IMPACT OF SAND TOPDRESSING ON TURF QUALITY, SURFACE PHYSICAL PROPERTIES AND DISEASE SEVERITY OF PUTTING GREEN TURFS

by

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ABSTRACT OF THE THESIS

Impact of Sand Topdressing on Turf Quality, Surface Physical Properties and Disease Severity of Putting Green Turfs

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Topdressing sand is applied to maintain desirable surface root zone characteristics on golf course putting greens; however, coarse sand interferes with mowing and playability. Additionally, sand topdressing applied to annual bluegrass (*Poa annua* L. f. *reptans* [Hauskins] T. Koyama) turf can reduce anthracnose severity (caused by *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman). Three field trials were conducted from 2010 to 2013 to evaluate the effect of sand size and topdressing rate on turf performance, disease severity and surface root zone characteristics. Increasing topdressing rate was more effective at improving the quality of 'Greenwich' velvet bentgrass (*Agrostis canina* L.) turf than varying sand size; however, a substantial quantity of sand particles remained on the surface when medium-coarse sand was applied. Conversely, topdressing with medium-fine sand was readily incorporated into the turf. All topdressing treatments increased saturated hydraulic conductivity estimated from tension infiltrometer measurements. Topdressing annual bluegrass turf with medium-coarse, medium, or medium-fine sand improved turf quality and suppressed anthracnose severity compared to non-topdressed turf, and finer sands were much easier to incorporate into the turf than medium-coarse sand. Increasing topdressing rate from 0 to 1.2 and 2.4 L m^{-2} during the spring was more effective at improving turf quality and reducing anthracnose severity than increasing the rate of autumn topdressing. Topdressing rates (0, 0.075 or 0.15 L m^{-2} applied every two weeks) during the summer were too low to consistently reduce anthracnose severity and increase turf quality. Increasing spring or autumn topdressing rate reduced organic matter concentration and increased mat layer depth more than summer topdressing. Across all trials, increasing topdressing rates also reduced volumetric water content of the 0- to 3.8-mm surface root zone. Plots topdressed with greater quantities of sand often had decreased surface hardness when measured with a Clegg Impact Soil Tester; however, a depth measuring penetrometer indicated that surface strength often increased. The beneficial effects of topdressing with medium-fine sand suggest that sands finer than typically used for construction of root zones may be useful for topdressing putting green turf. Additionally, topdressing during spring is more effective than autumn for suppressing anthracnose disease.

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LITERATURE REVIEW

Introduction

Topdressing is the practice of applying a thin layer of soil or soil-based mixture to the surface of a turf and has been practiced since the early days of golf in Scotland (Beard, 1973; Zontek, 1979). Topdressing was typically a practice for high-maintenance golf course putting greens due to the high cost of material, equipment and labor. Because of the development of more efficient equipment and greater availability of topdressing materials, the practice has become more common (Aylward, 2010). More recently, the use of topdressing has been extended to golf course fairways (Henderson and Miller, 2010), athletic fields (Goddard et al., 2008; Kowalewski et al., 2010) and home lawns (Carrow et al., 1987).

The primary considerations for developing a sound topdressing program should be material selection as well as the topdressing rate and timing of applications. Improper topdressing practice can cause permanent damage to the turf, which may only be corrected by reconstruction (Beard, 2002; Carrow, 1979; Christians, 2011). Alternating layers within the soil profile due to inconsistent topdressing can interfere with drainage, water retention, and rooting (Humbert and Grau, 1949; Zontek, 1979). Therefore, once initiated, topdressing should not be discontinued (Anonymous, 1977; Vavrek, 1995; Zontek, 1979).

Topdressing with sand was recommended by Piper and Oakley (1917) to improve drainage and texture of heavy clay putting greens and provide winter protection. Sand topdressing has been widely practiced on golf courses since the late-1970s (Cooper, 2004; Zontek, 1979). The United States Golf Association (USGA) recommends constructing and topdressing putting greens with sand that contains less than 20% fine sand (0.15–0.25 mm) and less than 5% very fine sand (0.05–0.15 mm) (United States Golf Association Green Section Staff, 2004). Recently, some golf courses have adopted the use of finer (medium-fine) sands than what the USGA recommends to improve the incorporation of topdressing (Murphy, 2012; Pippin, 2010). However it is risky to do so because research on topdressing with medium-fine sand is limited, and results have been variable (Henderson and Miller, 2010; Moeller, 2008; Taylor, 1986). A traditional topdressing program typically includes applying heavy amounts of sand in the spring and autumn, which may also be applied in conjunction with core aeration (Cooper, 2004). Light-rate, frequent applications of sand on putting greens have become very common over the last four decades (Cooper, 2004).

Topdressing is intended to improve root zone characteristics. The primary reasons for applying topdressing to golf course turf are to dilute thatch, smooth playing surfaces and modify the turfgrass growth medium (Beard, 1973). Many have stated that topdressing is one of the most effective practices for managing thatch (Barton et al., 2009; Beard, 1973; Carrow et al., 1987; Engel and Alderfer, 1967; Thompson and Ward, 1966). Topdressing increases surface hardness/firmness through the bridging of sand particles within the turf canopy and thatch (Inguagiato et al., 2012; Li et al., 2009), and maintains firm greens and improves playability during wet conditions (Baker and Canaway, 1992; Stowell et al., 2009). Sand topdressing has been also been reported to reduce mower scalping (McCarty et al., 2007; White and Dickens, 1984). Pressure infiltrometers have been used predominately in turf research to evaluate the impact of topdressing on infiltration but results have been inconsistent. McCarty et al. (2005) and

Espevig et al. (2012) noted that topdressing significantly increased water infiltration. On the other hand, Madison et al. (1974a) and Baker and Canaway (1990) reported that sand topdressing did not improve water conductivity. Classical undisturbed soil core method is also used to estimate hydraulic conductivity in laboratory, however, they can yield different measures of saturated conductivity compared to the use of pressure and tension infiltrometers (Reynolds et al., 2000). Tension infiltrometers have not been used to evaluate the effect of topdressing on infiltration of golf course putting greens.

Others have reported suppression of anthracnose disease on annual bluegrass [*Poa annua* L. f. *reptans* (Hausskn) T. Koyama] with sand topdressing during the summer (Hempfling et al., 2015; Inguagiato et al., 2012, 2013; Roberts and Murphy, 2014) and spring (Hempfling et al., 2015). Christians et al. (1985) reported protection of creeping bentgrass (*Agrostis stolonifera* L.) greens from winter desiccation and better spring recovery after sand topdressing in late autumn. The effects of autumn topdressing on anthracnose disease have not been reported.

Improving soil properties can require multiple years of continuous topdressing, and will only occur at the soil surface if topdressing is not combined with coring or other forms of cultivation that incorporate the sand into the growth medium (Beard, 1973). Also, the improvement in root zone characteristics with topdressing may not be immediate. Topdressing creeping bentgrass putting greens reduced thatch accumulation only in the last three years of a six-year study (Callahan et al., 1998), and increased water infiltration in the second year of the two-year study (McCarty et al., 2005). Surface soil modification can be very slow and requires adequate accumulation of topdressing material in the root zone.

Topdressing Material

Proper selection of topdressing material is critical because within a matter of a few years the majority of a turfgrass root system will be growing within the topdressing (mat) layer rather than the original root zone (Cooper, 2004). Material with undesirable characteristics will ultimately create a root zone that does not support adequate growth of roots and shoots. A wide range of materials have been studied as topdressing including soil with a sandy loam texture (Engel and Alderfer, 1967; Rogers and Waddington, 1989), sand-peat mixes (Madison et al., 1974a; Rieke et al., 1988b; Rieke et al., 1997), sand-soil-peat mixes (Christians et al., 1985; Rieke et al., 1988b), porous ceramic clay (Minner et al., 1997), composted manure (Johnson et al., 2006), and non-soil material such as crumb rubber (Goddard et al., 2008; Rogers et al., 1998). When topdressing with soil or soil-based mixes, two preparation steps are recommended: sterilization and composting for at least eight months to obtain weed-free mixture before use (Beard, 1973; Bengeyfield, 1969). Materials containing a large amount of an organic amendment are not preferable for the purpose of thatch dilution (Madison et al., 1974b; Turgeon, 2004). Cooper and Skogley (1981) reported that topdressing creeping bentgrass and velvet bentgrass (*Agrostis canina* L.) putting green turfs with sand contributed to significantly lower percentage of organic matter (by weight) in the upper 2.5 cm of soil compared to loamy sand.

As early as 1917, Piper and Oakley (1917) recommended topdressing with sand to improve drainage and texture of heavy clay putting greens and provide winter protection. Excessive drainage and nutrient leaching, low microbial activity, lack of organic matter, and soil layering were once suspected to be potential problems with the use of straight sand topdressing (Cooper and Skogley, 1981; Hall, 1978; Zontek, 1979). Field experiments revealed that topdressing with high organic content reduced turf quality and turf was more prone to supraoptimal temperatures and diseases such as pythium, whereas topdressing with sand had more desirable and consistent performance (Madison et al., 1974a). Thereafter, sand topdressing has been widely practiced on golf courses (Cooper, 2004; Zontek, 1979). Unlike topsoil, sand topdressing provides a clean and smooth putting surface three to four days after application when applied at the appropriate rate.

Topdressing Sand Size

The USGA recommends to use sand that contains more than 60% of the medium and coarse particles (0.25–1.0 mm), less than 20% fine sand (0.15–0.25 mm) and less than 5% very fine sand (0.05–0.15 mm) to construct putting greens (United States Golf Association Green Section Staff, 2004). These criteria are often used for selecting sands for topdressing on putting greens.

However, poor incorporation of sand into the turf canopy and thatch can be a problem on putting greens. Sand that remains on the turf surface after topdressing will interfere with mowing and putting quality (Madison et al., 1974a). Wear on mower reels and bedknives can be substantial when daily mowing removes sand particles (Foy, 1999; Murphy, 2012; Vavrek, 1995). Sand contamination in mower clippings will affect clipping yield and nutrient uptake measurements in experiments of turfs managed as putting greens (Johnston et al., 2005; Kreuser et al., 2011). Johnston et al. (2005) reported that more than 80% of the weight of clippings collected from creeping bentgrass putting greens immediately after topdressing was sand; sand content decreased with time but comprised 10% to 20% of the clipping weight two to four weeks after topdressing. The interruption to play and excessive wear on mowers discourages golf course superintendents from routinely implementing a topdressing program during the growing season.

Managing newer, ultra-dense cultivars of turfgrass, such as creeping bentgrass and velvet bentgrass, with a greater thatch forming tendency requires a more intensive and frequent topdressing program (Foy, 1999; Fraser, 1998; Stier and Hollman, 2003); however, incorporation of the sand into turf with a dense growth habit can be difficult. Additionally, frequent, ultra-light (< 0.15 L m^{-2}) applications of sand can substantially increase operational cost. Furthermore, the extremely low mowing heights of modern putting greens further increase the challenge of maintaining a smooth, sand free putting surface.

Coarse (0.5–1.0 mm) and very coarse (1.0–2.0 mm) sand particles are more likely to be picked up by mowers on turf with very low cutting heights, whereas the fine particles are more easily incorporated into the turf canopy (Stier and Hollman, 2003; Taylor, 1986). In the 1970s, Madison et al. (1974a) recommended the use of sand that contains 80% (by weight) in the 0.1 to 0.5 mm particle range, after noticing a commonly sold sand [32% in the coarse fraction (0.5–1.0 mm)] for topdressing was too coarse. Recently, some golf course superintendents have adopted the use of finer (medium-fine) sands to improve the incorporation of topdressing sand (Murphy, 2012; Pippin, 2010). Topdressing with sand that does not contain particles larger than a medium (0.25–0.5 mm) size has the advantage of easier incorporation and interferes less with mowing and play compared to sands contain coarse and very coarse particles.

Many scientists and agronomists agree that the particle size distribution of topdressing materials should match that of the original root zone mixtures (Beard, 1973; Beard, 2002; Christians, 2011; Zontek, 1979). Finer-textured sand layered over coarse-texture sand has the potential to restrict water movement at the interface of the layers (Christians, 2011). Because of the lower negative pressure (suction) in a finer-textured growing matrix, water will not move from the finer-textured upper layer into the coarse sub-layer unless sufficient pressure head builds up at the interface (Hillel, 2003). Excessive fine sand particles are also suspected to migrate down and clog the pore spaces within the underlying sand layer; to validate that, further research (potentially with computed tomography) is needed. In addition to sand particle size, the hydraulic properties of turfgrass root zone can also be impacted by actively growing turfgrass roots and accumulating thatch.

Excess fine sand in the root zone of a putting green can reduce saturated hydraulic conductivity (Murphy et al., 2001; Paul et al., 1970). Paul et al. (1970) noticed a reduction of hydraulic conductivity (from 300 mm h^{-1} to 20–40 mm h^{-1}) of the root zone as the fine and medium fractions (0.15–0.50 mm) of the sand increased from 25% to 89%. Lewis et al. (2010) speculated the decline of infiltration, increase of capillary porosity, and decrease of air-filled porosity were in part a result of fine sand accumulation from topdressing on top of a coarser textured root zone; however, the change of particle size distribution of the root zone mix was not documented in their study. Murphy et al. (2001) reported that root zones constructed with medium-fine sands had lower saturated hydraulic conductivity (K_{sat}) and air-filled porosity compared to coarse or coarse-medium sand, yet the K_{sat} of the medium-fine sand root zones were greater than the minimum (150 mm h^{-1}) recommended by the USGA for a root zone mixture (United States Golf Association Green Section Staff, 2004).

Research on topdressing with medium-fine sand has been limited, and results have been variable. Moeller (2008) reported that core aeration and topdressing of creeping bentgrass greens with a medium-fine sand (finer than the underlying root zone) reduced water infiltration and surface hardness compared to core aeration and topdressing with a medium-coarse sand. In contrast, Henderson and Miller (2010) observed greater resistance to penetration associated with medium-fine sand topdressing compared to coarser sands on creeping bentgrass fairway turf. Medium-fine sand has not been found to impede turfgrass performance; in fact, turf color was sometimes improved likely due to greater water retention (Moeller, 2008). Creeping bentgrass establishment was improved when root zones constructed with medium-fine sands compared to medium-coarse sand (Murphy et al., 2001; Neylan and Robinson, 1997). Additional research is needed to determine how topdressing with medium-fine sand changes the performance characteristics of turf before it can be recommended for use on putting greens.

Topdressing Rate and Timing

Equipment advancements and research have substantially shaped our understanding of how topdressing rate and timing affects turf performance. A traditional topdressing program typically includes applying heavy amounts of sand in the spring and autumn, which may also be applied in conjunction with core aeration (Cooper, 2004). Application of 1.5 to 2.5 L m^{-2} of topdressing during the spring and application of 2.5 to 4 L m^{-2} during autumn have been recommended as the minimum for annual bluegrass putting greens (Beard, 2002). Expanding a topdressing program beyond the minimum recommendation typically involves light and frequent topdressing during the summer. However, the public's demand for high quality putting surfaces during the summer places great importance on the ability to completely and rapidly incorporate topdressing sand into the turf canopy. Vertical mowing is commonly used to assist with sand incorporation (Boesch and Mitkowski, 2007; Foy, 1999). When applied at an appropriate rate during the summer (playing season), topdressing sand should rapidly settle into the shoot canopy and thatch of the turf and not be disruptive to play.

Light and frequent topdressing during the playing season to supplement heavy spring and autumn topdressing has become more common within the golf industry over the past 40 years (Cooper, 2004; Murphy et al., 2013). Madison et al. (1974a) advocated more frequent topdressing as an alternative to the traditional program of two to four topdressings a year; they recommended applying 0.9 L m^{-2} of sand every 21 d to avoid creating alternating layers of sand and thatch. Before 2000, topdressing at 0.6 to 1.6 L m^{-2} was typically recommended as a light application (Bengeyfield, 1969; Cooper and Skogley, 1981; Griffin, 1975; Rieke, 1994; Shearman, 1984). Newer cultivars of creeping bentgrass have been developed to produce greater shoot density at lower cutting heights and low N fertility to meet the public's demand for "fast" (longer ball roll distance) putting surfaces. It is very challenging to incorporate topdressing sand into this type of putting surface, which has prompted the use of ultra-light (< 0.15 L m^{-2}) application rates of sand to ensure better incorporation of the sand (Vavrek, 2007). Today an application rate of 0.15 L m^{-2} is considered light (O'Brien and Hartwiger, 2003). Additionally, topdressing applied as often as every 7 d on golf course putting greens throughout the season has replaced heavy, semiannual application programs on some golf courses

(Aylward, 2010; Cooper, 2004; Murphy et al., 2013).

Thatch Management

Thatch serves a greater role than soil as a plant holding matrix and growth medium once a substantial thatch layer develops (Hurto et al., 1980). Beard (1973) defined thatch as a layer of dead and living stems and roots that accumulated between the green vegetation and soil surface. Mat is defined by Beard (1973) as an organic layer intermixed with topdressing material. Moderate thatch thickness can provide surface resiliency, wear tolerance and a buffer to soil temperature extremes (Beard, 1973). However, excessive thatch can be detrimental and cause desiccation and hydrophobicity during dry conditions thus enhancing drought stress. On the opposite extreme, thatch can also retain excessive water thereby restricting air exchange in the root zone during wet periods. Excess thatch accumulation can restrict root growth into the underlying soil (Ledeboer and Skogley, 1967). As a result, restricted root growth and elevated crowns predispose thatchy turfs to drought and heat stresses as well as scalping from mowing. Excessive thatch can also harbor insects and disease organisms (Hurto et al., 1980; Thompson and Ward, 1966; White and Dickens, 1984), and reduce turf quality and playability on golf and sports turfs. Many factors contribute to excessive thatch accumulation including rapid and dense growth of the grass species, excessive fertility and irrigation, and infrequent cultivation programs.

