7	56.5	65.9	90.2
4.9	16.4	31.2	34.7	38.3	58.7
9.8	14.3	23.8	21.6	27.8	53.6
14.6	7.4	17.9	22.5	31.0	66.4
19.5	7.8	18.7	29.9	45.5	81.9
24.4	7.6	25.8	34.4	51.2	89.2
$LSD_{0.05}$‡	3.9	6.0	7.0	7.9	9.6
Planned F-test§	*p* > F				
Linear	***	***	***	*	*
Quadratic	***	***	***	***	***

*Significant at the 0.05 probability level.

***Significant at the 0.001 probability level.

†Ammonium nitrate treatments were applied from 25 May to 11 Aug. 2011.

‡Means separated using Fisher's protected least significant difference test at α= 0.05.

§Orthogonal polynomial contrasts used to determine response curve of the data.

Table 3. Turf quality response to nitrogen rate on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ, during 2010 and 2011.

	Turf quality						
Nitrogen	---------- 2010 ----------				---------- 2011 ----------		
rate†	7-Jun	2-Jul	16-Aug	3-Sep	21-Jun	5-Jul	1-Aug
kg N ha^{-1} wk^{-1}	---------- 1 - 9 scale‡ ----------						
0	6.0	5.0	4.5	5.4	4.5	4.3	1.8
4.9	6.9	6.9	6.8	6.9	6.8	7.0	5.0
9.8	7.1	7.4	7.8	6.8	7.4	8.3	6.5
14.6	7.9	8.3	6.4	4.3	8.1	9.0	4.5
19.5	8.8	8.8	5.3	3.5	8.8	8.8	2.5
24.4	8.9	7.9	4.0	2.0	8.8	8.9	1.8
$LSD_{0.05}$§	0.6	0.4	1.0	1.6	0.6	0.4	1.6
Planned F-test¶	---------- *p* > F ----------						
Linear	***	***	**	***	***	***	NS
Quadratic	NS#	***	***	**	***	***	***

**Significant at the 0.01 probability level.

***Significant at the 0.001 probability level.

†Ammonium nitrate treatments were applied from 24 May to 11 Aug. 2010 and 25 May to 11 Aug. 2011.

‡Turf quality was rated on a 1-9 scale where 9 = highest quality and 5 = minimally acceptable quality.

§Means separated using Fisher's protected least significant difference test at α= 0.05.

¶Orthogonal polynomial contrasts used to determine response curve of the data.

#NS, not significant.

Table 4. Turf color response to nitrogen rate on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ, during 2010 and 2011.

Nitrogen rate†	Turf color						
	2010				2011		
	7-Jun	2-Jul	16-Aug	3-Sep	21-Jun	5-Jul	1-Aug
kg N ha^{-1} wk^{-1}	1 - 9 scale‡						
0	5.5	5.0	5.1	5.8	5.0	4.3	1.0
4.9	6.1	7.3	7.4	7.0	6.6	6.8	5.0
9.8	6.9	7.9	8.3	7.8	7.6	8.3	7.0
14.6	7.5	8.4	9.0	8.1	8.1	9.0	5.3
19.5	8.3	9.0	8.9	8.5	8.6	8.9	3.8
24.4	9.0	9.0	8.3	8.0	9.0	8.8	2.5
$LSD_{0.05}$§	0.3	0.4	0.7	1.2	0.4	0.5	1.5
Planned F-test¶	*p* > F						
Linear	***	***	***	***	***	***	NS
Quadratic	NS#	***	***	*	***	***	***

*Significant at the 0.05 probability level.

***Significant at the 0.001 probability level.

†Ammonium nitrate treatments were applied from 24 May to 11 Aug. 2010 and 25 May to 11 Aug. 2011.

‡Turf color was rated on a 1-9 scale where 9 = darkest green color and 5 = minimally acceptable color.

§Means separated using Fisher's protected least significant difference test at α= 0.05.

¶Orthogonal polynomial contrasts used to determine response curve of the data.

#NS, not significant.

Table 5. Ball roll distance response to soluble-N rate on annual bluegrass turf mowed at 3.2 mm in North Burnswick NJ, during 2010 and 2011.

	Ball roll distance‡									
Nitrogen	2010					2011				
rate†	14-Jun	15-Jun	17-Jun	1-Jul	8-Jul	15-Jun	24-Jun	27-Jun	1-Jul	5-Jul
kg N ha^{-1} wk^{-1}	m									
0	3.00	3.11	3.28	3.19	2.85	3.29	2.72	3.19	3.19	3.04
4.9	2.94	2.83	3.29	3.22	2.84	3.25	2.60	3.01	3.22	2.86
9.8	2.82	2.87	3.22	3.11	2.68	3.16	2.38	2.93	3.11	2.79
14.6	2.78	2.71	3.19	3.10	2.59	3.09	2.38	2.84	3.10	2.71
19.5	2.81	2.76	3.07	3.00	2.55	3.12	2.30	2.76	3.00	2.66
24.4	2.69	2.69	3.14	3.05	2.50	3.00	2.32	2.82	3.05	2.69
$LSD_{0.05}$§	0.13	0.12	0.14	0.14	0.11	0.13	0.19	0.14	0.14	0.16
Planned F-test¶	*p* > F									
Linear	***	***	**	**	***	***	***	***	**	***
Quadratic	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.

†Ammonium nitrate treatments were applied from 24 May to 11 Aug. 2010 and 25 May to 11 Aug. 2011.

‡Ball roll distances are an average of six measurements in two directions.

§Means separated using Fisher's protected least significant difference test at α= 0.05.

¶Orthogonal polynomial contrasts used to determine response curve of the data.

#NS, not significant.

Table 6. Frequency distribution (n=10) of ball roll distances and comparison of mean ball roll for all nitrogen rate levels on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ, during 2010 and 2011.

Nitrogen rate[†]	Ball roll distance ranges (m)				Mean[‡]	SD	Equality of variances[§]	*t*-test[¶]
	2.3 - 2.6	2.6 - 2.9	2.9 - 3.2*	3.2 - 3.5				
kg N ha^{-1} wk^{-1}	---------- % ----------				--------- m ---------		*p* > *F*	*p* > *t*
0	0	20	60	20	3.06	0.197	0.432	0.089
4.9	10	30	20	40	2.98	0.224	---	---
9.8	10	40	40	10	2.88	0.254	0.434	0.076
14.6	20	40	40	0	2.81	0.254	0.444	0.002
19.5	20	40	40	0	2.77	0.253	0.454	0.001
24.4	20	40	40	0	2.74	0.263	0.319	0.001

[†]Ammonium nitrate treatments were applied from 24 May to 11 Aug. 2010 and 25 May to 11 Aug. 2011.

[‡]Mean ball roll distance of 10 observations made during 2010 and 2011 for each treatment

[§]Equality test between sample variances of ball roll distance distributions for each nitrogen rate compared to 4.9 kg ha^{-1} wk^{-1} using the ratio of the folded form *F* statistic. Sample variance are equal when $p > 0.05$.

[¶]Ball roll distance (BRD) distributions of each nitrogen treatment (rate) were compared to 4.9 kg N ha^{-1} wk^{-1} treatment using a pooled *t*-test to detect differences ($p > 0.05$) during 2010 and 2011.

*Acceptable ball roll distance range.

Table 7. Soil pH and electrical conductivity response to nitrogen rate on annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ, during 2010 and 2011.

Nitrogen rate[†]	pH			EC[‡]		
	1-Sep-10	29-Jun-11	15-Aug-11	1-Sep-10	29-Jun-11	15-Aug-11
kg N ha^{-1} wk^{-1}				dS m^{-1}		
0	6.1	5.6	5.3	0.34	0.16	0.12
4.9	6.1	5.6	5.2	0.39	0.15	0.11
9.8	6.1	5.6	5.3	0.33	0.14	0.11
14.6	6.0	5.5	4.9	0.35	0.17	0.12
19.5	5.7	5.5	4.8	0.38	0.14	0.13
24.4	5.7	5.5	4.5	0.39	0.15	0.13
$LSD_{0.05}$	0.1	ns	0.3	ns	ns	0.01
Planned F-test[¶]	*p* > F					
Linear	***	NS[§]	***	NS	NS	**
Quadratic	**	NS	NS	NS	NS	**

[†]Ammonium nitrate treatments were applied from 24 May to 11 Aug. 2010 and 25 May to 11 Aug. 2011.

[‡]EC, electrical conductivity; dS m^{-1} = mmho cm^{-1}.

[§]NS, not significant.

[¶]Orthogonal polynomial contrasts used to determine response curve of the data.

CHAPTER 3. Anthracnose Severity and Annual Bluegrass Quality as Influenced by Soluble Nitrogen Source

Abstract. Anthracnose (caused by *Colletotrichum cereale* Manns sensu lato Crouch, Clarke & Hillman) of annual bluegrass [ABG; *Poa annua* L. f. reptans (Hausskn) T. Koyama] turf is a destructive fungal disease that has been shown to be more severe under nitrogen deficiencies. Little is known about the effect of soluble N source on this disease. A 3-year field study was initiated in 2010 to evaluate the effect of soluble-N source on anthracnose severity and to determine if source alters the effect of N frequency (rate) on this disease during mid-season on an ABG turf maintained at 3.2 mm. Nitrogen treatments were applied at 4.9 kg N ha^{-1} every 7- or 14-d (frequency factor) as solutions of ammonium sulfate, ammonium nitrate, urea, calcium nitrate, or potassium nitrate. Both N frequency and N source affected disease severity throughout 2010, 2011, and 2012. In general, soluble N applied at 4.9 kg N ha^{-1} every 7-d reduced disease compared to N applied at the same rate every 14-d. Of the N sources, potassium nitrate provided the greatest reduction in disease severity over the three year study, whereas, ammonium sulfate treatments resulted in the greatest disease severity. Soil pH was also influenced by N source, with ammonium sulfate treatments resulting in the lowest soil pH (most acidic) and potassium nitrate consistently producing the highest soil pH (most basic) throughout the study. This study has shown that anthracnose severity on ABG putting green turf is influenced by N source, and that low-rate

applications of potassium nitrate every 7-d were the most effective at reducing disease severity under moderately acidic soil conditions.

INTRODUCTION

Annual bluegrass (ABG) [*Poa annua* L. f. reptans (Hausskn) T. Koyama] is one of the most widespread turfgrass species, commonly found on intensively managed golf courses areas (greens, fairways, and tees) throughout the world (Vargas and Turgeon, 2004). One of the major pests associated ABG turf is anthracnose, caused by *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, & Hillman (Crouch et al., 2006), a disease which can be particularly devastating at high temperatures during mid-summer. The increased incidence and severity of anthracnose in the US has been attributed to management practices used to improve playability (Murphy et al., 2008); including reduced nitrogen (N) fertility, a practice that is used by superintendents to decrease vertical growth and increase ball roll distance. It is not uncommon for golf course superintendents in the US to use N fertilization rates lower than 9.8 kg ha^{-1} $month^{-1}$ to maintain ball roll distance, which is less than half the recommended N rate (24.4 to 34.2 kg N ha^{-1} $month^{-1}$) for ABG putting green turf (Beard et al., 1978; Vargas and Turgeon, 2004).

A number of studies have documented the effect of N rate on anthracnose severity of ABG turf. Initial research by Danneberger et al. (1983) concluded that moderate rates of N (146 kg N ha^{-1} yr^{-1}) reduced anthracnose severity on an ABG fairway compared to a higher rates of N (292 kg N ha^{-1} yr^{-1}) and the untreated control. In a field study investigating the effect of N rate, growth regulators, and verticutting on anthracnose severity of ABG putting green turf, Inguagiato et al. (2008) reported that N rate had the greatest impact on disease severity, with ammonium nitrate applied at 4.9

kg N ha^{-1} every 7-d reducing disease severity compared to the same rate applied every 28-d. Similarly, Roberts et al. (2010) found that ammonium nitrate applied to ABG putting green turf at 4.9 kg ha^{-1} wk^{-1} or 9.8 kg ha^{-1} 2-wk^{-1} provided the greatest reduction in anthracnose severity compared to lower rates of N.

Numerous studies have documented the response of turfgrass diseases to nitrogen source and this research has been reviewed by Frank and Guertal (2013); however, to date, there is little published data on the effect of nitrogen source on anthracnose severity of ABG turf. Danneberger et al. (1983) compared two granular N sources (isobutylidene diurea [IBDU] and sulfur coated urea) and one soluble N source (urea) for their effect on anthracnose development on ABG maintained at 1.3 cm, and determined that the type of N fertilizer had no effect on the disease. In contrast, in a trade article Uddin et al. (2009) suggested that low rates of IBDU and methylene urea (4.9 kg N ha^{-1} every 14-d), reduced anthracnose severity compared to urea on a mixed stand of creeping bentgrass (*Agrostis stolonifera* L.)/ABG maintained at 3.2 mm. However, no differences between N sources were seen at higher rates of N (14.6 and 24.4 kg N ha^{-1} every 14-d) and this work was never published in a peer reviewed journal. Although there are indications that N source may affect anthracnose severity, research has yet to systematically investigate the effect of commonly used soluble N sources and rates (frequency) on this disease.

Historically, dry-granular applications of N fertilizers have been used as the main source of N for golf course putting greens; however, the use of light, frequent soluble-N applications in combination with granular fertilizers has become increasingly popular

(Beard, 2002). Soluble, solid forms of N fertilizers including ammonium nitrate, ammonium sulfate, calcium nitrate, potassium nitrate, and urea can be dissolved in water and applied as a liquid solution (Carrow et al., 2001). Despite the increased usage of soluble N sources on golf courses, previous studies have not investigated a broad range of soluble-N sources for their effect on anthracnose severity. Thus the objective of this field study was to evaluate the effect of soluble-N sources on anthracnose severity and to determine if N application frequency (rate) alters the effect of soluble-N source on this disease during mid-season.

MATERIALS AND METHODS

Site Description and Maintenance

A 3-year field study was initiated in June 2010 on an ABG turf grown on a Nixon sandy loam (fine-loamy, mixed, semiactive, mesic Typic Hapludults) with a sand topdressing layer at the Rutgers Horticultural Research Farm No. 2 in North Brunswick, NJ. Two locations were used; a 7-yr-old turf in 2010 and a 2 to 3-yr-old turf in 2011 and 2012. Both locations were monostands of ABG that were established using methods described by Inguagiato et al. (2008). Plots were mowed 7 times wk^{-1} using a walk-behind greens mower (model 1000; Toro Co.) equipped with a grooved (Wiley) front roller and bench set at 3.2 mm. A medium-fine sand topdressing was applied at a rate of 0.15 L m^{-2} and brushed into the sward with a coco mat every 14-d. Irrigation was applied to achieve moderately dry conditions typical of golf courses in the Northeast US. Phosphorus was applied at 12.2 kg P ha^{-1} yr^{-1} in 2012 based on soil test results, but was not applied in 2010 or 2011. Potassium was not applied during the study period. The plant growth regulator 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 19 Mar. to 2 Oct. 2010, 22 Mar. to 11 Oct. 2011, and 15 Mar. to 3 May 2012. Trinexapac-ethyl was applied at 0.05 kg ai ha^{-1} every 7-d from 3 May to 12 Nov. 2012 to conform to current industry practices (specifically in Northeastern US) used to improve uniformity and leaf texture on ABG putting greens. Ethephon [(2-chloroethyl) phosphonic acid] was applied at a rate of 3.76 kg a.i. ha^{-1} on 19 Mar., 2 Apr., and 23 Apr. 2010, 22 Mar., 6 Apr., and 25 Apr. 2011, and 15 Mar., 5 Apr., and 19 Apr. 2012 to

suppress ABG seedhead development. Pesticides that were shown to be ineffective at controlling anthracnose (Towers et al., 2003) were used to suppress dollar spot (*Sclerotinia homoeocarpa* F.T. Bennet), brown patch (*Rhizoctonia solani* Kuhn), summer patch (*Magnaporthiopsis poae* [Landsch. & N. Jacks.] J. Luo & N. Zhang), annual bluegrass weevil (*Listronotus maculicollis* Dietz), black cutworm (*Agrotis ipsilon* Hufnagel), and algae.

Treatment Design

Treatments were arranged as a 2 x 5 factorial using a randomized complete block design with four replications. Due to severe winter injury during 2010 – 2011, the study was relocated in the spring of 2011 and treatments were repeated on the same location in 2012. Treatment factors included N frequency (every 7 or 14-d) and soluble-N source (ammonium nitrate [NH_4NO_3], ammonium sulfate [$(NH_4)_2SO_4$], calcium nitrate [$Ca(NO_3)_2$], potassium nitrate [KNO_3], and urea [CH_4N_20]). Nitrogen treatments were applied during the mid-season; from 4 June to 20 Aug. 2010, 12 May to 26 Aug. 2011, and 4 May to 16 Aug. 2012 at a rate of 4.9 kg N ha^{-1}. Soluble-N treatments were applied as a solution using a gas powered backpack sprayer (model SHR – 210; Echo Inc.) attached to a five nozzle boom equipped with 0.3 MPa constant flow valves (model 11-16SY; G.A.T.E. LLC) and extended range flat fan spray tips (model XR8003VS; TeeJet® Technologies). Light irrigation (< 0.25 cm) was applied to each plot immediately following N application to prevent foliar injury (“burn”) or volatilization.

Additional N was applied in the fall and spring each year to stimulate growth and recover from anthracnose damage. In 2010, N was applied at 48.8 kg N ha^{-1} on 15

October and 11 November using each plots respective N source. Because of significant winter injury in 2010-2011, which may have been partially due to high rate applications of soluble-N sources in the fall (particularly ammonium sulfate), a more neutral (less acidic) source of soluble-N (urea) was applied to all plots for recovery in the spring (9.8 kg N ha^{-1} on 27 April prior to treatment initiation) and fall (periodically from 13 September to 26 October for a total of 78.1 kg N ha^{-1}) of 2011. Prior to treatment initiation in 2012, urea and urea + methylene urea (Nitro-30; Growth Products LTD) were applied to all plots on 19 March and 4 April, totaling 20.5 and 16.2 kg N ha^{-1}, respectively.

Data Collection and Analysis

Anthracnose severity was assessed routinely from June through September 2010 and from June through August in 2011 and 2012 using a line intercept-grid count method that produced 273 observations over 1.4 m^2 $plot^{-1}$ (Inguagiato et al., 2008). Turf quality was rated from June to October 2010, June to August 2011, and from May to August 2012 using a 1 to 9 scale, with 9 representing the best quality turf and 5 the minimum acceptable quality. Turf density and disease severity (damage) were taken into consideration when evaluating turf quality, but turf color was not considered during quality ratings. Turf color was rated on the same days as turf quality using a 1 to 9 scale, with 9 representing dark green color turf and 5 the minimally acceptable color. Soil samples were collected to a depth of 17 cm on 9 Sept. 2010, 7 July, 4 Aug., and 31 Aug. 2011, and 2 May, 28 June, and 20 Aug. 2012 to determine soil pH using the 1:1 soil:water (by volume) extract method (Thomas, 1996).

All data was subjected to analysis of variance using the generalized linear model (GLM) procedure for a randomized complete block design in the Statistical Analysis Software (SAS) package (v. 9.4; SAS Institute). Main effect and significant interaction means were separated using Fisher's protected least significant difference (LSD) test at $p < 0.05$ (Dowdy et al., 2004). The amount of variation attributed to each treatment factor (N frequency and N source) was determined by comparing the sum of squares for each factor with the total sum of squares.

RESULTS

Anthracnose Severity

The N frequency main effect accounted for the majority of variation in anthracnose severity on most rating dates during the 3-yr field study (data not shown), but during the second and third year of the trial the N application frequency x N source interaction also influenced disease severity, providing insight into the how N source affects anthracnose (Table 1). In general, the interaction indicated that the disease response to N source was greater when N was applied more frequently. Thus, the interaction between N application frequency and N source will be discussed in detail rather than the main effect, although both were significant.

Main Effects

The N frequency main effect had the greatest influence on anthracnose severity during July and August in 2010, 2011, and 2012, accounting for 42 to 46%, 26 to 61%, and 23 to 34% of the experimental variation, respectively (data not shown). N applied every 7-d at 4.9 kg N ha^{-1} reduced disease severity by 2 to 13% compared to the same rate applied every 14-d on 13 out of 15 observation dates over three years (Tables 1).

The soluble-N source main effect also had a significant influence on anthracnose severity on 14 out of 15 rating dates during the 3-yr study (Table 1), accounting for 5 to 43% of experimental variation in 2010, 10 to 40% in 2011, and 21 to 48% in 2012 (data not shown). On the first two observation dates of 2010 (14 June and 8 July), ammonium sulfate and potassium nitrate had the greatest disease severity (Table 1). However, by the end of 2010 (6 September), ammonium sulfate and urea had the greatest disease

severity; whereas, potassium nitrate and calcium nitrate had the lowest disease severity. Ammonium sulfate consistently had the greatest disease severity throughout 2011 (Table 1). On most dates in 2011 and 2012, the interaction between N application frequency and N source were significant (and will be discussed later), but on 16 July and 2 Aug. 2012 only the N source and frequency main effects influenced disease severity (not the interaction). On these dates, disease severity was lowest in plots fertilized with ammonium sulfate and potassium nitrate; however, plots fertilized with ammonium sulfate were among plots with the greatest disease severity by the end of the disease epidemic in 2012 (21 Aug.).

Interaction Effects

The N frequency x N source interaction was significant on nine of eleven dates during 2011 and 2012 (Tables 1) and generally indicated that there were more differences among N sources under the 7-d application frequency than 14-d.

Under the 7-d application frequency, potassium nitrate had the lowest anthracnose severity throughout the entire 2011 season; disease severity on calcium nitrate plots was similar to potassium nitrate plots on 22 June and 30 August and severity on ammonium nitrate plots was similar to potassium nitrate plots on 22 June and 7 July (Table 2). Ammonium sulfate was the only soluble-N source that did not consistently reduce disease when applied at a frequency of every 7-d compared to 14-d; this lack of disease suppression was observed on 4 out of 5 dates in 2011 (Table 2). Only a few, small differences in disease severity were observed between N sources applied

every 14-d during 2011; potassium nitrate was always among the N sources with the lowest anthracnose severity.

Potassium nitrate was always among the treatments with the lowest disease severity regardless of the N application interval during 2012 (Table 2). By mid-August 2012, potassium nitrate applied every 7-d had the lowest disease severity of all N sources, decreasing disease severity by at least 20 and 24% on 13 August and 21 August, respectively. Ammonium sulfate and urea were most frequently ranked (3 and 4 dates, respectively) among the N sources with the greatest disease severity under the 7-d application frequency (Table 2).

Turf Quality

The main effects of N application frequency and N source, which had a great influence on disease severity, also affected turf quality. An interaction between N application frequency and N source influenced turf quality during moderate to high disease severity in 2011 and before the disease epidemic occurred in 2012. These interaction data will be presented following the main effects.

Main Effects

The N application frequency main effect influenced turf quality on 15 out of 17 observation dates in 2010, 2011, and 2012; and as expected, N applied every 7-d produced better turf quality than applications every 14-d (Table 3). Nitrogen applied every 14-d produced unacceptable turf quality on 7 out of 17 observations over the 3-yr period; whereas, N applied every 7-d resulted in only one observation date with unacceptable turf quality.

Potassium nitrate was among the treatments with the best turf quality from August 2010 through August 2012 and had the best turf quality of all N sources by the end of the study (24 July and 10 Aug. 2012) (Table 3). Turf quality of ammonium sulfate was either the poorest or among the treatments with the poorest during the three year study, and was below acceptable quality on 8 out of 17 observations (Table 3).

Interaction Effects

The N frequency x N source interaction occurred on three observation dates (5 July, 1, and 31 August) in 2011 and two dates (16 and 29 May) in 2012 (Table 3). Similar to disease severity, differences in turf quality among N sources were more evident under the 7-d application frequency compared to 14-d (Table 4); in fact, there were no differences among N sources applied every 14-d on 5 July and 1 August 2011. Ammonium sulfate was the only N source that either had no change in turf quality or reduced turf quality when applied every 7-d compared to 14-d; all other sources produced better turf quality on most interaction dates when applied at the 7-d frequency (Table 4).

Turf Color

Similar to turf quality, N frequency and N source main effects were the dominate influence on turf color response during the 3-yr study, but a N frequency x N source interaction did occur during 2011 and before the disease epidemic in 2012. This interaction provided further insight regarding the response of N sources under the two application frequencies and will be presented following the main effects.

Main Effects

The N frequency main effect for turf color ratings was significant on all rating dates in 2010, 2011, and 2012 (17 dates; Table 5); nitrogen applied every 7-d produced darker green color ratings than N applied every 14-d. Color had an acceptable green color on all dates when N was applied every 7-d, whereas, N applied on 14-d interval produced unacceptable color on 6 out of 17.

The N source main effect did not have a significant effect on turf color until late (9 Sep.) in 2010, when all other N sources had a darker green color than ammonium sulfate (Table 5). By October 2010, turf color in the ammonium sulfate plots had improved and resulted in the darkest green turf color rating along with the urea treatment. Subtle differences in color were initially observed between N sources in 2011; however, by 1 August, potassium nitrate and calcium nitrate were the N sources producing the darkest green colored turf. And by 31 Aug. 2011, turf color was very poor (2.0) on ammonium sulfate treated plots. In 2012, ammonium sulfate plots continued to exhibit among the poorest turf color, with ratings indicating an unacceptable light-green/yellow color on 5 out of 8 observation dates. All other N source produced acceptable green turf color in 2012, until 10 August when only the potassium nitrate plots had an acceptable green color.

Interaction Effects

The N frequency x N source interaction had a significant effect on turf color on 3 observation dates in 2011 and 3 dates in 2012 (Table 5). Generally, differences among N sources were more evident under the 7-d application frequency than 14-d; in fact, no differences in turf color were observed between N sources applied every 14-d on 1 and

31 Aug. 2011 (Table 6). Turf color was not improved by applying ammonium sulfate every 7-d versus 14-d on 4 of the 6 interaction dates; in fact, color was reduced on 21 June 2011 (Table 6). Potassium nitrate and calcium nitrate applied every 7-d were either the darkest green treatments or among the treatments with the darkest green turf color on all interaction dates.

Soil pH

Nitrogen source was the dominant main effect on pH at the 0 to 17-cm soil depth (Table 7). While the main effect of N application frequency was not significant on any sampling date during the study, N sources did interact with N application frequency on 5 of the 7 sampling dates over a 3-yr period (Table 7). Both the N source main effect and the interaction will be presented in the following section.

Main Effects

Soil pH was typically greatest in plots fertilized by potassium nitrate and always lowest in plots fertilized with ammonium sulfate, except on 2 May 2012 when no difference were detected among the N sources. Soil pH was frequently greater in calcium nitrate plots than urea and ammonium nitrate plots, which had similar pH values throughout the study (Table 7).

Interaction Effects

On observation dates with interactions, urea was the only N source where the soil pH was similar across both application frequencies. Soil pH in ammonium nitrate plots was also relatively unaffected by application frequency; only lower under the 7-d frequency than the 14-d once (9 Sep. 2010) (Table 8). Conversely, frequency affected

the soil pH in plots of potassium nitrate (5 dates), ammonium sulfate (4 dates) and calcium nitrate (3 dates). Soil pH was typically greater in potassium nitrate and calcium nitrate plots, and lower in ammonium sulfate plots when N sources were applied every 7-d compared to 14-d.

DISCUSSION

While frequent, low rate soluble applications of N have been shown to reduce anthracnose severity on ABG turf (Inguagiato et al., 2008; Roberts et al., 2010), very few studies have examined the effect of N source on anthracnose severity of ABG turf. The most important finding from this study is that the severity of anthracnose disease on annual bluegrass turf is strongly influenced by N source, with potassium nitrate applied at 4.9 kg N ha^{-1} every 7-d providing the greatest reduction in disease severity throughout most of this study. Danneberger et al. (1983) investigated the effect of granular N sources on anthracnose severity of ABG turf maintained at 1.3 cm and found no differences in disease severity between IBDU, urea, and methylene urea. Uddin et al. (2009) investigated the effect of N source and rate on basal rot anthracnose on a creeping bentgrass/ABG mixture. They found that low rate (4.9 kg N ha^{-1}) applications of urea every 14-d resulted in a subtle increase in disease severity compared to methylene urea and IBDU applied at the same rate; no differences were found between N sources when applied every 14-d at a greater rate of 14.7 or 24.5 kg N ha^{-1}. One possible explanation for the minimal differences observed between N sources in the previous trials could be the fact that only acidifying N sources were used. In our study, the two N source treatments that provided the greatest reduction in anthracnose severity were potassium nitrate and calcium nitrate, both of which are basic N sources and resulted in less acidic (higher) soil pH levels. Hence, it is conceivable that soil pH could be influencing either the tolerance of ABG to the disease or directly influencing the pathogen *C. cereale*.

Previous research has shown that ABG growth can be limited under acidic soil conditions (Goss, 1974; Kato et al., 2000; Sprague and Burton, 1937; Sprauge and Evaul, 1930), which may predispose turf to infection by *C. cereale.* Infection from this pathogen is known to occur during stressful conditions (heat and drought stress), and disease development is favored when plants are exposed to soils with excessive or limited soil water, and/or inadequate nutrition (Smiley et al., 2005), so it is possible that stress(es) from acidic soil pH could weaken ABG and increase its susceptibility to this disease.

Another possible explanation for the response of anthracnose to the various N sources could be the presence of secondary nutrients in several of the N sources used in our study. The greatest reduction in anthracnose severity was observed in potassium nitrate and calcium nitrate treatments, which contain the nutrients K and Ca, respectively. Potassium fertilization has been associated with improved drought tolerance in creeping bentgrass (Waddington et al., 1978) and recovery from drought in Kentucky bluegrass (Schmidt and Breuninger, 1981). Anthracnose of annual bluegrass turf has been associated with drought stress, with severe stress (40% ET_o) causing increased disease severity (Roberts et al., 2011). Thus, it is plausible that potassium fertilization (potassium nitrate) may have reduced anthracnose severity by improving the drought tolerance of the turfgrass making it less susceptible to the disease. Previous studies have shown that K fertilization can reduce the incidence of take-all patch (*Gaeumannomyces graminis* var. *graminis* [Sacc.] Arx & D.L. Olivier) and red thread (*Laetisaria fuciformis* [McAlpine] Burdsall) (Goss, 1969; Goss and Gould, 1967).

Accordingly, calcium fertilization may have also played a role in reducing anthracnose severity. Calcium deficiencies in turfgrass are very rare in field situations; however, the addition of calcium in the presence of high concentrations of Al^{+3}, H^{+}, and Mn^{+2} under acidic soil conditions can improve turfgrass growth (Carrow et al., 2001). Deficiencies in calcium have been reported to cause turfgrasses to be more susceptible to diseases including red leaf spot (*Drechslera erythrospila* [Dreschsler] Shoemaker), Fusarium blight (*Fusarium* spp.), Pythium blight (*Pythium* spp.), and red thread (*Laetisaria fuciformis*) (Couch and Bedford, 1966; Moore et al., 1963; Muse, 1974; Muse and Couch, 1965). But there is very limited research investigating the effect of calcium nutrition on ABG growth and no information regarding the effect of this element on its susceptibility to *C. cereale*.

Turf quality of plots was decreased by fertilization with acidifying N sources (ammonium nitrate, ammonium sulfate, and urea), particularly during late summer (August – September). Additionally, both of the basic N sources (potassium nitrate and calcium nitrate) maintained acceptable quality ratings throughout most of the three years of this study. Previous research has shown that acidic soil conditions can reduce ABG growth (Ferguson, 1936; Sprauge and Evaul, 1930; Sprague and Burton, 1937). Thus, poor turf quality in this trial was likely a result of decreased soil pH limiting ABG growth and recovery from the disease.

Interestingly, potassium nitrate plots maintained slightly higher quality ratings than calcium nitrate plots throughout most of the study, even though the soil pHs of the two treatments were relatively similar. Improvement of turf quality in potassium nitrate

treatments may be explained by the additional K fertilization that this treatment received. Potassium fertilization has been shown to improve stress tolerance of turfgrass, including drought, heat, salinity, and wear tolerance (Frank and Guertal, 2013) This may explain why potassium nitrate treatments maintained greater turf quality ratings, especially during late summer when disease pressure and environmental stress (heat and drought) was most severe.

It is commonly known that fertilizers, especially nitrogen sources, can alter the soil pH. So, it was not surprising that ammonium sulfate treatment resulted in the most acidic soil pH, since it has the greatest equivalent acidity of the N sources (Carrow et al., 2001; Pierre, 1933). It is also not surprising that ammonium sulfate applied every 7-d versus every 14-d resulted in the lowest soil pH, since twice as much fertilizer was applied in this treatment. Potassium nitrate and calcium nitrate resulted in the greatest (least acidic) soil pH levels, which was expected since these sources have a similar equivalent basicity (26 and 20 kg $CaCO_3$ per 100 kg of material, respectively) (Carrow et al., 2001). Interestingly, no differences in soil pH were observed between N sources on 2 May 2012, which was likely due to winter precipitation leaching soluble salts from the soil profile. In acid soils, as the concentration of salts in the soil solution increases, soil pH values tend to get lower (Thomas, 1996), due to displacement of Al^{3+} from exchange sites and increased hydrolysis of Al species in the presences of salts (Ragland and Coleman, 1960). Seasonal variations in weather conditions can affect soil pH; pH generally decreases during the summer months and increases during the winter (Shuman et al., 1983).