Some researchers have found that topdressing did not reduce organic matter production; instead, it diluted thatch and formed a mat layer (McCarty et al., 2007; McCarty et al., 2005; Rieke et al., 1988a; Stier and Hollman, 2003; Vavrek, 1995; White and Dickens, 1984). Others noted topdressing contributed to thatch degradation as well as dilution (Espevig et al., 2012; Ledeboer and Skogley, 1967). Thatch is often characterized as thatch thickness (compressed or uncompressed) and organic matter content measured by weight loss-on-ignition in turfgrass research (Callahan et al., 1997; Gaussoin et al., 2013). Some researchers observed that frequent topdressing (Engel and Alderfer, 1967; McCarty et al., 2007; McCarty et al., 2005; Rieke et al., 1988b) as well as seasonal high rate topdressing (Barton et al., 2009; Carrow et al., 1987; Rieke et al., 1988b) with sand or a high sand-content soil mixture can reduce thatch calculated as percentage of organic matter by weight. Increasing the number of sand applications on putting greens was found to reduce the compressed thickness of thatch (Callahan et al., 1998; White and Dickens, 1984). Espevig et al. (2012) reported that increasing the application rate of topdressing sand from 0.5 to 1.0 L m^{-2} applied every two weeks on velvet bentgrass putting greens reduced organic matter content as measured by loss-on-ignition. However, Stier and Hollman (2003) indicated that topdressing every two weeks at 0.2 L m^{-2} or monthly at 0.4 L m^{-2} with sand on putting greens did not facilitate thatch decomposition as measured by the compressed thickness of thatch.

Surface Hardness and Strength

Topdressing is expected to increase surface hardness/firmness through the bridging of sand particles within the turf canopy and thatch (Inguagiato et al., 2012; Li et al., 2009). Topdressing sand applied to fairway turf increased the penetration resistance to surface displacement (Henderson et al., 2010). Sand topdressing can maintain firm greens even under wet conditions (Stowell et al., 2009), which typically can cause turf fields to become spongy and soft, unable to adequately support heavy maintenance equipment. Sand topdressing has been also been reported to reduce mower scalping of creeping bentgrass (McCarty et al., 2007) and bermudagrass (*Cynodon dactylon* L.) (White and Dickens, 1984) putting greens. Over time, a sand topdressed surface provides greater resistance to surface displacement from traffic and improved playability during wet conditions (Baker and Canaway, 1992; Henderson et al., 2010; Stowell et al., 2009).

Surface hardness is an important component of playability, and is assessed through the measurement of energy absorption or deformation of the surface from an impacting object (Baker and Canaway, 1993; Li et al., 2013; Rogers and Waddington, 1992). Several devices are available to measure surface hardness, including the Clegg Impact Soil Tester (CIST), USGA TruFrim (Brame, 2008) and penetrometer (Baker and Canaway, 1993; Li et al., 2013). The Clegg Impact Soil Tester measures the peak deceleration (g_{max}) of a hammer from a specific height. Developed by Dr. Baden Clegg of Australia in 1975, CIST was originally used for testing road base compaction (Clegg, 1976). A Bruel and Kjae vibration analyzer was used to measure surface hardness by obtaining a full impact curve (Li et al., 2009; Rogers and Waddington, 1989, 1992). The USGA TruFrim measures the penetration depth of the impact hammer as an indicator of surface firmness (Brame, 2008). The impact speed of the device mimics the impact energy of a golf ball (Brame, 2008), and was found to correlate well with CIST readings (Linde et al., 2011; Stowell et al., 2009). Soil strength can be assessed by measuring the resistance to penetration with a penetrometer (Cooper and Skogley, 1981; Guertal et al., 2003; Henderson and Miller, 2010; Li et al., 2009; Murphy, 1983). Among these devices, the CIST has been the most commonly used tool, and has been shown to be more reliable than penetrometers for evaluating hardness (Ford, 1999; Twomey et al., 2011). However, the effect of topdressing on surface hardness detected by CIST has varied; some have reported no differences (Barton et al., 2009; McCarty et al., 2005) and others indicated topdressing or increasing topdressing rate increased surface hardness (Espevig et al., 2012; Kauffman et al., 2011).

Water Infiltration

Hydraulic conductivity can be very variable and sensitive to sample size, flow geometry, and sample collection procedures. Tension infiltrometer, pressure infiltrometer and the use of undisturbed soil cores are common methods to estimate hydraulic conductivity, however these methods could yield different measures of saturated conductivity (Reynolds et al., 2000). In turf research, single or double ring infiltrometers with falling or static positive pressure heads are commonly used (Cooper and Skogley, 1981; Espevig et al., 2012; Gregory et al., 2005; Lewis et al., 2010; McCarty et al., 2007; McCarty et al., 2005; Moeller, 2008; Ok et al., 2003; Taylor and Blake, 1982; Taylor et al., 1991). Hydraulic conductivity measured by creating positive water pressure can be biased by preferential-flow along worm channels and cracks. This method does not reflect conditions under normal rainfall or sprinkler irrigation and, therefore, it is less informative for turf systems. On the other hand, tension infiltrometers provide a more realistic characterization of the soil matrix by supplying water at negative pressures, which excludes the larger pores from participating in the water flow process, therefore reducing or eliminating preferential-flow (Dohnal et al., 2010). Gibbs (1993) described the use of tension infiltrometers with a disc diameter of 20.5 cm on synthetic sports turf in New Zealand, but in general the use of tension infiltrometers has been limited in turf system. A rainfall simulator, developed by Ogden et al. (1997), was used for quantifying infiltration rates on a creeping bentgrass fairway (Henderson and Miller, 2010). Instead of creating positive water pressure by ponding, rainfall simulators simulate gradual wetting by rainfall or irrigation on golf courses.

Results of studies evaluating the impact of topdressing on infiltration measured with pressure infiltrometers have been inconsistent in the literature. McCarty et al. (2005) and Espevig et al. (2012) working with creeping bentgrass and velvet bentgrass putting green, respectively, noted that sand topdressing significantly increased water infiltration. On the other hand, Madison et al. (1974a) and Baker and Canaway (1990) reported that sand topdressing did not improve water conductivity of creeping bentgrass greens and a perennial ryegrass (*Lolium perenne* L.) sports field, respectively. When accumulated topdressing layer is saturated by initial wetting, the topdressing treatment effect may not be detected by pressure infiltrometer. Thatch layer was found to limit initial or early-time infiltration rate but not steady state infiltration rate because thatch has larger pore size than underlying profile (Taylor and Blake, 1982). Cooper and Skogley (1981) did not observe differences in infiltration response to topdressing treatments, they speculated that the initial wetting saturated the topdressing layer thus infiltration rate was only affected by the original soil underneath. In addition, Baker and Canaway (1990) found that an increase in sand topdressing rate reduced the incidence of surface ponding on a sports field. Surface ponding or water runoff after a heavy rain or irrigation event may reflect a low initial state infiltration rate, whereas rapid movement of water from turf surface into root zone profile probably suggests a high initial state infiltration rate. Therefore, unsaturated infiltration measurements probably better distinguish the topdressing layer from thatch layer under non-topdressing management. Unfortunately, there are no reports of how topdressing affects unsaturated infiltration using tension infiltrometers.

The mini disk infiltrometer (Decagon Devices, Inc.©), a tension infiltrometer, has become popular in soil science to assess unsaturated hydraulic properties (Madsen and Chandler, 2007). It has also been used to characterize soil water repellency (Lewis et al., 2006; Lichner et al., 2007). Automation of mini disk infiltrometers allows multiple simultaneous measurements and estimation of unsaturated hydraulic conductivity K(h) and sorptivity (S) (Madsen and Chandler, 2007). Mini disk infiltrometers can be repeatedly used to assess unsaturated hydraulic properties on relatively small areas on putting greens because they are compact and do not disturb the surface. Good hydraulic connection between the infiltrometer and the soil has always been a concern with tension infiltrometer, thus removal of surface vegetation or/and use of contact sand is often needed to ensure good contact (Perroux and White, 1988). However, these methods can disturb the turf surface and induce sand contamination to topdressing treatments. Using a small size disk is more likely to avoid an uneven turf surface therefore improving the contact with the turf surface. Although measurements taken with the smaller size disk compared to regular tension infiltrometer may be subjected to greater variation, increasing the number of measurements per plot can compensate for such limitation.

Many methods have been proposed in the literature to estimate hydraulic conductivity from the steady-state infiltration rate (the later stage of infiltration when water enters the soil at a constant rate). Zhang (1997) used Van Genuchten (1980) parameters to determine sorptivity and hydraulic conductivity. Van Genuchten parameters are often assumed from the soil texture. When measurements of initial and final water contents are obtained from soil cores, inverse methods may give better hydraulic conductivity estimates for heterogeneous soil profiles, i.e. non-uniform water content distribution, in a multi-layered system (Angulo-Jaramillo et al., 2000). However, initial and final water contents may be optional for highly homogenous sites. Highly disturbed sites, such as leveled athletic fields, were found to be more homogenous than less disturbed sites, such as forested sites (Poole, 2009). Without water content data, the nonlinear regression method (Logsdon and Jaynes, 1993) can be used because fitting all of the data simultaneously often gives better estimation of hydraulic conductivity than piecewise fitting infiltrometer measurements made at sequential pressure heads described by Ankeny et al. (1991).

Biology, Etiology and Control of Anthracnose Disease

Anthracnose, caused by *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman, is a major disease of grasses throughout the world (Browning et al., 1999; Crouch and Beirn, 2009; Crouch and Clarke, 2012; Landschoot and Hoyland, 1995; Mann and Newell, 2005; Smiley et al., 2005; Vargas, 2005). *C. cereale* was first described as a pathogen associated with cereals and grasses of the subfamily Pooideae in 1908 (Selby and Manns, 1909). Anthracnose on turfgrass was first reported in New Jersey in 1928 (Sprague and Evaul, 1930). Subsequent research described the morphologic features of the pathogen in details (Smith, 1954). During the late-1970s and early-1980s, the dying of annul bluegrass was often attributed to summer stresses or a multipathogen complex/syndrome rather than *C. cereale* (reported as *C. graminicola*) (Couch, 1979; Jackson and Herting, 1985). Later, the pathogenicity of *C. cereale* (reported as *C. graminicola*) was confirmed with Koch's postulates on annual bluegrass during the mid-1980s (Vargas and Detweiler, 1985). The frequency and severity of anthracnose occurrence on golf courses has been increasing since mid-1990s in North

America (Dernoeden, 2012; Landschoot and Hoyland, 1995) due to changes in management practices (e.g. mowing, fertility, irrigation and cultivation) to increase ball roll distance (Vermeulen, 2003; Zontek, 2004). Recently, over sixty percent of the golf courses surveyed across the United States and Canada (Inguagiato, 2012), and over seventy percent surveyed in England and Ireland (Mann and Newell, 2005) reported anthracnose being a problem on the greens.

The causal agent of anthracnose of turfgrass was previously described as *Colletotrichum graminicola* (Ces.) Wils. (Wilson, 1914). However, using molecular phylogenetic methods, Crouch et al. (2006) identified the pathogen as *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman. *C. cereale* exits in two lineages, designated clades “A” and “B” (Crouch et al., 2006). The clade A isolates are geographically widespread and were isolated from numerous turfgrass and noncultivated C3 pooideae grass species; they are the numerically dominant form of *C. cereale* (Beirn et al., 2014; Crouch et al., 2006). Natural populations of *C. cereale* are diverse and appear to have geographic and host preferences (Beirn et al., 2014; Crouch et al., 2009). Real-time PCR probes have been developed to identify each clade rapidly and accurately with cultured isolates, *in planta* samples as well as preserved fungarium specimens (Beirn et al., 2014).

Anthracnose can infect *Poa*, *Agrostis*, *Cynodon*, *Eremochloa*, *Festuca* and *Lolium* spp., but is most severe on annual bluegrass putting greens (Browning et al., 1999; Crouch and Clarke, 2012; Mann and Newell, 2005; Smiley et al., 2005). In the field, symptoms on annual bluegrass initially appear as bright yellow or reddish brown lesions on the foliage (foliar phase); when the disease progresses to the crowns, central shoots detach easily revealing rotten and dark colored leaf sheaths and crowns (basal rot phase) (Browning et al., 1999; Landschoot and Hoyland, 1995). The turf eventually loses density as infected tillers die. Infected areas often coalesce in large patches of dead and declining turf (Smiley et al., 2005) severely reducing the playability and aesthetics. When cultured on the media, *C. cereale* can be identified by the single-celled, falcate or fusiform conidia under light microscopy measured 6.0- to 33.8-μm (Crouch et al., 2006).

The general infection process of *C. cereale* (reported as *C. graminicola*) was investigated by traditional light microscopy with detached leaves of four different turfgrass species (Khan and Hsiang, 2003). Conidia germinate within 2 h after inoculation (AI) under favorable conditions (23°C, >95% relative humidity) (Khan and Hsiang, 2003). Dark brown/black, rounded and smooth or irregularly shaped appressoria (8.5- to 11.6-μm × 6.5- to 10.2-μm) form either at the tips of germ tube or directly from conidia within 6 h AI (Crouch et al., 2006; Khan and Hsiang, 2003). Septa were observed to form between appressoria and germ tubes (Crouch et al., 2006; Khan and Hsiang, 2003). Following appressorium, a penetration peg forms near the base of the appressorium but is not easily visible by light microscopy; instead, penetration pores, where penetration pegs emerge, are observed as small, circular bright spot in the middle of appressoria under light microscopy within 8 h AI (Crouch and Beirn, 2009; Khan and Hsiang, 2003). Infection hyphae were observed to invade epidermal cells within 24 h AI, and colonize mesophyll cells 48–72 h AI (Khan and Hsiang, 2003). Stroma forms under the cuticle, erupts through the cuticle and produces conidiophores and then conidia (Khan and Hsiang, 2003). Heavily melanized setae are observed to emerge from acervuli 96 h AI (Khan and Hsiang, 2003). Unfortunately, the observation of *C. cereale* penetrating and colonizing intact turfgrass plants in real-time has not been achieved. Conidia detached from the acervuli are disseminated to nearby plants by splashing, blowing or mechanical means to spread the infection.

Little is known about the disease cycle of *C. cereale* (Crouch and Beirn, 2009). *C. cereale* can overwinter as sclerotia on rhizomes of oat and barley plants, but this aspect of the fungal lifecycle has not been observed in turf (Crouch and Beirn, 2009). The sexual state of *C. cereale* has not been documented (Crouch and Beirn, 2009). *C. graminicola*, causes anthracnose disease of maize, is close related to *C. cereale* and has served as a model pathogen for *C. cereale* and other species in the genus *Colletotrichum*.

Infection on *P. annua* can occur almost any time of the year, but hot humid weather is most conducive to disease development (Smith et al., 1989; Vargas, 2005). An *in vitro* study indicated that the optimum growth of the fungus ranges from 21 to 31°C (Sprague and Evaul, 1930); and *in vivo* studies found that air temperatures up to 30°C and increasing leaf wetness increased disease severity (Danneberger et al., 1984; Vargas et al., 1993). Summer stresses such as high temperatures often shorten turfgrass roots and weaken plants (Fry and Huang, 2004). Stressed and weakened plants are more susceptible to infection and destructive damage caused by *C. cereale* (Landschoot and Hoyland, 1995; Murphy et al., 2012; Smiley et al., 2005; Sprague and Evaul, 1930; Vargas, 2005).

Cultural Management and Anthracnose Disease

Cultural practices have been found to affect disease management (Murphy et al., 2012). Nitrogen (Danneberger et al., 1983; Inguagiato et al., 2008; Smiley et al., 2005; Uddin et al., 2006) and potassium fertilization (Schmid et al., 2013) and repeated sand topdressing (Hempfling et al., 2015; Inguagiato et al., 2012, 2013; Roberts and Murphy,

2014) can substantially reduce anthracnose severity. On the contrary, insufficient irrigation (40% evapotranspiration) can enhance anthracnose disease (Roberts et al., 2011). Mowing annual bluegrass at 2.8 mm has been shown to increase anthracnose severity 3% to 21% compared with mowing at 3.6 mm (Inguagiato et al., 2009). Similar effect was seen by Uddin and Soika (2003); turf mowed at 4.3 mm had significantly less anthracnose than turf mowed at 3.0- and 2.0-mm. Unfortunately, due to elevated golfer demands for faster (longer ball roll distance) putting surfaces, the recent trend has been for golf course managers to mow putting greens lower and fertilize and irrigate them less than in the past (Mann and Newell, 2005; Murphy et al., 2008; Vermeulen, 2003). This change in management has enhanced the anthracnose disease severity over the past decade, making it difficult to control (Murphy et al., 2008).

Topdressing, verticutting and core aeration were suspected of predisposing turfgrass to anthracnose disease through abrasion and wounding (Dernoeden, 2012; Smiley et al., 2005). Laboratory experiment on maize with *C. graminicola* revealed that the pathogen was capable of penetrating and colonizing maize plants without wounds; although, this process was less efficient than infecting through wounds (Venard and Vaillancourt, 2007). Based on greenhouse experiments, Landschoot and Hoyland (1995) reported that inoculating annual bluegrass at wound sites on the crowns facilitated the development of anthracnose, whereas wounds made above the crown resulted in no obvious symptom of anthracnose. In field studies, the effect of wounding and mechanical injury caused by verticutting on anthracnose has varied. On a mixed stand of creeping bentgrass and annual bluegrass maintained as putting green, verticutting at either 3.3- or 5.1-mm increased disease severity compared to non-verticutting, however the turf was inoculated with *C. cereale* (reported as *C. graminicola*) 6 h after the treatment applications (Uddin and Soika, 2003). In another study, verticutting at 3.0 mm depth did not enhance anthracnose of annual bluegrass putting green turf, which was inoculated with *C. cereale* only before the initiation of the study, compared to non-verticutting (Inguagiato et al., 2008). With natural infestation of *C. cereale*, Hempfling (2013) reported that verticutting at 1.3 mm either had no effect or slightly reduced disease severity, whereas verticutting at 7.6 mm produced a 4% increase in disease on 2 of 32 observations over 2-year study compared to the non-verticutting control. Inguagiato et al. (2013) indicated that subtle wounding or bruising associated with several topdressing incorporation methods (vibratory rolling, soft bristled brush and stiff bristled brush) did not affect anthracnose severity on annual bluegrass putting green turf. Moreover, sub-angular sand, which causes more abrasion than rounded sand, did not enhance but occasionally reduced disease compared to round sand (Inguagiato et al., 2013). Furthermore, abrasion potentially caused by topdressing combined with foot traffic did not increase but slightly reduced disease (Roberts and Murphy, 2014). Limited knowledge of the infection and colonization process of *C. cereale* and concern about the impact of wounding has in the past prevented turf managers from implementing abrasive cultural management practices such as cultivation and sand topdressing.

Long-term sand topdressing programs have been shown to improve turf quality and actually suppress anthracnose severity of annual bluegrass putting green turf (Hempfling et al., 2015; Inguagiato et al., 2012, 2013; Roberts and Murphy, 2014). Sand topdressing applied weekly at 0.3 L m^{-2} or every two weeks at 0.6 L m^{-2} during the summer can substantially reduce anthracnose severity (Inguagiato et al., 2012). However, these relatively heavy summer topdressing rates on putting greens may be less likely to be adopted by golf course superintendents due to the disruption of the surface quality and playability, the high cost of material, equipment and labor, and concerns about wounding. In a subsequent study, summer topdressing applied every two weeks at 0, 0.075, 0.15, 0.3 and 0.6 L m^{-2} significantly reduced disease as rates increased, however this linear effect diminished in the end of the study (Hempfling, 2013). Topdressing at 1.2 and 2.4 L m^{-2} in the spring also suppressed anthracnose linearly compared to non-topdressed turf throughout most of the study (Hempfling, 2013). This suggests that combining low-rate summer topdressing with heavier-rate spring topdressing can be an effective and practical practice for disease reduction. As recommended by many researchers, heavy topdressing is also typically applied in the autumn on cool-season turfgrass greens (Beard, 2002; Christians et al., 1985; Cooper, 2004). However, the effects of autumn topdressing on anthracnose disease are not known.

The mechanisms by which sand topdressing suppresses anthracnose disease are not fully understood. Over time, topdressing may dilute the inoculum in the thatch thus potentially reducing disease (Madison et al., 1974a; Sprague and Evaul, 1930). Topdressing sand also reduces surface moisture (Henderson et al., 2010), and most fungal pathogens require extended periods of wetness on plants or high relative humidity in the atmosphere for spore release and germination (Agrios, 2005; Smiley et al., 2005). Sand topdressing may also reduce anthracnose indirectly. Annual bluegrass tillers from topdressed plots had larger and deeper crowns than tillers from non-topdressed plots (Inguagiato et al., 2012). Moreover, topdressing provides a better growing medium for turf, burying and protecting crowns and leaf sheaths, thereby enhancing plant vigor

(Inguagiato et al., 2012). Another important aspect of topdressing is that it firms and smooths the putting surface effectively raising the cutting height and better supporting the mower (Inguagiato et al., 2012). Increased cutting height has been shown to reduce anthracnose severity (Inguagiato et al., 2009).

Sand topdressing also affects other diseases. Hawes (1980) reported that sand topdressing reduced spring dead spot on bermudagrass mowed at 2.5 cm. Henderson and Miller (2010) observed less dollar spot (*Sclerotinia homoeocarpa* F.T. Bennett) incidence with topdressing treatments in their creeping bentgrass fairway trial; however, Stier and Hollman (2003) suggested that sand topdressing did not affect dollar spot disease on creeping bentgrass and annual bluegrass putting greens.

Chemical Control of Anthracnose

Fungicides are frequently used on golf course to control of *C. cereale*. Preventive fungicide applications are far more effective than curative applications to control anthracnose (Murphy et al., 2008; Smiley et al., 2005; Towers et al., 2003). However, best timing for preventive applications is not known due to the lack of knowledge of the disease cycle and epidemiology of the pathogen (Crouch and Clarke, 2012). Curative fungicide program can fail once crowns of turf are severely infected with anthracnose (Vargas, 2005). Benzimidazoles, dicarboximides (e.g., iprodione), DMIs (demethylation inhibitors), chloronitriles, phenylpyrrolles, phosphonates, polyoxins and QoIs (strobilurins) fungicides are recommended for the control of anthracnose in turfgrass (Vincelli, 2015). Unfortunately, reduced sensitivity and increased resistance to the benzimidazoles (Detweiler et al., 1989; Wong et al., 2008), QoIs (Avila-Adame et al., 2003; Wong et al., 2007; Young et al., 2010), and DMIs (Wong and Midland, 2007) fungicides chemistries have been reported. Fungicide resistance as well as poor cultural management such as inadequate topdressing practices can reduce the effectiveness of fungicide programs (Murphy et al., 2012).

Research Objectives

This research will provide information to develop a comprehensive topdressing program for golf course putting greens, including topdressing sand selection, rate and timing of applications. The objectives of this research were to

1. Determine effects of sand particle size distribution and application rate on the efficiency of sand incorporation, turfgrass quality, surface hardness and strength, root zone water retention and infiltration of velvet bentgrass putting green turf.
2. Evaluate the impact of topdressing sand particle size distribution, rate and timing of applications on anthracnose disease, turf quality, efficiency of sand incorporation, surface hardness and strength, root zone water retention and organic matter production of annual bluegrass putting green turf.

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CHAPTER 1. Impact of Sand Size and Topdressing Rate on Turf Surface Characteristics and Hydraulic Properties of Velvet Bentgrass Putting Green Turf

ABSTRACT

Topdressing sand is applied to smooth the surface of putting greens and maintain desirable root zone characteristics. The particle size of sand can impact the ability to incorporate topdressing into the turf canopy, and unincorporated sand can interfere with mowing and play on putting greens. A field trial was initiated July 2010 on 'Greenwich' velvet bentgrass (*Agrostis canina* L.) turf to determine the effect of topdressing rate and sand size on incorporation, turf quality, surface hardness and strength, volumetric water content and infiltration. Treatments were arranged in a 2 x 2 factorial and included an untreated control arranged in a randomized complete block design. The two factors were topdressing sand—medium-coarse and medium-fine sand—and topdressing rate—0.15 and 0.3 L m^{-2}. Initially, there was no turf response to topdressing; however, once responses occurred, topdressed typically improved turf quality compared to the non-topdressed control. Topdressing rate had a greater influence on turf quality than sand size; plots topdressed at 0.3 L m^{-2} had better quality than plots receiving the 0.15 L m^{-2} rate on 69% of the observation dates. Additionally, topdressing with medium-fine sand produced equivalent or better turf quality than plots topdressed with medium-coarse sand. As expected, medium-coarse sand was more difficult to incorporate compared to the medium-fine sand. Increasing topdressing rate from 0.15 to 0.3 L m^{-2} dramatically increased the quantity of unincorporated sand remaining on the turf surface with medium-coarse sand, whereas it often did not increase or only slightly increased the quantity of unincorporated medium-fine sand. In 2011, topdressing treatments did not affect surface

hardness measured with a 2.25-kg hammer, but topdressing decreased surface hardness for 50% of the measurements in 2012 and all measurements in 2013. However, topdressing reduced hardness on only 14% of the observation dates throughout the study when measured with a 0.5-kg hammer. Interestingly, topdressing did not reduce surface hardness on most dates when measured with a 0.5-kg hammer at the reduced height of 10 cm but occasionally increased surface hardness. Differences in surface hardness between topdressing rates and sand sizes were subtle and inconsistent when measured with either hammer. Furthermore, topdressing was observed to consistently decrease surface penetration depth during 2012 and 2013 when measured with a depth measuring penetrometer. Topdressing rate had a greater impact on decreasing penetration depth than sand size. Increasing topdressing rate from 0.15 to 0.3 L m^{-2} decreased the penetration depth on 89% of the observations. Medium-fine sand produced equivalent (82% of the dates) or reduced (18% of the dates) penetration depth compared to medium-coarse sand. Volumetric water content (VWC) at the 0–3.8 cm depth was lower in topdressed plots than control plots on 50% of the observation dates. Very few differences in VWC were found among sand sizes or topdressing rates. In 2013, all sand treatments significantly increased water infiltration at near-saturation (pressure potential of –0.5 cm) measured with mini disk infiltrometers, as well as saturated hydraulic conductivity, indicating that topdressing increased macroporosity at surface root zone. The lack of negative effects of medium-fine sand on measured parameters and the minimum disruption to the putting surface, even at higher topdressing rates, may encourage superintendents to apply greater quantity of topdressing during the summer months.

INTRODUCTION

Sand is often found in the mower clippings due to frequent topdressing (Johnston et al., 2005; Kauffman et al., 2011; Kreuser et al., 2011; Stier and Hollman, 2003; Taylor, 1986). The interruption to play and excessive wear on mowers can discourage golf course superintendents from implementing a routine topdressing program during the summer months. Velvet bentgrass (*Agrostis canina* L.) has very fine texture, high shoot density, and tends to accumulate excess thatch creating puffiness on greens (Boesch and Mitkowski, 2007). Proper management of velvet bentgrass requires a more aggressive topdressing program for diluting or/and removing thatch than other bentgrasses. However, the high shoot density of velvet bentgrass and the extremely low mowing heights of modern putting greens make it challenging to maintain a smooth, sand free putting surface when topdressing sand is applied at high rates.

Brushing or irrigating following topdressing is used to move sand particles into the turf canopy with varying degrees of success. Ultra-light applications (< 0.15 L m^{-2}) of sand have been adopted on putting greens to eliminate the problem of poor sand incorporation. However, ultra-light rates of topdressing need to be applied more frequently to achieve the same total quantity of sand applied, otherwise the benefits of topdressing may not be realized (Murphy et al., 2012; Vavrek, 2007). Applying topdressing more frequently at lower application rates can also substantially increase operational cost. Vertical mowing before topdressing applications is a commonly used practice to assist in sand incorporation by opening-up the turf canopy (Boesch and Mitkowski, 2007; Foy, 1999; Stier and Hollman, 2003). In addition to brushing, vibratory rolling can be used to enhance topdressing incorporation on ultradwarf bermudagrass

[*Cynodon dactylon* (L.) × *C. transvaalensis* Burtt Davy] putting greens (Kauffman et al., 2011). Recently, some golf courses have adopted the use of finer (medium-fine) sands to improve the incorporation of topdressing sand (Murphy, 2012; Pippin, 2010). However, hydraulic properties have been a concern with the use of medium-fine sand. Excess accumulation of fine sand in the root zone of a putting green can reduce air-filled porosity and saturated hydraulic conductivity (K_{sat}) compared to coarse or coarse-medium sand (Murphy et al., 2001). Moeller (2008) reported that core aeration and topdressing with a medium-fine sand reduced water infiltration compared to core aeration and topdressing with a medium-coarse sand measured with a pressure infiltrometer.

Tension and pressure infiltrometers are commonly used field methods to estimate hydraulic conductivity, however these methods can yield different measures of saturated conductivity (Reynolds et al., 2000). The pressure infiltrometer has been used predominately in turf research. Gibbs (1993) described the use of a tension infiltrometer with a disc diameter of 20.5 cm on synthetic sports turf but, in general, the use of tension infiltrometers is limited in turf systems. The mini-disk infiltrometer, a type of tension infiltrometer, can be repeatedly used to assess unsaturated hydraulic properties on relatively small plot areas on putting green turf due to its compact size and the fact that it does not disturb the surface. Good hydraulic connection between the infiltrometer and the soil has always been a concern with tension infiltrometers, thus removal of surface vegetation or/and the use of contact sand is often needed to ensure good contact (Perroux and White, 1988). However, these methods can disturb the turf surface and introduce sand contamination to topdressing treatments. Using a small size disk is more likely to avoid uneven turf surface conditions, therefore, improving contact with the turf surface.

Given that the measurements are representing small areas, the variation among measurements using a mini disk infiltrometer is probably greater than using regular tension infiltrometers; this can be compensated for by increasing the number of measurements per plot.

There has been very limited research on the impact of medium-fine sand topdressing on turfgrass performance and soil physical properties. Henderson and Miller (2010) reported that creeping bentgrass (*Agrostis stolonifera* L.) fairway turf topdressed with fine and medium sands had greater surface strength than coarse sand. Additionally, the finer sand tended to retain more water in the top 5 cm of the root zone (Henderson et al., 2010). Moeller (2008) reported that core aeration twice a year and topdressing (after coring or frequently during the summer) with a medium-fine sand (finer than the underlying root zone) resulted in an increase of fine sand (0.15–0.25 mm) at the 0–5.7 cm depth of the root zone. He also found that core aeration and topdressing with a medium-fine sand reduced surface hardness (0.5-kg hammer) compared to core aeration and topdressing with a medium-coarse sand. However, medium-fine sand did not impede turfgrass performance; in fact, turf color was sometimes improved likely due to greater water retention (Moeller, 2008). Concerns about the potential detrimental effects from the use of finer sand for topdressing should not be overlooked. Finer-texture sand layered over coarse-texture sand has the potential to restrict water movement at the interface of the layers (Christians, 2011). Excess fine sand in the root zone of a putting green can reduce saturated hydraulic conductivity (Murphy et al., 2001; Paul et al., 1970). Additional research is needed to investigate the effects of medium-fine sand on the performance characteristics of turf before medium-fine sand topdressing can be recommended on golf courses.

The objectives of this research were to determine effects of sand particle size distribution and application rate on turfgrass quality, efficiency of sand incorporation, surface hardness, root zone water retention and infiltration on a velvet bentgrass putting green turf with excessive thatch and a puffy turf surface.

MATERIALS AND METHODS

Research Methodology

The trial was initiated in July 2010 on a 7-year-old 'Greenwich' velvet bentgrass (*Agrostis canina* L.) putting green turf at the Rutgers Hort. Farm No. 2 in North Brunswick, NJ. The field had been previously topdressed with medium-coarse sand conforming to USGA guidelines (United States Golf Association Green Section Staff, 2004), and developed approximately a 50 mm deep topdressing layer on top of a Nixon sandy loam soil (fine-loamy, mixed, mesic Typic Hapludaults). Topdressing and cultivation had been insufficient and resulted in excessive thatch build-up that contributed to a puffy turf surface.

Treatments were arranged in a 2 x 2 factorial and included an untreated control in a randomized complete block design with three replications. The two factors were topdressing sand—medium-coarse and medium-fine sand (U.S. Silica, Co., Mauricetown, NJ)—and topdressing rate—0.15 and 0.3 L m^{-2}. Treatments were initiated in July 2010 and applications were applied weekly from 1 July to 28 August and on 21 September and additional quadruple rates (0.6 and 1.2 L m^{-2}) of sand were applied on 11 November to promptly build up a topdressing layer in the first year (2010). Thereafter, topdressing treatments were applied every two weeks from 13 June to 21 Sept. 2011, 10 May to 10 Oct. 2012 and 20 May to 14 Nov. 2013. Additional applications of sand were applied in spring and autumn to match the growth of the turf (thatch accumulation) at 0.15 and 0.3 L m^{-2} on 10 Apr. and 16 Nov. 2012, 11 Apr. and 1 May 2013; at double rates (0.3 and 0.6 L m^{-2}) on 21 Oct. and 7 Nov. 2011; and at quadruple rates (0.6 and 1.2 L m^{-2}) on 5 May 2011. The annual total quantities of sand applied for the two topdressing treatment rates were 2.1 and 4.2 L m^{-2} in 2010, 2012 and 2013, 2.4 and 4.8 L m^{-2} in 2011, respectively. Sand was measured for each treatment and applied with drop spreader (model SS-2, The Scotts Company, Marysville, OH) and incorporated immediately after topdressing with a stiff-bristled brush (Harper Brush Works, Inc., Fairfield, IA).

General Field Maintenance

Water-soluble nitrogen sources were applied every two weeks at 4.9 kg ha^{-1} from April to October and at heavier rates of 9.8 to 24.4 kg ha^{-1} in spring and autumn with the total of 134.3, 117.2, 87.9, 131.8 kg ha^{-1} of N in 2010, 2011, 2012 and 2013, respectively, using urea, ammonium nitrate or ammonium sulfate. Soil pH, P and K were managed based on soil test recommendations common for putting greens in the northeastern United States.

Turf was mowed daily with clippings collected during the growing season using a triplex greens mower (model 3150, Toro Co., Bloomington, MN) at bench-setting of 2.8 mm. Plots were rolled 3 to 5 times a week with a smooth pavement roller (1.7 metric ton tandem vibratory roller, Model RD11A, Wacker Neuson, Germany) to smooth the surface and to simulate traffic. Overhead irrigation and hand watering were applied to obtain moderately dry and uniform soil water content similar to a golf course setting. Sand topdressing was not applied as a broadcast application to the entire study. Fungicides were applied as needed to avoid disease damage. Chlorothalonil (tetrachloroisophthalonitrile) was applied at 10.1 kg a.i. ha^{-1} on 10 May 2011, 23 May 2012, 13 Oct. 2012 and 27 May 2013; at 8.2 kg a.i. ha^{-1} on 29 June 2012, 14 July 2012, 12 Aug. 2012 and 2 Oct. 2013; at 12.6 kg a.i. ha^{-1} on 1 Sept. 2012 and 3 Sept. 2013. Fosetyl-Al (O-ethyl phosphonate) was applied at 9.8 kg a.i. ha^{-1} on 29 June and 14 July

2012 in the mixture with chlorothalonil. Vinclozolin [3-(3,5-dichlorophenyl)-5-ethenyl-5-methyl-2,4- oxazolidinedione] was applied at 1.5 kg a.i. ha^{-1} on 31 May 2011 and 13 July 2013. Flutolanil {N-[3-(1-methylethoxy)phenyl]-2-(trifluoromethyl)benzamide} was applied at 6.4 kg a.i. ha^{-1} on 12 June 2011, 26 July 2012 and 25 Aug. 2012. Mefenoxam [*N*-(2,6-dimethylphenyl)-*N*-(methoxyacetyl)-*D*-alanine methyl ester] was applied at 0.77 kg a.i. ha^{-1} on 25 May 2011, 13 Oct. 2012, 3 July 2013, 1 Oct. 2013, 16 Oct. 2013 and 30 Oct. 2013. Triadimefon {1-(4-Chlorophenoxy)-3,3-dimethyl-1-(1H-1,2,4-triazol-1-yl)-2-butanone} was applied at 3.2 kg a.i. ha^{-1} on 4 and 18 Apr. 2012, 11 Apr. 2013 and at 1.6 kg a.i. ha^{-1} on 31 Oct. 2013. Cyazofamid [4-chloro-2-cyano-*N,N*-dimethyl-5-(4-methylphenyl)-1*H*-imidazole-1-sulfonamide] at 0.95 kg a.i. ha^{-1} and polyoxin D zinc salt at 0.3 kg a.i. ha^{-1} were applied on 29 July and 12 Aug. 2012, respectively. Tebuconazole (α-[2-(4-chlorophenyl)ethyl]-α-(1,1-dimethylethyl)-1H-1,2,4-triazole-1-ethanol) was applied at 0.9 and 0.7 kg a.i. ha^{-1} on 7 Aug. and 2 Oct. 2013, respectively. Fluoxastrobin {[(1*E*)-[2-[[6-(2-Chlorophenoxy)-5-fluoro-4- pyrimidinyl]oxy]phenyl]-5,6-dihydro-1,4,2-dioxazin-3-yl) methanone-*O*-methyloxime} was applied at 0.55 kg a.i. ha^{-1} on 13 July and 2 Aug. 2013. Metconazole 5-[(4-chlorophenyl)methyl]-2,2-dimethyl-1- (1H-1,2,4-triazol-1-ylmethyl)cyclopentanol was applied at 0.56 kg a.i. ha^{-1} on 19 Sept. 2013. Boscalid {3-pyridinecarboximide, 2-chloro-N-[4’chloro(1,1’- biphenyl)yl]} was applied at 0.4 kg a.i. ha^{-1} on 2 Aug. 2013. To control insects, indoxacarb {(S)-methyl 7-chloro-2,5-dihydro-2-[[(methoxycarbonyl)[4(trifluoromethoxy)phenyl]amino]-carbonyl]indeno[1,2-ae][1,3,4]oxadiazine-4a-(3H)-carboxylate} at 0.04 kg a.i. ha^{-1} was applied on 29 Sept. 2012, and chlorantraniliprole {3-Bromo-N-[4-chloro-2-methyl-6-

[(methylamino)carbonyl]phenyl]-1-(3-chloro-2-pyridinyl)-1H-pyrazole-5-carboxamide} at 0.06 and 0.12 kg a.i. ha^{-1} was applied on 30 June 2012 and 10 May 2013, respectively.