CONCLUSIONS

This is the first study that has documented pronounced differences in anthracnose severity of ABG caused by soluble N sources. Under moderately acidic conditions, potassium nitrate provided the greatest reduction in anthracnose severity compared to all other N sources and maintained acceptable turf quality (≥ 5) throughout the study. Conversely, application of acidifying N sources (ammonium nitrate, ammonium sulfate, and urea) resulted in the greatest disease severity throughout most of the three seasons. These sources also reduced turf quality compared to potassium nitrate treated plots, with ammonium sulfate plots having unacceptable turf quality (< 5) approximately 50% of the time over a three year period. It is important to note that these results may not be applicable to other soil types. For example, in calcareous soils where soil pH is greater than 7.0 and strongly buffered, fertilization with basic or acidic N sources may not significantly affect ABG quality or disease tolerance if pH is the principal stressor. Also, it is not clear what role potassium nutrition plays in disease development, but potassium may be important for reducing anthracnose severity in situations where deficiencies in soil K exist. Further research is needed to determine the effect of potassium fertilization on the tolerance of ABG to anthracnose disease. In addition, the response of ABG to a broad range of soil pH levels needs to be evaluated to identify a critical soil pH for ABG growth, and to determine the extent that anthracnose severity is influenced by pH without the potentially confounding effects of N-form (ammonium versus nitrate) and/or the presence of secondary nutrients.

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Table 1. Analysis of variance of the anthracnose disease response to N application frequency and N source applied to annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ, during 2010, 2011, and 2012.

Main effects	Turf area infested														
	2010				2011					2012					
	14-Jun	8-Jul	10-Aug	6-Sep	22-Jun	7-Jul	14-Jul	3-Aug	30-Aug	6-Jun	21-Jun	16-Jul	2-Aug	13-Aug	21-Aug
	%														
Frequency (F)[†]															
7 d	24	35	51	56	21	26	37	54	78	8	11	23	28	42	55
14 d	24	44	60	58	27	35	47	67	85	10	16	30	40	53	67
Source (S)															
Potassium nitrate	29	39	55	53	21	27	36	56	77	6	11	24	24	34	44
Calcium nitrate	24	38	54	52	24	31	43	58	78	7	12	28	37	52	61
Urea	22	41	55	59	24	31	43	62	84	11	14	30	41	55	67
Ammonium nitrate	20	35	55	58	23	30	43	62	82	9	10	28	38	54	66
Ammonium sulfate	27	44	58	64	28	33	46	65	88	13	19	21	29	44	65
$LSD_{0.05}$	5	5	---	5	3	3	4	4	3	3	3	6	6	7	7
	ANOVA														
Source of variation															
F	NS[‡]	***	***	NS	***	***	***	***	***	*	***	***	***	***	***
S	*	*	NS	***	**	**	***	**	***	**	***	*	***	***	***
F x S	NS	NS	NS	NS	*	**	*	**	***	*	***	ns	ns	*	*
CV (%)	20	13	8	9	13	8	8	7	4	35	25	22	18	14	11

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively.

[†] Nitrogen was applied at 4.9 kg N ha^{-1} from 4 Jun. to 20 Aug. 2010, 12 May to 26 Aug. 2011, and 4 May to 16 Aug. 2012.

[‡] NS, not significant.

Table 2. Anthracnose disease response to the interaction of N application frequency and N source applied to annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ, during 2011 and 2012.

N Frequency[†]	N Source	Turf area infested								
		2011					2012			
		22-Jun	7-Jul	14-Jul	3-Aug	30-Aug	6-Jun	21-Jun	13-Aug	21-Aug
		%								
7-d	Potassium nitrate	17	21	28	46	70	3	5	20	32
	Calcium nitrate	20	25	39	51	72	6	8	48	56
	Urea	21	27	39	54	82	12	16	52	66
	Ammonium nitrate	18	24	38	57	78	6	7	49	61
	Ammonium sulfate	29	32	44	63	89	15	21	40	58
14-d	Potassium nitrate	25	33	45	67	83	9	16	48	56
	Calcium nitrate	28	37	47	65	83	9	16	56	66
	Urea	27	35	48	70	86	10	13	57	68
	Ammonium nitrate	28	37	48	67	87	11	14	58	72
	Ammonium sulfate	28	35	49	67	87	12	18	48	72
	$LSD_{0.05}$	3	3	4	4	3	5	5	9	9

[†] Nitrogen was applied at 4.9 kg N ha^{-1} from 12 May to 26 Aug. 2011, and from 4 May to 16 Aug. 2012.

Table 3. Analysis of variance of the turf quality response to N application frequency and N source applied to annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ, during 2010, 2011, and 2012.

Main effects	Turf quality[†]																
	2010					2011				2012							
	17-Jun	2-Jul	16-Aug	9-Sep	19-Oct	21-Jun	5-Jul	1-Aug	31-Aug	10-May	16-May	29-May	8-Jun	2-Jul	13-Jul	24-Jul	10-Aug
	1 - 9 scale[†]																
Frequency (F)[‡]																	
7 d	6.0	7.5	6.9	6.0	7.9	6.6	7.3	5.1	4.7	6.3	5.2	6.1	6.7	5.8	7.1	6.6	5.5
14 d	5.5	6.3	5.8	5.5	7.8	5.4	6.0	3.6	3.2	5.9	4.2	5.3	4.9	4.5	5.0	3.8	3.5
Source (S)																	
Potassium nitrate	5.1	6.6	6.4	6.5	8.5	6.1	7.1	5.1	5.1	7.0	6.3	7.1	7.0	6.0	6.5	6.3	5.8
Calcium nitrate	5.8	6.9	6.7	6.2	8.5	6.1	6.9	4.6	4.9	6.5	5.8	6.6	6.4	5.3	5.9	5.0	3.8
Urea	6.0	6.8	6.5	5.6	7.6	6.2	6.4	4.1	3.5	6.3	5.0	5.6	6.0	5.0	6.1	4.3	4.3
Ammonium nitrate	5.9	7.0	6.3	5.6	7.9	6.2	6.8	4.1	4.2	5.5	3.8	6.0	6.3	5.6	6.5	5.1	4.0
Ammonium sulfate	5.8	6.9	5.6	4.8	6.9	5.3	6.1	3.6	2.1	5.1	2.5	3.0	3.4	3.6	5.0	5.3	4.5
$LSD_{0.05}$	---	---	0.6	0.7	0.5	0.4	0.4	0.5	0.7	0.6	0.6	0.8	1.0	0.6	0.5	0.7	0.9
	ANOVA																
Source of variation																	
F	NS[§]	***	***	*	NS	***	***	***	***	*	***	**	***	***	***	***	***
S	NS	NS	**	***	***	***	***	***	***	***	***	***	***	***	***	***	**
F x S	NS	NS	NS	NS	NS	NS	*	*	***	NS	***	***	NS	NS	NS	NS	NS
CV (%)	12.5	8.7	8.6	12.1	6.5	6.8	5.5	12.3	17.7	8.8	12.4	12.9	16.3	12.2	8.7	13.1	20.5

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively.

[†] Turf quality was rated on a 1 to 9 scale, with 9 = best quality and 5 = minimally acceptable quality.

[‡] Nitrogen was applied at 4.9 kg N ha^{-1} from 4 Jun. to 20 Aug. 2010, 12 May to 26 Aug. 2011, and 4 May to 16 Aug. 2012.

[§] NS, not significant.

Table 4. Turf quality response to the interaction of N application frequency and N source applied to annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ, during 2011 and 2012.

N Frequency[†]	N Source	Turf quality				
		2011			2012	
		5-Jul	1-Aug	31-Aug	16-May	29-May
		1 - 9 scale[‡]				
7-d	Potassium nitrate	8.0	6.3	6.8	7.8	8.0
	Calcium nitrate	7.5	5.5	5.8	6.8	7.5
	Urea	7.1	5.0	4.0	5.0	6.0
	Ammonium nitrate	7.5	5.0	5.4	4.0	7.0
	Ammonium sulfate	6.4	3.8	1.8	2.3	2.0
14-d	Potassium nitrate	6.1	4.0	3.5	4.8	6.3
	Calcium nitrate	6.3	3.8	4.0	4.8	5.8
	Urea	5.8	3.3	3.0	5.0	5.3
	Ammonium nitrate	6.0	3.3	3.0	3.5	5.0
	Ammonium sulfate	5.9	3.5	2.5	2.8	4.0
	$LSD_{0.05}$	0.5	0.8	1.0	0.8	1.1

[†] Nitrogen was applied at 4.9 kg N ha^{-1} from 12 May to 26 Aug. 2011, and from 4 May to 16 Aug. 2012.

[‡] Turf quality was rated on a 1 to 9 scale, with 9 = best quality and 5 = minimally acceptable quality

Table 5. Analysis of variance of the turf color response to N application frequency and N source applied to annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ, during 2010, 2011, and 2012.

Main effects	Turf color[†]															
	2010					2011				2012						
	17-Jun	2-Jul	16-Aug	9-Sep	19-Oct	21-Jun	5-Jul	1-Aug	31-Aug	10-May	16-May	29-May	8-Jun	2-Jul	13-Jul	24-Jul	10-Aug
	1 - 9 scale																
Frequency (F)[‡]																	
7 d	6.5	8.0	8.8	7.2	8.3	7.1	7.5	6.7	5.5	7.1	6.4	7.1	7.3	6.8	7.7	7.2	5.7
14 d	5.9	6.7	7.7	5.9	7.7	6.0	5.8	3.9	3.6	6.7	4.9	5.2	4.8	5.2	5.5	4.1	3.4
Source (S)																	
Potassium nitrate	5.8	7.3	8.0	7.3	7.4	6.6	6.9	6.0	6.1	7.6	6.8	7.4	7.0	6.8	6.9	6.3	5.9
Calcium nitrate	6.1	7.3	8.5	6.8	7.5	6.8	6.8	5.8	5.6	7.3	6.4	7.1	6.9	6.1	6.4	5.5	4.5
Urea	6.3	7.3	8.3	6.6	8.6	6.5	6.5	4.9	4.2	7.3	5.8	6.1	6.0	6.0	6.6	5.3	4.0
Ammonium nitrate	6.3	7.4	8.5	6.6	7.9	6.5	6.8	4.9	4.8	7.1	6.3	6.8	6.4	6.5	7.0	5.6	4.0
Ammonium sulfate	6.3	7.6	8.0	5.4	8.3	6.1	6.3	4.9	2.0	5.3	3.0	3.4	3.9	4.5	6.1	5.4	4.3
$LSD_{0.05}$	---	---	---	0.9	0.6	0.3	0.3	0.5	1.1	0.5	0.7	0.7	0.6	0.5	---	0.7	0.8
	ANOVA																
Source of variation																	
F	***	***	***	***	**	***	***	***	***	**	***	***	***	***	***	***	***
S	NS[§]	NS	NS	**	**	**	**	***	***	***	***	***	***	***	NS	*	***
F x S	NS	NS	NS	NS	NS	**	NS	*	**	*	*	***	NS	NS	NS	NS	NS
CV (%)	7.4	7.2	7.3	13.0	7.9	5.1	5.0	9.8	24.7	6.6	12.4	10.7	9.8	8.5	10.0	11.7	16.6

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively.

[†] Turf color was rated on a 1 to 9 scale, with 9 = dark green color and 5 = minimally acceptable color.

[‡] Nitrogen was applied at 4.9 kg N ha^{-1} from 4 Jun. to 20 Aug. 2010, 12 May to 26 Aug. 2011, and 4 May to 16 Aug. 2012.

[§] NS, not significant.

Table 6. Turf color response to the interaction of N application frequency and N source applied to annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ, during 2011 and 2012.

N Frequency[†]	N Source	Turf color					
		2011			2012		
		21-Jun	1-Aug	31-Aug	10-May	16-May	29-May
		1 - 9 scale[‡]					
7-d	Potassium nitrate	7.3	7.9	7.8	8.0	7.8	8.5
	Calcium nitrate	7.8	7.8	7.3	7.8	7.3	8.5
	Urea	7.0	7.4	6.3	7.5	6.5	7.3
	Ammonium nitrate	7.0	7.6	6.3	7.3	7.3	8.3
	Ammonium sulfate	6.3	6.9	5.8	5.0	3.0	3.0
14-d	Potassium nitrate	6.0	5.9	4.3	7.1	5.8	6.3
	Calcium nitrate	5.9	5.9	4.3	6.8	5.5	5.8
	Urea	6.0	5.6	3.5	7.0	5.0	5.0
	Ammonium nitrate	6.3	6.0	3.5	7.0	5.3	5.3
	Ammonium sulfate	7.3	5.6	4.0	5.5	3.0	3.8
	$LSD_{0.05}$	0.5	0.7	1.6	0.7	1.0	1.0

[†] Nitrogen was applied at 4.9 kg N ha^{-1} from 12 May to 26 Aug. 2011, and from 4 May to 16 Aug. 2012.

[‡] Turf color was rated on a 1 to 9 scale, with 9 = dark green color and 5 = minimally acceptable color.

Table 7. Analysis of variance of the soil pH response at the 17-cm soil depth to N application frequency and N source applied to annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ, during 2010, 2011, and 2012.

Main effects	Soil pH						
	2010	2011			2012		
	9-Sep	7-Jul	4-Aug	31-Aug	2-May	28-Jun	20-Aug
Frequency (F)							
7 d	6.03	5.26	5.71	5.61	5.62	5.26	5.48
14 d	6.00	5.23	5.65	5.63	5.72	5.24	5.50
Source (S)							
Potassium nitrate	6.30	5.35	5.88	5.83	5.70	5.37	5.73
Calcium nitrate	6.16	5.33	5.84	5.70	5.59	5.35	5.71
Urea	6.01	5.23	5.61	5.57	5.61	5.26	5.49
Ammonium nitrate	5.98	5.23	5.67	5.60	5.76	5.21	5.44
Ammonium sulfate	5.61	5.09	5.41	5.42	5.71	5.04	5.10
$LSD_{0.05}$	0.09	0.08	0.10	0.07	---	0.08	0.6
	ANOVA						
Source of variation							
F	NS	NS	NS	NS	NS	NS	NS
S	***	***	***	***	NS	***	***
F x S	***	NS	*	***	NS	**	***
CV (%)	1.49	1.43	1.77	1.26	3.76	1.55	1.14

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively.

† Soil pH was determined using the 1:1 soil:water (by volume) extract method (Thomas, 1996).

‡ Nitrogen was applied at 4.9 kg N ha^{-1} from 4 Jun. to 20 Aug. 2010, 12 May to 26 Aug. 2011, and 4 May to 16 Aug. 2012.

§ NS, not significant.

Table 8. Response of soil pH at the 17-cm soil depth to the interaction of N application frequency and N source applied to annual bluegrass turf mowed at 3.2 mm in North Brunswick, NJ, during 2010, 2011, and 2012.

N Frequency[†]	N Source	Soil pH				
		2010	2011		2012	
		9-Sep	4-Aug	31-Aug	28-Jun	20-Aug
7-d	Potassium nitrate	6.39	6.00	5.91	5.46	5.79
	Calcium nitrate	6.24	5.92	5.70	5.39	5.79
	Urea	6.02	5.66	5.57	5.27	5.45
	Ammonium nitrate	5.89	5.65	5.57	5.17	5.41
	Ammonium sulfate	5.45	5.31	5.32	4.98	4.98
14-d	Potassium nitrate	6.21	5.77	5.76	5.29	5.67
	Calcium nitrate	6.09	5.76	5.68	5.30	5.63
	Urea	6.00	5.56	5.57	5.24	5.53
	Ammonium nitrate	6.07	5.68	5.64	5.26	5.46
	Ammonium sulfate	5.77	5.51	5.52	5.10	5.23
	$LSD_{0.05}$	0.13	0.15	0.10	0.12	0.09

[†] Nitrogen was applied at 4.9 kg N ha^{-1} from 4 June to 20 Aug. 2010, 12 May to 26 Aug. 2011, and from 4 May to 16 Aug. 2012.

CHAPTER 4. Potassium Source and Fertilization Rate Effects on Anthracnose Severity and Turfgrass Performance of Annual Bluegrass

Abstract: Potassium fertilization has been shown to improve stress tolerances in turfgrass; however, its effects on turfgrass diseases have been inconsistent and not well understood. A 3-yr field study was initiated in 2012 to determine the effect of K fertilization rate and source on anthracnose disease and performance of annual bluegrass turf. Potassium chloride (KCl) and potassium sulfate (K_2SO_4) were applied at K rates of 54, 109, and 218 kg ha^{-1} yr^{-1} as a 2 x 3 factorial arranged in a randomized complete block design with four replications. Potassium nitrate (KNO_3) and potassium carbonate (K_2CO_3) were also included at the 218 kg K ha^{-1} yr^{-1} rate, as well as an untreated check. All K treatments reduced disease severity compared to the untreated check (no K), regardless of K rate or K source; however, KCl applied at 218 kg K ha^{-1} yr^{-1} was slightly less effective at reducing disease severity than all other sources applied at the same rate during August 2013 and throughout 2014. Critical mat K and leaf K concentrations needed to reduce anthracnose severity were calculated using nonlinear regression models (Cate-Nelson, linear plateau, and quadratic plateau). All regression models provided an acceptable fit and critical value for matl K; predicting critical K values between 43 to 70 mg K kg^{-1} (Mehlich III) in response to anthracnose. Only the Cate-Nelson and linear plateau models were able to provide an adequate fit and critical value for leaf K with respect to anthracnose severity (AUDPC), with critical leaf K values ranging from 17.3 to 28.6 g kg^{-1}. Potassium fertilization effect on turf quality was similar

to the disease severity response, with K fertilization improving turf quality. Turf color, NDVI, and CM1000 index were either not affected or only minor improvements were observed from K fertilization. This study to clearly show that deficiency in soil K can increase anthracnose severity and decrease turf quality.

INTRODUCTION

Potassium (K) is an important nutrient for turfgrass growth and is required in relatively large quantities, but unlike all other plant essential nutrients, K is not a constituent of any plant compound (Carrow et al., 2001). It is, however, a critical component for many physiological processes in grasses such as photosynthesis, carbohydrate and protein formation, water relations, and enzymatic activity (Turner and Hummel, 1992). Previous studies have reported that K fertilization can improve the tolerance of turfgrass to stresses such as: drought (Carroll and Petrovic, 1991; Ebdon et al., 1999; Waddington et al., 1978), heat (Jiang and Huang, 2001; Pellett and Roberts, 1963), wear (Shearman and Beard, 1975), and low temperature (Razmjoo and Kaneko, 1993; Schmid et al., 2016; Webster and Ebdon, 2005).

Relatively few studies have been conducted comparing K source on cool-season turfgrasses, which is partially due to the fact that limited sources are available for turf use [mainly potassium chloride (KCl) and potassium sulfate (K_2SO_4)] (Frank and Guertal, 2013). Miller and Dickens (1996) reported that K source (KCl and K_2SO_4) had no effect on cold tolerance (lethal temperature) of bermudagrass, and that extractable soil K was similar between sources. Miller (1999) also showed that K source (KCl and K_2SO_4) had no effect on soil or tissue K concentrations. In a study investigating a slow-release K product (fritted potash) on creeping bentgrass (*Agrostis stolonifera* L.), Waddington et al. (1972) noted that KCl treatments occasionally (16% of sampling dates) increased clipping yields compared to the slow-release K source, but no differences in turf color, leaf K, or soil K were observed.

The influence of K fertilization on cool-season turfgrass diseases including dollar spot (caused by *Sclerotinia homoeocarpa* F.T. Bennet), brown patch (caused by *Rhizoctonia solani* Kühn), red thread (caused by *Laetisaria fuciformis* [McAlpine] Burdsall), take-all patch (caused by *Gaeumannomyces graminis* var. *graminis* [Sacc.] Arx & D.L. Olivier), Microdochium patch (caused by *Microdochium nirvale* [Fr.] Samuels & I.C. Hallett), and Typhula blight (caused by *Typhula incarnate* Fr.) (Goss, 1969; Goss and Gould, 1967; Moody, 2011; Waddington et al., 1978; Webster and Ebdon, 2005; Woods et al., 2006) has been studied over the past 50 years; however, results from these studies are inconsistent and no clear patterns have emerged. A few studies have shown that K fertilization can decrease disease severity (Goss, 1969; Goss and Gould, 1967), whereas, the majority of studies have shown that K fertilization either had no effect or increased disease severity (Moody, 2001; Waddington et al., 1978; Webster and Ebdon, 2005; Woods et al., 2006). In general, it appears that when disease severity is increased it is the result of either exceptionally high rates of K or a nutrient imbalance (K, Ca, and Mg) in the soil and/or plant tissue.

Anthracnose (caused by *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, & Hillman) is a destructive fungal pathogen that is exacerbated by conditions that stress/weaken the turfgrass plants such as heat, drought, and mechanical injury (Roberts et al., 2011; Smiley et al., 2005). Numerous studies have examined the effect of N fertilization on anthracnose severity (see Chapters 1 – 3 of this dissertation; Danneberger et al., 1983; Inguagiato et al., 2008; Roberts et al., 2010; Uddin et al., 2009); however, there has been no detailed investigation of the effect of K fertilization

on anthracnose severity. Previous research investigating the influence of N source on the severity of anthracnose on annual bluegrass [*Poa annua* L. f. reptans (Hausskn) T. Koyama; ABG] turf found that potassium nitrate (KNO_3) applications reduced disease severity compared to all other N sources, but it was unclear whether the response was due to K nutrition or changes (an increase) in soil pH (Chapter 3). It is possible that K fertilization could improve the stress tolerance of the turf, making it less susceptible to infection by *C. cereale,* but this hypothesis has not been tested. Thus, additional research is needed to investigate the effects of K fertilization on anthracnose severity of ABG putting green turf, as well as its effect on overall turf performance.

The purpose of this study is to determine the impact of frequent, low-rate K applications on ABG performance and anthracnose severity. Our primary objectives were to: 1) determine whether K source or K rate influences anthracnose and overall performance of ABG turf, and 2) establish K sufficiency ranges for ABG turf based on soil test level and tissue concentration related to anthracnose severity and turf performance (quality, color, NDVI, and chlorophyll index).

MATERIALS AND METHODS

A 3-year field study was conducted on ABG putting green turf at Rutgers Horticulture Farm No. 2 in North Brunswick, NJ (40°28' N, 74°25' W), in 2012, 2013, and 2014. The soil was a Nixon sandy loam (fine-loamy, mixed, semiactive, mesic Typic Hapludults) with a sand topdressing layer (mat) ranging in depth from 6.0 to 7.5 cm. Pre-treatment pH of the mat and soil layers were 5.4 and 6.0 (1:1, soil:water; Thomas, 1996), respectively. Mehlich 3 (Mehlich, 1984) extractable P, K, Ca, and Mg concentrations in the mat region were 14, 18, 290, and 45 mg kg^{-1}, respectively. These values were considered low, very low, medium, and very low, respectively, according to the Rutgers Soil Testing Laboratory. Extractable P, K, Ca, and Mg concentrations in the soil region were 98, 74, 681, and 81 mg kg^{-1}, respectively, and were considered within the optimum range, except for Ca, which was within the medium range. All other micronutrients were adequate in both the mat and soil.

A component of the experiment was arranged as a 2 x 3 factorial in a randomized complete block design with 4 replications, where potassium chloride and potassium sulfate were applied at K rates of 54, 109, and 218 kg ha^{-1} yr^{-1}. Additionally, potassium nitrate and potassium carbonate (K_2CO_3) were included at a rate of 218 kg K ha^{-1} yr^{-1}, as well as a treatment that received no K (N alone) and a treatment that received KCl at 218 kg K ha^{-1} yr^{-1} but no N fertilization from May through September of each year (K alone). During each growing season the K rates of 54, 109, and 218 kg ha^{-1} yr^{-1} were achieved by applying K at rates of 3.4, 6.8, and 13.6 kg ha^{-1}, respectively, every 7-d for the first three applications, and then every 14-d over a 32-wk period from 25

Apr. through 6 Nov. 2012, 23 April through 8 Nov. 2013, and 21 Apr. through 10 Nov. 2014. Treatment solutions were applied using a gas powered backpack sprayer (model SHR – 210; Echo Inc., Lake Zurich, IL) with a five nozzle boom equipped with 0.3 MPa constant flow valves (model 11-16SY; G.A.T.E. LLC, Sebastian, FL) and extended range flat spray nozzles (model XR11003; TeeJet® Technologies, Springfield, IL). Immediately following treatment application, water (< 0.25 cm) was applied to each plot using a handheld hose equipped with a fan nozzle to prevent foliar injury ("burn").

Urea was applied to all plots, except the K alone treatment and KNO_3 treatment, at a N rate of 4.9 kg ha^{-1} at the same time as K treatments. To prevent N fertilization on K alone plots and KNO_3 plots, plastic covers (4 mm thick) were placed over plots just prior to and removed immediately following application. Additional N fertilization (66, 57, and 53 kg N ha^{-1} yr^{-1}) was applied to all plots (including N check and KNO_3) during the fall and early spring of 2012, 2013, and 2014, respectively, to stimulate growth and recovery from disease damage. Low-rate soluble applications of P were applied to the entire study area during the growing season at P rates totaling 26, 37, and, 30 kg ha^{-1} yr^{-1} in 2012, 2013, and 2014, respectively.

Plots were mowed 6-d per week at 2.8 mm using a triplex greens mower (Greensmaster® 3150; Toro Company, Bloomington, MN). Topdressing sand was applied every 14-d from May through October each year at a rate of 0.15 L m^{-2}, and was brushed in using a coco mat. Plant growth regulators trinexapac-ethyl [4-(cyclopropyl-α-hydroxy-methylene)-3,5-dioxocyclohexanecarboxylic acid ethylester] and ethephon [(2-chloroethyl) phosphonic acid] were applied to suppress ABG seed head development

at 0.05 and 3.76 kg a.i. ha^{-1}, respectively, on 15 Mar., 6 Apr. and 19 Apr. 2012, on 15 Mar., 3 Apr. and 17 Apr. 2013, and on 1 Apr., 21 Apr. and 6 May 2014. Following the last applications for seedhead suppression, trinexapac-ethyl was applied at 0.05 kg a.i. ha^{-1} every 7-d through November of each year. Fungicides that were reported to be ineffective at controlling anthracnose at this site (Towers et al., 2003) were used to control dollar spot, brown patch, summer patch (caused by *Magnaporthiopsis poae* [Landsch. & N. Jacks.] J. Luo & N. Zhang), and brown ring patch (caused by *Waitea circinata* var. *circinata* Warcup & Talbot). A 14-d rotational program of boscalid [3-pyridinecarboxamide 2-chloro-N-(4'-chloro[1,1'-biphenyl]-2-yl)] and vinclozolin [3-(3, 5-dichlorophenyl)-5-ethenyl-5-methyl-2, 4-oxazolidinedione] was used to control dollar spot, and a rotation of flutalonil [N-(3-[1-methylethoxy] phenyl)-2-(trifluoromethyl) benzamide] and azoxystrobin [methyl (E)-2-{2-[6-(2-cyanophenoxy)pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate] was used to control brown patch, summer patch, and brown ring patch. During periods of heavy rain fall, mancozeb (ethylene bisdithiocarbamate) was applied to suppress algae on 16 Jun. and 19 Aug. 2012, and on 16 Jul. and 5 Aug. 2014. Insecticides, including chlorantraniliprole [3-broom-N-[4-chloor-2-methyl-6-(methylcarbamoyl)fenyl]-1-(3-chloor-2-pyridine-2-yl)-1H-pyrazool-5-carboxamide] and bifenthrin [2-Methyl-3-phenylphenyl)methyl (1S,3S)-3-[(Z)-2-chloro-3,3,3-trifluoroprop-1-enyl]- 2,2-dimethylcyclopropane-1-carboxylate], were applied when necessary to control annual bluegrass weevil (*Listronotus maculicollis* Dietz), sod webworm (*Parapediasia teterrella* Zincken), and black cutworm (*Agrotis ipsilon* Hufnagel). The herbicide carfentrazone-ethyl (Ethyl 2-chloro-3-[2-chloro-4-fluoro-5-[4-

(difluoromethyl)-4,5-diydro-3-methyl-5-oxo-1H-1,2,4-trizol-1-yl)phenyl]propanoate) was applied during the late-spring and fall or 2013 and 2014 to control silvery thread moss (*Bryun argenteum* Hedw.), and fluazifop-P-butyl (butyl(R)-2-[4-(5-trifluoromethyl-2-pyridinyloxy)phenoxy]propionate) was applied in the fall of 2013 and 2014 to reduce creeping bentgrass encroachment.

Leaf tissue samples were collected over a 0.7 m^2 area from each plot on 3 Jul., 7 Aug., and 21 Sep. 2012, on 21 Jun., 2 Aug., and 18 Sep. 2013, and on 18 Jun., 31 Jul., and 15 Sep. 2014, using a walk-behind greensmower (model 1000; Toro Co.). Samples were dried in an oven at 65°C for at least 48-hrs, and then ground in a cyclone mill (model 3010; Udy Corp.) to pass through a 0.5-mm screen. Leaf P, K, Ca, and Mg were extracted using a modified high-temperature oxidation (dry-ashing) method (Miller, 1998), which replace 1.0N HCl solution with an aqua regia (25 mL HNO_3 and 75 mL HCl in 1 L water). The extract was analyzed using inductively coupled plasma spectroscopy (iCAP 6000 series; ThermoSci) (Isaac and Johnson, 1998).

Four soil cores were taken per plot to a depth of 17 cm with a 1.9 cm diam. soil probe on 17 Jun., 6 Aug., and 17 Sep. 2012, on 20 Jun., 31 Jul, and 18 Sep. 2013, and on 18 Jun., 31 Jul., and 17 Sep 2014, and. Verdure was removed from the sample cores, which then were divided into mat (sand topdressing layer) and soil layers. The four replicated samples for the mat and soil layer samples from within each plot were mixed and analyzed for Mehlich 3 extractable P, K, Ca, and Mg by inductively coupled plasma spectroscopy (iCAP 6000, Themo Scientific).

Anthracnose severity (turf area infested) was assessed routinely (every 10 to 14 day) from June through August in 2012, 2013 and 2014 using a line intercept-grid count method that produced 273 observations over each 1.4 m^2 $plot^{-1}$ (Inguagiato et al., 2008). Area under disease progress curve (AUDPC), which is a quantitative assessment of disease severity over time, was calculated using sequential disease data (within each year) according to the equation:

$$\mathrm{AUDPC} = \sum_{i=1}^{n} [\frac{(X_i + X_{i+1})}{2}(t_i + t_{i+1})]$$

in which X_i is the anthracnose disease severity at the ith observation, t is the time (days) at the ith observation, and n is the total number of observations (Madden et al., 2007).

Turfgrass quality was rated visually every 2-wk from May to August 2012 and from April to September 2013 and 2014, using a 1 to 9 scale (9 = ideal, 5 = minimum acceptable, 1= dormant or dead). Turf quality ratings took into account turf density, uniformity, disease severity, playability, and overall appearance using methods described by Skogley and Sawyer (1992). Turfgrass color was also rated visually every 2-wk during the same time period, using a 1 to 9 scale (9 = optimal dark green, 5 = minimum acceptable green-yellow color, 4 to 2 = increasing unacceptable chlorosis, 1= most chlorotic).

Normalized difference vegetative index (NDVI) was collected with a Field Scout TCM 500 meter (Spectrum Techmologies), which measures reflected light in the red (660 nm) and near red (850 nm – NIR) spectral bands. Four measurements were taken from the center of each plot and the average was recorded for each plot. A Spectrum

CM1000 chlorophyll meter (Spectrum Technologies, Plainfield, IL) was used to measure reflectance (700 and 840 nm wavelength) of the turf canopy. Previous work has shown a correlation between chlorophyll concentration in turfgrass and index values collected with this meter (Mangiafico and Guillard, 2005). From this point forward this measurement will be referred to as "chlorophyll index". An average of four measurements was taken per plot holding the meter approximately 1 m from the turf canopy. Both NDVI and chlorophyll index measurements were collected every 2-wk from May through August 2012 and April through September 2013 and 2014.

Anthracnose data (turf area infested) was subjected to analysis of variance to identify significant treatment effects using the generalized linear model (GLM) procedure in Statistical Analysis Software (SAS) package (v. 9.4; SAS Institute). Main effect and significant interaction means were separated using Fisher's protected least significant difference (LSD) test at $p < 0.05$ (Dowdy et al., 2004). Orthogonal contrasts were used to make individual comparisons between K sources (KCl, K_2SO_4, KNO_3, and K_2CO_3) applied at 262 kg K ha^{-1} yr^{-1}.

Mat K and leaf K concentrations from individual plots on each sampling date were compared to the AUDPC within their respective year using nonlinear regression models: Cate-Nelson (Cate and Nelson, 1971), linear-plateau (Waugh et al., 1973), and quadratic-plateau (SAS Institute, 2009). Similarly, mean mat K and mean leaf K concentrations within each year were regressed with the turf performance measurements: mean turf color, mean turf quality, mean NDVI, and mean chlorophyll index. Critical mat K and leaf K concentrations were determined at a 100% sufficiency

level for all models, meaning that no further decrease in disease severity or improvement in turf performance was predicted when soil K or tissue K values increased beyond the critical concentration. In cases where a significant ($\alpha = 0.05$) nonlinear regression model could not be found, or models predicted a critical concentration outside of the data range, a linear and/or quadratic regression model was applied to the data set. Extractable mat K was compared to leaf K concentrations using a quadratic plateau model, and to K fertilization rates using linear and quadratic models. To determine the effect of K fertilization on other base cations (Ca and Mg), mat K and leaf K concentrations were compared to mat and leaf Ca and Mg concentrations, respectively, using a linear regression model. Linear and nonlinear regression models were generated with the REG and NLIN procedures in Statistical Analysis Software (SAS) package (v. 9.4; SAS Institute).

RESULTS AND DISCUSSION

Anthracnose severity

K fertilization (all pooled K treatments with N) reduced anthracnose severity compared to treatments that did not receive K (N alone) on the majority (16 out of 18) of disease observations in 2012, 2013, and 2014 (Table 1). The only two observations when K fertilization (with N) did not reduce disease severity were 8 June and 6 July 2012, the first two observations after the study was initiated. Surprisingly, throughout most of 2012 and 2013 K fertilization alone (no N) reduced disease severity compared to N fertilization alone (no K) on 9 out of 12 rating dates in 2012 and 2013, indicating the importance of K fertilization in suppressing anthracnose disease (Table 1). Throughout 2014, however, no difference was observed between these treatments, probably because the K fertilization alone (no N) treatment had become severely deficient in N by the third year of the study. Potassium source had little influence on disease severity until mid-August 2013; from this point forward fertilization with KCl was less effective at reducing anthracnose severity than all other K sources (KNO_3, K_2CO_3, and K_2SO_4), but was still more effective than no K fertilization (N alone) (Table 1). Reduced effectiveness of KCl treatments may be a result of salt accumulation in the soil profile. Potassium chloride has a greater salt index (measure of the osmotic pressure created in the soil solution by the addition of fertilizers) compared to other K sources (Carrow et al., 2001). However, since soil EC was not measured, it was not possible to confirm that salt levels were high enough to cause plant stress resulting greater disease severity. Additionally, on one date in 2014 (16 July), turf treated with K_2SO_4 exhibited increased disease

severity compared to the KNO_3 and K_2CO_3 treatments, while no difference were detected between KNO_3 and K_2CO_3 on this date (Table 1).

In general, K fertilization reduced disease severity regardless of K rate, except on 6 Aug. and 19 Aug. 2013, and 16 July 2014 when K applied at 54 kg K ha^{-1} yr^{-1} was less effective at reducing anthracnose severity than K applied at 218 kg K ha^{-1} yr^{-1} (Table 1). However, all rates of K were more effective than no K fertilization in reducing disease severity on these dates. Other than research presented in this dissertation (Chapter 3) where applications of potassium nitrate was shown to reduce anthracnose severity compared to other N sources, previous studies have not examined the influence of K rate or K source on anthracnose severity. Moreover, few studies have shown that K fertilization can reduce the severity of any turfgrass disease (Goss, 1969; Goss and Gould, 1967). Results from the current study provide consistent evidence that K fertilization can reduce anthracnose severity of ABG putting green turf.

Critical Mat K Concentration

The Cate-Nelson, linear plateau, and quadratic plateau models were all found to be significant ($p < 0.05$) when comparing mat K concentrations to AUDPC for all sampling dates throughout the study (Figures 1, 2, and 3, respectively). Of the three models, the Cate-Nelson model provided the most conservative (least likely to overestimate) prediction of the critical mat K concentration needed to optimize the suppression of anthracnose, with the critical mat K concentration ranging from 33 to 56 mg kg^{-1} and a mean critical mat K concentration of 43 mg kg^{-1} (Figure 1). The linear plateau model estimated slightly higher critical mat K concentrations, ranging from 39 to

69 mg kg^{-1} and a mean of 55 mg kg^{-1} (Figure 2). Quadratic plateau models were the least conservative (least likely to underestimate) of the three models, and estimated the highest critical mat K concentration on each soil sampling date. The critical mat K concentrations for this model ranged from 45 to 84 mg kg^{-1}, with a mean of 70 mg kg^{-1} (Figure 3). Together these results indicate the critical mat K concentration, with respect limiting to AUDPC (the cumulative anthracnose severity each year), was approximately 56 mg K kg^{-1}. This is similar to the lower limit of the moderate K sufficiency ranking (51 to 116 mg kg^{-1}) suggested by Carrow et al. (2001) for recreational turfgrasses grown on most soils. However, previous studies have not attempted to determine a critical soil K concentration for ABG turf.

The Cate-Nelson, linear plateau, and quadratic plateau models were found to be significant ($p < 0.05$) when comparing mat K concentrations to mean ABG quality within each year (Figure 4). The three nonlinear regression models exhibited responses of mean turf quality to mat K that were similar to the responses of mat K to AUDPC, with critical mat K concentrations ranging from 42.7 to 80.4 mg kg^{-1} (Figure 4). A significant quadratic (or linear) response was found when comparing mean mat K concentration and mean turf color, mean NDVI index, or mean chlorophyll index during some years (1, 2, and 3 out of 3 years, respectively), with increases in mean mat K concentration providing subtle increases in mean turf color, mean NDVI, and mean chlorophyll index (Figure A.2, A.3, A.4). However, the magnitude of the change in mean turf color, mean NDVI index, or mean chlorophyll index in response to mat K concentrations was relatively small, indicating that they were probably not biologically meaningful. The

subtle decrease in these parameters in response to low mat K concentration may be explained by the increased anthracnose severity in these plots compared with greater mat K concentrations. The chlorosis and blighting of the turf caused by this disease is likely responsible for the subtle decrease in mean turf color, mean NDVI index, and mean chlorophyll index. Christians et al. (1979) noted that Kentucky bluegrass (*Poa pratensis* L.) and creeping bentgrass quality was responsive (increased) to K fertilization in a controlled environment study; whereas, Fitzpatrick and Guillard (2004) and Shearman et al. (2005) observed that K had no effect on Kentucky bluegrass quality. Previous studies have also reported that K fertilization had little to no effect on turfgrass color (Shearman et al., 2005; Waddington et al., 1978; Woods et al.). Whereas, Waddington et al. (1978) found that creeping bentgrass that received no K fertilization had slightly darker green color than plots receiving K fertilization, except during one spring period, when no K fertilized plots had increased chlorosis compared to fertilized plots. Woods et al. (2006) observed that K fertilization had no influence on creeping bentgrass color or chlorophyll content. A possible explanation for the general lack of response for K in previous field studies is due to the lack of stress imposed on the turfgrass in these trials. Generally, K fertilization does not have a dramatic effect on turfgrass quality unless the plant is exposed to stress (environmental or mechanical) or is growing K deficient soils (Carrow et al., 2001).

Critical Leaf K Concentration

The Cate-Nelson and linear plateau models were significant ($p < 0.05$) when comparing leaf K concentrations to AUDPC from each sampling date throughout the

study (Figures 5 and 6). Quadratic plateau models did not provide an acceptable fit, predicting critical leaf K concentration outside of the data range on 4 of 9 sampling dates (Figure A.5). The estimated critical leaf K concentrations to optimize the suppression of anthracnose using the Cate-Nelson model ranged from 17.3 to 21.8 g kg^{-1} with a mean of 19.3 g kg^{-1} (Figure 5). The linear plateau model predicted slightly higher critical leaf K concentrations ranging from 20.1 to 28.6 g kg^{-1} and a mean of 23.1 g kg^{-1} (Figure 6). Taken together, these results indicate that the critical leaf K concentration required to suppress anthracnose disease is approximately 20 g kg^{-1}. Although previous study have not attempted to determine a critical leaf K concentration using disease severity as an index, the current study found that the critically low value for ABG turf falls within than the general recommendation of 10 to 25 g K kg^{-1} for turfgrass (Turner and Hummel, 1992). Kelling and Matocha (1990) reported that leaf K concentrations below 21, 22, and 15 g kg^{-1} were deficient for ryegrasses (*Lolium multifloum* Lam. and *Lolium perenne* L.), tall fescue [*Schedonorus arundinaceae* (Schreb.) Dumort.], and Kentucky bluegrass, respectively. Thus, the leaf tissue K requirement of ABG appears to be similar to ryegrasses and tall fescue but greater than Kentucky bluegrass.

The Cate-Nelson and linear plateau models were significant ($p < 0.05$) when comparing mean leaf K concentrations to mean ABG quality within each year (Figure 7). The nonlinear regression models exhibited responses for mean turf quality that were similar to the AUDPC response, where estimated critical mat K concentrations to optimize turf quality ranged from 19.3 to 26.8 mg kg^{-1} (Figure 7). Quadratic plateau models did not provide an acceptable fit, suggesting that maximum turf quality was not

achieved within the data range during 2013 and was at the end of the data range in 2014 (Figure 7). A significant quadratic (or linear) response was found between leaf K concentration and mean turf color, mean NDVI index, or mean chlorophyll index during most years (1, 3, and 3 out of 3 years, respectively), with increasing leaf K concentration providing a subtle increase in mean turf color, mean NDVI, and mean chlorophyll index (Figure A.2, A.3, A.4). Similar to extractable mat K, the response of mean turf color, mean NDVI index, or mean chlorophyll index to leaf K concentrations was relatively small and not biologically meaningful. Fitzpatrick and Guillard (2004) reported no correlation between tissue K concentration and turf quality rating, which may be explained by the fact that the turf in their study was not subjected to any significant stresses during the trial period. Environmental factors such as drought or biological (pathogens) stresses may have provided separation between leaf K concentrations.

K Rate Effect on Extractable Mat and Soil K

Mat and soil extractable K concentrations were both affected by K fertilization rate (Table 2). Extractable mat K concentrations increased quadratically with increasing K rates on all sampling dates in 2012, 2013, and 2014 (Table 2). Similarly, extractable soil K concentration increased quadratically with increasing K rates on all dates except June 2012 (Table 2). These results were not surprising, considering that the initial extractable mat and soil K concentrations (18 and 74 mg K kg^{-1}, respectively) of the experimental area were considered very low and low, respectively (Carrow et al., 2001). Potassium treatments applied at 109 or 218 kg ha^{-1} yr^{-1} were sufficient to build K concentrations in both the mat and soil regions on most sampling dates in the study (7

and 8 of 9 dates, respectively), whereas K applied at 54 kg ha^{-1} yr^{-1} (or 3.4 kg ha^{-1} 14-d^{-1}) increased K concentration in the mat (8 of 9 dates), but had no effect on soil K concentrations throughout the study. The moderate rate of N (~137 kg N ha^{-1} yr^{-1}) in combination with K fertilization at 54 kg ha^{-1} yr^{-1} was close to a maintenance rate under these conditions (soil type), meaning the K fertilization rate was similar to the rate of K uptake and removal (clippings) by the turf. Mat and soil K concentration in plots that received no K fertilization decreased to 28 and 68 mg K kg^{-1}, respectively, by September 2014. Woods et al. (2006) found a much higher rate of K (20 kg ha^{-1} 14-d^{-1}) was required to maintain soil K levels in a calcareous sand rootzone. This discrepancy could be attributed to differences in rootzone material (sand in their trial vs. sandy loam with sand topdressed mat layer in the current study) and N rate. Previous studies have shown that sand rootzones are susceptible to leaching of K (Lodge and Lawson, 1993; Sheard et al., 1985), especially calcareous sands. Additionally, a greater rate of N (190 kg ha^{-1} yr^{-1}) was used by Woods et al. (2006) in the first year of their study, which may have influenced (decreased) the soil K concentration. Potassium removal from the soil is increased with greater N fertilization rate (Fitzpatrick and Guillard, 2004). Thus, a much lower rate of K (54 kg ha^{-1} yr^{-1}, or 3.4 kg ha^{-1} 14-d^{-1}) would be required on finer-textured soil because the leaching of K should be less. Additionally, it is likely that turf systems that receive lower N rate (< 146 kg ha^{-1} yr^{-1}) would also require lower K rates to maintain soil K levels due to reduced growth rate.

Mat K Effect on Tissue K

The quadratic plateau models were significant ($p < 0.05$) when comparing extractable mat K concentration to leaf K concentrations on all sampling dates throughout the study (Figure 8). Critical mat K concentrations (point at which leaf K concentration is maximized) ranged from 73 to 105 mg kg^{-1} across all sampling dates, with a mean of 88 mg kg^{-1} (Figure 8). Maximum (plateau) leaf K concentration ranged from 24.1 to 29.9 g kg^{-1} across all sampling dates, with a mean concentration of 27.1 g kg^{-1} (Figure 8). Waddington and Zimmerman (1972) observed much greater average leaf K concentrations (36 g kg^{-1}) for annual bluegrass turf grown in greenhouse pots, which was likely due to the greater N fertilization rate (195 kg ha^{-1} over 14-wks) and the more conductive temperatures (greenhouse vs. hot summer weather) compared to the current study. This suggests that K rate interact with N rate or ambient temperatures; however, additional research is needed to test these hypotheses. Moreover, critical mat K levels were greater for samples collected in June compared with those collected in August or September, suggesting that higher mat K levels may be required to achieve maximum leaf K concentration during periods of increased shoot growth (i.e. spring and early summer). Additionally, greater rates of N applied to all plots in the spring (additional 23 kg N ha^{-1} from April through early May), to encourage growth and recovery from disease, likely resulted in greater turf growth and K uptake by plants. Thus, a greater mat K concentration was required to achieve maximum leaf K content in the spring. Moreover, maximum (plateau) leaf K concentrations were greater in September than any other sampling time. This may be due to the severe stress during

late summer (anthracnose infection and environmental stress) reducing plant growth resulting in K becoming more concentrated in slow growing leaf tissue.

Woods et al. (2005) also observed that a maximum leaf K concentration was achieved at a lower soil K level) in September versus July on a calcareous sand rootzone using various soil extraction methods (Mehlich 3, Morgan, 1 *N* NH_4OAc, 0.01 *M* $SrCl_2$, and 1:5 H_2O. However, plots were sampled within one year, so it is unclear whether this trend was consistent over years. In contrast, Woods et al. (2006) failed to show a consistent relationship between soil K and leaf K levels on a calcareous sand rootzone regardless of the extraction method (Mehlich 3, Morgan, 1 *N* NH_4OAc, 0.01 *M* $SrCl_2$, and 1:5 H_2O).

Mat Layer Ca and Mg Response to K Fertilization

Mehlich 3 extractable mat Ca and Mg had significant positive linear relationships with mat K on most sampling dates throughout the trial, except extractable Ca on 20 June 2012 (Figures 9 and 10). A subtle increase in mat Ca and Mg concentration was observed with increasing mat K concentrations on all significant dates (Figures 9 and 10). In contrast, leaf Ca and Mg concentrations exhibited a negative linear relationship with leaf K concentrations on most dates except for leaf Ca on June 2012 (Figures 11 and 12), which indicated that K fertilization inhibited Ca and Mg uptake. Thus, lower mat Ca and Mg concentrations at low mat K concentrations was likely due to greater Ca and Mg uptake by the turf relative to K uptake. Previous studies have shown that K fertilization can reduce the uptake of Ca and Mg (Waddington et al., 1972; Waddington et al., 1978; Woods et al., 2005). At high leaf K concentrations, leaf Ca concentrations

were deficient (< 5 g kg^{-1}) according Carrow et al. (2001); however, no negative turf response was observed (Figure 11). Conversely, leaf Mg concentrations were within the sufficient range of 1.5 to 5 g kg^{-1} across all leaf K concentration for a majority of the dates in the current study (Figure 12).

CONCLUSIONS

This is the first study to document the impact of K fertilization on anthracnose severity of ABG turf. A deficiency in soil K can increase anthracnose severity and decrease turf quality. Subtle decreases in turf color, NDVI index, and chlorophyll index were also observed in response to deficiencies in soil K. Models used to predict critical mat K concentration needed to optimize the suppression of anthracnose ranged from 43 to 70 mg kg^{-1}, with a maximum leaf K concentration attained at mat K concentrations ranging from 73 to 105 mg kg^{-1}. Thus, the soil sufficiency range for ABG turf appears to be between 50 and 100 mg K kg^{-1}, using the Mehlich 3 extraction method. It is important to note that this sufficiency range may not apply to rootzones with high sand and low organic matter content, which cannot retain K and buildup concentrations to within the sufficiency range compared to higher organic matter soils. On high sand content soils, K should be applied to meet the requirements of plant growth. The critical leaf K concentration ranged from 19.3 to 23.1 g kg^{-1} using the Cate-Nelson and linear plateau models, and maximum leaf K concentrations ranged from 24.1 to 29.9 g kg^{-1}. Thus, a leaf K concentration between 20 to 30 g kg^{-1} should be sufficient for ABG turf. Potassium fertilization rates of 54 kg ha^{-1} yr^{-1} met the K requirements of the turf without building up K in mat or underlying soil; whereas, K applied at rate of $\geq$ 109 kg ha^{-1} yr^{-1} exceeded the requirements of the turf and built-up mat (and soil) K concentrations. Thus, for soils having a sufficient quantity of K, K fertilization at 54 kg ha^{-1} yr^{-1} appears to be sufficient to meet the maintenance fertilization needs of the turf;

whereas, K fertilization rate of 109 to 218 kg ha^{-1} yr^{-1} would build-up K in soils that can retain K.

All K sources were effective at reducing anthracnose severity compared to no K fertilization; however, KCl was not as effective as KNO_3, K_2CO_3, and K_2SO_4 later in the study. This study also confirms that K fertilization can inhibit plant uptake of Ca and Mg. Although, no negative effect from low Ca was observed, care should be taken to prevent high rates of K ($\geq$ 109 kg K ha^{-1} yr^{-1}) from causing potential Ca and Mg deficiency responses. This study evaluated K rate at one rate of N fertilization and previous studies have shown that K rate can interact with N rate. Thus, further work is needed to determine whether the effect of K rate is consistent over a range of N rates.

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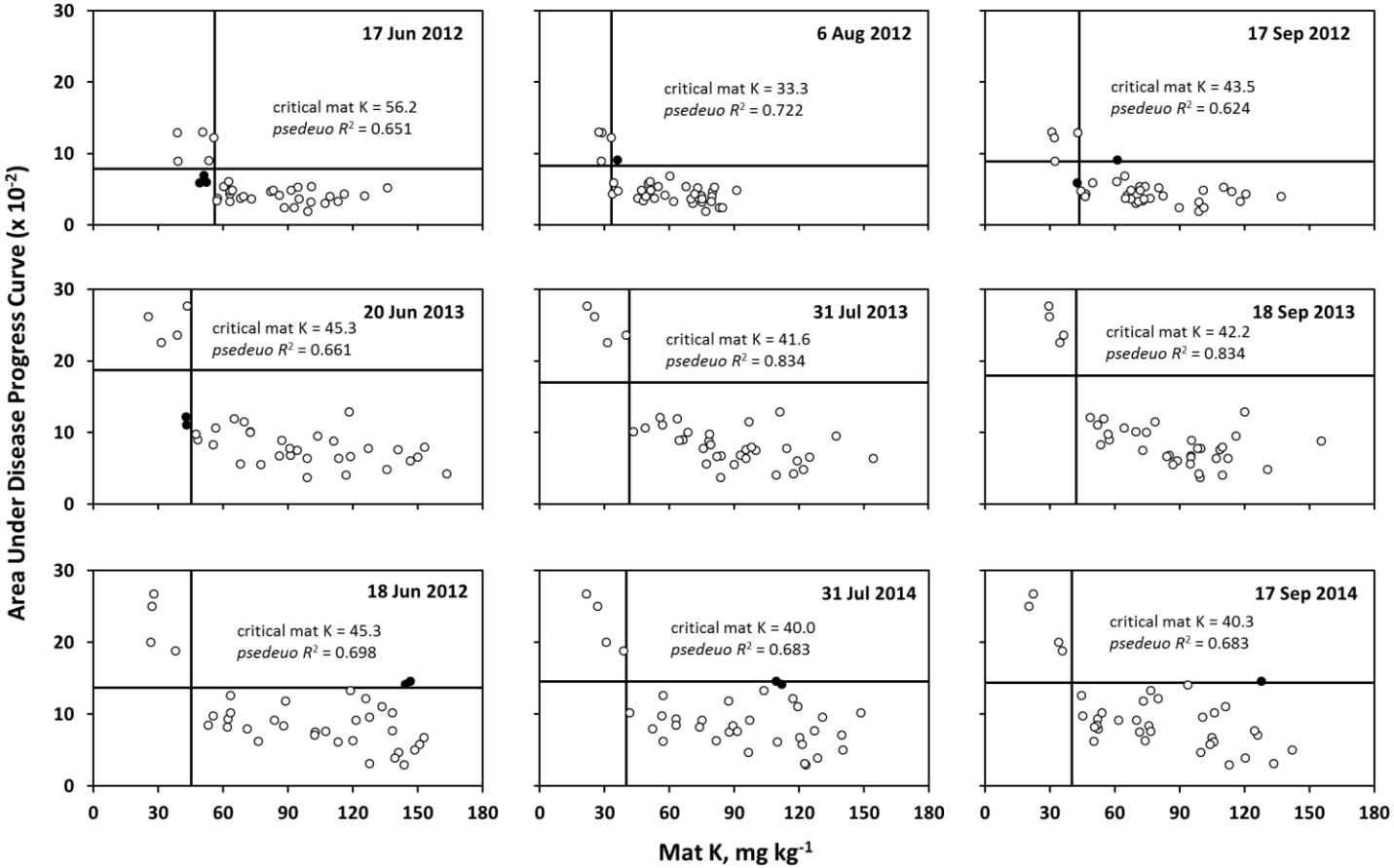

Figure 1. Mehlich 3 extractable mat K in relation to the area under disease progress curve on annual bluegrass turf infested with anthracnose in North Brunswick, NJ. Potassium was applied for 32-wk period each growing season, from May through November, for a total of between 0 to 218 kg K ha^{-1} yr^{-1}. Cate-Nelson models are shown for all dates in 2012, 2013, and 2014. Line vertical to the *x* axis indicates the critical mat K concentration estimated by the Cate-Nelson model. Solid symbols indicate errors in the prediction by the model.

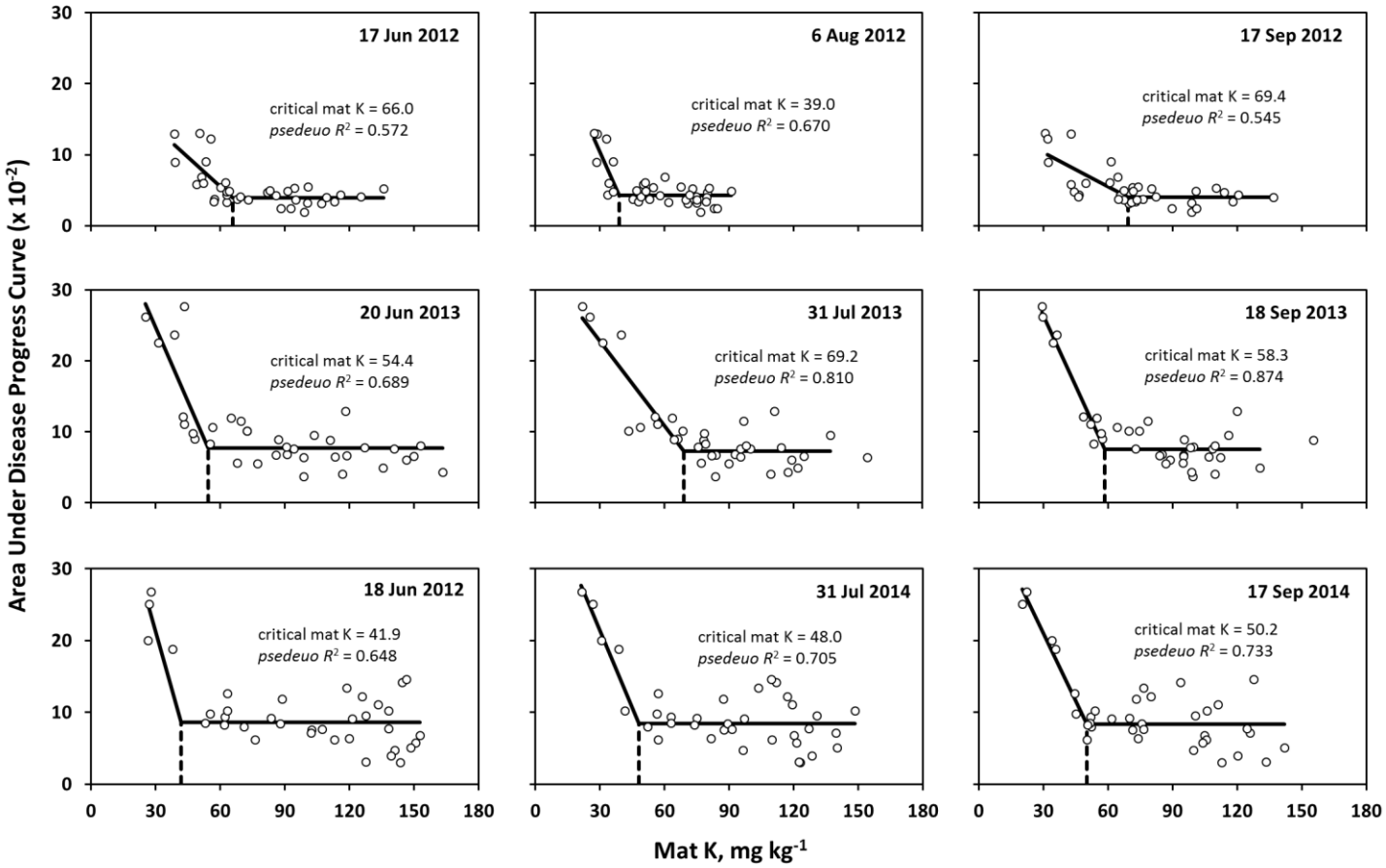

Figure 2. Mehlich 3 extractable mat K in relation to the area under disease progress curve on annual bluegrass turf infested with anthracnose in North Brunswick, NJ. Potassium was applied for 32-wk period each growing season, from May through November, for a total of between 0 to 218 kg K ha^{-1} yr^{-1}. Linear plateau models are shown for all dates in 2012, 2013, and 2014. Line vertical to the *x* axis indicates the critical K concentration estimated by the linear plateau model.

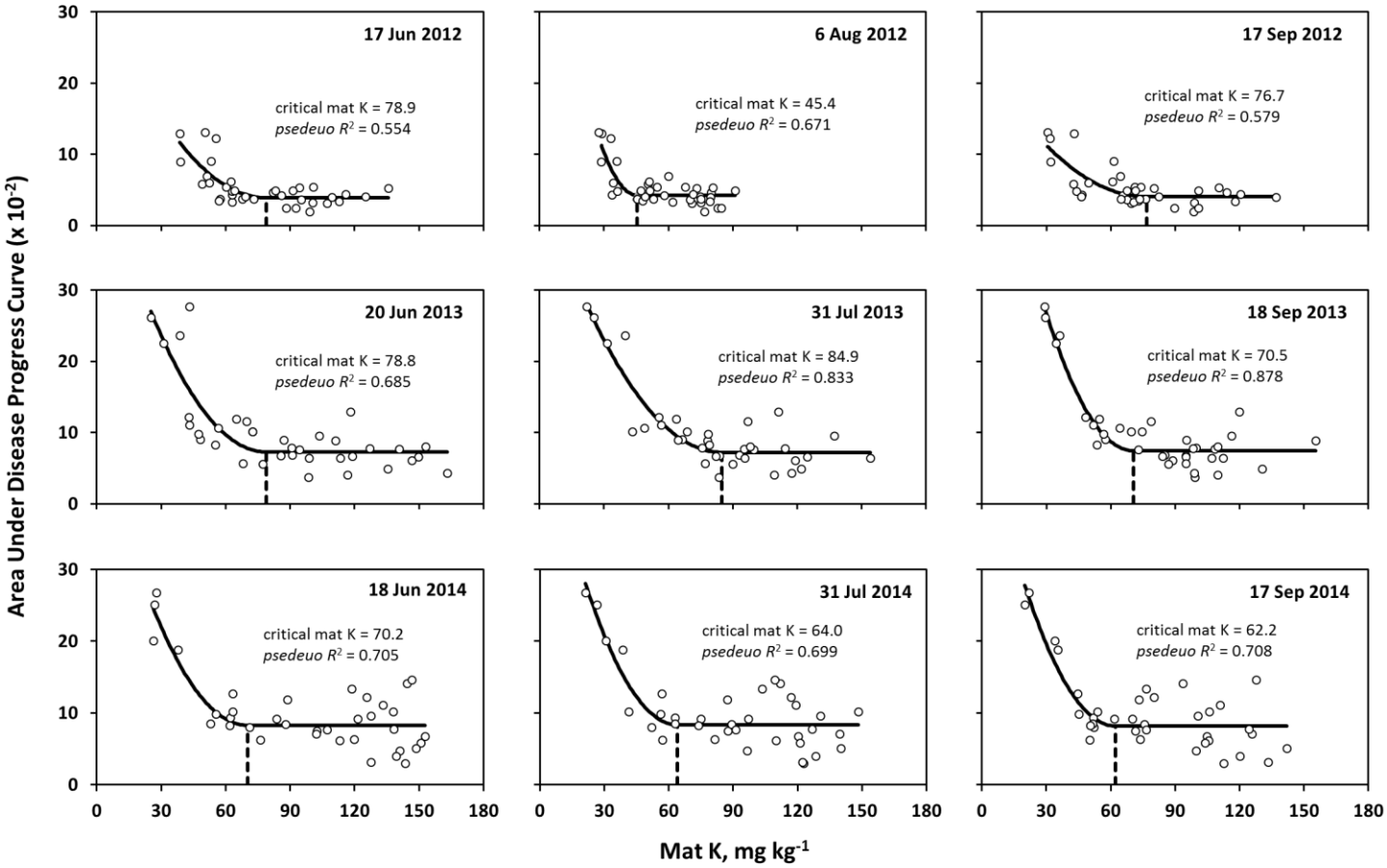

Figure 3. Mehlich 3 extractable mat K in relation to the area under disease progress curve on annual bluegrass turf infested with anthracnose in North Brunswick, NJ. Potassium was applied for 32-wk period each growing season, from May through November, for a total of between 0 to 218 kg K ha^{-1} yr^{-1}. Quadratic plateau models are shown for all dates in 2012, 2013, and 2014. Line vertical to the *x* axis indicates the critical mat K concentration estimated by the quadratic plateau model.

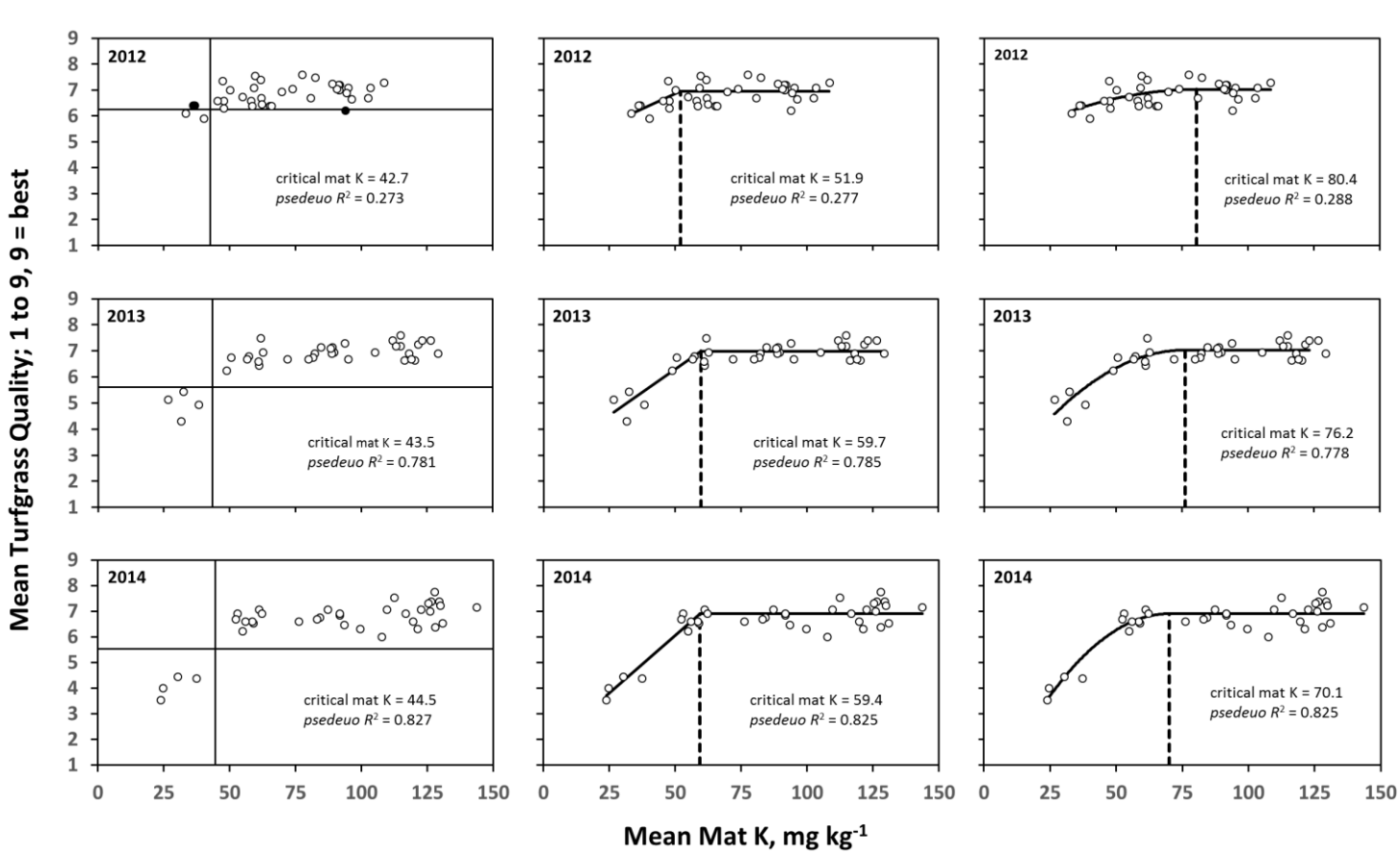

Figure 4. Mean Mehlich 3 extractable mat K in relation to mean turf quality of annual bluegrass putting green turf in North Brunswick, NJ. Potassium was applied for 32-wk period each growing season, from May through November, for a total of between 0 to 218 kg K ha^{-1} yr^{-1}. Cate-Nelson (left), linear plateau (center), and quadratic plateau (right) models are shown for all years (2012, 2013, and 2014). Line vertical to the *x* axis indicates the critical mat K concentration estimated by the Cate-Nelson, linear plateau, and quadratic plateau models.