Data Collection

Visual evaluation of turf quality was assessed based on plant density, uniformity and disease severity on a 1–9 scale, where 9 represented the best turf quality and 5 was the minimum acceptable quality. Color was not included as a component of turf quality. Turf color was rated visually on a scale of 1–9, where 9 represented the darkest green color and 5 was an acceptable green color.

The completeness of sand incorporation after topdressing was assessed visually on a 1 to 9 scale, 9 represented complete incorporation of sand into the turf canopy and 5 represented a visible but acceptable quantity of sand remaining (unincorporated) on the canopy surface. Incorporation of sand was also documented with a digital camera (Canon PowerShot G12, Canon USA, Inc., Melville, NY) attached to a metal light box with dimensions of 61 cm (length) × 51 cm (width) × 56 cm (height) with four 13 Watt compact fluorescent bulbs (Model BLDS139355T, BlueMax Lighting, Jackson, MI) inside similar to what described by Karcher and Richardson (2013). This allowed images to be taken at a consistent height and artificial light conditions (5500 Kelvin, 900 lumens and 93 color rendering index). The camera was set at a focal length of 7.4 mm, aperture of F2.8 and shutter speed of 1/50 s. One digital image was taken from the center of each plot. Images were 1200 × 1600 pixels and were saved in JPEG format.

Post-topdressing clippings were collected the day after topdressing with a walk behind mower (Toro Greensmaster® 1000, Bloomington, MN) at bench-setting of 3.4 mm equivalent to daily mowing with a triplex greens mower (model 3150, Toro Co., Bloomington, MN) at bench-setting of 2.8 mm. Clipping samples were dried at 55°C for 72 h and combusted in a muffle furnace at 600°C for 4 h. Sand was separated from ash using a sieve with a 106 μm opening and weighed as described by Johnston et al. (2005).

The 2.25- and 0.5-kg Clegg Impact Soil Testers (Models 95049 and 95048A, respectively, Lafayette Company, Lafayette, IN) were used to measure surface hardness. The maximum deceleration of a single drop of the 2.25- or 0.5-kg hammer from a 46- or 30-cm height, respectively, was recorded four times per plot. Maximum deceleration was recorded in gravities (g_{max}) and the four measurements for each plot were averaged before statistical analysis. The 0.5-kg hammer was also dropped from 10- and 20-cm heights. In 2012, a depth-measuring micrometer (F2750-1 Wisdom 2700 Electronic Indicator 65847, The L.S. Starrett Company, Athol, MA) was modified to function as a shallow depth measuring penetrometer to assess surface strength. A flat metal base was mounted to the micrometer to serve as a standing base and zero reference for the upper height of the turf canopy. This penetrometer measures the penetration depth of the 4.5-mm diameter probe with an applied pressure of 262 kPa. The shorter penetration depth, the greater surface strength (resistance to penetration). The average of eight depth measurements taken per plot was used for statistical analysis. Volumetric water content (VWC) was measured simultaneously with surface hardness and strength using a time domain reflectometry (Field Scout TDR 300 model, Spectrum Technologies, Inc., Plainfield, IL) equipped with two 38 mm probes. The average of four VWC measurements taken per plot was used for statistical analysis.

Water infiltration was measured using mini disk infiltrometers with 4.5 cm diameter disks (Decagon Devices, Inc.©) customized with support stands (Fig. 1.1).

Three metal support legs were held in grooves in a metal ring clamping around the infiltrometer tube to keep the infiltrometers upright during measurement. Infiltrometers were automated by using differential pressure transducers connected to a data logger, as described by Madsen and Chandler (2007). One port of the differential pressure transducer was installed at the bottom position of the reservoir and the other port was connected, using tubing, to the head-space of the reservoir (top of the lower chamber). Based on research conducted by Ankeny et al. (1988) who showed a direct linear relationship between the height of water in the infiltrometer reservoir and the pressure difference between the two ports connected to the transducers; each pressure transducer was calibrated by placing a bottom-sealed infiltrometer on a balance and determining the linear relationship between the volume of water in the reservoir and the differential pressure transducer output voltage (Fig. A.1). Voltage outputs were recorded every 1 s during calibration and weights of water was recorded whenever water was added or removed from the reservoir.

In-situ infiltration measurements were initiated at the lowest pressure potential of –5.5 cm and sequentially at higher pressure potentials (less negative) of –3.5, –2.5, –1.5, and –0.5 cm at the same location (Jarvis and Messing, 1995; Logsdon and Jaynes, 1993; Reynolds et al., 2000; Reynolds and Elrick, 1991; Simunek et al., 1998). Infiltration was measured for 25 min at a pressure potential of –5.5 cm and for 15 min at each of the other pressure potentials used. Pressure transducers were read every 3 s. The different test lengths were used to ensure enough water was used for each test and that an accurate measurement of steady-state infiltration was obtained. Infiltration into dry soil at lower (more negative) pressure potentials sometimes was slow and infiltration did not appear to reach a steady state; in such cases, infiltration measurements were extended and the duration of the test was noted. Infiltrometers were stopped in between tensions for 2 min. Water temperature was recorded every 30 min.

Data Analysis

Digital images were analyzed with a SigmaScan Pro (v. 5.0, SPSS, Inc., Chicago, IL) software based on the macro developed by researchers at the University of Arkansas (Karcher and Richardson, 2003, 2005; Richardson et al., 2001); however, instead of using hue and saturation, a color intensity (gray scale) threshold range was used to select sand particles remaining on the turf surface and measure the percentage of turf area covered by unincorporated sand. Hietz (2011) used the intensity threshold function in SigmaScan to measure and analyze tree rings; ring boundaries were detected as an abrupt change from high (lighter early-wood) to low intensity (darker late-wood). In our case, the high intensity white sand was differentiated from the lower intensity green turfgrass.

The voltage readings recorded every 3 s from the differential transducers were converted to depth of water in the infiltrometers using laboratory transducer calibrations to calculate the amount of water that infiltrated into soil (cumulative infiltration, cm). Data were smoothed using the Savitzky and Golay (1964) filter; steady-state infiltration rate i (cm d^{-1}) was calculated as the derivative of cumulative infiltration at each tension using R-project (Fig. A.2). Steady state of water infiltration was determined when the second derivative of cumulative infiltration was equal to zero. Values of infiltration rates (i) were expressed at a standard temperature of 20°C by correcting for the effect of temperature on the viscosity (η) and density (ρ) of water (Iwata et al., 1988):

$$i_{20} = i_T \times \frac{\eta_T / \rho_T}{\eta_{20} / \rho_{20}} \qquad [1]$$

where subscripts 20 and T represent water temperature at standard conditions (20°C) and during field measurements, respectively. Five infiltrometer measurements within each plot were pooled using geometric means.

Saturated hydraulic conductivity K_{sat} was calculated using a non-linear regression technique developed by Logsdon and Jaynes (1993). Unsaturated hydraulic conductivity K(h) at a given supply pressure potential –h is was obtained from the exponential function (Gardner, 1958):

$$K(h) = K_{sat} \exp(\alpha h) \qquad [2]$$

where α is the exponential slope of the function. Wooding's (1968) formula for steady state infiltration from a circular source with radius r under a constant pressure potential of –h, i(h), is:

$$i(h) = (1 + 4/\pi r\alpha)\, K(h) \qquad [3]$$

Combining [2] and [3] gives (Logsdon and Jaynes, 1993):

$$i(h) = (1+4/\pi r\alpha)\, K_{sat} \exp(\alpha h) \qquad [4]$$

where i(h) is expressed in cm d^{-1}. A nonlinear least squares regression of equation [4] to i(h)-h pair data was used to estimate α and K_{sat} using bootstrap (Efron, 1979). To do this, we randomly sampled the observed dataset with replacement for 1000 times, computed α and K_{sat} for each of these bootstrap samples using nonlinear least square function in R-project and reported the mean of α and K_{sat} from bootstrap estimates.

Pores with effective pore radii r greater than equivalent pore radii of the applied pressure potential –h do not receive water from the infiltrometer. Thus, pore radii can be estimated using the capillary rise equation,

$$h = \frac{2\gamma \cos\theta}{\rho g r} \qquad [5]$$

where γ is liquid–air surface tension (force/unit length), θ is the contact angle, ρ is the density of liquid, and g is local acceleration due to gravity. If assumed standard condition, $\gamma = 0.0728$ N m^{-1} at 20°C, $\theta = 0°$, $\rho = 1000$ kg m^{-3}, and g = 9.81 m s^{-2}, therefore the corresponding pore radii (r) to the applied pressure potentials of –5.5, –3.5, –2.5, –1.5 and –0.5 cm are 0.27, 0.42, 0.59, 0.99 and 2.96 mm, respectively.

Data were subjected to analysis of variance using the General Linear Model procedure in the Statistical Analysis System software v. 9.3 (SAS Institute Inc., Cary, NC), and Fisher's protected LSD at the 0.05 probability levels was used to determine treatment differences. In the analysis, the factorial structure (sand size × topdressing rate) was nested within the factor topdressing (topdressing or non-topdressing).

RESULTS

Turf Quality

Sand topdressing every two weeks provided better turfgrass quality than non-topdressed control on 60 of 67 rating dates in 2011, 2012 and 2013 (Tables 1.2a, 1.2b, 1.3a, 1.3b, 1.4a and 1.4b). Topdressing rate had a greater impact on turf quality than sand size. Plots topdressed at 0.3 L m^{-2} had better turfgrass quality than plots topdressed at 0.15 L m^{-2} on 46 of 67 rating dates and had lower quality ratings on 7 rating dates (Tables 1.2a, 1.2b, 1.3a, 1.3b, 1.4a and 1.4b). The medium-fine sand produced turf quality equivalent to the medium-coarse sand plots on most rating dates and better quality on 10 dates (Tables 1.2a, 1.2b, 1.3a, 1.3b, 1.4a and 1.4b). Topdressing rate and sand size interacted five times during the study. Varying sand size did not significantly affect turf quality when sands were applied at 0.15 L m^{-2}; however the plots topdressed with medium-fine sand exhibited better turf quality than those topdressed with medium-coarse sand when sands were applied at 0.3 L m^{-2} (Table 1.5).

Sand Incorporation

Visual ratings indicated that both sand size and rate significantly affected sand incorporation (Tables 1.6, 1.7 and 1.8). The 0.15 L m^{-2} rate of topdressing and medium-fine sand both incorporated better into the turf canopy after topdressing compared to the 0.3 L m^{-2} rate and the medium-coarse sand, respectively (Tables 1.6, 1.7 and 1.8). Interaction effects (13 of 31 dates) indicated that increasing the medium-coarse sand rate from 0.15 to 0.3 L m^{-2} dramatically decreased sand incorporation (Table 1.9). Whereas, increasing the medium-fine sand rate from 0.15 to 0.3 L m^{-2} did not affect sand incorporation or decreased sand incorporation to a lesser extent than medium-coarse sand

(Table 1.9).

Sand size and topdressing rate affected incorporation of sand immediately after topdressing and brushing (0 dat; Tables 1.10, 1.11 and 1.12) on 8 and 9 of 10 observations, respectively, as assessed with digital image analysis during 2011, 2012 and 2013; a substantially greater quantity of unincorporated sand was observed in August, September and October than in July (Tables 1.10, 1.11 and 1.12). The 0.3 L m^{-2} rate of topdressing and the medium-coarse sand both required more time for sand to dissipate from the turf surface after topdressing compared to the 0.15 L m^{-2} rate and medium-fine sand, respectively (Tables 1.10, 1.11 and 1.12). Interactions occurred during 7 of 10 topdressing events evaluated with digital image analysis during 2011, 2012 and 2013 (Tables 1.10, 1.11 and 1.12). Increasing topdressing rate from 0.15 to 0.3 L m^{-2} dramatically increased the quantity of unincorporated sand remaining on the turf surface with medium-coarse sand, whereas it often did not increase or slightly increased the quantity of unincorporated sand with medium-fine sand (Tables 1.13, 1.14 and 1.15). When applied at 0.3 L m^{-2}, medium-fine sand was much better incorporated than medium-coarse sand; when applied at 1.5 L m^{-2}, medium-fine sand was found to be similar or only slightly better incorporated compared to medium-coarse sand (Tables 1.13, 1.14 and 1.15).

Mower clippings were collected after topdressing on three dates each year in 2011, 2012 and 2013. Both topdressing rate and sand size significantly affected the quantity of sand removed by mowing (Table 1.16). Topdressing rate and sand size interacted on all dates in the study (Table 1.16). Consistent with visual observations of unincorporated sand, increasing the medium-coarse sand rate from 0.15 to 0.3 L m^{-2}

significantly increased the quantity of sand picked up with the mower clippings (Table 1.17). There was no significant increase in sand removal between these rates when topdressing with medium-fine sand (Table 1.17). At the rate of 0.3 L m^{-2}, medium-fine sand always incorporated better than medium-coarse sand, whereas at the rate of 0.15 L m^{-2}, medium-fine sand only incorporated better than medium-coarse sand on 4 of 9 rating dates (Table 1.17). Only small quantities of sand particles were collected from non-topdressed treatments, which was due to contamination from adjacent sand treated plots during mowing (Table 1.16).

Surface Hardness and Strength

Surprisingly, surface hardness rarely increased among topdressing treatments as measured by the Clegg Impact Soil Tester (CIST). Topdressing treatments did not affect surface hardness in 2011 when using either the 2.25- or 0.5-kg hammer (Tables 1.18 and 1.21). Hardness decreased on 50% of the 2.25-kg hammer measurements for topdressed plots compared to non-topdressed plots in 2012 (Table 1.19), and on all dates in 2013 (Table 1.20). Topdressing decreased hardness for 21% of the 0.5-kg hammer measurements compared to non-topdressed during 2012 and 2013 (Tables 1.22 and 1.24). Increasing topdressing rate decreased surface hardness as measured with the 0.5-kg hammer on 2 of 28 dates but increased surface hardness on 1 date during 2011, 2012 and 2013 (Tables 1.21, 1.22 and 1.23). A surface hardness response to sand size was detected by the 0.5-kg hammer on 17 June 2013; plots receiving medium-fine sand had greater hardness than plots receiving medium-coarse sand (Table 1.24).

Interestingly, topdressing did not reduce surface hardness on most of the measurement dates when measured with 0.5-kg hammer at the reduced height of 10 cm but increased surface hardness on 2 of 20 dates (Tables 1.21, 1.24 and 1.25). On one of those two observations, topdressing at 0.3 L m^{-2} increased surface hardness compared to topdressing at 0.15 L m^{-2} (Table 1.25). Plots treated with medium-fine sand exhibited greater surface hardness than turf receiving medium-coarse sand on only one observation date (17 June 2013; Table 1.25). The surface hardness response to the interaction of topdressing rate and sand size was observed twice during the study but indicated different effects. On 16 May 2013, increasing topdressing rate from 0.15 to 0.3 L m^{-2} increased surface hardness only when applied with medium-fine sand; on 20 Sept. 2013, topdressing with medium-coarse sand produced greater surface hardness compared to topdressing with medium-fine sand only when sands were applied at 0.15 L m^{-2} (Table 1.26)

Topdressing was observed to consistently decreased penetration depth on 17 of 18 dates during 2012 and 2013 when measured with the fabricated penetrometer (Tables 1.27 and 1.28). The topdressing rate main effect had a greater impact on penetration depth than the sand size main effect. Increasing topdressing rate from 0.15 to 0.3 L m^{-2} decreased penetration depth on 16 of 18 dates during 2012 and 2013 (Tables 1.27 and 1.28). Medium-fine sand decreased penetration depth to a larger extent than medium-coarse sand on 3 of 18 dates (Tables 1.27 and 1.28). Interaction effects for penetration depth occurred twice in 2013, which indicated that penetration depth was shorter when plots were topdressed with medium-fine sand compared to medium-coarse sand at the topdressing rate of 0.3 L m^{-2} (Table 1.29). These interactions also indicated that penetration depth was greater in plots topdressed with the 0.15 L m^{-2} rate compared to 0.3 L m^{-2} only when medium-fine sand was applied (Table 1.29).

Volumetric Water Content

Topdressing reduced the volumetric water content (VWC) of topdressed plots compared to non-topdressed plots on 19 of 41 observations in 2011, 2012 and 2013 (Tables 1.30a, 1.30b, 1.31 and 1.32). The main effects of topdressing rate and sand size had limited effects on VWC (3 and 1 date, respectively). Plots topdressed with sand at 0.3 L m^{-2} had lower VWC than those topdressed at 0.15 L m^{-2} (Tables 1.31 and 1.32). Moreover, plots topdressed with medium-coarse sand decreased VWC by an average of 0.02 m^3 m^{-3} compared to plots topdressed with medium-fine sand (Table 1.32).