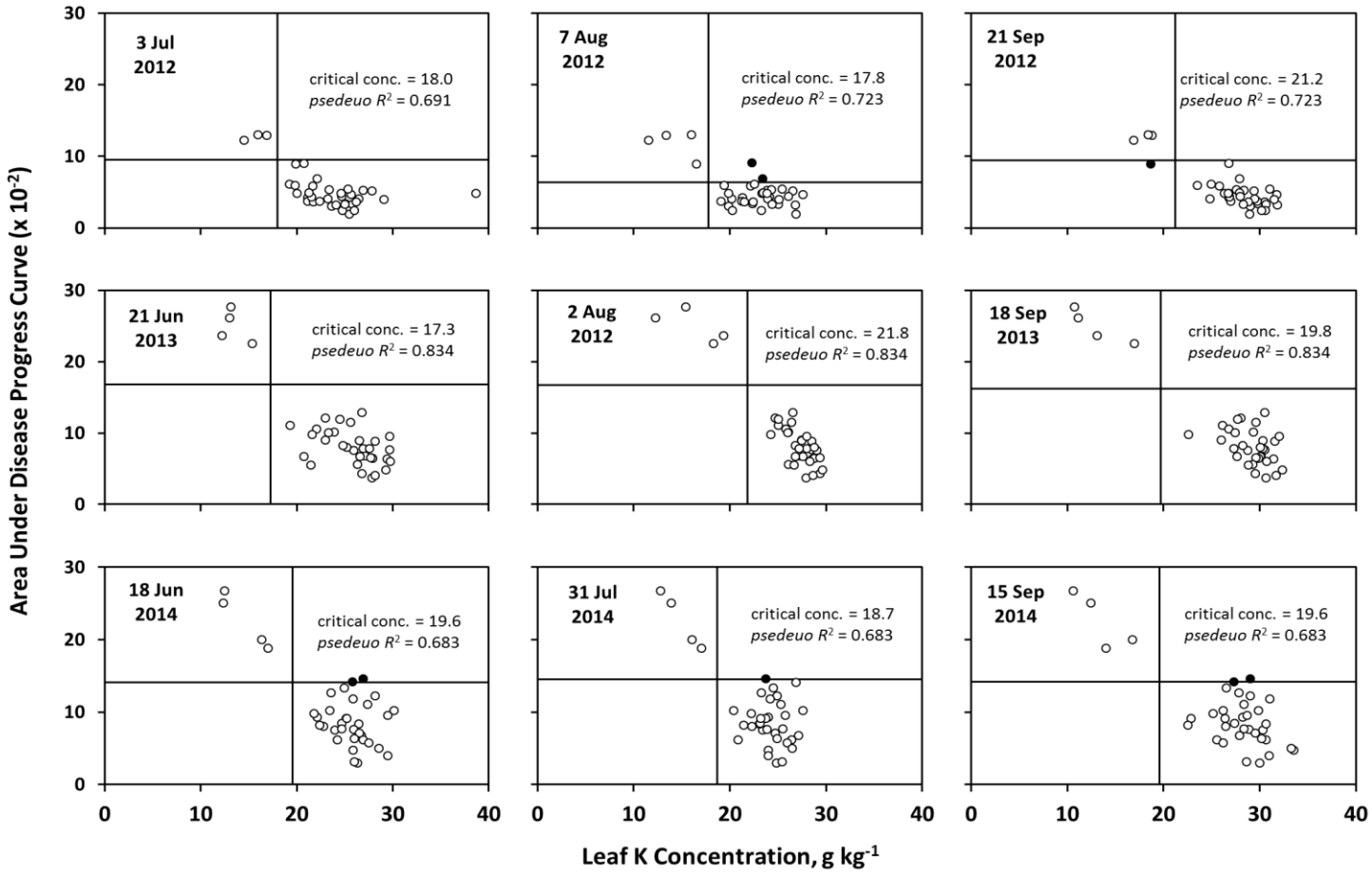

Figure 5. Leaf K concentration in relation to the area under disease progress curve on annual bluegrass turf infested with anthracnose in North Brunswick, NJ. Potassium was applied for 32-wk period each growing season, from May through November, for a total of between 0 to 218 kg K ha^{-1} yr^{-1}. Cate-Nelson models are shown for all dates in 2012, 2013, and 2014. Line vertical to the *x* axis indicates the critical mat K concentration estimated by the Cate-Nelson model. Solid symbols indicate errors in the prediction by the model.

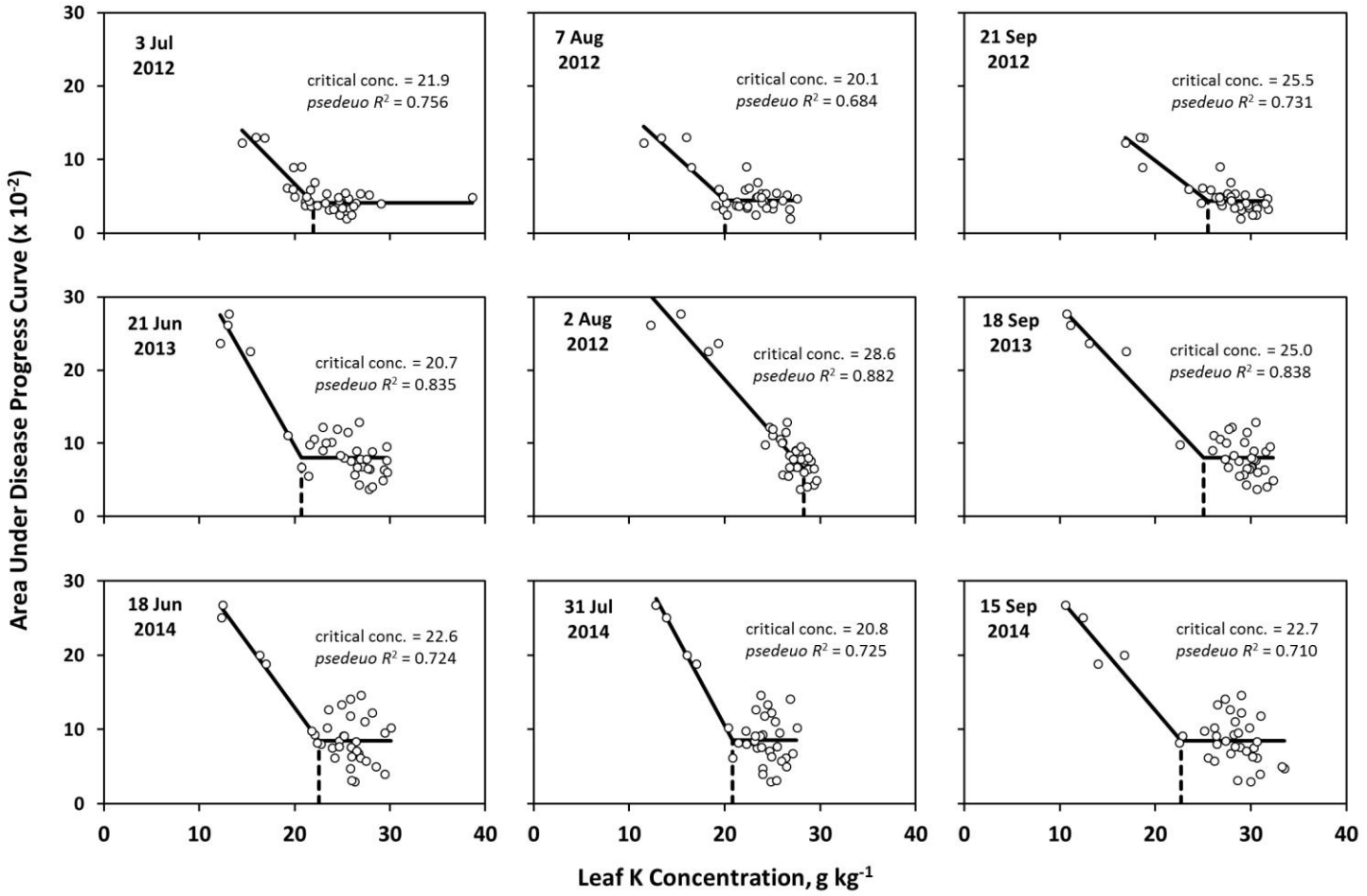

Figure 6. Leaf K concentration in relation to the area under disease progress curve on annual bluegrass turf infested with anthracnose in North Brunswick, NJ. Potassium was applied for 32-wk period each growing season, from May through November, for a total of between 0 to 218 kg K ha^{-1} yr^{-1}. Linear plateau models are shown for all dates in 2012, 2013, and 2014. Line vertical to the *x* axis indicates the critical mat K concentration estimated by the linear plateau model.

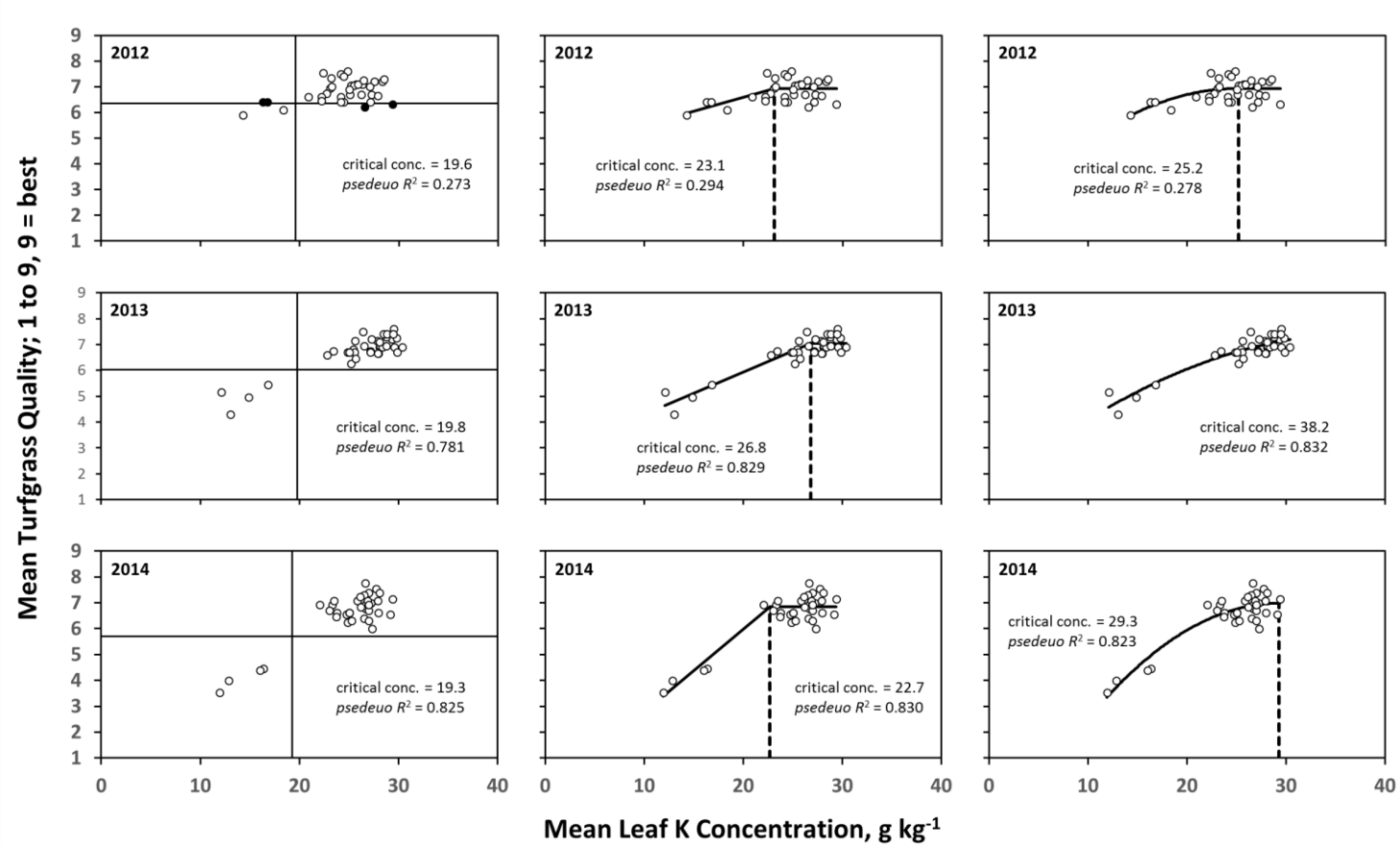

Figure 7. Mean leaf K conc. in relation to mean turf quality of annual bluegrass putting green turf in North Brunswick, NJ. Potassium was applied for 32-wk period each growing season, from May through November, for a total of between 0 to 218 kg K ha^{-1} yr^{-1}. Cate-Nelson (left), linear plateau (center), and quadratic plateau (right) models are shown for all years (2012, 2013, and 2014). Line vertical to the *x* axis indicates the critical mat K concentration estimated by the Cate-Nelson, linear plateau, and quadratic plateau models.

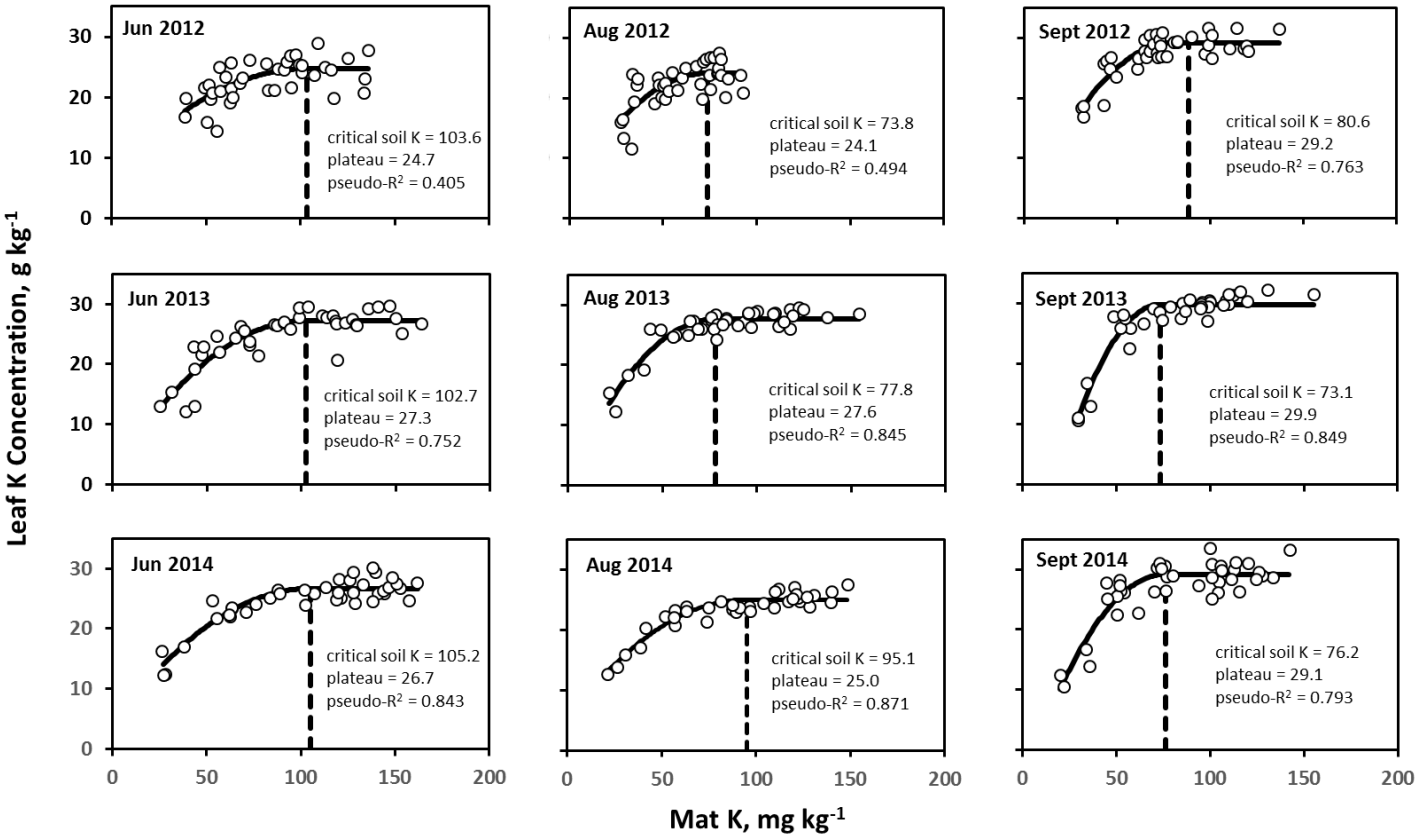

Figure 8. Leaf K concentration in relation to Mehlich III extractable mat K for annual bluegrass putting green turf in North Brunswick, NJ. Potassium was applied for 32-wk period each growing season, from May through November, for a total of between 0 to 218 kg K ha^{-1} yr^{-1}. Quadratic plateau models are shown for all dates in 2012, 2013, and 2014. Line vertical to the *x* axis indicates the critical mat K concentration estimated by the quadratic plateau model (point at which leaf K concentration is maximized). Plateau indicates the plateau value from quadratic plateau model (maximum leaf K concentration).

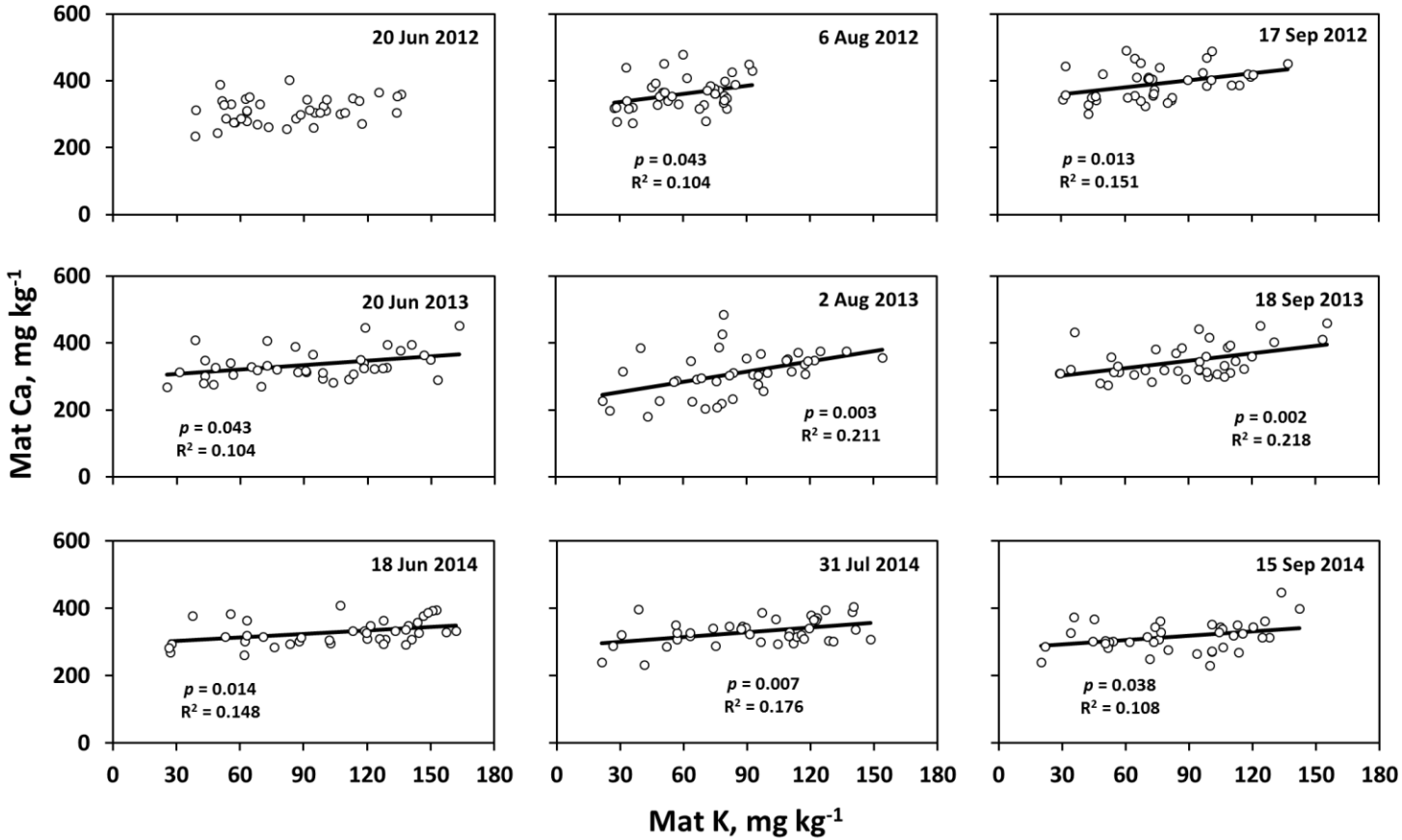

Figure 9. Mehlich 3 mat K in relation to Mehlich 3 mat Ca concentration of annual bluegrass putting green turf in North Brunswick, NJ. Potassium was applied for 32-wk period each growing season, from May through November, for a total of between 0 to 218 kg K ha^{-1} yr^{-1}. Linear regression models are shown for all dates in 2012, 2013, and 2014.

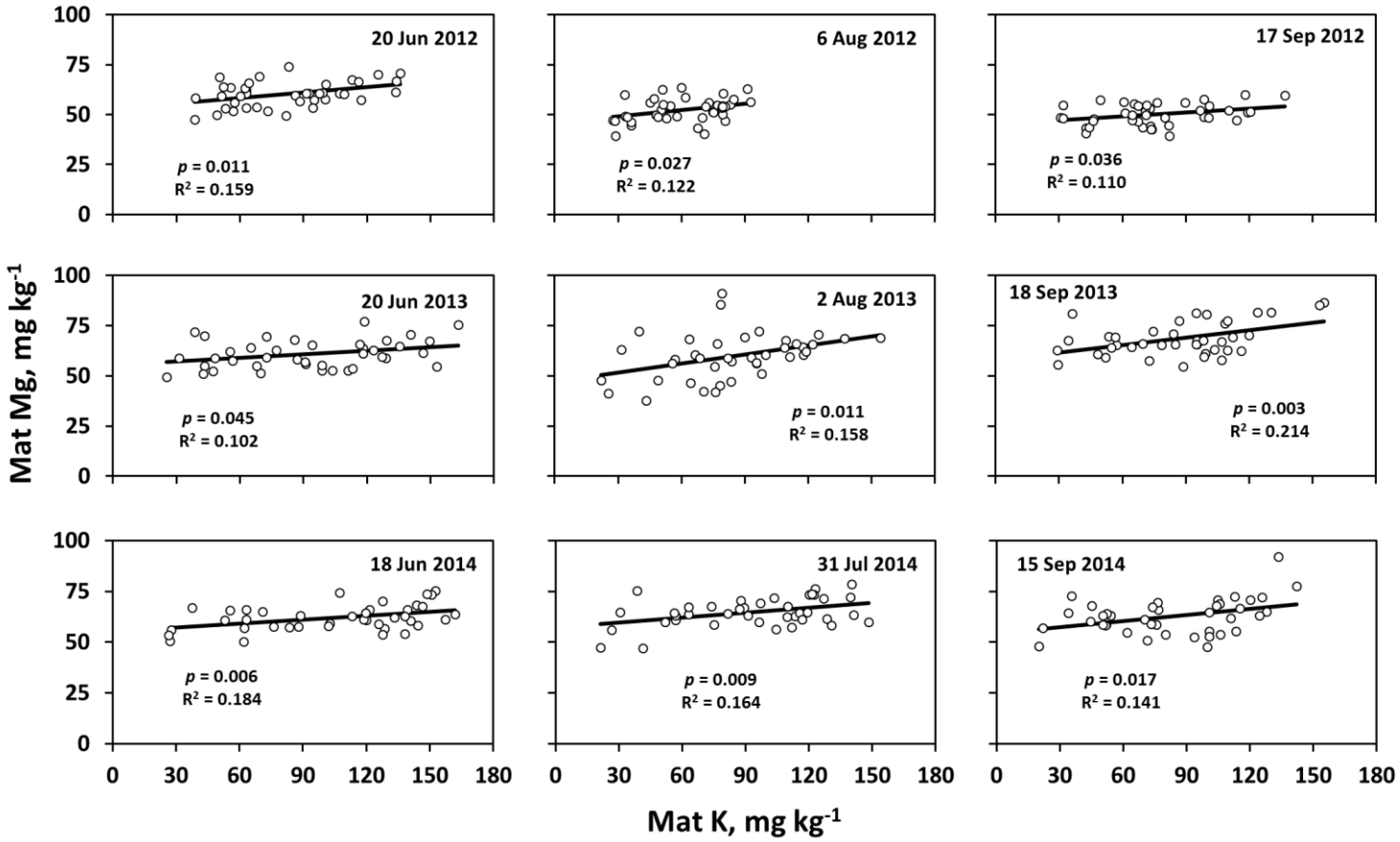

Figure 10. Mehlich 3 mat K in relation to Mehlich 3 mat Mg concentration of annual bluegrass putting green turf in North Brunswick, NJ. Potassium was applied for 32-wk period each growing season, from May through November, for a total of between 0 to 218 kg K ha^{-1} yr^{-1}. Linear regression models are shown for all dates in 2012, 2013, and 2014.

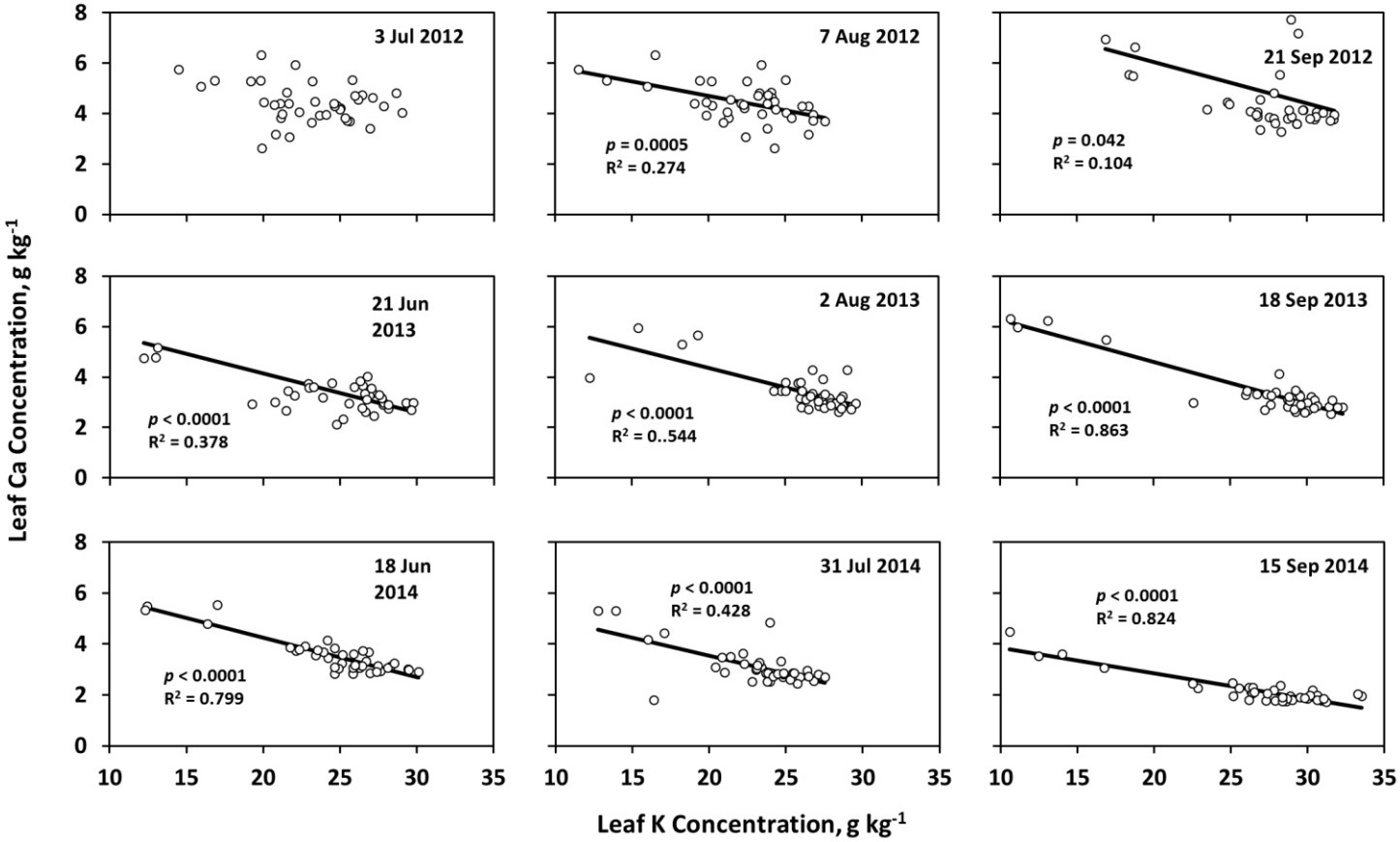

Figure 11. Leaf K concentration in relation to leaf Ca concentration of annual bluegrass putting green turf in North Brunswick, NJ. Potassium was applied for 32-wk period each growing season, from May through November, for a total of between 0 to 218 kg K ha^{-1} yr^{-1}. Linear regression models are shown for all dates in 2012, 2013, and 2014.

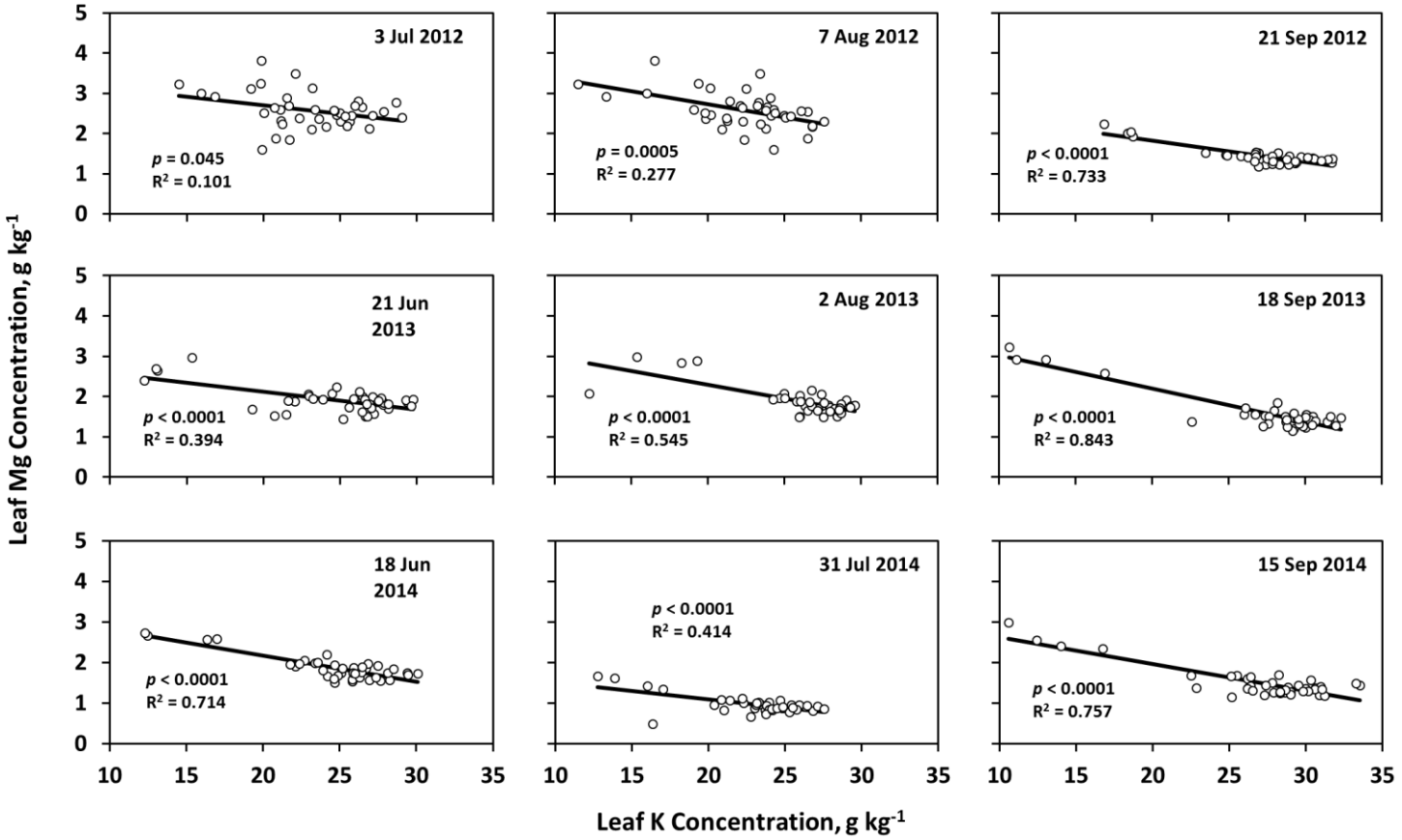

Figure 12. Leaf K concentration in relation to leaf Mg concentration of annual bluegrass putting green turf in North Brunswick, NJ. Potassium was applied for 32-wk period each growing season, from May through November, for a total of between 0 to 218 kg K ha^{-1} yr^{-1}. Linear regression models are shown for all dates in 2012, 2013, and 2014.

Table 1. Analysis of variance summary for anthracnose severity in response to potassium rate and source applied to annual bluegrass turf maintained at 3.2 mm in North Brunswick, NJ, during 2012, 2013, and 2014.

Treatments	2012						2013						2014					
	8-Jun	6-Jul	23-Jul	3-Aug	15-Aug	28-Aug	12-Jun	24-Jun	9-Jul	24-Jul	6-Aug	19-Aug	1-Jul	16-Jul	23-Jul	5-Aug	13-Aug	27-Aug
	%																	
Source																		
KCl	3	3	11	5	8	10	1	3	6	23	26	22	6	11	20	27	28	22
K_2SO_4	3	3	12	5	8	11	1	2	5	21	21	18	4	6	15	19	19	16
Rate																		
54 kg ha^{-1} yr^{-1}	4	3	11	5	11	13	2	3	7	27	28	24	4	7	17	24	22	17
109 kg ha^{-1} yr^{-1}	3	3	12	5	7	9	0	2	5	21	22	18	5	8	17	23	24	19
218 kg ha^{-1} yr^{-1}	4	3	9	4	7	9	1	3	5	19	21	17	5	11	18	22	25	21
$LSD_{0.05}$	---	---	---	---	---	---	1	---	---	6	6	5	---	3	---	---	---	---
K sources at 218 kg ha^{-1} yr^{-1}																		
KCl	3	4	8	5	8	12	1	3	7	20	26	21	7	14	21	30	33	28
K_2SO_4	4	3	11	4	5	6	1	2	4	19	16	13	4	8	15	15	17	14
K_2CO_3	3	1	9	5	6	4	0	1	7	21	17	9	1	1	11	12	14	10
KNO_3	2	2	6	3	6	5	0	1	2	16	15	12	1	1	14	16	18	14
Source of variation	ANOVA																	
Source	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	**	***	*	***	**	*
Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	*	NS	*	NS	NS	NS	NS
Source x Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*
Orthogonal contrasts																		
N alone vs K alone	NS	**	**	ns	*	*	**	***	***	***	***	NS	NS	NS	NS	NS	NS	NS
No K vs K (all pooled)	NS	NS	**	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
KCl vs K_2SO_4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	*	*	NS	NS	***	**	**
KCl vs K_2CO_3	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	*	**	***	***	*	***	***	***
KCl vs KNO_3	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	**	*	***	***	ns	***	**	**
K_2SO_4 vs K_2CO_3	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS
K_2SO_4 vs KNO_3	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS
K_2CO_3 vs KNO_3	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively; NS, not significant.

† Orthogonal contrast between individual K sources applied at a rate of 218 kg K ha^{-1} yr^{-1}.

Table 2. Mehlich 3 mat and soil test K response to K fertilization rate on annual bluegrass putting green turf in North Brunswick, NJ, during 2012, 2013, and 2014.

K rate	2012			2013			2014		
	Jun	Aug	Sep	Jun	Aug	Sep	Jun	Aug	Sep
					Mat K[†]				
kg K ha^{-1} yr^{-1}	---------- mg kg^{-1} ----------								
0	46	29	34	35	30	32	30	29	28
54	59	42	53	54	65	58	63	58	50
109	66	54	69	84	80	85	104	89	72
218	105	78	95	123	105	111	137	122	107
$LSD_{(0.05)}$	16	7	14	17	18	16	14	10	12
Linear	***(0.73)[‡]	***(0.90)	***(0.68)	***(0.79)	***(0.62)	***(0.78)	***(0.87)	***(0.88)	***(0.89)
Quadratic	***(0.75)	***(0.90)	***(0.69)	***(0.79)	***(0.65)	***(0.80)	***(0.89)	***(0.90)	***(0.89)
					Soil K				
0	77	66	59	57	52	60	46	62	68
54	76	70	61	61	60	68	55	74	76
109	78	71	73	72	82	95	83	110	101
218	79	85	92	109	130	140	128	178	170
$LSD_{(0.05)}$	7	7	9	8	14	8	10	13	30
Linear	NS	***(0.50)	***(0.74)	***(0.84)	***(0.86)	***(0.89)	***(0.90)	***(0.93)	***(0.64)
Quadratic	NS	***(0.51)	***(0.75)	***(0.87)	***(0.88)	***(0.90)	***(0.91)	***(0.93)	***(0.66)

*** Significant at the 0.001 probability level, respectively; NS, not significant.

[†] Mehlich 3 extractable mat and soil K.

[‡] Percent variation is shown in parentheses for significant factors within the factorial analysis.

CHAPTER 5. Influence of Mat pH and Extractable Ca on Anthracnose Severity and Performance of Annual Bluegrass Turf

Abstract. The effect of soil pH on turfgrass growth varies depending species; however, most turfgrasses are adapted to slightly acid soil conditions (pH 6 – 7). In general, annual bluegrass [ABG; *Poa annua* L. f. reptans (Hausskn) T. Koyama] is considered intolerant of low or high soil pH; however, it is unclear what the optimum soil pH is for ABG growth and quality under field conditions. The objectives of this field study were to quantify the responses of ABG over a range of mat (organic layer intermixed with topdressing sand) pH, identify a critical level for ABG performance, and determine whether these response were due to modification in mat pH or Ca nutrition. The trial was initiated in 2011 on ABG turf that had an initial pH value of 5.3 in the 0- to 60-mm mat layer. Five limestone ($CaCO_3$) rates were applied on 12 Dec. 2011 and 1 Apr. 2014 based on target pH levels of 5.8, 6.3, 6.8, 7.3, and 7.8 in the mat layer. Two elemental sulfur and two gypsum ($CaSO_4*2H_2O$) treatments were applied on the same dates as limestone to decrease pH and provide Ca checks, respectively. Limestone reaction in the soil was slow and treatments did not reach their target pH by the end of 2014; however, a relatively broad range of acidic soil pH (~ 5.0 to 6.5) was present throughout the majority of the study. Linear plateau and quadratic plateau models identified a critical mat pH level for anthracnose severity (AUDPC), turfgrass quality, color, NDVI, and chlorophyll index, indicating a critical pH between pH 6.0 to 6.5. Linear plateau and quadratic plateau models were also used to identify the relationship between extractable mat Ca and turf performance parameters, and indicated a critical mat Ca

concentration of between 392 and 825 mg kg^{-1}. Although this study was unable to determine that mat pH was the only factor influencing the ABG responses measured, it is clear that acidic soil conditions (< 5.5) and/or deficiencies in extractable Ca can increase anthracnose severity and cause a reduction in turfgrass performance. Further research is need to better distinguish the effect of soil pH modification and Ca nutrition on anthracnose severity and ABG performance.

INTRODUCTION

The effect of soil pH (or soil reaction) on turfgrass growth has been the subject of interest for more than a century (Wheeler and Tillinghas, 1900), and is one of the most commonly measured soil characteristics (Carrow et al., 2001). Soil pH can have a significant influence on nutrient availability in the soil (Troug, 1947), causing nutrient deficiencies that can affect turfgrass growth and quality. As soil pH becomes more acidic, plant deficiencies in N, P, K, Mg, and S are more likely to occur. This is especially true for N, due to progressively decreasing mineralization of organic N at soil pHs below 6.0 (Adams, 1984). In contrast, increasingly more alkaline soil pH, plants tends to be deficient in Fe, Mn, P, and B (Carrow et al., 2001; Troug, 1947). In addition, under very acidic (pH < 4.8) conditions Al and Mn become more soluble and can reach levels high enough to cause direct toxicity to plant roots, and below a pH of 4.0, high levels of H+ can damage roots as well (Carrow et al., 2001; Foy, 1992).

The response of turfgrasses to soil pH varies by species, but most are adapted to slightly acidic soil conditions (pH 6 to 7) (Beard, 1973). In general, cool-season species including the bluegrass [Kentucky (*Poa pratensis* L.) and rough (*P. trivialis* L.)] and ryegrasses [perennial (*Lolium perenne* L.) and Italian (*L. perenne* L. subsp. *Multiflorum* (Lam.) Husnot)] tend to favor slightly more basic conditions (pH 6 to 7) compared to bentgrasses [creeping (*Agrostis stolonifera* L.), colonial (*A. capillaries* L.), and velvet (*A. canina* L.)] and fescues [Chewing's (*Festuca rubra* L. subs. *fallax* (Thuill.) Nyman), red (*F. rubra* L.), and sheep (*F.ovina*L.)], which favor more acidic conditions (pH 5.5 to 6.5) (Beard, 1973). Annual bluegrass [*Poa annua* L. f. reptans (Hausskn) T. Koyama; ABG] is

generally considered to be less tolerant of moderately acid soils compared to bentgrasses (Vargas and Turgeon, 2004).

Annual bluegrass is one of the most common putting green species in the Northeastern US and Pacific Northwest. Despite the prevalence of ABG, the critical soil pH at which growth is inhibited has not been well defined. Recommendations for optimum soil pH for ABG have ranged from pH 6.0 to 7.0 (Spurway, 1941), pH 5.1 to 7.6 (Musser, 1962), and pH 5.5 to 6.5 (Beard, 1973). A number of studies have investigated the effect of soil pH on ABG in mixed swards of turf; however, most of this work was conducted in an effort to reduce the population of ABG, not to promote growth. Early research by Sprauge and Evaul (1930) investigated the influence of soil pH on ABG/bentgrass putting green turf, noting that strongly acidic soils (pH < 5.4) reduced the growth of ABG. Greenhouse experiments were also conducted to further understand this relationship and found that ABG exhibited very little growth and eventually died at soil pH < 4.0 and > 7.0. In another greenhouse study, Sprague and Burton (1937) noted that increasing soil pH from 5.3 to 6.3 with limestone produced an increase in ABG growth regardless of fertilizer treatment. Ferguson (1936) observed that acidifying fertilizers (ammonium sulfate and iron sulfate) reduced ABG populations, which he attributed to a failure of ABG seeds to establish at low soil pH rather than toxicity on mature plants. In addition, several studied have reported that sulfur applications reduced ABG populations in mixed turf stands (Goss, 1974; Kato et al., 2000). Although it is clear that strongly acidic soil can inhibit the growth of ABG turf, research has yet to produce a definitive critical soil pH level or an optimum pH range. Moreover, there is a

paucity of research on the effect of soil pH on ABG performance (color and quality) in a monostand.

Several studies have examined the influence of soil pH on turfgrass diseases such as take-all patch (*Gaeumannomyces graminis* var. *graminis* [Sacc.] Arx & D.L. Olivier) (Goss and Gould, 1967; Jackson, 1958; Smith, 1956; Smith et al., 1989), Microdochium patch (*Microdochium nirvale* [Fr.] Samuels & I.C. Hallett) (Lawson, 2000; Robinson, 1980; Smith, 1958), and summer patch (*Magnaporthiopsis poae* [Landsch. & N. Jacks.] J. Luo & N. Zhang; reported as *Magnaporthe poae*) (Davis and Dernoeden, 1991; Thompson et al., 1993). The severity of all three of these diseases has been reported to increase as soil pH increases above 6.0 to 6.5. However, few studies have investigated the influence of soil pH on stress related diseases such as anthracnose (*Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman)

Previous research investigating the impact of N source on the severity of anthracnose on ABG turf found that basic N source (potassium nitrate and calcium nitrate) reduced disease severity compared to acidic N sources (ammonium sulfate and ammonium nitrate), suggesting that soil pH may influence this disease (Schmid et al., 2012). But, this hypothesis has yet to be confirmed. The increased incidence of anthracnose on ABG putting green turf has been attributed to management practices that weaken turf such as low nitrogen rates, soil water, and mowing height that are often employed to increase ball roll distance (Inguagiato et al., 2008; Vermeulen, 2003; Wong and Midland, 2004). Thus, it is possible that a soil pH low enough (or high

enough) to inhibit ABG growth would also increase the incidence or severity of anthracnose.

The objectives of this study were to 1) quantify the responses of ABG over a range of soil pH, 2) identify a critical level that can be used to reduce anthracnose severity and enhance turf performance(turf color and quality, NDVI, and chlorophyll index), and 3) determine whether these responses are due to soil pH adjustments and/or calcium nutrition.

MATERIALS AND METHODS

Experimental Design and Treatments

A field study was initiated Dec 2011 on ABG putting green turf at Rutgers Hort Farm II in North Brunswick, NJ (40°28' N, 74°25' W). A monostand of ABG putting green turf was established using methods described by Inguagiato et al. (2008). Soil in the study area was a Nixon sandy loam (fine-loamy, mixed, semiactive, mesic Typic Hapludults) with mat (organic layer intermixed with sand topdressing; Beard, 1973) layer that ranged from 5 to 6 cm in depth at treatment initiation. From this point forward the term "mat" will be used to describe the 5 to 6 cm layer at the surface of the rootzone that is comprised of topdressing sand intermixed with organic matter (dead and decaying roots and shoots). Chemical properties of the mat and soil layers are listed in Table 1. Extractable P, K, Ca, and Mg concentrations in the mat region were considered below optimum, according to soil fertility reports from the Rutgers Soil Testing Laboratory; whereas, all nutrients in the soil were within the optimum range, except K which was just below optimum. All micronutrients were adequate in both the mat and soil layers.

The experiment was arranged as a randomized complete block design with four replications. Seven soil reaction (limestone, sulfur) treatments and three checks (untreated and two calcium checks) were applied to 1.8 by 1.8 m plots to establish a broad range in soil pH and extractable Ca concentration. Five limestone ($CaCO_3$) treatments were applied on 12 Dec. 2011 (118, 569, 1184, 1739, and 2247 kg $CaCO_3$ ha^{-1}) and 1 Apr. 2014 (112, 889, 1631, 2148, and 2617 kg $CaCO_3$ ha^{-1}) based on target mat

pH levels of 5.8, 6.3, 6.8, 7.3, and 7.8, respectively. Lime requirements to achieve each target pH were determined using an Adam-Evans buffer solution (Adams and Evans, 1962) and calculated based on mat depth. Pre-treatment samples indicated a low buffering capacity (lime requirement index = 7.90) of the mat layer within the study area. Average lime requirement index values (range =7.84 to 7.97) for each treatment collected on September 2013 were used to calculate limestone rates applied on 1 Apr. 2014. A medium-fine (98, 55, and 30% passing through 20, 60, and 100 mesh sieve, respectively) calcitic limestone (EasySpread Lawn Lime, Southdown Inc., Sparta, NJ) was applied using a 0.9 m drop spreader (Gandy Company, Owatonna, MN). Two sulfur treatments were applied at 24 and 49 kg S ha^{-1} on 12 Dec. 2011 and 12 and 24 kg S ha^{-1} on 3 Apr. 2014. Sulfur rates were selected based on preliminary unpublished research conducted at the study site that indicated that these rates were safe to apply to ABG turf without causing significant burn (injury) or loss of turf. Elemental sulfur (micro fine wettable sulfur; Yellow Jacket Brand, Valdosta, GA) was applied as a suspension using a CO_2 backpack sprayer equipped with a single nozzle (Turbo Floodjet FT-7.5; TeeJet® Technologies, IL) wand at a water carrier volume of 0.41 L m^{-2} and a spray pressure of 0.21 MPa. Two gypsum ($CaSO_4*2H_2O$) treatments were included as Ca checks and were applied at 199 and 380 kg Ca ha^{-1} on 12 Dec. 2011 and at 356 and 653 kg Ca ha^{-1} on 3 Apr. 2014. Rates were selected to match the Ca applied in the 569 + 889 kg $CaCO_3$ ha^{-1} (a lower rate Ca) and 1184 + 1631 kg CaCO3 ha^{-1} (a higher rate Ca) treatments. A pelletized gypsum (Pro Pelleted gypsum; Oldcastle Lawn & Garden Inc., Atlanta, GA) was used as the gypsum source for the first application (12 Dec. 2011). A reagent grade

gypsum (calcium sulfate, 99%, pure, anhydrous; Themo Fisher Scientific, Waltham, MA) was used for the second application (3 Apr. 2014).

Field Maintenance

Turf was mowed 6-d wk^{-1} during the growing season using a triplex greens mower (Greensmaster® 3150; Toro Co.) bench set at 2.8 mm to represent typical golf green conditions in the Northeastern US. Moderate fertilization (N, P, and K) was applied throughout the study in an effort to prevent excessive growth from masking visual soil pH responses, as well as to encourage anthracnose disease. Nitrogen was applied at 4.9 kg ha-1 every 2-wk during May to November with slightly higher ($\leq$ 18.5 kg N ha-1) rates applied in fall and spring to promote recovery from disease. Total N applied during 2012, 2013, and 2014 was 139, 126, and 131 kg N ha^{-1} yr^{-1}, respectively. Likewise, low-rate soluble applications of P (0.5 to 4.0 kg ha^{-1}) and K (2.0 to 15.2 kg ha^{-1}) were also made throughout growing season, totaling 26, 37, and 30 kg P ha^{-1} yr^{-1} and 130, 119, and 41 kg K ha^{-1} yr^{-1} during 2012, 2013, and 2014, respectively. Sand topdressing was applied every 14-d from May through October each year at a rate of 0.15 L m^{-2}, and was incorporated into the turf canopy with a coco mat. Plant growth regulators trinexapac-ethyl [4-(cyclopropyl-α-hydroxy-methylene)-3,5-dioxocyclohexanecarboxylic acid ethylester] and ethephon [(2-chloroethyl) phosphonic acid] were applied as a tank mixture to suppress ABG seed head development at 0.05 and 3.76 kg a.i. ha^{-1}, respectively, on 15 Mar., 6 Apr. and 19 Apr. 2012, 15 Mar., 3 Apr. and 17 Apr. 2013, and 1 Apr., 21 Apr. and 6 May 2014. Trinexapac-ethyl was applied at 0.05 kg a.i. ha^{-1} every 7-d from 3 May through 1 Nov. 2012, 12 May through 20 Nov.

2013, and 1 May through 12 Nov. 2014. Fungicides that were ineffective at controlling anthracnose (Towers et al., 2003) were used to control other diseases including: dollar spot (*Sclerotinia homoeocarpa* F.T. Bennet), brown patch (*Rhizoctonia solani* Kühn), summer patch, and brown ring patch (*Waitea circinata* var. *circinata* Warcup & Talbot); as well as insect pest such as: annual bluegrass weevil (*Listronotus maculicollis* Kirby), sod webworm (*Parapediasia teterrella* Zincken), and black cutworm (*Agrotis ipsilon* Hufnagel).

Data Collection

Four soil samples were collected from each plot with a 1.9 cm diameter soil probe to a depth of 17 cm on 3 May, 13 July and 31 Aug. 2012, on 10 May, 9 July, and 10 Sept. 2013, and on 14 May, 10 July, and 6 Sept. 2014. Cores from each plot were divided at the interface of the mat layer (organic layer intermixed with sand topdressing) and soil. Soil samples were stratified into the two layers (mat and soil) because the layers have distinctly different chemical properties (Table 1). Moreover, the majority (if not all) of ABG roots are found in the mat layer during the growing season. Each layer of all four cores was thoroughly mixed to form two composite samples (mat and soil) for each plot. Samples were allowed to air dry and were then frozen with liquid N (LN_2) and ground using a mortar and pestle to ensure that soil and surface organic matter passed through a #10 mesh sieve (2 mm). A subsample from each plot was analyzed for pH using the 1:1 soil to water ratio (by volume) procedure described by Thomas (1996), and nutrient availability (P, K, Ca, and Mg) was determined

using the Mehlich 3 extraction method (Mehlich 1984) and analyzed by inductively coupled plasma spectroscopy (iCAP 6000, Themo Scientific).

Anthracnose severity (turf area infested) was assessed every 7- to 14-d from June through August each year, using a line intercept-grid count method (Inguagiato et al., 2008) producing 273 observations over a 1.4 m^2 $plot^{-1}$. Area under disease progress curve (AUDPC), which is a quantitative assessment of disease severity over time, was calculated using sequential disease data (within each year) according to the equation:

$$\mathrm{AUDPC} = \sum_{i=1}^{n} [\frac{(X_i + X_{i+1})}{2}(t_i + t_{i+1})]$$

in which X_i is the anthracnose disease severity at the ith observation, t is the time (days) at the ith observation, and n is the total number of observations (Madden et al., 2007). Turfgrass quality was rated visually every 2-wk using a 1 to 9 scale (9 = best quality, 5 = minimum acceptable quality, 1= dormant or dead turf), from May to August 2012, from April to September 2013, and from April to October 2014. Turf quality was rated in accordance with methods described by Skogley and Sawyer (1992) and took into account turf density, uniformity, disease severity, playability, and overall appeal. Turfgrass color was also rated visually every 2-wk using a 1 to 9 scale (9 = optimal dark green turf, 5 = minimum acceptable green-yellow color, 4 to 2 = increasing unacceptable color [chlorosis], 1= completely necrotic and/or chlorotic). Turf color was rated on the same date as turf quality throughout the entire study.

In addition to visual ratings, turfgrass performance was measured every 2-wk from May through September each year using a CM1000 chlorophyll meter (Spectrum

Technologies, Plainfield, IL) and a TCM 500 turf color meter (Spectrum Technologies, Plainfield, IL). The CM1000 chlorophyll meter measures reflectance (700 and 840 nm wavelength) of the turf canopy and has been correlated to chlorophyll concentrations present in turfgrass (Magniafico and Guillard, 2005). From this point forward this measurement will be referred to as "chlorophyll index". Four reflectance measurements were collected per plot and averaged. Measurements were taken by holding the meter approximately 1 m above the turf surface, yielding a 62 cm^2 circular area of evaluation for each measurement. Normalized difference vegetative index (NDVI) was collected with the TCM 500 turf color meter (Spectrum Technologies, Plainfield, IL), which measures two reflectance readings from light in the red (660 nm) and near red (850 nm) spectral bands to calculate NDVI. Four measurements were taken from the center of each plot and the average was recorded.

Data Analysis

Anthracnose data (turf area infested) and mat and soil chemical properties were subjected to analysis of variance to identify significant treatment effects using the generalized linear model (GLM) procedure in the Statistical Analysis Software (SAS) package (v. 9.4; SAS institute, Cary, NC). Treatment means were separated using Fisher's protected least significant difference (LSD) test at $p< 0.05$ (Dowdy et al., 2004). The regression (REG) procedure in SAS was used to determine the rate response of sulfur treatments, limestone treatments, and gypsum treatments. Orthogonal contrasts were used to make comparisons between limestone and gypsum (Ca check) treatments that were applied at the same rate of Ca, to distinguish between a Ca response and a

soil pH response. Turf quality, turf color, chlorophyll index, NDVI, and AUDPC responses were subjected to linear plateau and quadratic plateau regression as a function of mat pH and extractable mat Ca concentration using the nonlinear regression (NLIN) procedure in SAS. In cases where a significant ($\alpha = 0.05$) nonlinear regression model could not be found, or models predicted a critical mat pH outside of the data range, a linear and/or quadratic regression models were applied to the data set.

RESULTS AND DISCUSSION

Mat and Soil Chemical Properties Response to Soil Reaction Treatments

Soil reaction treatments (sulfur and/or limestone) had a significant effect on mat pH on all sampling dates throughout the study (Table 2). A significant ($p < 0.0001$) positive cubic response was observed between limestone rate and mat pH on all sampling dates; however, the anticipated target pH for each limestone treatment rate was not attained (Table 2). The maximum soil pH (pH = 6.5) was observed at the end of 2014 (September) for turf treated with limestone at 2247 + 2617 kg $CaCO_3$ ha^{-1} (on 12 Dec 11 and 1 Apr 14, respectively). Mat pH response to sulfur was more subtle exhibiting a quadratic response to sulfur rate in September of each year, as well as May 2014 and a linear response July 2012; on all other sampling dates, mat pH was not responsive to sulfur rates (Table 2). Not surprisingly, limestone treatments reacted very slowly over the first two years of the study (prior to the second application), gradually increasing mat pH until September 2013 when a subtle decrease was observed indicating that the limestone reaction was essentially complete. Likewise, limestone treatments applied on 1 April 2014 gradually increased mat pH throughout 2014. Particle size of the liming material can influence the rate of reaction in soils since the rate of neutralization is dependent on dissolution and hydrolysis rate of $CaCO_3$ (Thomas and Hargrove, 1984). Previous research has shown that medium sized limestone particles (20 – 60 mesh sieve; 0.85 to 0.25 mm) can take up to 18 months to fully react in the soil (Meyer and Volk, 1952). In the current study, 45% of the limestone particles were within the medium particle size range. In addition, limestone treatments were not

incorporated/mixed with the soil in the current study, which could also have decreased the rate of neutralization (Thomas and Hargrove, 1984). Compared to limestone treatments, sulfur treatments react much quicker, but their effects on mat pH also diminished more rapidly (Table 2). This was illustrated by a rapid decrease in mat pH on sampling dates after sulfur treatments were applied (14 Dec. 2011 and 1 Apr. 2014), then a gradual rise in mat pH on the subsequent sampling dates. Unlike limestone, sulfur is insoluble in water and requires microbial conversion of sulfur to sulfuric acid to acidify the soil (Carrow et al., 2001). Rapid sulfur reaction in the mat layer was likely due to size of the particle (micro fine), which provided faster chemical reactions than coarser particles. It is unclear what caused the gradual rise in mat pH of the sulfur treated plots. Analysis of irrigation water and topdressing sand indicated that both had neutral pHs (pH 7.09 and 7.01, respectively). It is possible that repeated applications of both irrigation water and topdressing sand may have increased mat pH.

The finding that lime requirements estimated by the Adam-Evans buffer method were unable to increase mat pH to target levels was unanticipated. However, several possible acidifying processes many have offset the liming effect, including fertilization with an acidifying N source (i.e. urea) and natural acidification processes such as acid rain or organic matter decomposition. Fox (1980) found that the Adams-Evans buffer method was well correlated ($r = 0.919$) with incubation lime requirements for a pH of 6.5, but tended to underestimate for high lime requirement soils. Warman et al. (2000) found that the Adams-Evans buffer method underestimated the lime requirements of a Pugwash sandy loam. The Adams-Evans buffer method is based on an assumption that

there is a constant relationship between soil pH and base unsaturation for a particular soil, but not for all soils. It is possible that the relationship between soil pH and base unsaturation in the current study was different from those described by Adams and Evans (1962), and thus the lime requirement recommendations were not accurate. Additional, the majority of previous studies that have evaluated the effectiveness of the Adams-Evans methods have used a target pH of 6.5 (Adams and Evans, 1962; Fox, 1980; Tran and van Lierop, 1981; Warman et al., 1996; Warman et al., 2000). It is possible that the Adams-Evans buffer solution is not a reliable method for estimating lime requirements for target pH values > 6.5.

Surprisingly, gypsum treatments increased mat pH to the extent that no differences in mat pH were observed between limestone and gypsum treatments applied at the same rate of Ca (both high and low rates) in 2012 and 2013 (Table 2). This suggested that the gypsum material applied on 14 Dec. 2011 had a significant neutralizing ability. Gypsum is generally considered to have no effect on soil pH; however, several field and laboratory studies have shown that gypsum applications can slightly increase soil pH (Farina and Channon, 1988; Hue et al., 1985; Richey et al., 1980; Shainberg et al., 1989). However, increases in mat pH as a result of gypsum applications in the current study were much greater than those observed in previous studies, suggesting that the gypsum was contaminated with a carbonate source. Chemical analysis of the gypsum source indicated a $CaCO_3$ equivalent (CCE) of 57.1% which was nearly as much as the limestone source (CCE = 63%). After the second gypsum application (using reagent grade gypsum) on 1 April 2014 both gypsum rate treatments

had lower mat pH than the Ca-equivalent limestone rates on all subsequent sampling dates (Table 2). Mat pH was not responsive to gypsum rate on the May and July 2014 sampling dates, but did exhibited a positive quadratic response to gypsum rate on the last sampling date of 2014 (September; Table 2).

Soil pH at the 5.5 to 17-cm depth zone was not influenced by limestone treatments until September 2013, but then had a significant effect on soil pH throughout the remainder of the study (Table 3). A significant ($p < 0.05$) positive cubic relationship was observed between limestone rate and soil pH on the September 2013 and July and September 2014 sampling dates (Table 3). Soil pH exhibited a quadratic and linear response to sulfur rate on July 2012 and May 2013 sampling dates, respectively (Table 3). These results are consistent with those observed in the mat layer, with limestone treatments taking much longer to react (raise pH) and leach through the mat layer into the underlying soil compared to sulfur treatments. Brown et al. (1956) reported that surface applications of limestone to a fine sandy loam at 2242 kg $CaCO_3$ ha^{-1} only affected the pH in the upper 2.5 cm 2-yr after application. Gypsum treatments had little effect on soil pH throughout the study; however, soil pH did exhibit a small, negative quadratic relationship with gypsum rate on two sampling dates (July 2012 and July 2014; Table 3). Few differences in soil pH were observed between limestone and gypsum treatments during 2013 and 2014, only resulting in a different soil pH on one sampling date (July 2012; Table 3). However, during 2014, limestone treatments had a greater soil pH than equivalent gypsum treatments on all sampling dates.

Soil reaction treatments influenced Mehlich 3 extractable mat K, Ca, and Mg during 2013 and 2014 but had no effect on exchangeable P, except for lime in 2013 (quadratic effect) (Table 4). Limestone rate had the greatest influence on extractable Ca concentration ($p < 0.001$), exhibiting a positive cubic relationship to Ca concentrations. A positive cubic relationship was also observed between extractable mat Mg and limestone rate, whereas extractable K exhibited a negative cubic response to limestone rate. Extractable mat Ca in 2013 and 2014 and extractable K in 2014 decreased quadratically with increasing sulfur rate decreased, but sulfur had no influence on extractable mat P or Mg. Both extractable Ca and Mg increased quadratically (or linearly) with increasing gypsum rate in 2013 and 2014 (Table 4). No difference in extractable mat Ca was observed between limestone and gypsum treatments at either rate (low or high) in 2013. After the second application of treatments in 2014, both rates of gypsum had lower extractable Ca compared to the equivalent rates of limestone. The decreased Ca concentration compared to limestone treatments was likely due to the greater leaching of Ca through the mat layer due to the greater water solubility and very fine particle size of reagent grade gypsum compared to limestone. By September 2014, gypsum treatment had a greater extractable soil (5.5 to 17 cm depth) Ca concentration than equivalent limestone treatments (Table 5), indicating that Ca from gypsum treatments were leaching through the mat layer (0 to 5.5 cm depth) more quickly than limestone treatments. It was not surprising that both mat Ca and Mg concentration increased as a result of limestone treatments since both elements are present in limestone (Lathwell and Reid, 1984). It was, however, somewhat unexpected

that extractable mat K concentrations were decreased by limestone treatments. Several studies have noted an interaction between base cations (K, Ca, and Mg) in soils and plant tissue (Cripps et al., 1989; Miller, 1999; Sartain, 1993; Waddington et al., 1972). Waddington et al. (1972) observed a decrease in extractable soil Ca as a result of KCl applications. Sartain (1993) also noted a decrease in extractable soil Ca from applications of K and Mg. Analysis of extractable soil K concentrations indicates that K was not leached from the mat layer (0 to 5.5 cm depth) into the soil (5.5 to 17 cm depth) (Table 5). It is, however, possible that the improvement of turfgrass performance (i.e. growth) as a result of limestone treatments could have resulted in an increase in plant uptake of K. Further analysis of leaf K concentrations are need to confirm this hypothesis.

Anthracnose Severity Response to Soil Reaction Treatments

Soil reaction treatments influenced the severity of anthracnose on ABG putting green turf on all dates in 2012, 2013, and 2014 (Tables 6, 7, and 8). Anthracnose severity decreased cubically with increasing limestone rate on most dates (15 out of 18 observations; Tables 6, 7, and 8). The increase in anthracnose severity under acidic soil conditions is likely due to nutrients deficiencies. Acidic soils tend to be deficient in N, P, K, and Mg, which may increase the susceptibility of ABG turf to anthracnose disease. Limestone had a greater impact on disease severity during the second and third years of the study. This was likely due to the relatively low solubility of limestone and its slow chemical reaction rate in soils. Sulfur rate influenced anthracnose severity on 9 of 18

observation dates, with disease severity increasing quadratically with increasing sulfur rate (Tables 6, 7, and 8).