Infiltration

Infiltration was not statistically different among sand sizes and topdressing rates at all tensions in the study (Table 1.33). The pooled steady-state infiltration rate from all topdressing treatments was marginally ($p < 0.1$) higher than untreated control at –1.5 cm tension (Table 1.33). All sand treatments significantly increased steady-state infiltration rate at –0.5 cm tension compared to the non-topdressed control (Table 1.33). Regardless of sand size and rate, topdressing increased estimated K_{sat}; however, estimated α did not differ among treatments (Table 1.33).

DISCUSSION

Topdressing with either medium-coarse or medium-fine sand improved overall performance of velvet bentgrass turf except when a significant quantity of sand particles remained on the turf surface. Sand particles on the turf surface can substantially decrease visual and putting surface quality. Improved turf quality with sand topdressing has also been reported in numerous studies with other grass species (Henderson and Miller, 2010; Inguagiato et al., 2012; Madison et al., 1974; Rieke et al., 1988; Whitlark et al., 2001).

Topdressing rate had a greater impact than sand size on improving performance, which has also been observed on creeping bentgrass fairway by Henderson and Miller (2010). In our study, heavier topdressing rate often produced better turf quality except on seven observations immediately after topdressing when sand, particularly medium-coarse sand, reduced turf quality due to large sand particles remaining on the turf surface (Tables 1.2a, 1.2b, 1.3a, 1.3b, 1.4a and 1.4b). Similarly in another study on a velvet bentgrass green, plots received 1.0 L m^{-2} of sand every two weeks exhibited better turf quality than plots received 0.5 L m^{-2} of sand every two weeks (Espevig et al., 2012). Inguagiato et al. (2012) reported that increasing topdressing rate increased turf quality and decreased anthracnose disease on an annual bluegrass [*Poa annua* L. f. *reptans* (Hausskn) T. Koyama] putting green. Increasing topdressing rate also improved green up of a creeping bentgrass fairway in the spring and increased turf color throughout the growing season (Henderson and Miller, 2010). In our study, medium-fine sand occasionally produced better turf quality than medium-coarse sand. Improved turf establishment and turf color were speculated to be the result of greater water retention associated with medium-fine sands (Moeller, 2008; Murphy et al., 2001; Neylan and

Robinson, 1997). However, increased VWC was only observed once with medium-fine sand treatment throughout our study.

We found that a greater rate of medium-fine sand can be applied without a substantial increase in the quantity of sand removed by mowing. Daily mowing on golf courses often removes sand particles remaining on putting surface from routine topdressing (Johnston et al., 2005; Murphy, 2012; Stier and Hollman, 2003; Taylor, 1986). Coarse (0.5–1.0 mm) and very coarse (1.0–2.0 mm) sand particles are more likely to be removed by mowing than particles less than 0.5 mm in diameter (Stier and Hollman, 2003; Taylor, 1986). In our study, the medium-coarse sand contained 31% of particles larger than 0.5 mm in diameter whereas medium-fine sand did not contain particles above 0.5 mm. Similar to what Taylor (1986) reported, substantially greater quantities of medium-coarse sand were removed by mowing than medium-fine sand in our study. Although both sands were applied at the same rate, medium-fine sand was better incorporated into the turf canopy, whereas greater quantities of medium-coarse sand were removed by daily mowing. Overtime, this process could possibly contribute to lower quantities of sand accumulated in the root zone of plots treated with medium-coarse sand than plots treated with medium-fine sand.

Results of sand removal by mowing were supported by our visual evaluations and digital image analysis of sand incorporation. Increasing the rate of medium-coarse sand from 0.15 to 0.3 L m^{-2} substantially increased the time required to incorporate sand. On the other hand, the same increase in rate for the medium-fine sand typically did not affect the time to incorporate. We used digital image analysis, originally developed by Richardson et al. (2001) to evaluate turfgrass cover, to accurately measure the percentage of turf area covered by unincorporated sand. Although the percentage of sand on the turf surface calculated from digital image analysis were usually small (< 10%), on golf courses greens more than 1% of the area covered by sand is likely to be considered to be visually unacceptable and significantly affect turf aesthetics and playability. In our study, the same rates of topdressing applied later in the season (August–October) were more difficult to incorporate than when applied in July. This is because as sand from routine topdressing accumulating within the turf canopy causing bridging among sand particles and with plant material creating a firm surface that inhibited the movement of sand deep into the turf canopy. Recently, some golf courses have adopted sands that are finer than USGA standard due to the advantage of easier incorporation and less interference to mowing and play (Murphy, 2012; Pippin, 2010).

Sand topdressing is expected to increase surface firmness through the bridging of sand particles within the turf canopy and the layer of accumulating thatch (Inguagiato et al., 2012; Li et al., 2009). However, measurements taken with the Clegg Impact Soil Tester (CIST), the most commonly used tool for evaluating surface hardness in turf systems, have not always detected differences due to topdressing treatments (Barton et al., 2009; McCarty et al., 2005). Gibbs et al. (2000) concluded that immediate surface firmness on golf putting greens was better represented by a single drop of the 0.5-kg hammer; and recommended the 2.25-kg hammer for assessing firmness (compaction) deeper in the profile. Impact energy produced by the 0.5-kg hammer is lower than that produced by 2.25-kg hammer (Rogers and Waddington, 1990b). In two additional studies, both the 2.25- and 0.5-kg hammers detected soil compaction caused by a 364 kg roller, but differences in surface hardness due to various cutting heights and the presence and absence of verdure and thatch were only characterized by 0.5-kg hammer (Rogers and Waddington, 1989, 1992). In our study, non-topdressed plots had greater surface hardness measured by both 0.5- and 2.25-kg hammers than topdressed plots. This could be attributed to more compacted soil underneath the thatch layer of non-topdressed plots as a result of traffic from a pavement roller routinely used to smooth the turf surface. However, further investigation is needed to validate this hypothesis. On the other hand, Kauffman et al. (2011), reported topdressing incorporated by brushing increased 2.25-kg CIST readings on ultradwarf bermudagrass putting greens, but the soil water content was not reported. Both devices may be more representative of hardness deeper in the soil profile than within the topdressing layer at the surface.

The 2.25-kg hammer did not detect an effect of topdressing rate on surface hardness in our study; however, Espevig et al. (2012) observed that increasing annual topdressing rates from 7 to 14 L m^{-2} increased surface hardness on velvet bentgrass putting greens. Baker and Canaway (1992) reported that surface hardness of a perennial ryegrass (*Lolium perenne* L.) sports field measured with a 0.5-kg hammer increased with increasing sand topdressing rate under wet conditions, but decreased under dry conditions; they speculated soil underneath (rather than topdressing layer) determined the hardness of surface layer under dry conditions. However, water content was not observed to affect the topdressing rate response in our study. In general, there was no response of surface hardness to sand size in our study; and when a response was detected, plots topdressed with a medium-fine sand was firmer than those topdressed with a medium-coarse sand. Conversely, Moeller (2008) indicated that plots that received medium-fine sand via topdressing and core cultivation had a softer surface (measured with 0.5-kg hammer) compared to medium-coarse sand; however, the effect may have been confounded by core cultivation.

Hardness responses measured with the 0.5-kg hammer dropped from a reduced height (10 cm) in our study differed from those obtained with a 30-cm drop height and the 2.25-kg hammer. The impact energy generated by the hammer falling from 10 cm is smaller than from 30 cm, thus the deceleration recorded by the CIST at this height probably better represents the impact absorption characteristics of the turf surface. McClements and Baker (1994) used 30- and 55-cm drop heights of the 0.5-kg hammer to measure the hardness of various natural turfgrasses, such as fescue (*Festuca* spp.), bentgrass (*Agrostis* spp.) and perennial ryegrass, used for hockey pitch, and concluded that results from 55-cm drop height better represented players' evaluation of the surface for running; varying drop heights was also described as custom protocol in the CIST user's manual.

The depth measuring penetrometer detected greater surface strength (shorter penetration depth) on topdressed plots than non-topdressed controls on every evaluation date in our study. Additionally, topdressing rate had a greater impact than sand size on improving surface strength. Results observed on a fairway with a different penetrometer (a proving ring soil penetrometer) also suggested that increasing topdressing rate was more effective on improving surface strength than varying sand size from coarse to fine (Henderson and Miller, 2010). On the contrary, a self recording penetrometer (Mathieu and Toogood, 1958) indicated that with the build-up of topdressing material the hardness of the top 2.5 cm layer was reduced as topdressing frequency increased; however this penetrometer failed to detect the softness of non-topdressed plots even though the thatch of the non-topdressed plots was observed to be very easily compressed and spongy (Murphy, 1983). Similarly in our study, the 0.5- and 2.25-kg hammer measurements did not represent the thatch sponginess. As explained by Murphy (1983), the penetrometer he used did not reflect the surface conditions (thatch sponginess), instead the reduced hardness due to frequent topdressing suggested that topdressing alleviated soil compaction.

Although effects of topdressing rate and sand size on VWC were limited in our study, results were consistent with findings of Henderson et al. (2010). Their fairway topdressing study indicated that coarser sand or higher topdressing rate resulted in less water retained in the upper 5 cm profile (Henderson and Miller, 2009). In our study, medium-fine sand retained 0.02 m^3 m^{-3} higher VWC than medium-coarse sand at the 0–3.8 cm depth only on one observation date throughout the study. Higher VWC at the 0–5.7 cm depth with frequent medium-fine sand topdressing was also observed on a creeping bentgrass putting green by Moeller (2008); however the effect might have been affected by core cultivation. Many have reported a negative association between surface hardness and moisture content (Linde et al., 2011; McClements and Baker, 1994; McNitt and Landschoot, 2001; Rogers and Waddington, 1989; Rogers and Waddington, 1990a; Rogers and Waddington, 1992). However, that relationship did not appear in our study, except on two evaluation dates using the 0.5 kg CIST released from 10 cm. Stowell et al. (2009) attributed the lack of correlation between surface hardness and moisture content to sand topdressing. Soil water content is known to have little effect on surface hardness of root zones with high sand content (Baker, 1991; Li et al., 2009; McNitt and Landschoot, 2003), but can greatly influence hardness of root zones with high soil content (Baker, 1991).

Although pressure and tension infiltrometers are the most common field devices used to determine infiltration rate, they often yielded different values of hydraulic conductivity (Reynolds et al., 2000). Results of topdressing effects on infiltration measured with pressure infiltrometers are inconsistent in the literature. McCarty et al. (2005) and Espevig et al. (2012) noted that topdressing significantly increased water infiltration. On the other hand, Madison et al. (1974) and Baker and Canaway (1990) reported that sand topdressing did not improve water conductivity. To date, tension infiltrometers have not been used to evaluate the effect of topdressing on water conductivity in turfgrass systems.

When the soil surface is porous the initial infiltration rate is greater than the saturated infiltration rate; however, the saturated infiltration rates of soils with different surface layer do not differ, as they are determined by the soil beneath (Hillel, 2003). Similarly, despite the fact that thatch layer at the soil surface is hydrophobic when it is dry, thatch was reported to only lower the initial infiltration rate but not the later sustained infiltration rate under a 1.6 cm positive pressure head (Taylor and Blake, 1982). Topdressing sand accumulates at the surface of the soil profile and intermixes with thatch and surface soil forming a porous mat layer. Therefore, a pressure infiltrometer may not defect the increase in infiltration rate as a mat layer develops. Cooper and Skogley (1981) did not observe differences in infiltration response to topdressing treatments using a pressure infiltrometer. They speculated that initial wetting saturated the topdressing layer, thus infiltration rate was predominately affected by the original soil underneath. In addition, Baker and Canaway (1990) found that increasing sand topdressing rate reduced the incidence of surface ponding on a sports field. Surface ponding after a heavy rain or irrigation event may indicate a low initial state infiltration rate, whereas rapid movement of water from the turf surface into the root zone profile probably suggests a high initial state infiltration rate. Therefore, measuring unsaturated infiltration rate may better characterize the improvement in hydraulic properties of thatch and soil surface due to topdressing treatments.

Sand topdressing increased water infiltration at the –0.5 cm pressure potential indicating that sand treatments increased macroporosity of pores 2.96 mm or larger. Pore sizes estimated from pressure potentials with the capillarity theory (Equation 5; Pg. 49) are approximations because the theory is limited to vertical pores (Perroux and White, 1988). Additionally, contact angle can vary considerably affected by soil type and hydrophobicity; in order to accurately estimate the equivalent pore radii to pressure potentials, further experiments are need to accurately measure the contact angle.

The steady-state infiltration rates measured at five pressure potentials were fitted simultaneously using nonlinear regression to estimate hydraulic conductivity as shown in Fig. A.3. According to Logsdon and Jaynes (1993), the nonlinear regression method often gives better estimation of hydraulic conductivity than piecewise fitting steady-state infiltration rates measured at sequential pressure potentials as described by Ankeny et al. (1991). Soil cores were not extracted to determine the initial and final water contents due to limited experiment plot space and the continuing nature of the experiment which precluded destructive sampling. Van Genuchten parameters could not be assumed from the soil texture in our study because of the highly cultivated and distinct soil profile—sand topdressing layer on top of the Nixon sandy loam. Therefore, other methods could not be used to accurately estimate hydraulic conductivity in this study.

Due to the limited use of tension infiltrometer in turf research, we could not find any comparable research evaluating topdressing effects with this method. Although, the direct comparison of infiltration rates obtained from tension infiltrometer and others methods is not appropriate, our conclusion is consistent with Henderson and Miller (2010) who used a rain simulator developed by Ogden et al. (1997) and reported that sand size or topdressing rate did not affect infiltration. However, Moeller (2008) used a pressure infiltrometer and concluded that medium-fine sand used for topdressing as well as filling coring holes significantly lowered the infiltration rate compared to medium-coarse sand on creeping bentgrass putting green turf; however, coring effects probably affected the infiltration thus confounding the results. Placing a finer-textured sand layered over a coarse-texture sand has been suspected of restricting water movement at the interface of the layers (Christians, 2011). The biological activities in the root zone of a turf, such as actively growing turfgrass roots and accumulating thatch, can also impact soil hydraulic properties. Our research with the mini disk tension infiltrometer confirmed the expectation of many other researchers that routinely topdressing turfgrass with sand can increase non-capillary pore space and water infiltration (Anonymous, 1977; Bengeyfield, 1969; Cooper, 2004; Hall, 1978).

CONCLUSIONS

The high shoot density and tendency of velvet bentgrass to rapidly accumulate thatch requires an aggressive topdressing program to maintain acceptable turfgrass quality and playability. Routine topdressing with both sand sizes improved overall performance of velvet bentgrass turf. Increasing topdressing rate was often more effective than varying sand size at improving turfgrass performance. Compared to medium-coarse sand, it is apparent from this study that a greater rate of medium-fine sand can be applied without substantially increasing sand removal by mowing. The lack of negative effects of medium-fine sand on measured parameters suggests that further research is warranted to confirm the benefits of applying this sand to a sand-based root zone maintained as velvet bentgrass or another turfgrass species. If our current results are confirmed, medium-fine sand could have an important impact on putting green management. Less disruption to the putting surface, even at higher topdressing rates, may encourage superintendents to apply a greater quantity of topdressing during the summer months to improve turfgrass quality and playability during this very stressful season.

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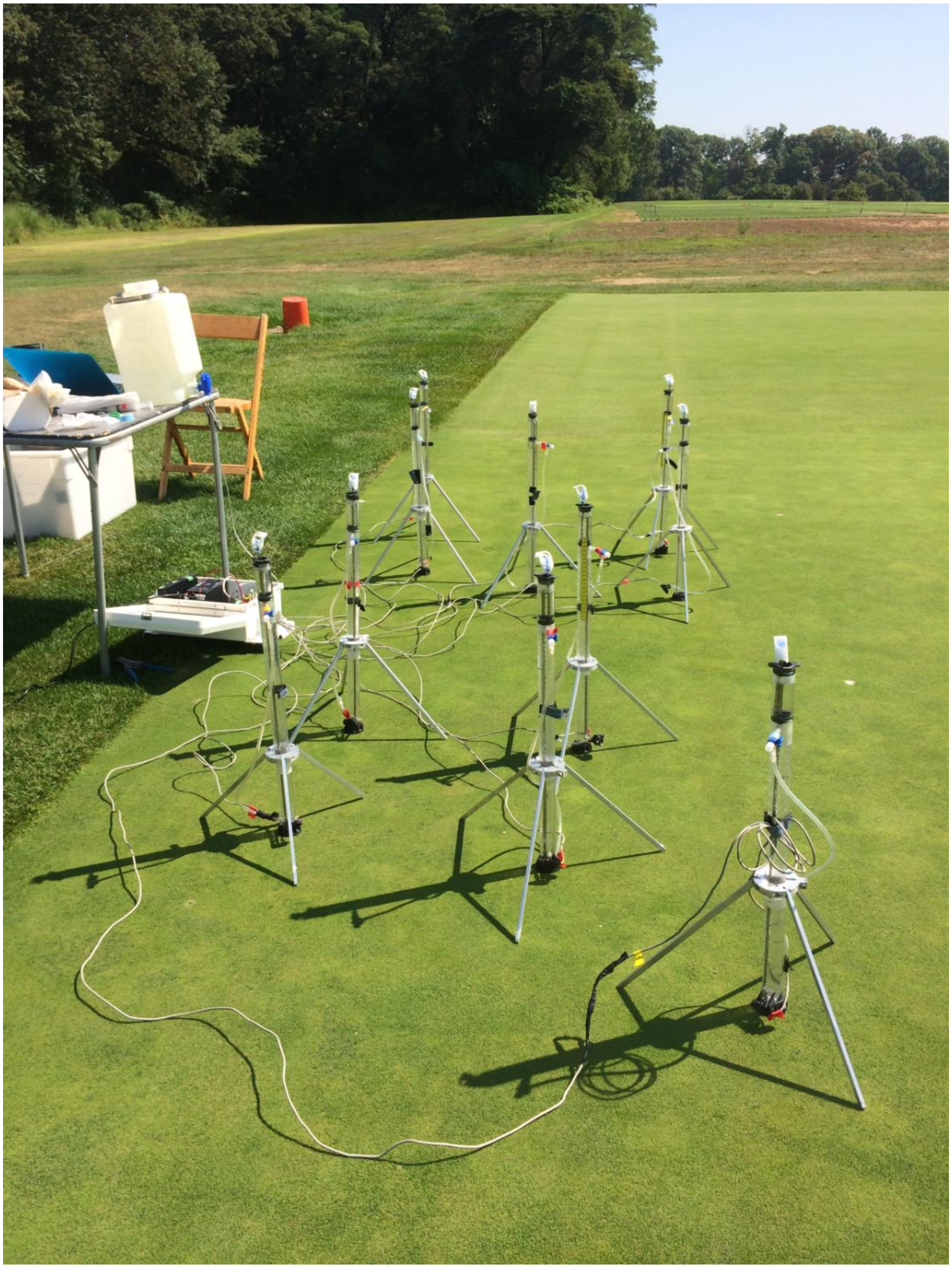

Figure 1.1. Customized mini disk infiltrometers with support stands.