Anthracnose severity occasionally (4 out of 12 dates) exhibited a negative quadratic response to gypsum rate during 2012 and 2013 (Tables 6 and 7). However, during 2014, disease severity decreased quadratically with increasing gypsum rate on the majority of observations (5 out of 6; Table 8). Few difference in disease severity was observed between limestone and gypsum treatments (at the equivalent rate of Ca) during 2012 and 2013 (Tables 6 and 7). This comparison of Ca source was confounded by the substantial and unanticipated increase in mat pH caused by the gypsum treatments applied on 14 Dec. 2011. Because the original gypsum source was contaminated with a carbonate source (CCE = 57%) and gypsum treatments significantly increased mat pH during 2012 and 2013, no difference in pH was observed between equivalent (Ca) gypsum and limestone treatments. Thus, it is not possible to distinguish between a pH response or a Ca nutrition response to anthracnose severity during these years. However, for the May and July 2014 sampling dates, mat pH of gypsum treatments were not different from the untreated check, but gypsum treatments still caused a decrease in anthracnose severity compared to the untreated check, suggesting Ca nutrition may play a role in anthracnose suppression. Calcium deficiencies in turf are rare, but have been associated with acidic (pH < 5.5) pH on low cation exchange capacity soils (Carrow et al., 2010), similar to the soils found in the current study (untreated check and sulfur treatments). Additionally, low levels (deficiency) of Ca in turf had been reported to favor red leaf spot (*Drechslera erythrospila* [Dreschsler] Shoemaker),

Fusarium blight (*Fusarium* spp.), Pythium blight (*Pythium* spp.), and red thread (*Laetisaria fuciformis* [McAlpine] Burdsall) (Carrow et al., 2001; Couch, 1995; Turner and Hummel, 1992); however, there are no reports of association between Ca nutrition and anthracnose severity in turfgrasses. A previous study investigating the response of anthracnose severity to N source noted that basic N sources (potassium nitrate and calcium nitrate) increased soil pH and reduced the severity of anthracnose, but it was unclear whether this response was due to an increase in soil pH or addition of a secondary nutrient (K and/or Ca) (Schmid et al., 2012). In the current study, the cause (pH or Ca nutrition) of the anthracnose suppression could not be definitively determined, thus, further research is need to better understand the complex relationship between soil pH and Ca nutrition and their effect on this disease severity.

Area Under Disease Progress Curve Response to Mat pH and Extractable Mat Ca

Significant linear plateau and quadratic plateau models were identified when comparing mean mat pH to AUDPC in 2012 and 2014 (Figure 1). Critical mat pH ranged from 5.2 to 5.7 and 5.7 to 6.0 using the linear plateau and quadratic plateau models, respectively. During 2013, both nonlinear regression models were significant but predicted critical mat pH outside of the data range, therefore, linear and quadratic response models were used to describe the response for 2013. These models indicate that disease severity decreased with increasing mat pH and that maximum disease suppression was not observed at the highest pH present in 2013 (pH = 6.5; Figure 1). Collectively, these results suggest that ABG turf should be maintained between pH 5.7 and 6.5 to reduce the susceptibility to anthracnose disease. This range falls within the

range recommended by Spurway (1941) (pH = 6.0 to 7.0) and within the upper end of the range (pH = 5.5 to 6.5) recommended by Beard (1973) for ABG turf. This range of 5.7 to 6.5 is also consistent with previous soil pH recommendations (pH = 6.0 to 6.5) for the control of summer patch (Hill et al., 2001; Thompson et al., 1993).

Significant linear plateau and quadratic plateau models were also found when comparing mat Ca concentration to AUDPC during 2013 and 2014 (Figure 2). Critical mat Ca concentration from the linear plateau model ranged from 499 to 530 mg kg^{-1}, whereas, the quadratic plateau model predicted higher critical mat Ca concentrations of 653 and 685 mg kg^{-1} (Figure 2). These critical values are much greater than the critical Mehlich 3 extractable Ca concentration (375 mg Ca kg^{-1}) recommended by Carrow et al. (2001) for turfgrass. Increased severity of several diseases, including red leaf spot, Fusarium blight, Pythium blight, and red thread, has been reported when deficiencies in Ca are present (Carrow et al., 2001; Couch, 1995; Turner and Hummel, 1992); however, no previous study has attempted to determine a critical soil Ca concentration in relation to disease severity data.

Turf Quality and Color Response to Mat pH and Extractable Mat Ca

Significant linear plateau and quadratic plateau models were found relating mean turf quality and mean turf color to mean mat pH during all three years (Figures 3 and 4). The critical mat pH for turf quality and turf color ratings ranged from pH 5.5 to 5.9 for the linear plateau model. The quadratic plateau model predicted a greater critical mat pH that ranged from 5.7 to 6.4 for turf quality and turf color ratings. The response of turf quality and turf color to mat pH was similar to the response of AUDPC

to mat pH, and provided comparable critical mat pH values. Several studies have investigated the influence of soil pH on ABG growth, but the objectives of these studies were to reduce (inhibit) ABG growth/encroachment (Ferguson, 1936; Goss, 1974; Kato et al., 2000). Thus the current data represents the first attempt to determine a critical mat pH value for optimizing performance (turf quality and turf color) of ABG putting green turf.

Significant linear plateau and quadratic plateau models were observed relating extractable mat Ca concentrations to mean turf quality and mean turf color during 2013 and 2014 (Figures 5 and 6). Linear plateau models indicated critical mat Ca concentrations of 445 and 421 mg Ca kg^{-1} for turf quality and 403 and 593 mg Ca kg^{-1} for turf color in 2013 and 2014, respectively. As expected, quadratic plateau models predicted higher critical mat Ca concentration of 587 and 764 mg Ca kg^{-1} for turf quality and 556 and 825 mg Ca kg^{-1} for turf color in 2013 and 2014, respectively. Few studies have demonstrated a turf response to applications of Ca, and those that have, likely observed a turf response to soil pH modification (Turner and Hummer, 1992). Jiang and Huang (2001) did report that Ca applications subtly improved the turf quality of tall fescue and Kentucky bluegrass exposed to drought stress. However, previous studies have not reported an improvement in ABG quality or color as a result of Ca applications.

Chlorophyll index and NDVI Response to Mat pH and Extractable Mat Ca

Significant linear plateau and quadratic plateau models were identified relating mean mat pH to mean chlorophyll index (measured with CM 1000 meter) and mean NDVI (measured with TCM 500 meter) measurements in most years of the study

(Figures 7 and 8). On several occasions in 2012 and 2013, linear plateau and/or quadratic plateau models indicated that a critical mat pH was not observed within the data, so linear or quadratic responses are presented (Figures 7 and 8). When linear plateau models were used to determine a critical mat pH, the values ranged from pH 5.3 to 6.2 across CM 1000 index and NDVI measurements, whereas, quadratic plateau models predicted critical mat pH that ranged from 6.0 to 6.4. For chlorophyll index and NDVI measurements, critical soil pH values were comparable to those determined for disease severity (AUDPC) and visual (turf quality and color). To date, previous studies have not attempted to determine a critical soil pH value using these instruments.

Significant linear plateau and quadratic plateau models were found relating extractable mat Ca concentrations to mean chlorophyll index and mean NDVI measurements to during 2013 and 2014 (Figures 9 and 10). Critical mat Ca concentrations based on linear plateau models were 458 and 664 mg Ca kg^{-1} for chlorophyll index and 554 and 392 mg Ca kg^{-1} NVDI measurements in 2013 and 2014, respectively. Once again, quadratic plateau models provided higher critical mat Ca concentrations compared to linear plateau models, with critical Ca values of 623 and 763 mg Ca kg^{-1} being obtained for chlorophyll index and 695 and 823 mg Ca kg^{-1} for NDVI measurements in 2013 and 2014, respectively. A similar chlorophyll response was observed by Jiang and Huang (2001), who observed that Ca treated tall fescue and Kentucky bluegrass plants maintained higher chlorophyll content than untreated plants under drought stress conditions. However, they did not report soil or tissue Ca concentrations, so comparisons of critical Ca concentrations cannot be made. In

general, NDVI measurements were not as effective at predicting critical mat Ca concentrations (pseudo R^2 = 0.536 to 0.575) compared to chlorophyll index measurements (pseudo R^2 = 0.710 to 0.706) and visual ratings (turf quality and turf color; pseudo R^2 = 0.774 to 0.814). Numerous studies have shown a strong correlation between measurements of NDVI and N fertilization (Flowers et al., 2010; Geng et al., 2015; Guillard et al., 2016; Kruse et al., 2006; Xiong et al., 2007; Zhu et al., 2012); however, NDVI measurements may not be sensitive to plant responses to Ca fertilization. Kruse et al. (2005) found few correlations between NDVI measurements and P fertilization rate. To date, previous studies have not attempted to quantify a Ca response using NDVI measurements.

CONCLUSIONS

The purpose of this study was to determine the response of ABG putting green turf to a broad range of mat pH values, as well as, to determine whether the observed responses were due to pH modification or Ca nutrition. This study has shown that under moderately acidic (pH < 5.5) conditions anthracnose severity increased, and turf quality, turf color, chlorophyll index and NDVI measurements decreased. Nonlinear regression models indicated an optimum mat pH range between pH 6.0 and 6.5. Mat pH below this range can result in increased disease severity; however, it is unclear from the current research whether the soil pH can become too basic and inhibit growth of ABG. Models relating the same turf performance parameters to extractable mat Ca indicate critical Ca concentration is between 392 and 825 mg kg^{-1}. This range of critical soil Ca concentration is greater than the sufficiency range for turfgrass reported by Carrow et al. (2001). The current study, however, was limited by the fact that the original gypsum source was contaminated. As a result, we were unable to definitively (only one year of data) determine whether the observed disease and performance responses were due to modifications to mat pH, calcium nutrition, or both. Moreover, the upper target pH values (6.8, 7.3, and 7.8) in the current study were not attained. Therefore, further research is needed to determine whether soil pH or Ca nutrition is primarily responsible for disease suppression and improvement in ABG performance, as well as the response of ABG turf under more basic soil pH (pH > 7.0) conditions.

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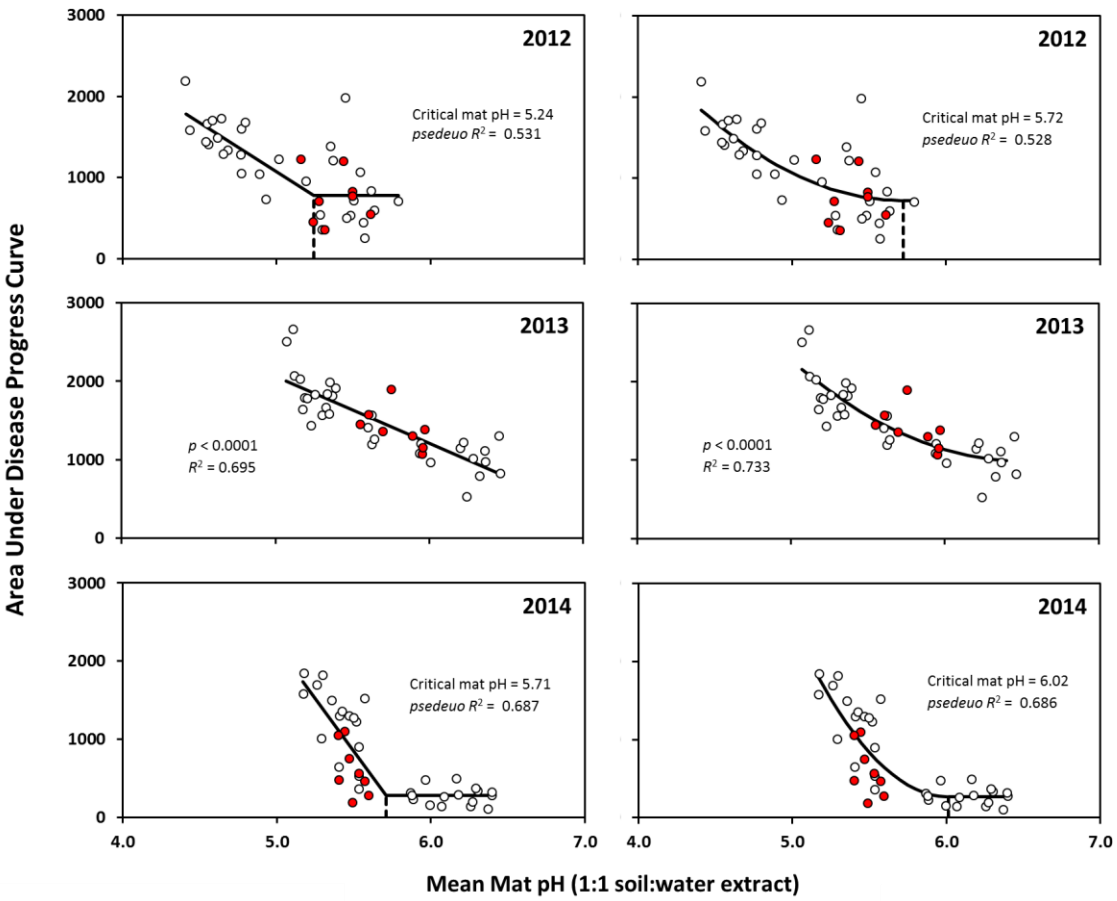

Figure 1. Mean mat (0 to 5.5 cm depth) pH in relation to AUDPC (anthracnose severity) of annual bluegrass putting green turf in North Brunswick, NJ. Linear plateau (left) and quadratic plateau (right) models are shown for all years (2012, 2013, and 2014). Line vertical to the *x* axis indicates critical level for both models. Filled in circles indicate gypsum treatments. Linear and/or quadratic models are shown on dates where linear plateau and/or quadratic plateau models were not significant or predicted critical values were outside of data range.

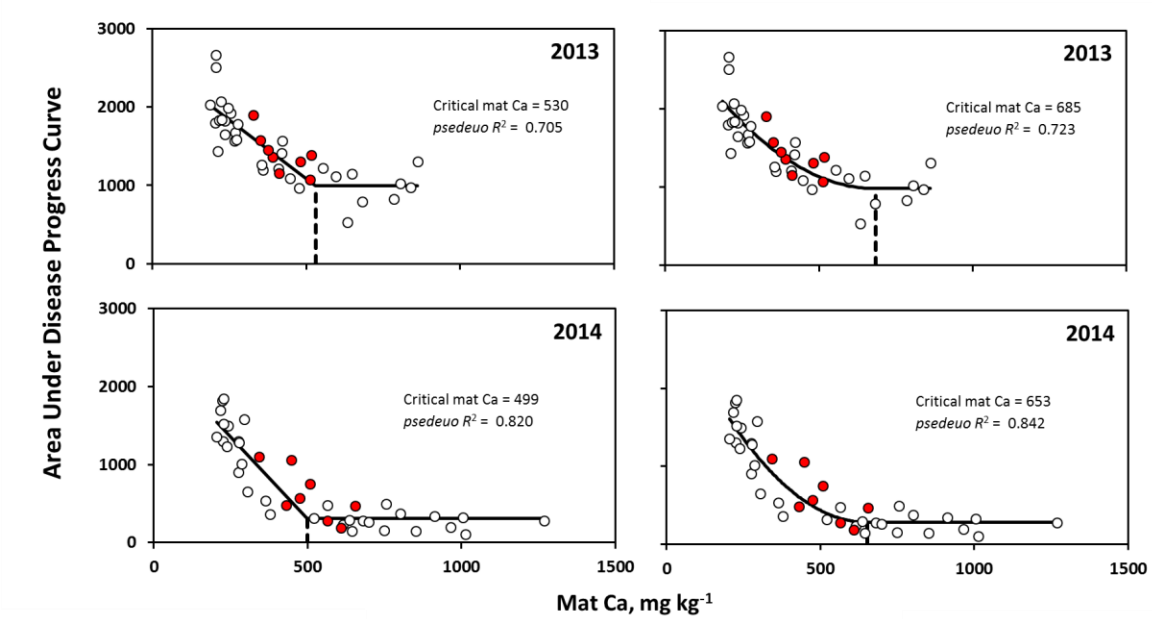

Figure 2. Extractable mat (0 to 5.5 cm depth) Ca concentration in relation to AUDPC (anthracnose severity) of annual bluegrass putting green turf in North Brunswick, NJ. Linear plateau (left) and quadratic plateau (right) models are shown for 2013, and 2014. Line vertical to the *x* axis indicates critical level for both models. Filled in circles indicate gypsum treatments.

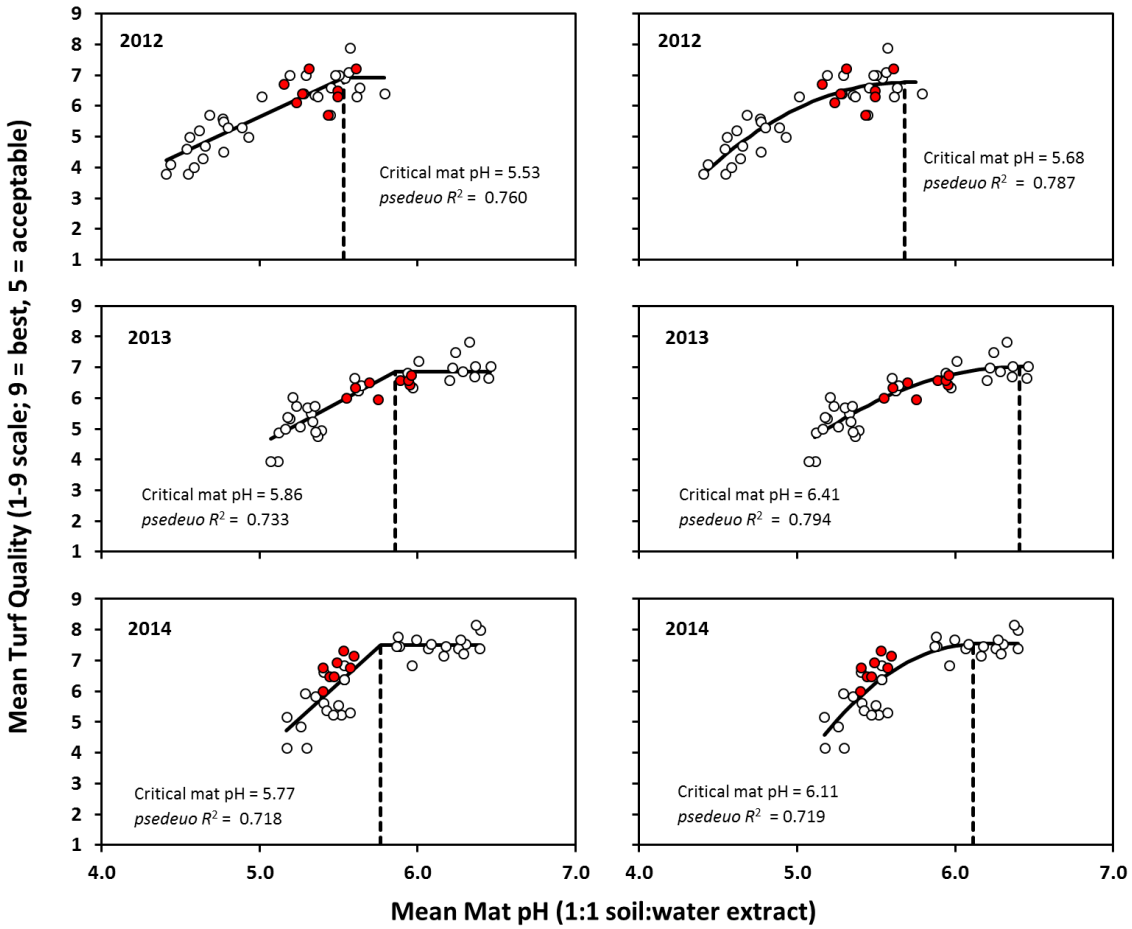

Figure 3. Mean mat (0 to 5.5 cm depth) pH in relation to mean turf quality of annual bluegrass putting green turf in North Brunswick, NJ. Linear plateau (left) and quadratic plateau (right) models are shown for all years (2012, 2013, and 2014). Line vertical to the *x* axis indicates critical level for both models. Filled in circles indicate gypsum treatments.

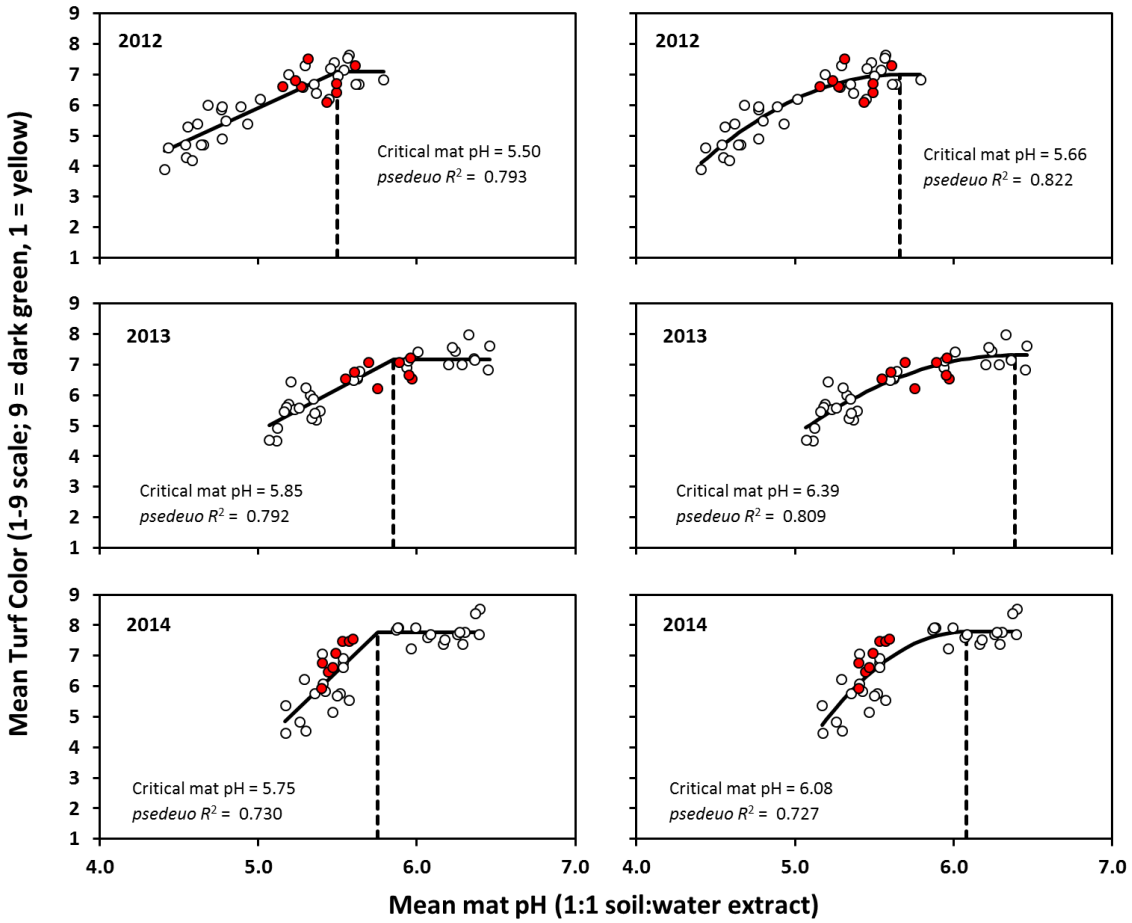

Figure 4. Mean mat pH (0 to 5.5 cm depth) in relation to mean turf color of annual bluegrass putting green turf in North Brunswick, NJ. Linear plateau (left) and quadratic plateau (right) models are shown for all years (2012, 2013, and 2014). Line vertical to the *x* axis indicates critical level for both models. Filled in circles indicate gypsum treatments.

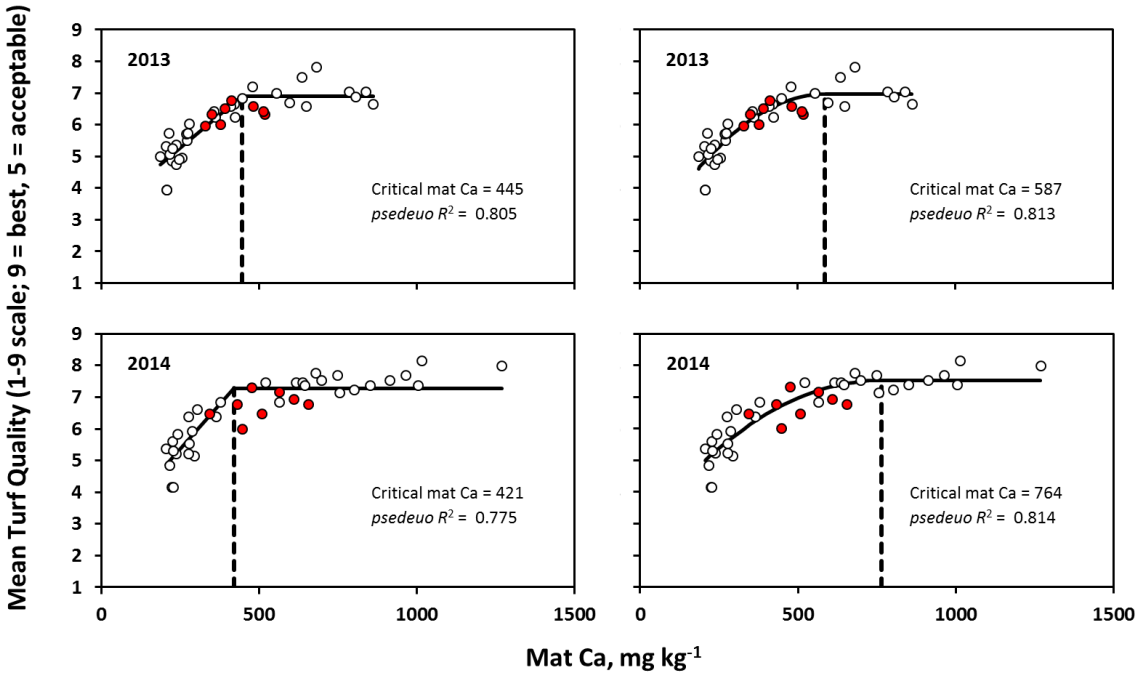

Figure 5. Extractable mat (0 to 5.5 cm depth) Ca concentration in relation to mean turf quality of annual bluegrass putting green turf in North Brunswick, NJ. Linear plateau (left) and quadratic plateau (right) models are shown for 2013 and 2014. Line vertical to the *x* axis indicates critical level for both models. Filled in circles indicate gypsum treatments.

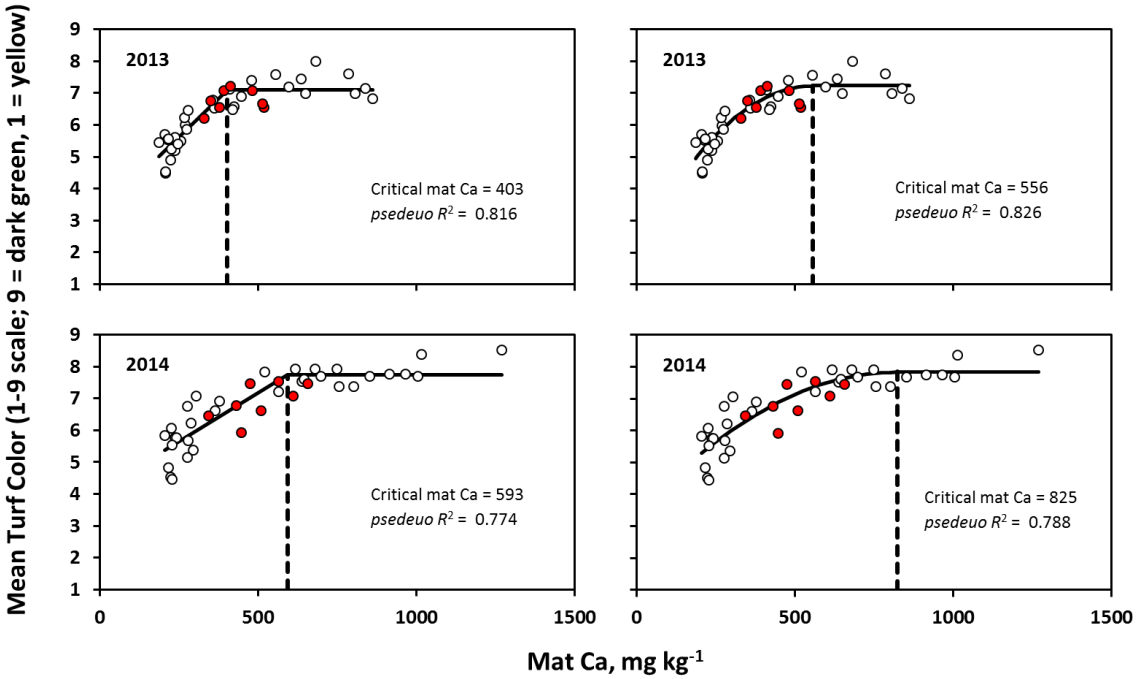

Figure 6. Extractable mat (0 to 5.5 cm depth) Ca concentration in relation to mean turf color of annual bluegrass putting green turf in North Brunswick, NJ. Linear plateau (left) and quadratic plateau (right) models are shown for 2013 and 2014. Line vertical to the *x* axis indicates critical level for both models. Filled in circles indicate gypsum treatments.

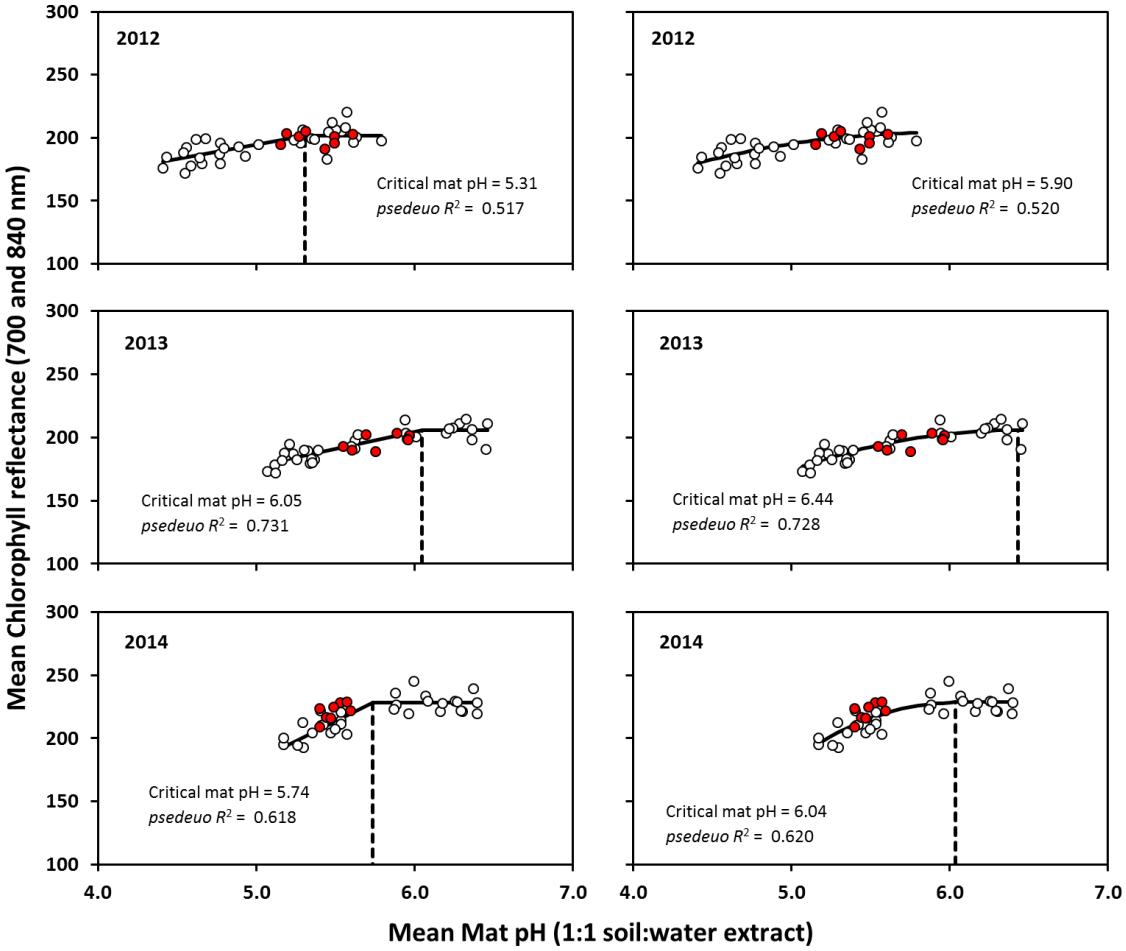

Figure 7. Mean mat (0 to 5.5 cm depth) pH in relation to mean chlorophyll reflectance (700 and 840 nm) of annual bluegrass putting green turf in North Brunswick, NJ. Linear plateau (left) and quadratic plateau (right) models are shown for all years (2012, 2013, and 2014). Line vertical to the *x* axis indicates critical level for both models. Filled in circles indicate gypsum treatments.