Table 1.1. Particle size distribution of topdressing sands.

	Particle Size (mm)					
	Very Coarse	Coarse	Medium	Fine	Very Fine	
Sand Size	2–1	1–0.5	0.5–0.25	0.25–0.15	0.15–0.05	<0.05
	---------------------------------- % (by weight) ----------------------------------					
Medium-coarse	0.07	31.27	65.05	3.32	0.27	0.01
Medium-fine	0.03	0.25	72.38	24.40	2.92	0.03

Table 1.2a. Turf quality response to sand size and topdressing rate on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ from 21 May to 12 Aug. 2011.

Main Effects	21-May	27-May	4-Jun	11-Jun	18-Jun	29-Jun	5-Jul	18-Jul	21-Jul	28-Jul	3-Aug	12-Aug
	1–9 scale‡											
Sand Size												
Medium-coarse	7.8	8.5	8.5	8.2	8.5	8.2	7.7	8.3	7.8	8.4	7.8	7.7
Medium-fine	8.0	8.7	8.3	8.7	8.7	8.3	8.7	8.5	7.8	8.5	8.0	7.8
Topdressing Rate†												
0.15 L m^{-2}	7.7	8.3	8.2	8.2	8.3	7.6	7.8	8.0	7.5	8.0	7.2	7.0
0.30 L m^{-2}	8.2	8.8	8.7	8.7	8.8	8.8	8.5	8.8	8.2	8.9	8.7	8.5
No Sand	6.3	8.0	7.3	7.0	7.3	7.0	7.0	7.7	6.3	6.3	5.8	5.7
$LSD_{0.05}$	0.7	0.7	0.8	0.6	0.8	0.6	0.6	0.6	0.6	0.6	0.8	0.9
ANOVA	$p > F$											
No Sand vs Sand	***	NS	*	***	**	**	**	*	***	***	***	***
Sand Size	NS§	NS	NS	NS	NS	NS	**	NS	NS	NS	NS	NS
Topdressing Rate	NS	NS	NS	NS	NS	***	*	**	*	**	**	**
Size x Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV%	6.4	5.7	6.5	4.8	6.8	5.0	4.9	4.7	5.4	5.2	7.6	8.4

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Topdressing was applied every two weeks from June to September with the total amount of 2.4 and 4.8 L m^{-2} in 2011.
‡ 9 = best turf quality, 5 = acceptable, 1 = dead or necrotic turf.
§ NS, not significant.

Table 1.2b. Turf quality response to sand size and topdressing rate on a ‘Greenwich’ velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ from 17 Aug. to 17 Nov. 2011.

Main Effects	17-Aug	23-Aug‡	2-Sep	9-Sep	23-Sep‡	28-Sep	6-Oct	14-Oct	22-Oct	17-Nov‡
	-------------------	-------------------	-------------------	-------------------	1–9 scale§	-------------------	-------------------	-------------------	-------------------	-------------------
Sand Size										
Medium-coarse	7.8	6.2	8.3	7.7	6.5	6.5	7.7	7.3	7.7	5.5
Medium-fine	8.2	7.2	7.8	7.7	7.2	7.2	7.7	7.7	7.5	6.5
Topdressing Rate†										
0.15 L m^{-2}	7.2	6.7	7.3	7.0	6.8	6.2	7.0	7.0	6.8	6.8
0.30 L m^{-2}	8.8	6.7	8.8	8.3	6.8	7.5	8.3	8.0	8.3	5.2
No Sand	5.3	5.3	6.0	6.0	5.0	5.0	6.0	5.3	5.3	5.3
$LSD_{0.05}$	0.8	0.8	0.5	0.6	0.5	1.4	0.7	1.5	1.0	0.9
ANOVA	-------------------	-------------------	-------------------	-------------------	$p > F$	-------------------	-------------------	-------------------	-------------------	-------------------
No Sand vs Sand	***	**	***	***	***	*	***	*	***	NS¶
Sand Size	NS	*	NS	NS	**	NS	NS	NS	NS	*
Topdressing Rate	**	NS	***	***	NS	*	***	NS	**	**
Size x Rate	NS	*	NS	NS	**	NS	NS	NS	NS	**
CV%	7.1	8.8	4.8	5.3	4.9	14.4	6.1	14.4	9.6	10.6

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Topdressing was applied every two weeks from June to September with the total amount of 2.4 and 4.8 L m^{-2} in 2011.
‡ Ratings were taken when considerable sand particles visible on the turf surface.
§ 9 = best turf quality, 5 = acceptable, 1 = dead or necrotic turf.
¶ NS, not significant.

Table 1.3a. Turf quality response to sand size and topdressing rate on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ from 21 Apr. to 8 Aug. 2012.

Main Effects	21-Apr	14-May	28-May	7-Jun	16-Jun	23-Jun	1-Jul	9-Jul	16-Jul	29-Jul	8-Aug
	-- 1–9 scale[‡] --										
Sand Size											
Medium-coarse	7.0	7.0	7.3	7.3	7.8	8.3	8.2	7.5	7.5	7.8	8.3
Medium-fine	6.5	7.3	7.5	7.5	8.2	8.0	8.2	7.2	7.8	8.0	8.3
Topdressing Rate[†]											
0.15 L m^{-2}	5.7	6.5	6.8	7.0	7.3	7.5	7.5	6.8	7.2	7.2	7.8
0.30 L m^{-2}	7.8	7.8	8.0	7.8	8.7	8.8	8.8	7.8	8.2	8.7	8.8
No Sand	4.3	5.3	5.5	6.0	6.0	6.7	6.0	5.3	5.7	6.0	5.7
$LSD_{0.05}$	1.0	1.0	0.4	0.4	0.7	0.8	0.5	1.0	1.2	0.9	0.7
ANOVA	-- $p > F$ --										
No Sand vs Sand	***	**	***	***	***	**	***	**	**	**	***
Sand Size	NS[§]	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Topdressing Rate	***	**	***	***	***	**	***	*	NS	**	**
Size x Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV%	11.1	9.7	3.8	3.6	5.9	7.0	4.7	9.9	10.8	10.8	5.7

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Topdressing was applied every two weeks from May to September with the total amount of 2.25 and 4.5 L m^{-2} in 2012.
‡ 9 = best turf quality, 5 = acceptable, 1 = dead or necrotic turf.
§ NS, not significant.

Table 1.3b. Turf quality response to sand size and topdressing rate on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ from 13 Aug. to 20 Nov. 2012.

Main Effects	13-Aug	19-Aug	25-Aug	30-Aug	3-Sep	13-Sep	27-Sep[‡]	8-Oct	15-Oct	20-Nov[‡]
	------------	------------	------------	------------	1–9 scale[§]	------------	------------	------------	------------	------------
Sand Size										
Medium-coarse	7.8	7.7	8.2	7.2	8.2	8.3	3.8	7.7	6.8	6.0
Medium-fine	7.7	8.2	8.3	7.8	8.2	8.2	6.0	7.5	7.3	6.2
Topdressing Rate[†]										
0.15 L m^{-2}	7.2	7.3	7.7	7.3	7.5	7.5	6.5	7.0	7.7	7.7
0.30 L m^{-2}	8.3	8.5	8.8	7.7	8.8	9.0	3.3	8.2	6.5	4.5
No Sand	5.7	4.7	6.0	5.3	4.7	6.0	5.0	5.0	4.3	5.7
$LSD_{0.05}$	1.6	1.0	0.7	1.0	0.6	0.9	0.8	1.1	0.6	0.5
ANOVA	------------	------------	------------	------------	$p > F$	------------	------------	------------	------------	------------
No Sand vs Sand	*	***	***	**	***	***	NS[¶]	***	***	NS
Sand Size	NS	NS	NS	NS	NS	NS	***	NS	NS	NS
Topdressing Rate	NS	*	**	NS	***	**	***	*	**	***
Size x Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	**
CV%	14.5	9.1	5.7	9.7	5.5	7.8	11.4	10.2	6.6	5.7

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Topdressing was applied every two weeks from May to September with the total amount of 2.1 and 4.2 L m^{-2} in 2012.
‡ Ratings were taken when considerable sand particles visible on the turf surface.
§ 9 = best turf quality, 5 = acceptable, 1 = dead or necrotic turf.
¶ NS, not significant.

Table 1.4a. Turf quality response to sand size and topdressing rate on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ from 4 Apr. to 20 July 2013.

Main Effects	4-Apr	15-Apr	2-May[‡]	11-May	16-May	25-May	31-May	12-Jun	22-Jun	27-Jun	5-Jul	20-Jul
	---------- 1–9 scale[§] ----------											
<u>Sand Size</u>												
Medium-coarse	5.2	6.2	4.8	6.7	7.7	7.7	7.7	8.0	8.2	7.8	8.0	7.7
Medium-fine	4.8	6.2	5.2	6.2	7.3	7.7	7.3	7.5	8.0	8.2	8.0	8.2
<u>Topdressing Rate</u>[†]												
0.15 L m^{-2}	4.5	5.8	6.0	6.2	6.7	6.7	6.8	7.0	8.2	7.3	7.3	7.3
0.30 L m^{-2}	5.5	6.5	4.0	6.7	8.3	8.7	8.2	8.5	8.0	8.7	8.7	8.5
No Sand	4.0	4.3	5.0	5.0	5.7	5.7	6.0	5.7	6.7	6.0	5.7	5.7
$LSD_{0.05}$	0.8	1.0	0.7	1.1	0.5	0.9	0.5	0.7	0.8	0.7	0.7	0.6
<u>ANOVA</u>	---------- $p > F$ ----------											
No Sand vs Sand	*	**	NS[¶]	*	***	**	***	***	**	***	***	***
Sand Size	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Topdressing Rate	*	NS	***	NS	***	***	***	***	NS	***	**	**
Size x Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
CV%	11.1	12.0	9.3	12.3	4.8	8.7	4.7	6.1	7.2	5.9	6.4	5.7

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Topdressing was applied every two weeks from May to September with the total amount of 2.1 and 4.2 L m^{-2} in 2013.
‡ Ratings were taken when considerable sand particles visible on the turf surface.
§ 9 = best turf quality, 5 = acceptable, 1 = dead or necrotic turf.
¶ NS, not significant.

Table 1.4b. Turf quality response to sand size and topdressing rate on a ‘Greenwich’ velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ from 25 July to 28 Oct. 2013.

Main Effects	25-Jul	2-Aug	8-Aug	16-Aug	23-Aug	5-Sep	12-Sep[‡]	19-Sep	27-Sep	4-Oct[‡]	16-Oct	28-Oct
	------------------------------ 1–9 scale[§] ------------------------------											
Sand Size												
Medium-coarse	7.2	8.2	7.3	7.2	7.0	7.5	3.3	7.7	8.0	5.0	7.5	7.8
Medium-fine	7.7	8.3	8.0	7.5	7.7	8.2	5.3	8.0	8.5	6.2	8.0	8.0
Topdressing Rate[†]												
0.15 $L\ m^{-2}$	6.3	7.5	6.8	6.5	6.3	7.2	5.8	7.0	7.7	6.8	7.2	7.3
0.30 $L\ m^{-2}$	8.5	9.0	8.5	8.2	8.3	8.5	2.8	8.7	8.8	4.3	8.3	8.5
No Sand	4.7	5.3	5.3	5.0	5.0	5.3	5.3	5.3	5.0	5.0	5.0	6.0
$LSD_{0.05}$	0.6	0.5	0.9	0.6	0.6	0.7	0.7	0.8	0.5	0.8	0.8	0.5
ANOVA	------------------------------ $p > F$ ------------------------------											
No Sand vs Sand	***	***	***	***	***	***	*	***	***	NS[¶]	***	***
Sand Size	NS	NS	NS	NS	*	*	***	NS	*	**	NS	NS
Topdressing Rate	***	***	**	***	***	***	***	***	***	***	**	***
Size x Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV%	6.2	4.8	8.4	6.2	5.6	6.1	10.7	7.5	4.5	9.7	7.4	4.5

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Topdressing was applied every two weeks from May to September with the total amount of 2.1 and 4.2 $L\ m^{-2}$ in 2013.

‡ Ratings were taken when considerable sand particles visible on the turf surface.

§ 9 = best turf quality, 5 = acceptable, 1 = dead or necrotic turf.

¶ NS, not significant.

Table 1.5. Turf quality response to the interaction of sand size and topdressing rate on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2011, 2012 and 2013.

Sand Size	Topdressing Rate†	2011			2012	2013
		23-Aug	23-Sep	17-Nov	20-Nov	5-Jul
		1–9 scale‡				
Medium-coarse	0.15 L m^{-2}	6.7	7.0	7.0	8.0	7.7
Medium-coarse	0.30 L m^{-2}	5.7	6.0	4.0	4.0	8.3
Medium-fine	0.15 L m^{-2}	6.7	6.7	6.7	7.3	7.0
Medium-fine	0.30 L m^{-2}	7.7	7.7	6.3	5.0	9.0
$LSD_{0.05}$		1.06	0.60	1.17	0.64	0.90

† Topdressing was applied every two weeks from June to September in 2011 and from May to September in 2012 and 2013.

‡ 9 = best turf quality, 5 = acceptable, 1 = dead or necrotic turf.

Table 1.6. Sand incorporation response to topdressing sand size and rate on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2011.

Main Effects	7-May 2 dat‡	13-May 8 dat	28-Jun 1 dat	23-Aug 1 dat	17-Nov 10 dat
	------------------------- 1–9 scale§				-------------------------
Sand Size					
Medium-coarse	2.5	5.8	7.8	5.5	6.8
Medium-fine	4.3	7.0	8.7	7.3	8.0
Topdressing Rate†					
0.15 L m^{-2}	5.3	7.7	9.0	7.5	8.5
0.30 L m^{-2}	1.5	5.2	7.5	5.3	6.3
No Sand	9.0	9.0	9.0	9.0	9.0
$LSD_{0.05}$	0.4	0.7	0.5	0.8	0.4
ANOVA	----------------------------- $p > F$				---------------------------
No Sand vs Sand	***	***	**	***	***
Sand Size	***	**	**	***	***
Topdressing Rate	***	***	***	***	***
Size x Rate	***	NS¶	**	*	NS
CV%	5.7	7.0	4.1	8.1	3.3

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Topdressing was applied every two weeks from June to September with the total amount of 2.4 and 4.8 L m^{-2} in 2011.
‡ Number of days after topdressing (dat), 0 = ratings were taken on the same day after topdressing.
§ 9 represents no sand visible at turf surface, and 5 represents the minimally acceptable rating.
¶ NS, not significant.

Table 1.7. Sand incorporation response to topdressing sand size and rate on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2012.

Main Effects	14-Sep 0 dat‡	19-Sep 5 dat	26-Sep 0 dat	27-Sep 1 dat	28-Sep 2 dat	12-Oct 0 dat	14-Oct 2 dat	16-Oct 4 dat
	------------	------------	------------	------------	1–9 scale§	------------	------------	------------
Sand Size								
Medium-coarse	4.8	7.0	2.7	3.7	5.3	3.5	4.0	6.2
Medium-fine	7.4	8.8	5.0	7.2	8.2	6.3	7.3	8.7
Topdressing Rate†								
0.15 L m^{-2}	7.0	8.5	5.5	6.8	8.2	6.5	7.0	8.5
0.30 L m^{-2}	5.3	7.3	2.2	4.0	5.3	3.3	4.3	6.3
No Sand	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
$LSD_{0.05}$	0.9	0.7	1.0	0.8	0.7	0.8	0.4	0.5
ANOVA	------------	------------	------------	------------	$p > F$	------------	------------	------------
No Sand vs Sand	***	**	***	***	***	***	***	***
Sand Size	***	***	***	***	***	***	***	***
Topdressing Rate	**	**	***	***	***	***	***	***
Size x Rate	NS¶	*	NS	NS	**	*	*	***
CV%	9.3	5.7	13.5	8.9	6.2	9.0	4.1	4.1

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Topdressing was applied every two weeks from May to September with the total amount of 2.25 and 4.5 L m^{-2} in 2012.

‡ Number of days after topdressing (dat), 0 = ratings were taken on the same day after topdressing.

§ 9 represents no sand visible at turf surface, and 5 represents the minimally acceptable rating.

¶ NS, not significant.

Table 1.8. Sand incorporation response to topdressing sand size and rate on a ‘Greenwich’ velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2013.

Main Effects	10 Apr 0 dat[‡]	1 May 0 dat	4 Jun 0 dat	5 Jun 1 dat	5 Jul 0 dat	7 Jul 2 dat	8 Jul 3 dat	9 Jul 4 dat	10 Jul 5 dat	15 Jul 0 dat	19 Aug 0 dat	20 Aug 1 dat	21 Aug 2 dat	23 Aug 4 dat	24 Aug 5 dat	3 Oct 0 dat	4 Oct 1 dat	7 Oct 4 dat
	------------------------------ 1–9 scale[§] ------------------------------																	
Sand Size																		
Medium-coarse	4.0	3.8	4.7	5.9	6.3	7.3	7.3	8.0	8.7	5.0	3.8	4.7	6.5	8.3	8.7	4.0	6.2	8.2
Medium-fine	6.0	5.2	6.5	7.8	7.7	8.5	8.5	9.0	9.0	7.5	6.0	7.3	8.8	9.0	9.0	6.2	8.2	8.8
Topdressing Rate[†]																		
0.15 L m^{-2}	6.8	5.3	6.8	8.0	7.8	8.5	8.5	8.8	9.0	7.5	6.3	7.3	8.5	9.0	9.0	6.7	8.3	8.8
0.30 L m^{-2}	3.2	3.7	4.4	5.7	6.2	7.3	7.3	8.2	8.7	5.0	3.5	4.7	6.8	8.3	8.7	3.5	6.0	8.2
No Sand	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
$LSD_{0.05}$	0.8	0.9	0.6	0.7	0.6	0.4	0.4	0.5	0.4	0.8	0.7	0.9	0.4	0.4	0.4	0.7	0.7	0.5
ANOVA	------------------------------ $p > F$ ------------------------------																	
No Sand vs Sand	***	***	***	***	***	***	***	NS[¶]	NS	***	***	***	***	NS	NS	***	***	*
Sand Size	***	**	***	***	***	***	***	**	NS	***	***	***	***	**	NS	***	**	**
Topdressing Rate	***	**	***	***	***	***	***	**	NS	***	***	***	***	**	NS	***	***	**
Size x Rate	NS	NS	NS	NS	NS	NS	NS	**	NS	*	NS	NS	***	**	NS	NS	*	NS
CV%	8.9	11.2	6.5	6.0	5.2	3.2	3.2	4.0	2.9	7.8	8.4	9.2	3.3	3.0	2.9	8.2	6.4	3.7

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Topdressing was applied every two weeks from May to September with the total amount of 2.1 and 4.2 L m^{-2} in 2013.
‡ Number of days after topdressing (dat), 0 = ratings were taken on the same day after topdressing.
§ 9 represents no sand visible at turf surface, and 5 represents the minimally acceptable rating.
¶ NS, not significant.