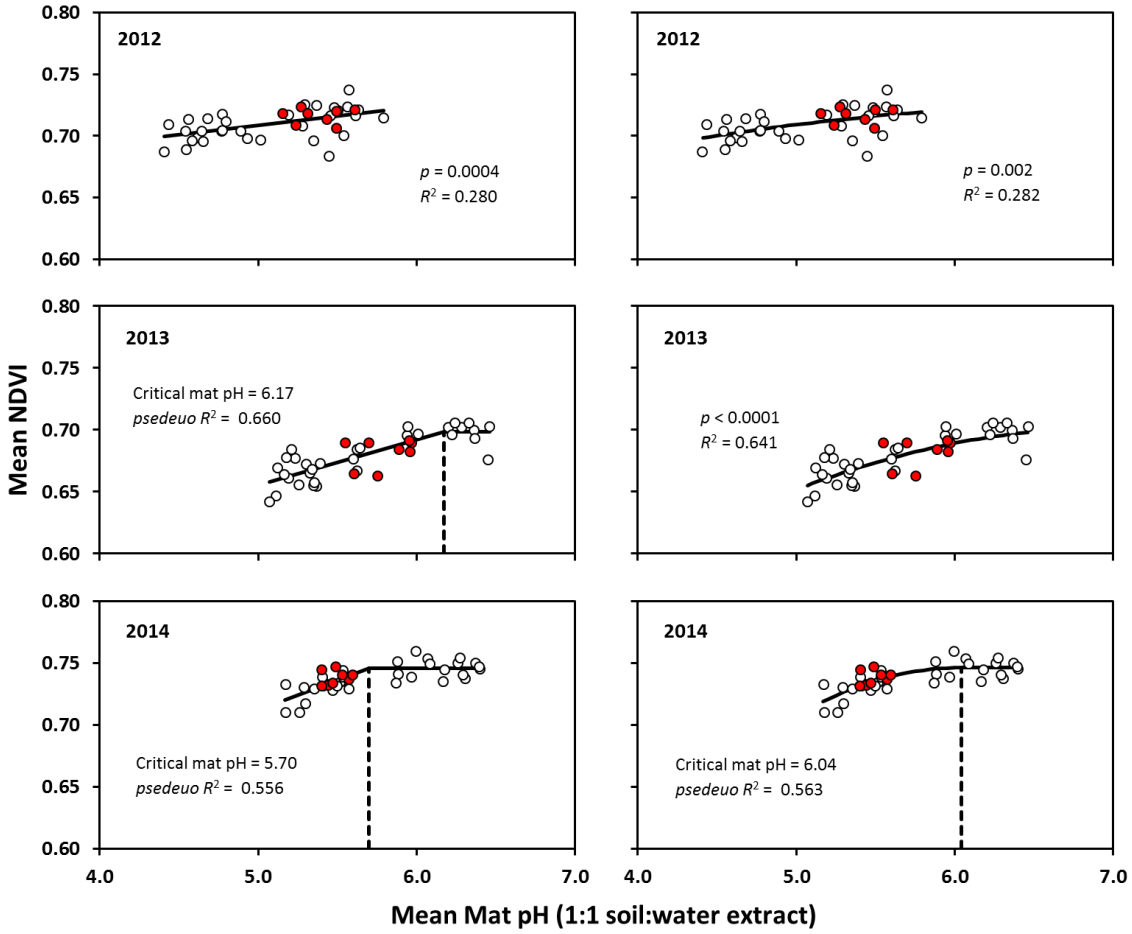

Figure 8. Mean mat (0 to 5.5 cm depth) pH in relation to mean normalized difference vegetative index (NDVI) of annual bluegrass putting green turf in North Brunswick, NJ. Linear plateau (left) and quadratic plateau (right) models are shown for all years (2012, 2013, and 2014). Line vertical to the *x* axis indicates critical level for both models. Filled in circles indicate gypsum treatments. Linear and/or quadratic models are shown on dates where linear plateau and/or quadratic plateau models were not significant or predicted critical values were outside of data range.

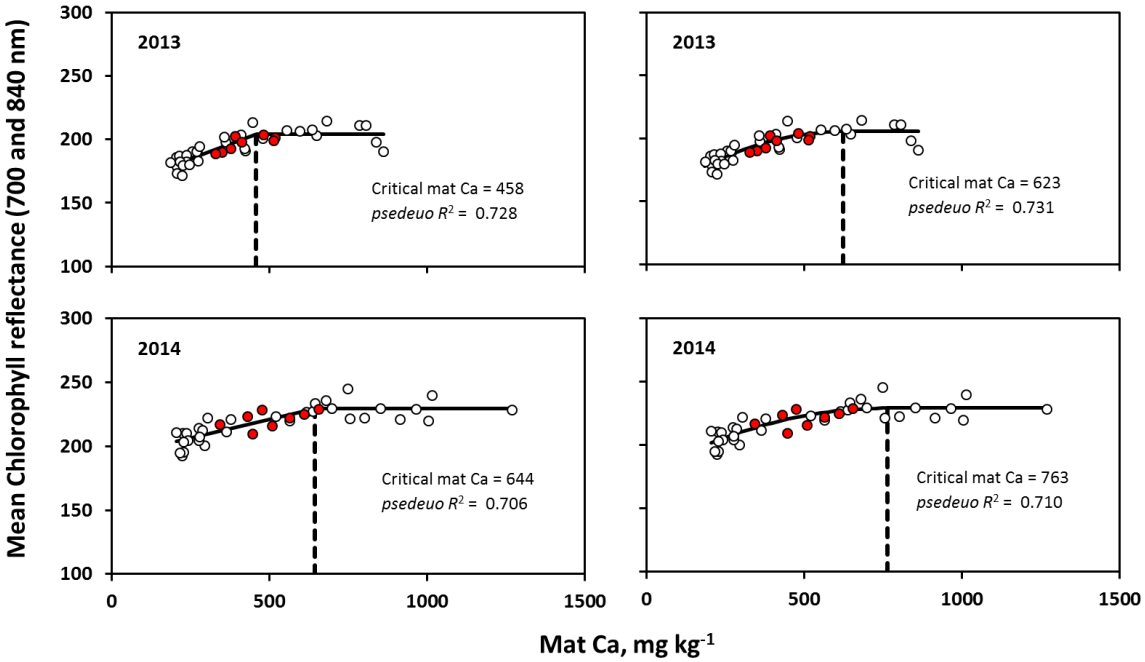

Figure 9. Extractable mat (0 to 5.5 cm depth) Ca concentration in relation to chlorophyll reflectance measurements (700 and 840 nm) of annual bluegrass putting green turf in North Brunswick, NJ. Linear plateau (left) and quadratic plateau (right) models are shown for 2013 and 2014. Line vertical to the *x* axis indicates critical level for both models. Filled in circles indicate gypsum treatments.

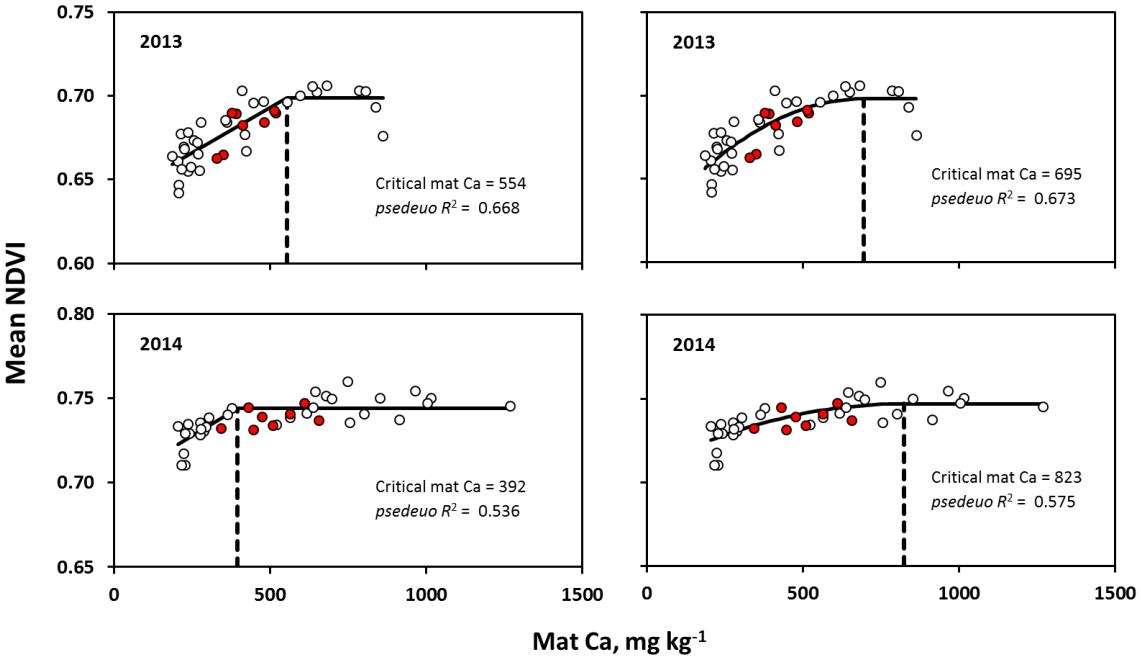

Figure 10. Extractable mat (0 to 5.5 cm depth) Ca concentration in relation to mean normalized difference vegetative index (NDVI) of annual bluegrass putting green turf in North Brunswick, NJ. Linear plateau (left) and quadratic plateau (right) models are shown for 2013 and 2014. Line vertical to the *x* axis indicates critical level for both models. Filled in circles indicate gypsum treatments.

Table 1. Chemical properties of mat (0 to 5.5 cm depth) and soil (5.5 to 17 cm depth) layers under an annual bluegrass turf prior to initiation of soil reaction treatments in fall of 2011.

Soil layer	pH[†]	LRI[‡]	P[§]	K	Ca	Mg
			---------- mg kg^{-1} ----------			
Mat	5.3	7.9	14	28	215	41
Soil	6.0	7.8	85	70	710	91

[†] pH determined using 1:1 soil:water extraction.

[‡] LRI, lime requirement index determined using the Adams Evans buffer solution (Adams and Evans, 1962).

[§] Mehlich 3 extractable P, K, Ca, and Mg.

Table 2. Mat pH response at the 0 to 5.5 cm depth to soil reaction treatments on annual bluegrass turf in North Brunswick, NJ, during 2012, 2013, and 2014.

Treatments[†]	Mat pH (1:1 soil:water extract)								
	2012			2013			2014		
	May	Jul	Sept	May	Jul	Sept	May	Jul	Sept
Untreated Check	4.6	4.9	4.6	5.0	5.4	5.4	5.3	5.5	5.4
Sulfur									
24 + 12 kg S ha^{-1}	4.5	4.8	4.6	5.1	5.4	5.4	5.2	5.6	5.7
49 + 24 kg S ha^{-1}	4.5	4.7	4.3	4.9	5.2	5.2	5.0	5.3	5.4
Limestone									
118 + 112 kg $CaCO_3$ ha^{-1}	4.7	5.1	4.7	5.2	5.4	5.3	5.3	5.6	5.6
569 + 889 kg $CaCO_3$ ha^{-1}	4.9	5.5	5.2	5.6	5.7	5.6	5.6	6.0	6.1
1184 + 1631 kg $CaCO_3$ ha^{-1}	5.1	5.8	5.5	6.1	6.1	5.9	5.9	6.1	6.3
1739 + 2148 kg $CaCO_3$ ha^{-1}	5.1	5.8	5.6	6.3	6.3	6.2	6.1	6.3	6.4
2247 + 2617 kg $CaCO_3$ ha^{-1}	5.2	5.9	5.8	6.4	6.4	6.4	6.3	6.3	6.5
Gypsum									
199 + 356 kg Ca ha^{-1}	5.0	5.5	5.2	5.6	5.7	5.6	5.1	5.5	5.8
380 + 889 kg Ca ha^{-1}	5.2	5.8	5.5	5.9	5.9	6.0	5.3	5.5	5.8
$LSD_{(0.05)}$[‡]	0.2	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.2
Orthogonal contrasts									
Sulfur - linear	NS	*	**	NS	NS	**	**	NS	NS
Sulfur - quadratic	NS	NS	*	NS	NS	**	*	NS	*
Lime - linear	***	***	***	***	***	***	***	***	***
Lime - quadratic	***	***	***	***	***	***	***	***	***
Lime - cubic	***	***	***	***	***	***	***	***	***
Gypsum - linear	***	***	***	***	***	***	NS	NS	**
Gypsum - quadratic	***	***	***	***	**	***	NS	NS	**
Check vs $CaCO_3$ and $CaSO_4$[§]	***	***	***	***	***	***	***	***	***
Lime vs gypsum	NS	NS	NS	NS	NS	NS	***	***	***
Low Ca vs High Ca	***	***	***	***	***	***	***	*	NS
Source vs rate	NS	NS	NS	NS	NS	NS	NS	NS	NS

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively; NS, not significant.

[†] Soil reaction (sulfur, limestone, and gypsum) treatments, where the first number in each row represents the quantity applied on 14 Dec. 2011 and the second number the amount applied on 1 Apr. 2014.

[‡] Fisher's protected least significant difference was used to separate treatment means.

[§] low rate, limestone at 569 + 889 kg $CaCO_3$ ha^{-1} vs gypsum at 199 + 356 kg Ca ha^{-1}; high rate, limestone at 1184 + 1631 kg $CaCO_3$ ha^{-1} vs gypsum 380 + 889 kg Ca ha^{-1}

Table 3. Soil pH response at the 0 to 5.5 cm depth to soil reaction treatments on annual bluegrass turf in North Brunswick, NJ, during 2012, 2013, and 2014.

Treatments[†]	Soil pH (1:1 soil:water extract)							
	2012		2013			2014		
	May	Jul	May	Jul	Sept	May	Jul	Sept
Untreated Check	5.7	5.8	5.9	5.8	5.9	6.3	5.9	6.0
Sulfur								
24 + 12 kg S ha^{-1}	5.6	5.7	5.8	5.6	5.7	6.1	5.9	6.0
49 + 24 kg S ha^{-1}	5.6	5.7	5.7	5.6	5.8	6.1	5.8	5.9
Limestone								
118 + 112 kg $CaCO_3$ ha^{-1}	5.7	5.8	5.9	5.9	5.8	6.3	5.9	5.9
569 + 889 kg $CaCO_3$ ha^{-1}	5.7	5.8	5.8	5.8	5.8	6.3	6.0	5.9
1184 + 1631 kg $CaCO_3$ ha^{-1}	5.7	5.8	5.9	5.9	5.9	6.3	6.1	6.1
1739 + 2148 kg $CaCO_3$ ha^{-1}	5.8	5.8	5.9	5.9	6.0	6.3	6.1	6.1
2247 + 2617 kg $CaCO_3$ ha^{-1}	5.7	5.8	6.0	6.0	6.1	6.4	6.1	6.3
Gypsum								
199 + 356 kg Ca ha^{-1}	5.6	5.7	5.8	5.8	5.9	5.9	5.8	5.9
380 + 889 kg Ca ha^{-1}	5.7	5.7	5.8	5.9	5.9	6.0	5.8	5.8
$LSD_{(0.05)}$[‡]	---	---	---	---	0.1	0.2	0.1	0.2
Orthogonal contrasts								
Sulfur - linear	NS	*	*	NS	NS	NS	NS	NS
Sulfur - quadratic	NS	*	NS	NS	NS	NS	NS	NS
Lime - linear	NS	NS	NS	NS	***	NS	**	**
Lime - quadratic	NS	NS	NS	NS	***	NS	**	**
Lime - cubic	NS	NS	NS	NS	***	NS	*	**
Gypsum - linear	NS	NS	NS	NS	NS	NS	*	NS
Gypsum - quadratic	NS	*	NS	NS	NS	NS	*	NS
Check vs $CaCO_3$ and $CaSO_4$[§]	NS	NS	NS	NS	NS	NS	NS	NS
Lime vs gypsum	NS	*	NS	NS	NS	***	***	*
Low Ca vs High Ca	NS	NS	NS	NS	NS	NS	NS	NS
Source vs rate	NS	NS	NS	NS	NS	NS	NS	NS

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively; NS, not significant.

[†] Soil reaction (sulfur, limestone, and gypsum) treatments, where the first number in each row represents the quantity applied on 14 Dec 2011 and the second number the amount applied on 1 April 2014.

[‡] Fisher's protected least significant difference was used to separate treatment means.

[§] low rate, limestone at 569 + 889 kg $CaCO_3$ ha^{-1} vs gypsum at 199 + 356 kg Ca ha^{-1}; high rate, limestone at 1184 + 1631 kg $CaCO_3$ ha^{-1} vs gypsum 380 + 889 kg Ca ha^{-1}.

Table 4. Response of extractable P, K, Ca, and Mg to soil reaction treatments in the mat layer (0 to 5.5 cm depth) of annual bluegrass turf in North Brunswick, NJ, during 2013 and 2014.

Treatments[†]	2013				2014			
	P[‡]	K	Ca	Mg	P	K	Ca	Mg
	mg kg^{-1}							
Untreated Check	23	86	230	55	22	102	257	58
Sulfur								
24 + 12 kg S ha^{-1}	27	101	227	54	19	97	236	52
49 + 24 kg S ha^{-1}	23	89	205	51	22	100	240	53
Limestone								
118 + 112 kg $CaCO_3$ ha^{-1}	24	91	272	60	19	91	330	57
569 + 889 kg $CaCO_3$ ha^{-1}	24	86	389	59	22	84	595	64
1184 + 1631 kg $CaCO_3$ ha^{-1}	23	73	495	54	19	82	711	58
1739 + 2148 kg $CaCO_3$ ha^{-1}	26	70	647	49	21	82	841	53
2247 + 2617 kg $CaCO_3$ ha^{-1}	27	75	792	52	23	77	1022	53
Gypsum								
199 + 356 kg Ca ha^{-1}	23	78	362	68	21	100	424	50
380 + 889 kg Ca ha^{-1}	27	78	481	74	23	113	585	48
LSD $_{(0.05)}$[§]	---	16	88	7	---	16	113	7
Orthogonal contrasts								
Sulfur - linear	NS	NS	NS	NS	NS	NS	NS	NS
Sulfur - quadratic	NS	NS	***	NS	NS	*	***	NS
Lime - linear	*	**	***	**	NS	**	***	NS
Lime - quadratic	*	**	***	*	NS	**	***	*
Lime - cubic	NS	*	***	**	NS	*	***	*
Gypsum - linear	NS	NS	***	***	NS	NS	***	*
Gypsum - quadratic	NS	NS	***	**	NS	NS	***	NS
Check vs $CaCO_3$ and $CaSO_4$[¶]	NS	NS	***	**	NS	NS	***	NS
Lime vs gypsum	NS	NS	NS	***	NS	***	***	***
Low Ca vs High Ca	NS	NS	**	NS	NS	NS	**	NS
Source vs rate	NS	NS	NS	*	NS	NS	NS	NS

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively; NS, not significant.

[†] Soil reaction (sulfur, limestone, and gypsum) treatments, where the first number in each row represents the quantity applied on 14 Dec 2011 and the second number the amount applied on 1 April 2014.

[‡] Extractable P, K, Ca, and Mg determined using Mehlich 3 method.

[§] Fisher's protected least significant difference was used to separate treatment means.

[¶] low rate, limestone at 569 + 889 kg $CaCO_3$ ha^{-1} vs gypsum at 199 + 356 kg Ca ha^{-1}; high rate, limestone at 1184 + 1631 kg $CaCO_3$ ha^{-1} vs gypsum 380 + 889 kg Ca ha^{-1}.

Table 5. Response of extractable P, K, Ca, and Mg to soil reaction treatments in the soil layer (5.5 to 17 cm depth) of annual bluegrass turf in North Brunswick, NJ, during 2013 and 2014.

Treatments[†]	2013				2014			
	P[‡]	K	Ca	Mg	P	K	Ca	Mg
	mg kg^{-1}							
Untreated Check	100	132	641	97	98	152	683	101
Sulfur								
24 + 12 kg S ha^{-1}	98	118	606	92	97	143	663	98
49 + 24 kg S ha^{-1}	99	128	628	96	94	148	673	100
Limestone								
118 + 112 kg $CaCO_3$ ha^{-1}	97	128	648	95	93	144	679	98
569 + 889 kg $CaCO_3$ ha^{-1}	91	127	668	94	86	141	658	93
1184 + 1631 kg $CaCO_3$ ha^{-1}	96	129	712	99	96	146	782	99
1739 + 2148 kg $CaCO_3$ ha^{-1}	95	127	729	93	86	135	791	88
2247 + 2617 kg $CaCO_3$ ha^{-1}	98	131	749	96	88	131	830	91
Gypsum								
199 + 356 kg Ca ha^{-1}	98	126	667	97	94	135	751	93
380 + 889 kg Ca ha^{-1}	98	131	699	93	90	131	861	86
$LSD_{(0.05)}$[§]	---	---	63	---	---	14	58	7
Orthogonal contrasts								
Sulfur - linear	NS	NS	NS	NS	NS	NS	NS	NS
Sulfur - quadratic	NS	NS	NS	NS	NS	NS	NS	NS
Lime - linear	NS	NS	**	NS	NS	NS	***	*
Lime - quadratic	NS	NS	**	NS	NS	NS	**	NS
Lime - cubic	NS	NS	*	NS	*	NS	***	*
Gypsum - linear	NS	NS	NS	NS	NS	NS	***	**
Gypsum - quadratic	NS	NS	NS	NS	NS	NS	**	**
Check vs $CaCO_3$ and $CaSO_4$[¶]	NS	NS	NS	NS	NS	*	**	**
Lime vs gypsum	NS	NS	NS	NS	NS	*	***	*
Low Ca vs High Ca	NS	NS	NS	NS	NS	NS	***	NS
Source vs rate	NS	NS	NS	NS	NS	NS	NS	*

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively; NS, not significant.

[†] Soil reaction (sulfur, limestone, and gypsum) treatments, where the first number in each row represents the quantity applied on 14 Dec 2011 and the second number the amount applied on 1 April 2014.

[‡] Extractable P, K, Ca, and Mg determined using Mehlich 3 method.

[§] Fisher's protected least significant difference was used to separate treatment means.

[¶] low rate, limestone at 569 + 889 kg $CaCO_3$ ha^{-1} vs gypsum at 199 + 356 kg Ca ha^{-1}; high rate, limestone at 1184 + 1631 kg $CaCO_3$ ha^{-1} vs gypsum 380 + 889 kg Ca ha^{-1}.

Table 6. Anthracnose disease severity response to soil reaction treatments on annual bluegrass turf in North Brunswick, NJ, during 2012.

Treatments[†]	Turf area infested						
	21-Jun	9-Jul	23-Jul	3-Aug	16-Aug	29-Aug	AUDPC[‡]
	%						
Untreated Check	4	18	29	23	22	31	1450
Sulfur							
24 + 12 kg S ha^{-1}	4	24	28	22	24	33	1548
49 + 24 kg S ha^{-1}	10	25	30	24	28	42	1788
Limestone							
118 + 112 kg $CaCO_3$ ha^{-1}	5	14	16	13	20	24	1031
569 + 889 kg $CaCO_3$ ha^{-1}	3	8	14	9	16	21	774
1184 + 1631 kg $CaCO_3$ ha^{-1}	3	12	16	15	22	26	1046
1739 + 2148 kg $CaCO_3$ ha^{-1}	3	11	17	8	15	23	862
2247 + 2617 kg $CaCO_3$ ha^{-1}	3	9	10	7	12	17	660
Gypsum							
199 + 356 kg Ca ha^{-1}	3	10	13	7	12	14	687
380 + 889 kg Ca ha^{-1}	3	13	17	8	14	16	838
$LSD_{(0.05)}$[§]	2	6	9	8	12	13	471
Orthogonal contrasts							
Sulfur - linear	*	NS	NS	NS	NS	*	*
Sulfur - quadratic	*	NS	NS	NS	NS	*	NS
Lime - linear	NS	NS	*	*	NS	NS	*
Lime - quadratic	NS	NS	NS	*	NS	NS	NS
Lime - cubic	NS	*	*	*	NS	NS	NS
Gypsum - linear	NS	NS	NS	**	NS	*	*
Gypsum - quadratic	NS	NS	NS	**	NS	*	*
Check vs $CaCO_3$ and $CaSO_4$[¶]	NS	**	***	***	NS	*	**
Lime vs gypsum	NS	NS	NS	NS	NS	NS	NS
Low Ca vs High Ca	NS	NS	NS	NS	NS	NS	NS
Source vs rate	NS	NS	NS	NS	NS	NS	NS

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively; NS, not significant.

[†] Soil reaction (sulfur, limestone, and gypsum) treatments, where the first number in each row represents the quantity applied on 14 Dec 2011 and the second number the amount applied on 1 April 2014.

[‡] AUDPC, area under disease progress curve

[§] Fisher's protected least significant difference was used to separate treatment means.

[¶] low Ca rate, limestone at 569 + 889 kg $CaCO_3$ ha^{-1} vs gypsum at 199 + 356 kg Ca ha^{-1}; high Ca rate, limestone at 1184 + 1631 kg $CaCO_3$ ha^{-1} vs gypsum 380 + 889 kg Ca ha^{-1}.

Table 7. Anthracnose disease severity response to soil reaction treatments on annual bluegrass turf in North Brunswick, NJ, during 2013.

Treatments[†]	Turf area infested						
	12-Jun	27-Jun	10-Jul	25-Jul	6-Aug	19-Aug	AUDPC[‡]
	%						
Untreated Check	3	4	18	34	53	55	1814
Sulfur							
24 + 12 kg S ha^{-1}	4	5	18	32	50	54	1758
49 + 24 kg S ha^{-1}	12	12	26	45	57	58	2319
Limestone							
118 + 112 kg $CaCO_3$ ha^{-1}	3	8	21	30	43	43	1653
569 + 889 kg $CaCO_3$ ha^{-1}	2	5	16	27	35	38	1363
1184 + 1631 kg $CaCO_3$ ha^{-1}	1	3	11	22	33	28	1105
1739 + 2148 kg $CaCO_3$ ha^{-1}	2	2	10	21	29	23	972
2247 + 2617 kg $CaCO_3$ ha^{-1}	1	2	11	23	26	24	976
Gypsum							
199 + 356 kg Ca ha^{-1}	2	3	21	29	44	44	1568
380 + 889 kg Ca ha^{-1}	2	2	15	25	37	27	1228
$LSD_{(0.05)}$[§]	2	3	6	9	11	11	310
Orthogonal contrasts							
Sulfur - linear	**	**	*	NS	NS	NS	*
Sulfur - quadratic	**	*	*	*	NS	NS	*
Lime - linear	**	***	***	**	***	***	***
Lime - quadratic	**	**	***	**	***	***	***
Lime - cubic	**	**	***	*	***	***	***
Gypsum - linear	NS	NS	NS	NS	***	***	***
Gypsum - quadratic	NS	NS	NS	NS	**	***	**
Check vs $CaCO_3$ and $CaSO_4$[¶]	NS	NS	NS	*	***	***	***
Lime vs gypsum	NS	NS	*	NS	NS	NS	NS
Low Ca vs High Ca	NS	NS	**	NS	NS	**	**
Source vs rate	NS	NS	NS	NS	NS	NS	NS

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively; NS, not significant.

[†] Soil reaction (sulfur, limestone, and gypsum) treatments, where the first number in each row represents the quantity applied on 14 Dec 2011 and the second number the amount applied on 1 April 2014.

[‡] AUDPC, area under disease progress curve

[§] Fisher's protected least significant difference was used to separate treatment means.

[¶] low Ca rate, limestone at 569 + 889 kg $CaCO_3$ ha^{-1} vs gypsum at 199 + 356 kg Ca ha^{-1}; high Ca rate, limestone at 1184 + 1631 kg $CaCO_3$ ha^{-1} vs gypsum 380 + 889 kg Ca ha^{-1}.

Table 8. Anthracnose disease severity response to soil reaction treatments on annual bluegrass turf in North Brunswick, NJ, during 2014.

Treatments[†]	Turf area infested						
	1-Jul	16-Jul	24-Jul	5-Aug	13-Aug	27-Aug	AUDPC[‡]
	%						
Untreated Check	7	13	23	28	35	26	1273
Sulfur							
24 + 12 kg S ha^{-1}	7	15	23	28	37	31	1352
49 + 24 kg S ha^{-1}	14	19	28	35	45	41	1737
Limestone							
118 + 112 kg $CaCO_3$ ha^{-1}	3	6	13	15	15	11	613
569 + 889 kg $CaCO_3$ ha^{-1}	2	2	8	8	9	5	328
1184 + 1631 kg $CaCO_3$ ha^{-1}	1	3	7	8	5	3	265
1739 + 2148 kg $CaCO_3$ ha^{-1}	1	2	7	6	6	4	245
2247 + 2617 kg $CaCO_3$ ha^{-1}	1	3	7	5	8	3	272
Gypsum							
199 + 356 kg Ca ha^{-1}	2	7	16	20	22	14	797
380 + 889 kg Ca ha^{-1}	2	3	11	11	10	7	419
$LSD_{(0.05)}$[§]	3	4	7	7	8	7	267
Orthogonal contrasts							
Sulfur - linear	*	NS	NS	NS	**	***	**
Sulfur - quadratic	*	NS	NS	NS	*	**	**
Lime - linear	**	*	***	***	***	***	***
Lime - quadratic	**	**	***	***	***	***	***
Lime - cubic	**	**	***	***	***	***	***
Gypsum - linear	*	**	*	**	***	**	***
Gypsum - quadratic	NS	*	*	*	**	**	**
Check vs $CaCO_3$ and $CaSO_4$[¶]	***	***	***	***	***	***	***
Lime vs gypsum	NS	NS	*	**	**	*	**
Low Ca vs High Ca	NS	NS	NS	NS	**	NS	*
Source vs rate	NS	NS	NS	NS	NS	NS	NS

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively; NS, not significant.

[†] Soil reaction (sulfur, limestone, and gypsum) treatments, where the first number in each row represents the quantity applied on 14 Dec 2011 and the second number the amount applied on 1 April 2014.

[‡] AUDPC, area under disease progress curve

[§] Fisher's protected least significant difference was used to separate treatment means.

[¶] low Ca rate, limestone at 569 + 889 kg $CaCO_3$ ha^{-1} vs gypsum at 199 + 356 kg Ca ha^{-1}; high Ca rate, limestone at 1184 + 1631 kg $CaCO_3$ ha^{-1} vs gypsum 380 + 889 kg Ca ha^{-1}.

SUPPLEMENTAL DATA

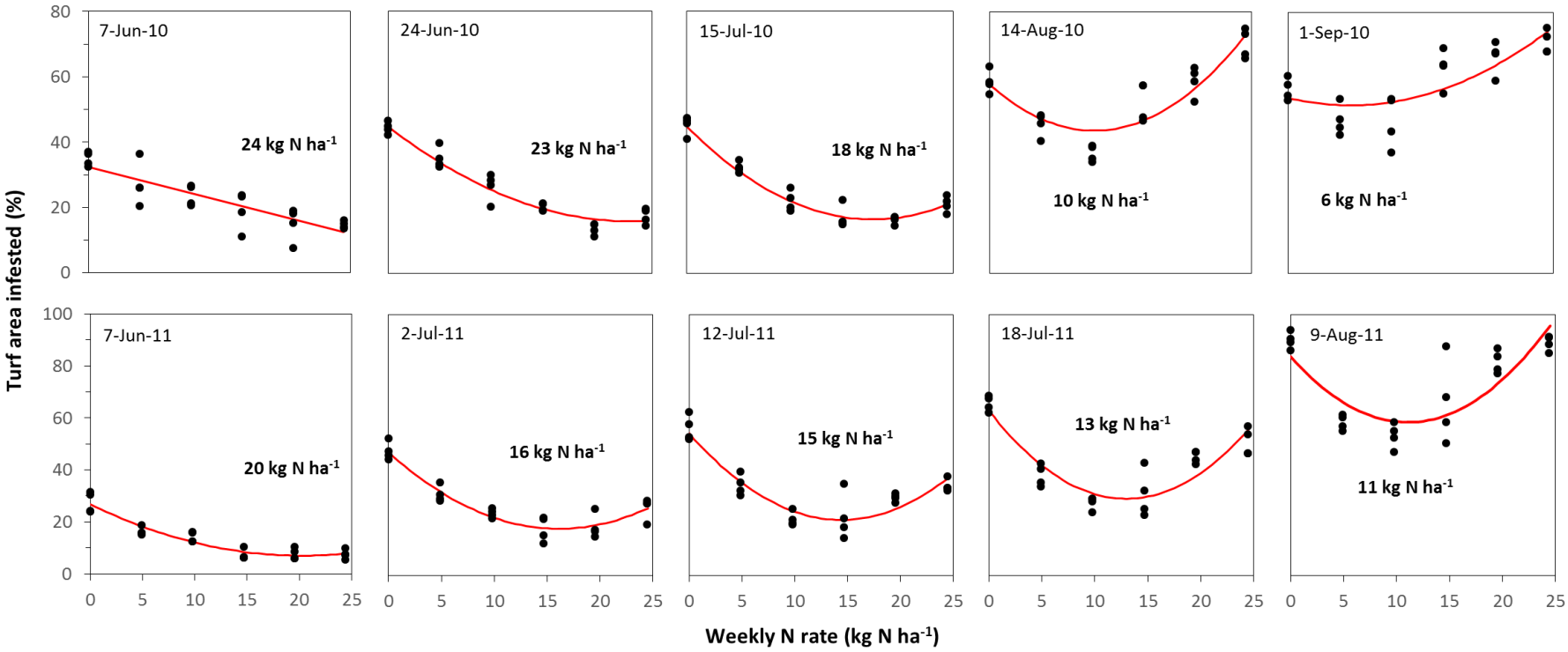

Figure A.1. Response (linear or quadratic) of anthracnose severity (turf area infested) of annual bluegrass turf to weekly application rate of ammonium nitrate for each rating date in 2010 (top) and 2011 (bottom); N treatments were applied weekly from 24 May to 11 Aug. 2010 and 25 May to 3 Aug. 2011.