Table 1.9. Sand incorporation response to the interaction of sand size and topdressing rate on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2011, 2012 and 2013.

		2011			2012					2013				
		7-May	28-Jun	23-Aug	19-Sep	28-Sep	12-Oct	14-Oct	16-Oct	9-Jul	15-Jul	21-Aug	23-Aug	4-Oct
Sand Size	Topdressing Rate†	2 dat‡	1 dat	1 dat	5 dat	2 dat	0 dat	2 dat	4 dat	4 dat	0 dat	2 dat	4 dat	1 dat
		1–9 scale§												
Medium-coarse	0.15 L m^{-2}	4.0	9.0	7.0	8.0	7.3	4.7	5.0	8.0	8.7	6.7	8.0	9.0	7.7
Medium-coarse	0.30 L m^{-2}	1.0	6.7	4.0	6.0	3.3	2.3	3.0	4.3	7.3	3.3	5.0	7.7	4.7
Medium-fine	0.15 L m^{-2}	6.7	9.0	8.0	9.0	9.0	8.3	9.0	9.0	9.0	8.3	9.0	9.0	9.0
Medium-fine	0.30 L m^{-2}	2.0	8.3	6.7	8.7	7.3	4.3	5.7	8.3	9.0	6.7	8.7	9.0	7.3
$LSD_{0.05}$		0.49	0.64	1.06	0.88	0.84	0.97	0.49	0.60	0.64	1.00	0.49	0.49	0.91

† Topdressing was applied every two weeks from June to September in 2011 and from May to September in 2012 and 2013.

‡ Number of days after topdressing (dat), 0 = ratings were taken on the same day after topdressing.

§ 9 represents no sand visible at turf surface, and 5 represents the minimally acceptable rating.

Table 1.10. Sand incorporation response to topdressing sand size and rate assessed with a light box on a ‘Greenwich’ velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2011.

Main Effects	11 Jul 0 dat‡	12 Jul 1 dat	13 Jul 2 dat	26 Jul 0 dat	27 Jul 1 dat	28 Jul 2 dat	9 Aug 0 dat	11 Aug 2 dat	12 Aug 3 dat	22 Aug 0 dat	23 Aug 1 dat	24 Aug 2 dat	26 Aug 4 dat	5 Sep 0 dat
	%§													
Sand Size														
Medium-coarse	1.0	0.3	0.1	1.8	0.1	0.0	2.7	0.2	0.1	6.7	1.0	0.7	0.2	7.5
Medium-fine	0.3	0.1	0.1	1.1	0.0	0.0	0.2	0.1	0.0	0.7	0.0	0.0	0.2	3.2
Topdressing Rate†														
0.15 L m^{-2}	0.5	0.1	0.1	0.4	0.0	0.0	0.5	0.1	0.0	1.1	0.1	0.2	0.2	1.2
0.30 L m^{-2}	0.8	0.2	0.1	2.5	0.1	0.0	2.5	0.1	0.1	6.3	0.9	0.6	0.2	9.4
No Sand	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.2	0.0
$LSD_{0.05}$	0.46	0.12	0.06	1.79	0.11	0.00	1.08	0.06	0.04	1.29	0.66	0.27	0.07	3.77
ANOVA	$p > F$													
No Sand vs Sand	*	*	NS#	NS	NS	NS	*	NS	NS	***	NS	*	NS	*
Sand Size	**	**	NS	NS	NS	**	***	**	*	***	**	***	NS	*
Topdressing Rate	NS	NS	NS	*	*	*	**	NS	NS	***	*	**	NS	***
Size x Rate	NS	NS	NS	NS	NS	*	**	NS	NS	***	*	**	NS	NS
CV%	57.6	64.1	57.3	101.9	113.2	34.1	61.1	35.0	52.5	28.9	111.9	58.2	23.1	59.7

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Topdressing was applied every two weeks from June to September with the total amount of 2.4 and 4.8 L m^{-2} in 2011.
‡ Number of days after topdressing (dat), 0 = ratings were taken on the same day after topdressing.
§ Percentage of turf surface covered with unincorporated sand.
# NS, not significant.

Table 1.11. Sand incorporation response to topdressing sand size and rate assessed with a light box on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2012.

Main Effects	26-Sep 0 dat‡	27-Sep 1 dat	28-Sep 2 dat	12-Oct 0 dat	14-Oct 2 dat	16-Oct 4 dat
	------ %§ ------					
Sand Size						
Medium-coarse	10.5	4.5	1.7	5.2	3.3	1.2
Medium-fine	6.4	1.7	0.6	2.6	1.7	0.8
Topdressing Rate†						
0.15 L m^{-2}	3.2	1.2	0.5	1.5	0.9	0.5
0.30 L m^{-2}	13.6	4.9	1.9	6.3	4.1	1.5
No Sand	0.1	0.1	0.1	0.2	0.2	0.3
$LSD_{0.05}$	1.61	1.01	0.42	3.88	1.70	0.82
ANOVA	------ $p > F$ ------					
No Sand vs Sand	***	***	***	NS#	*	NS
Sand Size	***	***	***	NS	*	NS
Topdressing Rate	***	***	***	*	**	*
Size x Rate	NS	*	**	NS	NS	NS
CV%	16.1	27.4	29.7	82.6	56.3	63.7

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Topdressing was applied every two weeks from May to September with the total amount of 2.25 and 4.5 L m^{-2} in 2012.
‡ Number of days after topdressing (dat), 0 = ratings were taken on the same day after topdressing.
§ Percentage of turf surface covered with unincorporated sand.
# NS, not significant

Table 1.12. Sand incorporation response to topdressing sand size and rate assessed with a light box on a ‘Greenwich’ velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2013.

Main Effects	5 Jul 0 dat[‡]	7 Jul 2 dat	8 Jul 3 dat	9 Jul 4 dat	19 Aug 0 dat	20 Aug 1 dat	21 Aug 2 dat	23 Aug 4 dat	24 Aug 5 dat	3 Oct 0 dat	4 Oct 1 dat	7 Oct 4 dat	8 Oct 5 dat
	------------	------------	------------	------------	------------	------------	%[§]	------------	------------	------------	------------	------------	------------
Sand Size													
Medium-coarse	1.0	0.3	0.3	0.3	5.1	1.4	0.9	0.2	0.1	5.9	1.7	0.5	0.2
Medium-fine	0.2	0.1	0.1	0.3	1.1	0.3	0.2	0.1	0.1	3.0	1.3	0.3	0.1
Topdressing Rate[†]													
0.15 L m^{-2}	0.3	0.1	0.2	0.3	1.6	0.5	0.3	0.1	0.1	1.8	0.8	0.3	0.1
0.30 L m^{-2}	0.9	0.2	0.2	0.3	4.6	1.2	0.8	0.2	0.1	7.1	2.2	0.5	0.2
No Sand	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1
$LSD_{0.05}$	0.31	0.03	0.06	0.11	2.22	0.62	0.07	0.06	0.04	1.24	0.63	0.19	0.06
ANOVA	------------	------------	------------	------------	------------	------------	$p > F$	------------	------------	------------	------------	------------	------------
No Sand vs Sand	**	***	*	NS[#]	*	*	***	NS	NS	***	**	*	NS
Sand Size	***	***	***	NS	**	**	***	***	NS	***	NS	*	*
Topdressing Rate	**	***	NS	NS	**	*	***	**	NS	***	***	*	NS
Size x Rate	**	***	*	NS	NS	NS	***	NS	NS	*	NS	NS	NS
CV%	41.0	16.7	25.2	28.2	59.6	60.1	9.2	22.4	24.4	23.1	34.8	39.8	33.8

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Topdressing was applied every two weeks from May to September with the total amount of 2.1 and 4.2 L m^{-2} in 2013.
‡ Number of days after topdressing (dat), 0 = ratings were taken on the same day after topdressing.
§ Percentage of turf surface covered with unincorporated sand.
# NS, not significant.

Table 1.13. Sand incorporation response to the interaction of sand size and topdressing rate assessed with a light box on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2011.

Sand Size	Topdressing Rate†	28-Jul 2 dat‡	9-Aug 0 dat	22-Aug 0 dat	23-Aug 1 dat	24-Aug 2 dat
				%§		
Medium-coarse	0.15 L m^{-2}	0.01	0.91	2.08	0.21	0.29
Medium-coarse	0.30 L m^{-2}	0.01	4.55	11.33	1.69	1.14
Medium-fine	0.15 L m^{-2}	0.00	0.03	0.20	0.02	0.05
Medium-fine	0.30 L m^{-2}	0.00	0.42	1.23	0.05	0.03
$LSD_{0.05}$		0.004	1.365	1.627	0.837	0.341

† Topdressing was applied every two weeks from June to September with the total amount of 2.4 and 4.8 L m^{-2} in 2011.

‡ Number of days after topdressing (dat), 0 = ratings were taken on the same day after topdressing.

§ Percentage of turf surface covered with unincorporated sand.

Table 1.14. Sand incorporation response to the interaction of sand size and topdressing rate assessed with a light box on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2012.

Sand Size	Topdressing Rate†	27-Sep 1 dat‡	28-Sep 2 dat
		%§	
Medium-coarse	0.15 L m^{-2}	2.00	0.76
Medium-coarse	0.30 L m^{-2}	6.96	2.71
Medium-fine	0.15 L m^{-2}	0.43	0.18
Medium-fine	0.30 L m^{-2}	2.93	1.01
$LSD_{0.05}$		1.280	0.536

† Topdressing was applied every two weeks from May to September with the total amount of 2.25 and 4.5 L m^{-2} in 2012.

‡ Number of days after topdressing (dat), 0 = ratings were taken on the same day after topdressing.

§ Percentage of turf surface covered with unincorporated sand.

Table 1.15. Sand incorporation response to the interaction of sand size and topdressing rate assessed with a light box on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2013.

Sand Size	Topdressing Rate†	5-Jul 0 dat‡	7-Jul 2 dat	8-Jul 3 dat	21-Aug 2 dat	3-Oct 0 dat
				%§		
Medium-coarse	0.15 L m^{-2}	0.52	0.17	0.20	0.54	2.60
Medium-coarse	0.30 L m^{-2}	1.51	0.34	0.30	1.34	9.27
Medium-fine	0.15 L m^{-2}	0.14	0.06	0.12	0.15	1.07
Medium-fine	0.30 L m^{-2}	0.25	0.06	0.09	0.28	5.01
$LSD_{0.05}$		0.391	0.043	0.078	0.082	1.565

† Topdressing was applied every two weeks from May to September with the total amount of 2.1 and 4.2 L m^{-2} in 2013.

‡ Number of days after topdressing (dat), 0 = ratings were taken on the same day after topdressing.

§ Percentage of turf surface covered with unincorporated sand.

Table 1.16. Sand removed by mowing as influenced by sand size and topdressing rate from a ‘Greenwich’ velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2011, 2012 and 2013.

	2011			2012			2013		
Main Effects	12-Jul	9-Aug	23-Aug	11-May	1-Aug	29-Aug	5-Jun	16-Jul	20-Aug
	---------- $g\ m^{-2}$ ----------								
<u>Sand Size</u>									
Medium-coarse	12.9	39.7	26.8	10.4	24.1	16.0	19.5	11.2	8.2
Medium-fine	7.6	6.5	5.8	5.2	8.3	6.5	8.7	3.1	2.0
<u>Topdressing Rate</u>†									
0.15 L m^{-2}	9.4	12.0	8.6	5.1	10.6	7.0	10.8	5.0	2.9
0.30 L m^{-2}	11.1	34.2	24.0	10.5	21.8	15.5	17.3	9.4	7.3
No Sand	2.3	0.7	3.7	1.8	0.8	0.6	1.1	0.2	0.1
$LSD_{0.05}$	3.0	8.3	13.5	2.2	8.2	4.6	3.2	1.2	2.0
<u>ANOVA</u>	---------- $p > F$ ----------								
No Sand vs Sand	***	***	NS	***	**	***	***	***	***
Sand Size	**	***	**	***	**	***	***	***	***
Topdressing Rate	NS‡	***	*	***	**	**	***	***	***
Size x Rate	*	***	*	*	*	*	**	***	**
CV%	23.3	30.1	65.8	22.9	42.2	34.2	19.0	13.6	32.9

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Topdressing was applied every two weeks from June to September in 2011 and from May to September in 2012 and 2013.

‡ NS, not significant.

Table 1.17. Sand removed by mowing as influenced by the interaction of sand size and topdressing rate from a ‘Greenwich’ velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2011, 2012 and 2013.

Sand Size	Topdressing Rate†	2011			2012			2013		
		12-Jul	9-Aug	23-Aug	11-May	1-Aug	29-Aug	5-Jun	16-Jul	20-Aug
						$g\ cm^{-2}$				
Medium-coarse	0.15 L m^{-2}	10.6	19.4	10.9	6.3	14.1	9.2	13.4	7.6	4.3
Medium-coarse	0.30 L m^{-2}	15.1	60.0	42.7	14.6	34.1	22.8	25.5	14.9	12.1
Medium-fine	0.15 L m^{-2}	8.2	4.5	6.3	3.9	7.1	4.8	8.3	2.4	1.4
Medium-fine	0.30 L m^{-2}	7.0	8.5	5.4	6.5	9.4	8.2	9.1	3.9	2.6
$LSD_{0.05}$		3.81	10.55	17.09	2.85	10.40	5.87	4.10	1.48	2.54

† Topdressing was applied every two weeks from June to September in 2011 and from May to September in 2012 and 2013.

Table 1.18. Surface hardness response to sand size and topdressing rate measured with 2.25 kg Clegg Impact Soil Tester on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2011.

Main Effects	26 Apr	13 May	19 May	31 May	13 Jun	20 Jun	27 Jun	5 Jul	11 Jul	18 Jul	28 Jul	8 Aug	22 Aug	29 Aug	5 Sep	19 Sep	11 Oct
	Surface hardness (g_{max})																
Sand Size																	
Medium-coarse	62	76	61	65	67	62	66	59	64	67	63	61	54	53	58	56	70
Medium-fine	62	76	59	65	64	62	66	59	65	65	63	60	52	52	57	54	68
Topdressing Rate†																	
0.15 L m^{-2}	63	76	60	66	66	63	66	59	65	66	65	61	52	52	57	54	69
0.30 L m^{-2}	62	77	60	65	65	62	66	59	64	66	60	60	53	53	58	55	69
No Sand	61	78	60	66	66	64	67	60	64	68	66	62	53	52	55	54	73
$LSD_{0.05}$	2.6	3.3	2.2	2.2	5.3	2.3	4.2	3.4	2.6	6.4	7.1	4.4	4.6	4.0	7.6	8.7	3.8
ANOVA	$p > F$																
No Sand vs Sand	NS‡	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Sand Size	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Topdressing Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Size x Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV%	2.8	2.9	2.5	2.2	5.4	2.5	4.3	3.9	2.7	6.4	7.5	4.8	5.8	5.1	9.0	10.8	3.6

† Topdressing was applied every two weeks from June to September with the total amount of 2.4 and 4.8 L m^{-2} in 2011.

‡ NS, not significant.

Table 1.19. Surface hardness response to sand size and topdressing rate measured with 2.25 kg Clegg Impact Soil Tester on a ‘Greenwich’ velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2012.

Main Effects	3-Apr	14-May	11-Jun	15-Jun	26-Jun	30-Jul	6-Aug	13-Aug	16-Aug	24-Aug
	Surface hardness (g_{max})									
Sand Size										
Medium-coarse	61	68	59	66	65	62	59	70	60	70
Medium-fine	60	68	58	67	63	61	58	71	60	70
Topdressing Rate†										
0.15 L m^{-2}	60	69	58	67	65	61	58	71	60	71
0.30 L m^{-2}	60	67	59	66	63	62	58	70	60	69
No Sand	64	71	61	69	68	64	62	75	64	77
$LSD_{0.05}$	1.9	3.8	2.2	2.3	3.9	6.4	5.6	4.7	5.5	4.1
ANOVA	$p > F$									
No Sand vs Sand	**	NS‡	*	*	NS	NS	NS	*	NS	**
Sand Size	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Topdressing Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Size x Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV%	2.1	3.7	2.5	2.3	4.1	6.9	6.4	4.4	6.0	3.9

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† Topdressing was applied every two weeks from May to September with the total amount of 2.25 and 4.5 L m^{-2} in 2012.
‡ NS, not significant.

Table 1.20. Surface hardness response to sand size and topdressing rate measured with 2.25 kg Clegg Impact Soil Tester on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2013.

Main Effects	16-May	17-Jun	28-Jun	10-Jul	22-Jul	8-Aug	16-Aug	20-Sep
	------------------------- Surface hardness (g_{max}) ------------------------							
Sand Size								
Medium-coarse	69	61	52	68	64	64	60	68
Medium-fine	68	61	52	68	62	65	60	66
Topdressing Rate†								
0.15 L m^{-2}	69	62	53	69	65	65	60	70
0.30 L m^{-2}	68	60	51	66	61	63	59	65
No Sand	72	67	59	77	72	73	68	77
$LSD_{0.05}$	2.7	2.9	2.2	6.2	6.1	3.8	2.8	5.8
ANOVA	------------------------------------ $p > F$ ------------------------------------							
No Sand vs Sand	**	**	***	*	*	***	***	**
Sand Size	NS‡	NS	NS	NS	NS	NS	NS	NS
Topdressing Rate	NS	NS	NS	NS	NS	NS	NS	NS
Size x Rate	NS	NS	NS	NS	NS	NS	NS	NS
CV%	2.6	3.2	2.8	6.0	6.4	3.9	3.1	5.6

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Topdressing was applied every two weeks from May to September with the total amount of 2.1 and 4.2 L m^{-2} in 2013.
‡ NS, not significant.