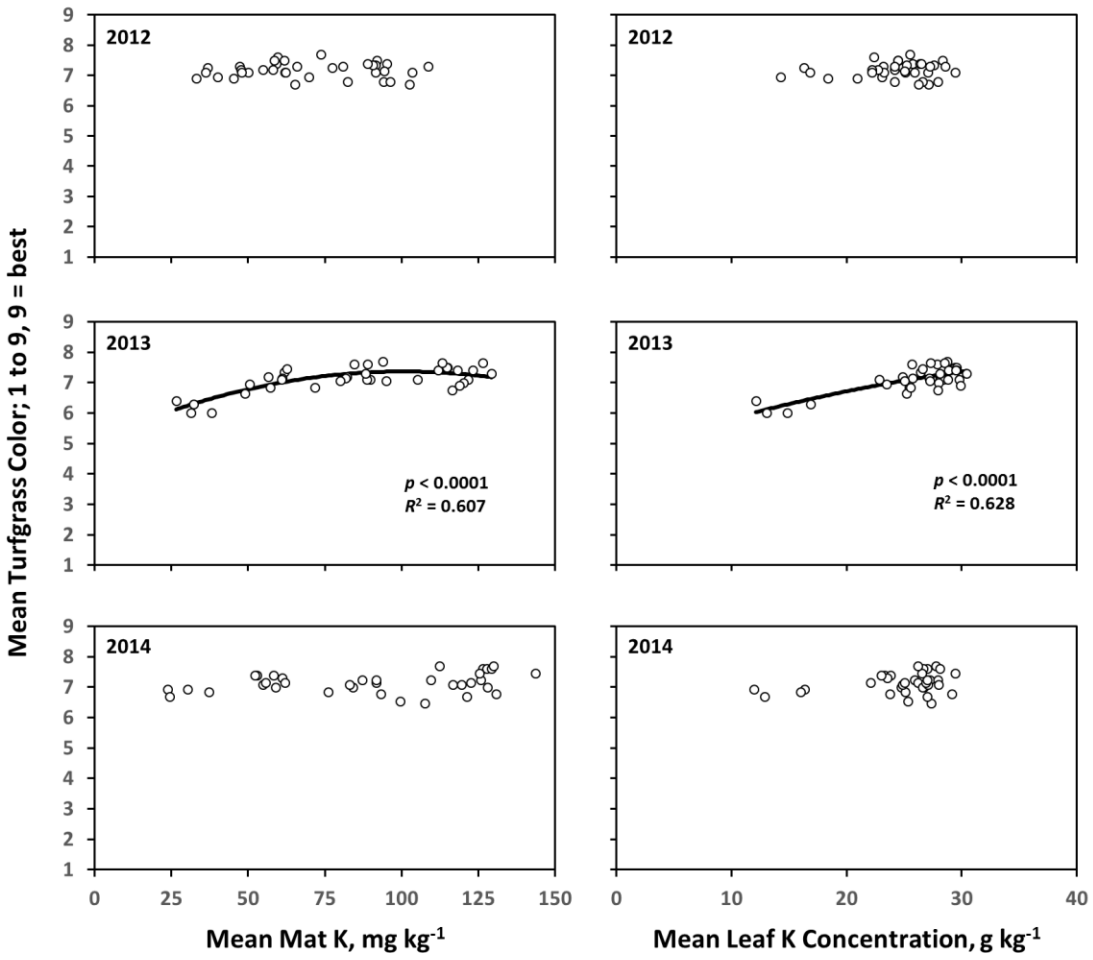

Figure A.2. Mean Mehlich 3 mat K and mean leaf K conc. in relation to mean turf color of annual bluegrass putting green turf in North Brunswick, NJ. Potassium was applied for 32-wk period each growing season, from May through November, for a total of between 0 to 218 kg K ha^{-1} yr^{-1}. Quadratic regression models are shown on all significant ($p > 0.05$) dates in 2012, 2013, and 2014. If no line is present, quadratic and linear regression models were not significant.

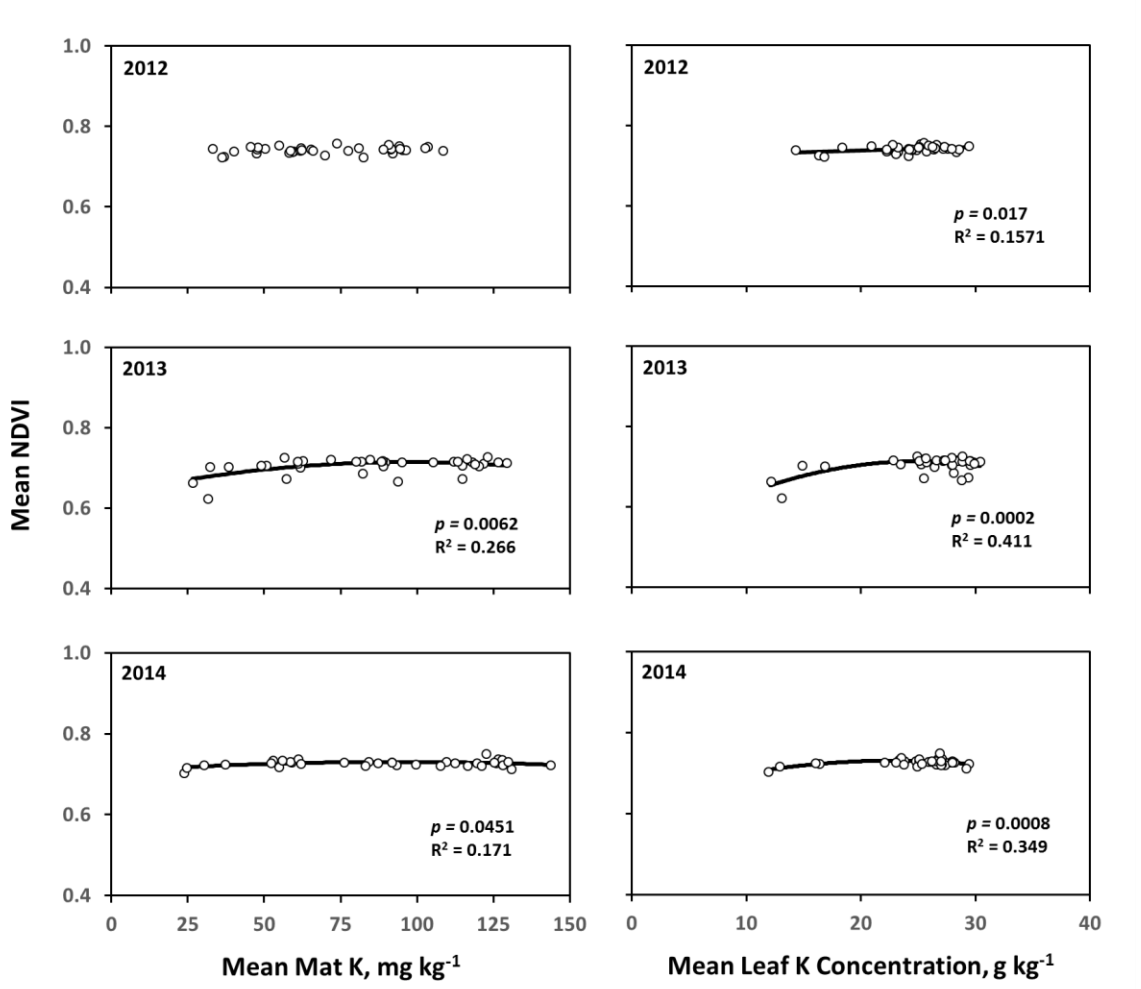

Figure A.3. Mean Mehlich 3 mat K and mean leaf K conc. in relation to mean NDVI index of annual bluegrass putting green turf in North Brunswick, NJ. Potassium was applied for 32-wk period each growing season, from May through November, for a total of between 0 to 218 kg K ha^{-1} yr^{-1}. Quadratic regression models are shown on all significant ($p > 0.05$) dates in 2012, 2013, and 2014. If a significant quadratic model could not be found, a linear model is presented. If no line is present, quadratic and linear regression models were not significant.

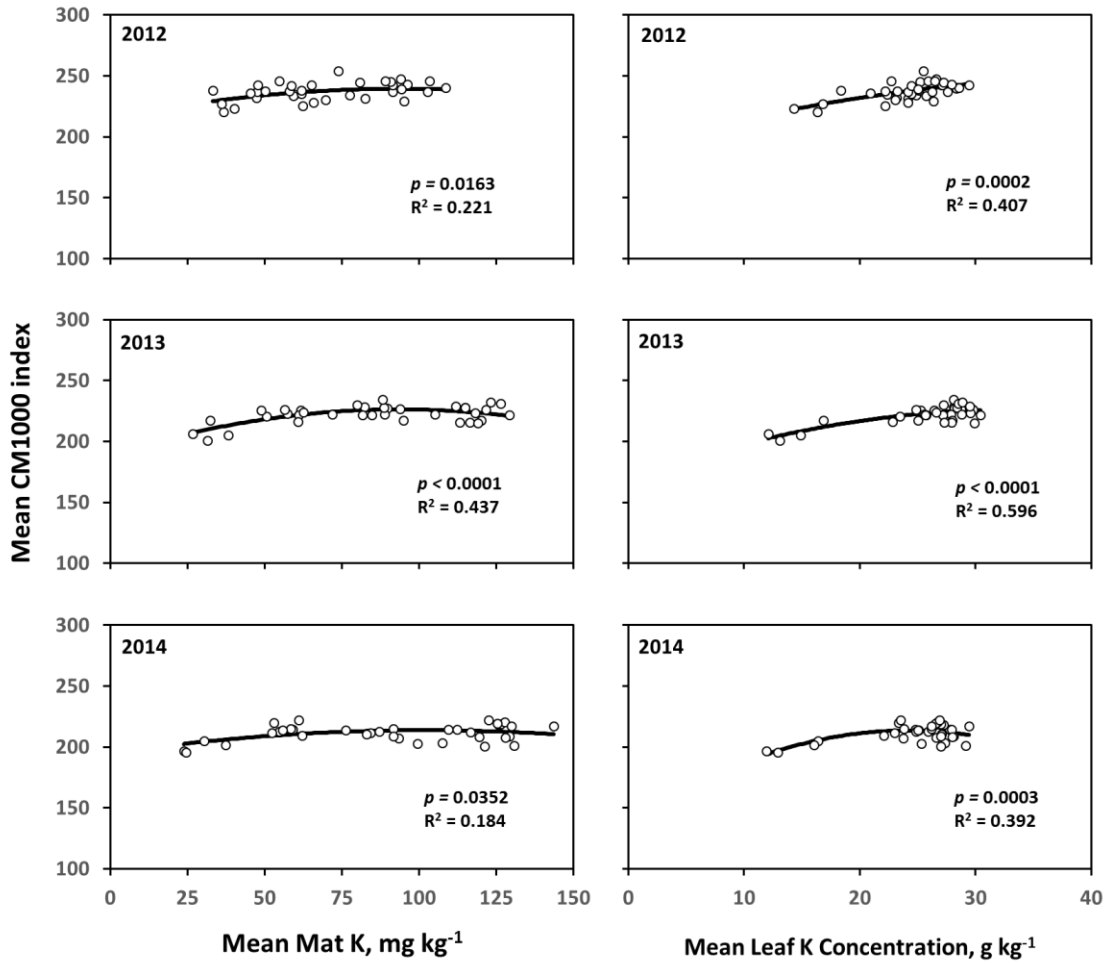

Figure A.4. Mean Mehlich 3 mat K and mean leaf K conc. in relation to mean CM1000 index of annual bluegrass putting green turf in North Brunswick, NJ. Potassium was applied for 32-wk period each growing season, from May through November, for a total of between 0 to 218 kg K ha^{-1} yr^{-1}. Quadratic regression models are shown on all significant ($p > 0.05$) dates in 2012, 2013, and 2014. If a significant quadratic model could not be found, a linear model is presented. If no line is present, quadratic and linear regression models were not significant.

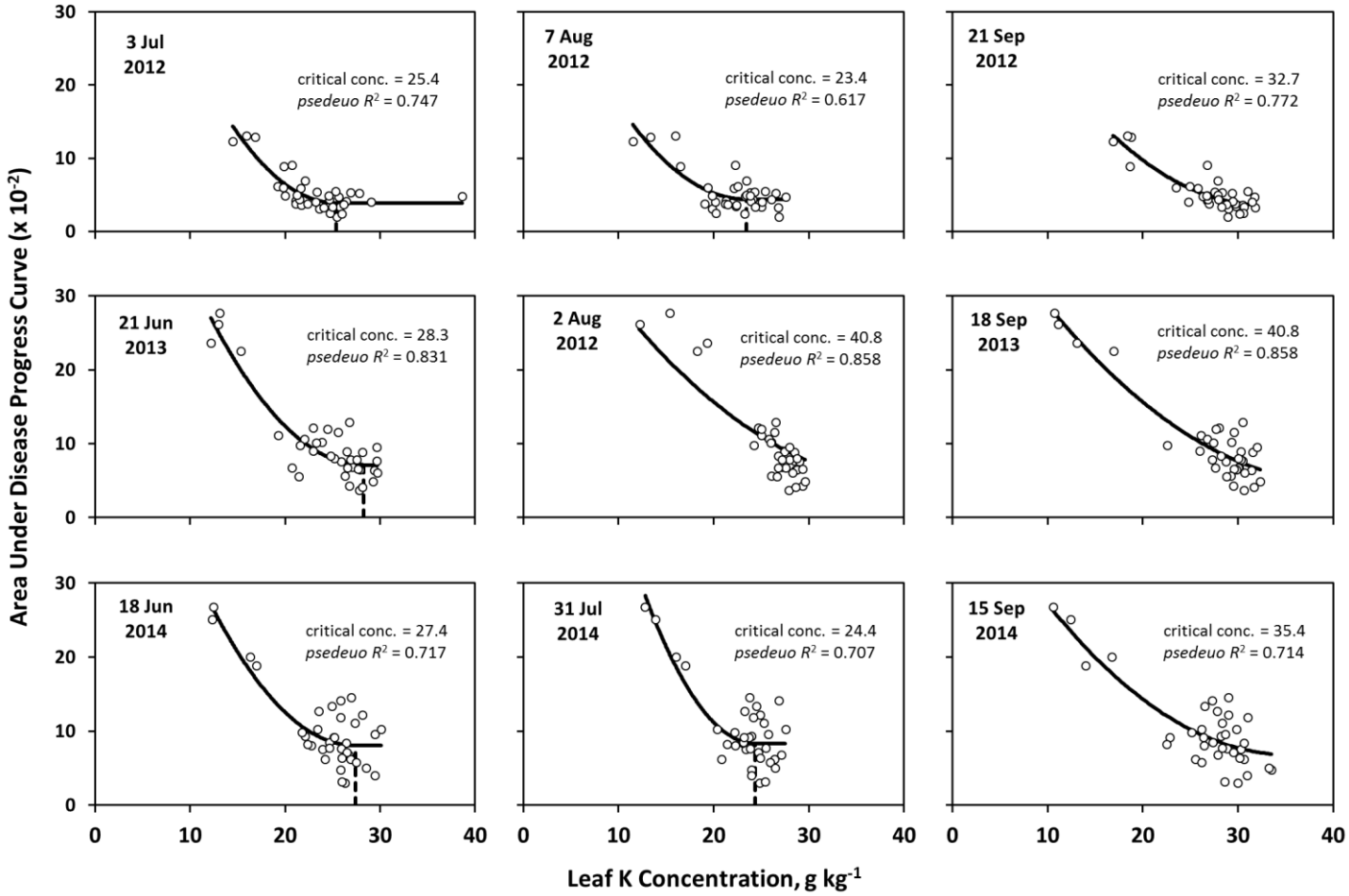

Figure A.5. Leaf K concentration in relation to the area under disease progress curve on annual bluegrass turf infested with anthracnose in North Brunswick, NJ. Potassium was applied for 32-wk period each growing season, from May through November, for a total of between 0 to 218 kg K ha^{-1} yr^{-1}. Quadratic plateau models are shown for all dates in 2012, 2013, and 2014. Line vertical to the *x* axis indicates the critical mat K concentration estimated by the quadratic plateau model.

Table A.1. Anthracnose disease severity response to granular N rate and season of granular N fertilization interaction on annual bluegrass turf in North Brunswick, NJ, during 2009 and 2010.

Granular N Rate	2009								2010	
	23-Jun		3-Jul		28-Jul		12-Aug		21-May	
					Season[†]					
	Autumn	Spring	Autumn	Spring	Autumn	Spring	Autumn	Spring	Autumn	Spring
kg N ha^{-1} yr^{-1}	%									
73	5.9a[‡]A[§]	5.7aA	7.2aA	6.8aA	19.4aA	19.4aA	33.1aA	33.8aA	13.4aA	13.9aA
147	6.0aA	3.3bB	7.7aA	3.9bB	18.6aA	11.5bB	31.3aA	23.29bB	11.5bA	10.9bA
220	6.3aA	2.9bB	7.7aA	3.5bB	12.5bA	5.7cB	26.2bA	23.7bA	6.5cA	4.2cB

[†]Season in which two thirds of the total granular N is applied.

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

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

Table A.2. Mean turf quality ratings of annual bluegrass turf as influenced by season of granular N fertilization and soluble N rate interaction in North Brunswick, NJ, from 20 May to 31 August 2009 (summer).

Soluble N Rate	Turf Quality[†]	
	Season	
	Autumn	Spring
kg N ha^{-1} yr^{-1}	---------- 1 to 9 scale ----------	
0	5.2d[‡]B[§]	6.3dA
18	6.4cB	7.2cA
37	7.1bB	7.9bA
73	8.3aA	8.4aA

[†] Turf quality was rated on a 1 to 9 scale, with 9 = best quality and 5 = minimally acceptable quality.

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

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

Table A.3. Analysis of variance of the turf quality response to granular N rate, season of granular fertilization, and soluble N rate applied to annual bluegrass turf in North Brunswick, NJ, during 2008.

Main effects	Turf Quality				
	8-Sep	**2-Oct**	**15-Oct**	**11-Nov**	**5-Dec**
	---------- 1 - 9 scale ----------				
Granular N Rate					
73 kg N ha^{-1} yr^{-1}	8.7	8.3	8.6	7.9	6.8
147 kg N ha^{-1} yr^{-1}	8.4	8.4	8.6	8.4	7.8
220 kg N ha^{-1} yr^{-1}	8.1	8.7	8.6	8.7	8.4
$LSD_{0.05}$	0.3	0.3	NS	0.3	0.3
Season					
Autumn	8.4	8.7	8.7	8.7	8.2
Spring	8.4	8.2	8.6	7.9	7.2
Soluble N Rate					
0 kg N ha^{-1} yr^{-1}	8.4	8.6	8.3	8.3	7.7
18 kg N ha^{-1} yr^{-1}	8.2	8.4	8.8	8.3	7.7
37 kg N ha^{-1} yr^{-1}	8.6	8.4	8.6	8.2	7.7
73 kg N ha^{-1} yr^{-1}	8.4	8.4	8.7	8.4	7.6
$LSD_{0.05}$	NS	NS	NS	NS	NS
Source of variation	ANOVA				
Granular N Rate (GNR)	**	*	NS	***	***
Linear	**	**	NS	***	***
Quadratic	NS	NS	NS	NS	NS
Season (S)	NS	***	NS	***	***
GNR x S	NS	NS	NS	NS	NS
Soluble N Rate (SNR)	NS	NS	NS	NS	NS
Linear	NS	NS	NS	NS	NS
Quadratic	NS	NS	NS	NS	NS
Cubic	NS	NS	NS	NS	NS
GNR x SNR	NS	NS	NS	NS	NS
S x SNR	NS	NS	NS	NS	NS
GNR x S x SNR	NS	NS	NS	NS	NS
CV (%)	6.4	6.6	6.7	5.7	7.4

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively; NS, not significant.

Table A.4. Analysis of variance of the turf quality response to granular N rate, season of granular fertilization, and soluble N rate applied to annual bluegrass turf in North Brunswick, NJ, during 2009.

Main effects	Turf Quality												
	31-Mar	14-Apr	29-Apr	12-May	28-May	24-Jun	27-Jul	7-Aug	24-Aug	6-Oct	30-Oct	17-Nov	4-Dec
	1 - 9 scale												
Granular N Rate													
73 kg N ha^{-1} yr^{-1}	5.0	6.1	5.2	5.7	7.1	6.9	5.6	5.7	4.7	3.8	3.1	3.4	2.6
147 kg N ha^{-1} yr^{-1}	6.0	6.8	6.3	6.6	8.4	8.2	7.0	7.0	5.7	4.7	4.2	4.4	3.8
220 kg N ha^{-1} yr^{-1}	6.2	7.8	7.3	7.3	8.9	8.8	8.1	8.0	6.5	5.9	5.8	5.9	5.5
$LSD_{0.05}$	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.4	0.3	0.4
Season													
Autumn	6.3	6.9	6.2	6.2	7.9	7.7	6.4	6.5	5.4	5.0	4.6	4.9	4.3
Spring	5.2	6.9	6.3	6.8	8.4	8.2	7.3	7.3	5.9	4.6	4.1	4.2	3.6
Soluble N Rate													
0 kg N ha^{-1} yr^{-1}	5.8	7.0	6.3	6.7	7.7	6.9	5.2	5.1	3.7	4.1	3.7	3.9	3.3
18 kg N ha^{-1} yr^{-1}	5.8	6.8	6.2	6.4	8.2	7.9	6.5	6.6	5.2	4.7	4.1	4.2	3.6
37 kg N ha^{-1} yr^{-1}	5.6	6.9	6.2	6.5	8.1	8.2	7.4	7.5	6.3	4.9	4.6	4.8	4.1
73 kg N ha^{-1} yr^{-1}	5.7	6.9	6.4	6.5	8.5	8.8	8.4	8.4	7.2	5.5	5.1	5.3	4.7
$LSD_{0.05}$	NS	NS	NS	NS	0.3	0.3	0.5	0.4	0.5	0.5	0.4	0.4	0.5
Source of variation	ANOVA												
Granular N Rate (GNR)	***	***	***	***	***	***	***	***	***	***	***	***	***
Linear	***	***	***	***	***	***	***	***	***	***	***	***	***
Quadratic	**	NS	NS	NS	***	**	NS	NS	NS	NS	NS	NS	NS
Season (S)	***	NS	NS	***	***	***	***	***	*	NS	***	***	***
GNR x S	NS	NS	NS	***	NS	NS	NS	NS	NS	NS	*	NS	*
Soluble N Rate (SNR)	NS	NS	NS	NS	***	***	***	***	***	***	***	***	***
Linear	NS	NS	NS	NS	***	***	***	***	***	***	***	***	***
Quadratic	NS	NS	NS	NS	NS	**	***	***	***	NS	NS	NS	NS
Cubic	NS	NS	NS	NS	*	*	NS	NS	NS	NS	NS	NS	NS
GNR x SNR	NS	NS	NS	NS	NS	***	***	***	**	NS	NS	NS	NS
S x SNR	NS	NS	NS	NS	NS	*	*	*	NS	NS	NS	NS	NS
GNR x S x SNR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	9.4	8.0	9.5	8.0	5.9	5.6	9.9	9.4	14.5	16.3	15.1	12.6	17.4

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively; NS, not significant.

Table A.5. Analysis of variance of the turf quality response to granular N rate, season of granular fertilization, and soluble N rate applied to annual bluegrass turf in North Brunswick, NJ, during 2010.

Main effects	Turf Quality					
	24-Mar	**29-Apr**	**19-May**	**9-Jun**	**8-Jul**	**16-Sep**
	---------- 1 - 9 scale ----------					
Granular N Rate						
73 kg N ha^{-1} yr^{-1}	2.9	3.5	3.4	4.0	5.0	4.4
147 kg N ha^{-1} yr^{-1}	3.7	4.4	4.8	5.2	5.9	4.8
220 kg N ha^{-1} yr^{-1}	5.0	6.0	6.6	6.7	6.5	5.5
$LSD_{0.05}$	0.3	0.3	0.4	0.3	0.4	0.4
Season						
Autumn	4.3	4.9	4.8	4.7	5.4	4.7
Spring	3.5	4.3	5.1	5.9	6.2	5.1
Soluble N Rate						
0 kg N ha^{-1} yr^{-1}	3.4	4.1	4.6	4.4	4.1	3.8
18 kg N ha^{-1} yr^{-1}	3.9	4.4	4.8	4.9	4.8	4.4
37 kg N ha^{-1} yr^{-1}	4.0	4.7	5.0	5.2	6.0	5.2
73 kg N ha^{-1} yr^{-1}	4.3	5.2	5.2	6.7	8.3	6.1
$LSD_{0.05}$	0.4	0.4	0.4	0.4	0.4	0.5
Source of variation	ANOVA					
Granular N Rate (GNR)	***	***	***	***	***	***
Linear	***	***	***	***	***	***
Quadratic	NS	*	NS	NS	NS	NS
Season (S)	***	***	*	***	***	*
GNR x S	**	NS	NS	NS	*	NS
Soluble N Rate (SNR)	***	***	*	***	***	***
Linear	***	***	**	***	***	***
Quadratic	NS	NS	NS	*	NS	NS
Cubic	NS	NS	NS	NS	NS	NS
GNR x SNR	NS	NS	NS	*	NS	NS
S x SNR	NS	NS	NS	NS	NS	NS
GNR x S x SNR	NS	NS	NS	NS	NS	NS
CV (%)	14.6	12.9	13.2	10.7	11.0	15.6

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively; NS, not significant.

Table A.6. Turf color response to granular N rate, season of granular fertilization, and soluble N rate on annual bluegrass turf in North Brunswick, NJ, during 2008.

Main effects	Turf Color			
	2-Oct	15-Oct	11-Nov	5-Dec
	---------- 1 - 9 scale ----------			
Granular N Rate				
73 kg N ha^{-1} yr^{-1}	7.2	6.5	5.5	4.5
147 kg N ha^{-1} yr^{-1}	7.5	7.0	6.9	6.1
220 kg N ha^{-1} yr^{-1}	8.2	7.3	7.6	7.2
$LSD_{0.05}$	0.4	0.3	0.2	0.3
Season				
Autumn	7.9	7.3	7.5	6.8
Spring	7.4	6.6	5.8	5.1
Soluble N Rate				
0 kg N ha^{-1} yr^{-1}	7.7	7.1	6.6	6.0
18 kg N ha^{-1} yr^{-1}	7.7	6.8	6.7	6.0
37 kg N ha^{-1} yr^{-1}	7.6	6.9	6.6	5.8
73 kg N ha^{-1} yr^{-1}	7.7	6.9	6.8	5.9
$LSD_{0.05}$	---	---	---	---
Source of variation	ANOVA			
Granular N Rate (GNR)	***	***	***	***
Linear	***	***	***	***
Quadratic	NS	NS	**	*
Season (S)	***	***	***	***
GNR x S	***	***	***	***
Soluble N Rate (SNR)	NS	NS	NS	NS
Linear	NS	NS	NS	NS
Quadratic	NS	NS	NS	NS
Cubic	NS	NS	NS	NS
GNR x SNR	NS	NS	NS	NS
S x SNR	NS	NS	NS	NS
GNR x S x SNR	NS	NS	NS	NS
CV (%)	8.1	7.4	6.5	8.0

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively; NS, not significant.

Table A.7. Turf color response to granular N rate, season of granular fertilization, and soluble N rate on annual bluegrass turf in North Brunswick, NJ, during 2009.

Main effects	Turf Color												
	31-Mar	14-Apr	29-Apr	12-May	28-May	24-Jun	27-Jul	7-Aug	24-Aug	6-Oct	30-Oct	17-Nov	4-Dec
	1 - 9 scale												
Granular N Rate													
73 kg N ha^{-1} yr^{-1}	3.0	4.2	4.2	5.1	5.4	5.5	5.0	5.1	4.7	4.0	3.4	3.5	3.0
147 kg N ha^{-1} yr^{-1}	3.9	5.5	5.8	6.5	6.7	6.8	5.9	6.0	5.5	5.2	4.8	4.8	4.3
220 kg N ha^{-1} yr^{-1}	4.6	7.3	7.6	7.9	8.1	8.0	7.0	7.0	6.1	6.4	6.3	6.3	5.7
$LSD_{0.05}$	0.3	0.3	0.3	0.2	0.3	0.2	0.4	0.4	0.4	0.4	0.4	0.4	0.3
Season													
Autumn	4.4	5.7	5.7	6.1	6.2	6.2	5.5	5.6	5.1	5.6	5.5	5.5	4.8
Spring	3.3	5.6	6.1	6.9	7.3	7.3	6.4	6.5	5.7	4.8	4.2	4.3	3.9
Soluble N Rate													
0 kg N ha^{-1} yr^{-1}	3.8	5.6	5.7	6.4	6.2	5.8	4.5	4.2	3.6	4.9	4.2	4.3	4.0
18 kg N ha^{-1} yr^{-1}	3.8	5.7	5.9	6.6	6.6	6.7	5.6	5.7	4.8	5.0	4.4	4.6	4.0
37 kg N ha^{-1} yr^{-1}	3.8	5.5	5.8	6.6	6.7	6.8	6.1	6.3	5.9	5.4	5.1	5.1	4.6
73 kg N ha^{-1} yr^{-1}	3.8	5.8	6.1	6.4	7.3	7.8	7.7	8.0	7.3	5.5	5.6	5.5	4.9
$LSD_{0.05}$	---	---	---	---	0.3	0.2	0.4	0.5	0.5	0.5	0.4	0.4	0.4
Source of variation	ANOVA												
Granular N Rate (GNR)	***	***	***	***	***	***	***	***	***	***	***	***	***
Linear	***	***	***	***	***	***	***	***	***	***	***	***	***
Quadratic	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Season (S)	***	NS	**	***	***	***	***	***	**	***	***	***	***
GNR x S	***	*	**	***	***	***	*	*	NS	***	***	**	***
Soluble N Rate (SNR)	NS	NS	NS	NS	***	***	***	***	***	*	***	***	***
Linear	NS	NS	NS	NS	***	***	***	***	***	**	***	***	***
Quadratic	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS
Cubic	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS
GNR x SNR	NS	NS	NS	NS	NS	***	NS	*	NS	NS	NS	NS	*
S x SNR	NS	NS	NS	NS	NS	**	NS	NS	NS	NS	NS	NS	NS
GNR x S x SNR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	12.2	8.2	8.3	5.8	7.1	5.5	10.9	11.3	14.1	14.0	13.5	13.3	12.4

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively; NS, not significant.

Table A.8. Turf color response to granular N rate, season of granular fertilization, and soluble N rate on annual bluegrass turf in North Brunswick, NJ, during 2010.

Main effects	Turf Color					
	24-Mar	**29-Apr**	**19-May**	**9-Jun**	**8-Jul**	**16-Sep**
	1 - 9 scale					
Granular N Rate						
73 kg N ha^{-1} yr^{-1}	2.6	3.0	3.2	4.6	5.0	4.9
147 kg N ha^{-1} yr^{-1}	3.8	3.9	5.0	5.6	5.8	5.4
220 kg N ha^{-1} yr^{-1}	4.8	5.2	6.3	6.8	6.2	6.2
$LSD_{0.05}$	0.4	0.3	0.4	0.4	0.4	0.4
Season						
Autumn	4.2	4.2	4.1	4.9	5.3	5.3
Spring	3.3	3.9	5.5	6.5	6.1	5.7
Soluble N Rate						
0 kg N ha^{-1} yr^{-1}	3.4	3.7	4.8	5.2	4.3	4.5
18 kg N ha^{-1} yr^{-1}	3.6	4.1	4.8	5.1	4.8	4.8
37 kg N ha^{-1} yr^{-1}	3.9	4.0	4.8	5.5	5.9	5.8
73 kg N ha^{-1} yr^{-1}	4.1	4.4	4.9	6.9	7.8	6.9
$LSD_{0.05}$	0.4	0.4	---	0.4	0.5	0.5
Source of variation	ANOVA					
Granular N Rate (GNR)	***	***	***	***	***	***
Linear	***	***	***	***	***	***
Quadratic	NS	NS	NS	NS	NS	NS
Season (S)	***	**	***	***	***	*
GNR x S	*	NS	NS	NS	**	NS
Soluble N Rate (SNR)	**	*	NS	***	***	***
Linear	***	**	NS	***	***	***
Quadratic	NS	NS	NS	**	NS	NS
Cubic	NS	NS	NS	NS	NS	NS
GNR x SNR	NS	NS	NS	**	NS	NS
S x SNR	NS	NS	NS	NS	NS	NS
GNR x S x SNR	NS	NS	NS	NS	NS	NS
CV (%)	16.8	14.1	14.2	11.0	12.0	12.8

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level, respectively; NS, not significant.