Table 1.21. Surface hardness response to sand size and topdressing rate measured with 0.5 kg Clegg Impact Soil Tester released from the standard height of 30 cm and reduced height of 10- or 20-cm on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2011.

	30 cm‡									20 cm§	10 cm¶
Main Effects	18-Jul	19-Jul	28-Jul	8-Aug	22-Aug	29-Aug	5-Sep	19-Sep	11-Oct	19-Jul	19-Jul
	Surface hardness (g_{max})										
Sand Size											
Medium-coarse	74	77	77	71	64	66	73	72	88	51	34
Medium-fine	79	78	74	74	64	65	72	69	86	52	34
Topdressing Rate†											
0.15 L m^{-2}	79	78	77	73	64	65	73	71	85	54	34
0.30 L m^{-2}	74	77	74	72	64	67	72	70	88	49	34
No Sand	74	80	76	77	64	68	74	70	86	55	32
$LSD_{0.05}$	7.7	7.8	9.8	4.4	4.6	5.8	5.8	9.2	7.5	6.4	2.2
ANOVA	$p > F$										
No Sand vs Sand	NS#	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Sand Size	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Topdressing Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Size x Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV%	6.8	6.7	8.8	4.1	4.8	5.9	5.4	8.8	5.8	8.2	4.3

† Topdressing was applied every two weeks from June to September with the total amount of 2.4 and 4.8 L m^{-2} in 2011.
‡ The hammer of 0.5 kg CIST was released from the standard height of 30 cm above ground
§ The hammer of 0.5 kg CIST was released from a reduced height of 20 cm above ground.
¶ The hammer of 0.5 kg CIST was released from a reduced height of 10 cm above ground.
# NS, not significant.

Table 1.22. Surface hardness response to sand size and topdressing rate measured with 0.5 kg Clegg Impact Soil Tester released from the standard height of 30 cm on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2012.

Main Effects	3-Apr	5-Apr	14-May	11-Jun	15-Jun	26-Jun	30-Jul	6-Aug	13-Aug	16-Aug	24-Aug
	---------- Surface hardness (g_{max}) ----------										
Sand Size											
Medium-coarse	67	74	73	70	74	77	64	65	79	66	79
Medium-fine	65	73	74	70	75	79	61	62	81	65	81
Topdressing Rate†											
0.15 L m^{-2}	67	74	74	70	75	78	64	65	81	66	80
0.30 L m^{-2}	65	73	73	70	74	78	61	62	79	64	80
No Sand	64	75	78	70	75	78	66	69	80	69	87
$LSD_{0.05}$	6.2	4.1	6.5	4.8	3.2	4.8	3.8	4.7	4.9	3.3	8.1
ANOVA	---------- $p > F$ ----------										
No Sand vs Sand	NS‡	NS	NS	NS	NS	NS	NS	*	NS	*	NS
Sand Size	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Topdressing Rate	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS
Size x Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV%	6.4	3.7	5.9	4.6	2.9	4.2	4.0	4.9	4.1	3.4	6.7

* Significant at the 0.05 probability level.

† Topdressing was applied every two weeks from May to September with the total amount of 2.25 and 4.5 L m^{-2} in 2012.

‡ NS, not significant.

Table 1.23. Surface hardness response to sand size and topdressing rate measured with 0.5 kg Clegg Impact Soil Tester released from the standard height of 30 cm on a ‘Greenwich’ velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2013.

Main Effects	16-May	17-Jun	28-Jun	10-Jul	22-Jul	8-Aug	16-Aug	20-Sep
	Surface hardness (g_{max})							
Sand Size								
Medium-coarse	76	68	67	77	77	80	78	82
Medium-fine	78	71	66	78	73	81	79	82
Topdressing Rate†								
0.15 L m^{-2}	76	68	68	78	76	81	79	83
0.30 L m^{-2}	78	71	65	76	74	80	79	80
No Sand	77	69	70	80	80	82	80	88
$LSD_{0.05}$	4.8	2.6	3.5	6.5	5.6	3.2	3.1	4.6
ANOVA	$p > F$							
No Sand vs Sand	NS‡	NS	*	NS	NS	NS	NS	*
Sand Size	NS	*	NS	NS	NS	NS	NS	NS
Topdressing Rate	NS	*	*	NS	NS	NS	NS	NS
Size x Rate	NS	NS	NS	NS	NS	NS	NS	NS
CV%	4.2	2.5	3.5	5.7	4.9	2.6	2.6	3.7

* Significant at the 0.05 probability level.

† Topdressing was applied every two weeks from May to September with the total amount of 2.1 and 4.2 L m^{-2} in 2013.

‡ NS, not significant.

Table 1.24. Surface hardness response to sand size and topdressing rate measured with 0.5 kg Clegg Impact Soil Tester released from the reduced height of 10- or 20-cm on a ‘Greenwich’ velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2012.

	20 cm‡	10 cm§										
Main Effects	5-Apr	5-Apr	16-May	18-May	11-Jun	15-Jun	26-Jun	30-Jul	6-Aug	13-Aug	16-Aug	24-Aug
	Surface hardness (g_{max})											
Sand Size												
Medium-coarse	55	35	29	39	34	37	36	30	30	37	29	35
Medium-fine	55	34	28	39	35	39	36	32	31	37	28	38
Topdressing Rate†												
0.15 L m^{-2}	54	35	27	40	35	38	35	31	31	37	28	37
0.30 L m^{-2}	56	35	30	37	33	37	37	31	30	37	29	36
No Sand	52	34	30	35	34	35	38	30	31	37	31	38
$LSD_{0.05}$	3.3	3.8	2.8	4.0	3.7	2.5	2.9	3.1	2.0	2.7	2.7	4.0
ANOVA	$p > F$											
No Sand vs Sand	NS¶	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Sand Size	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS
Topdressing Rate	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS
Size x Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV%	4.1	7.3	6.5	7.1	7.3	4.6	5.3	6.7	4.3	4.9	6.4	7.2

* Significant at the 0.05 probability level.

† Topdressing was applied every two weeks from May to September with the total amount of 2.25 and 4.5 L m^{-2} in 2012.

‡ The hammer of 0.5 kg CIST was released from a reduced height of 20 cm above ground.

§ The hammer of 0.5 kg CIST was released from a reduced height of 10 cm above ground.

¶ NS, not significant.

Table 1.25. Surface hardness response to sand size and topdressing rate measured with 0.5 kg Clegg Impact Soil Tester released from the reduced height of 10 cm on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2013.

Main Effects	16-May	17-Jun	28-Jun	10-Jul	22-Jul	8-Aug	16-Aug	20-Sep
	------------------------- Surface hardness (g_{max}) -------------------------							
Sand Size								
Medium-coarse	37	33	34	36	34	36	35	41
Medium-fine	37	34	35	35	34	36	37	39
Topdressing Rate†								
0.15 L m^{-2}	36	32	35	36	34	36	35	41
0.30 L m^{-2}	38	35	35	36	34	35	37	40
No Sand	32	30	35	37	32	32	34	41
$LSD_{0.05}$	1.6	2.7	3.8	3.5	2.9	3.7	2.5	4.0
ANOVA	---------------------------------- $p > F$ ----------------------------------							
No Sand vs Sand	***	*	NS‡	NS	NS	NS	NS	NS
Sand Size	NS	NS	NS	NS	NS	NS	NS	NS
Topdressing Rate	NS	*	NS	NS	NS	NS	NS	NS
Size x Rate	*	NS	NS	NS	NS	NS	NS	*
CV%	3.0	5.5	7.4	6.6	5.8	7.1	4.7	6.6

* Significant at the 0.05 probability level.
*** Significant at the 0.001 probability level.
† Topdressing was applied every two weeks from May to September with the total amount of 2.1 and 4.2 L m^{-2} in 2013.
‡ NS, not significant.

Table 1.26. Surface hardness response to the interaction of sand size and topdressing rate measured with 0.5 kg Clegg Impact Soil Tester released from the reduced height of 10 cm on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2013.

Sand Size	Topdressing Rate†	16-May-13	20-Sep-13
		g_{max}	
Medium-coarse	0.15 L m^{-2}	36.7	43.4
Medium-coarse	0.30 L m^{-2}	36.6	38.7
Medium-fine	0.15 L m^{-2}	35.5	38.1
Medium-fine	0.30 L m^{-2}	38.4	40.8
$LSD_{0.05}$		2.05	5.00

† Topdressing was applied every two weeks from May to September with the total amount of 2.1 and 4.2 L m^{-2} in 2013.

Table 1.27. Penetration depth response to sand size and topdressing rate on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2012.

Main Effects	9-Apr	18-Apr	18-May	11-Jun	15-Jun	26-Jun	30-Jul	6-Aug	13-Aug	16-Aug	24-Aug
	------------------------------					mm[‡]					------------------------------
Sand Size											
Medium-coarse	4.67	4.58	3.70	3.48	3.73	3.84	4.05	3.94	3.70	4.01	3.36
Medium-fine	4.47	4.39	3.59	3.48	3.52	3.73	3.91	3.91	3.64	3.82	3.29
Topdressing Rate[†]											
0.15 L m^{-2}	4.70	4.52	3.83	3.73	3.82	4.01	4.15	4.20	3.79	4.18	3.43
0.30 L m^{-2}	4.44	4.45	3.45	3.22	3.43	3.56	3.82	3.66	3.56	3.65	3.22
No Sand	5.42	5.35	4.12	4.20	4.23	4.44	4.49	4.35	4.14	4.60	3.79
$LSD_{0.05}$	0.147	0.246	0.153	0.203	0.177	0.146	0.262	0.156	0.190	0.201	0.223
ANOVA	------------------------------					$p > F$					------------------------------
No Sand vs Sand	***	***	***	***	***	***	**	***	***	***	**
Sand Size	**	NS[§]	NS	NS	*	NS	NS	NS	NS	*	NS
Topdressing Rate	**	NS	***	***	***	***	*	***	*	***	*
Size x Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV%	2.1	3.5	2.7	3.8	3.2	2.5	4.3	2.6	3.4	3.3	4.4

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Topdressing was applied every two weeks from May to September with the total amount of 2.25 and 4.5 L m^{-2} in 2012.
‡ Distance the indicator tip penetrated into the turf canopy.
§ NS, not significant.

Table 1.28. Penetration depth response to sand size and topdressing rate on a ‘Greenwich’ velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2013.

Main Effects	17-Jun	28-Jun	10-Jul	22-Jul	8-Aug	16-Aug	20-Sep
				---------------------------------- mm‡ ----------------------------------			
Sand Size							
Medium-coarse	4.27	4.61	4.00	4.47	4.03	3.57	3.29
Medium-fine	4.18	4.52	4.00	4.40	3.99	3.61	3.25
Topdressing Rate†							
0.15 L m^{-2}	4.47	4.82	4.15	4.55	4.25	3.74	3.38
0.30 L m^{-2}	3.97	4.32	3.85	4.32	3.78	3.44	3.16
No Sand	4.78	5.22	4.45	4.91	4.32	4.14	3.83
$LSD_{0.05}$	0.242	0.204	0.211	0.177	0.344	0.207	0.278
ANOVA				--------------------------------- $p > F$ ---------------------------------			
No Sand vs Sand	***	***	**	***	NS	***	**
Sand Size	NS§	NS	NS	NS	NS	NS	NS
Topdressing Rate	***	***	**	*	**	**	NS
Size x Rate	*	NS	NS	*	NS	NS	NS
CV%	3.7	2.9	3.5	2.6	5.7	3.8	5.5

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Topdressing was applied every two weeks from May to September with the total amount of 2.1 and 4.2 L m^{-2} in 2013.
‡ Distance the indicator tip penetrated into the turf canopy.
§ NS, not significant.

Table 1.29. Penetration depth response to the interaction of sand size and topdressing rate on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2013.

Sand Size	Topdressing Rate†	17-Jun-13	22-Jul-13
		mm‡	
Medium-coarse	0.15 L m^{-2}	4.38	4.49
Medium-coarse	0.30 L m^{-2}	4.16	4.46
Medium-fine	0.15 L m^{-2}	4.57	4.61
Medium-fine	0.30 L m^{-2}	3.79	4.19
$LSD_{0.05}$		0.306	0.224

† Topdressing was applied every two weeks from May to September with the total amount of 2.1 and 4.2 L m^{-2} in 2013.

‡ Distance the indicator tip penetrated into the turf canopy.

Table 1.30a. Volumetric water content (measured at a 0–38 mm depth with time domain reflectometry) response to sand size and topdressing rate on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ from 26 Apr. to 28 July 2011.

Main Effects	26-Apr	13-May	19-May	31-May	13-Jun	20-Jun	27-Jun	5-Jul	11-Jul	18-Jul	19-Jul	28-Jul
	m^3 m^{-3}											
Sand Size												
Medium-coarse	0.308	0.249	0.397	0.316	0.318	0.302	0.251	0.330	0.277	0.291	0.306	0.247
Medium-fine	0.306	0.239	0.401	0.321	0.343	0.298	0.261	0.320	0.267	0.285	0.301	0.235
Topdressing Rate†												
0.15 L m^{-2}	0.317	0.255	0.408	0.330	0.334	0.303	0.264	0.334	0.272	0.293	0.311	0.230
0.30 L m^{-2}	0.297	0.232	0.391	0.308	0.327	0.298	0.248	0.315	0.272	0.284	0.296	0.252
No Sand	0.345	0.254	0.435	0.346	0.349	0.337	0.296	0.344	0.309	0.297	0.306	0.282
$LSD_{0.05}$	0.014	0.045	0.030	0.030	0.056	0.029	0.029	0.034	0.025	0.062	0.051	0.065
ANOVA	$p > F$											
No Sand vs Sand	***	NS‡	*	NS	NS	*	*	NS	**	NS	NS	NS
Sand Size	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Topdressing Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Size x Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV%	3.0	12.2	4.9	6.2	11.2	6.3	7.4	6.9	5.9	14.4	11.3	17.4

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Topdressing was applied every two weeks from June to September with the total amount of 2.4 and 4.8 L m^{-2} in 2011.
‡ NS, not significant.

Table 1.30b. Volumetric water content (measured at a 0–38 mm depth with time domain reflectometry) response to sand size and topdressing rate on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ from 8 Aug. to 11 Oct. 2011.

Main Effects	8-Aug	22-Aug	29-Aug	5-Sep	19-Sep	11-Oct
	----------------------------	------	------ $m^3\ m^{-3}$	------	------	----------------------------
Sand Size						
Medium-coarse	0.296	0.371	0.321	0.323	0.359	0.212
Medium-fine	0.294	0.380	0.329	0.322	0.364	0.217
Topdressing Rate†						
0.15 L m^{-2}	0.298	0.383	0.328	0.332	0.367	0.221
0.30 L m^{-2}	0.293	0.369	0.322	0.313	0.357	0.209
No Sand	0.329	0.397	0.356	0.362	0.381	0.247
$LSD_{0.05}$	0.042	0.030	0.030	0.057	0.061	0.030
ANOVA	----------------------------	------	------ $p > F$	------	------	----------------------------
No Sand vs Sand	NS‡	NS	*	NS	NS	*
Sand Size	NS	NS	NS	NS	NS	NS
Topdressing Rate	NS	NS	NS	NS	NS	NS
Size x Rate	NS	NS	NS	NS	NS	NS
CV%	9.4	5.2	6.1	11.6	11.3	9.1

* Significant at the 0.05 probability level.

† Topdressing was applied every two weeks from June to September with the total amount of 2.4 and 4.8 L m^{-2} in 2011.

‡ NS, not significant.

Table 1.31. Volumetric water content (measured at a 0–38 mm depth with time domain reflectometry) response to sand size and topdressing rate on a ‘Greenwich’ velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2012.

Main Effects	3 Apr	5 Apr	9 Apr	18 Apr	14 May	16 May	18 May	11 Jun	15 Jun	26 Jun	30 Jul	6 Aug	13 Aug	16 Aug	24 Aug
	----------	----------	----------	----------	----------	----------	----------	m^3 m^{-3}	----------	----------	----------	----------	----------	----------	----------
Sand Size															
Medium-coarse	0.268	0.256	0.247	0.277	0.364	0.409	0.304	0.377	0.290	0.304	0.294	0.330	0.242	0.309	0.246
Medium-fine	0.288	0.269	0.248	0.290	0.385	0.428	0.325	0.368	0.296	0.313	0.319	0.324	0.249	0.316	0.254
Topdressing Rate†															
0.15 L m^{-2}	0.285	0.276	0.255	0.294	0.396	0.427	0.327	0.371	0.304	0.321	0.318	0.334	0.253	0.326	0.258
0.30 L m^{-2}	0.271	0.249	0.240	0.273	0.353	0.410	0.302	0.374	0.282	0.297	0.295	0.321	0.238	0.299	0.243
No Sand	0.303	0.279	0.276	0.284	0.418	0.464	0.343	0.405	0.338	0.346	0.358	0.370	0.284	0.360	0.272
$LSD_{0.05}$	0.027	0.060	0.071	0.108	0.079	0.036	0.041	0.026	0.019	0.029	0.055	0.035	0.050	0.041	0.041
ANOVA	----------	----------	----------	----------	----------	----------	----------	$p > F$	----------	----------	----------	----------	----------	----------	----------
No Sand vs Sand	NS‡	NS	NS	NS	NS	*	NS	*	***	*	NS	*	NS	*	NS
Sand Size	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Topdressing Rate	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS
Size x Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV%	6.4	15.2	18.8	25.7	13.8	5.7	8.7	4.5	4.3	6.1	11.7	7.0	13.4	8.6	10.9

* Significant at the 0.05 probability level.

*** Significant at the 0.001 probability level.

† Topdressing was applied every two weeks from May to September with the total amount of 2.25 and 4.5 L m^{-2} in 2012.

‡ NS, not significant.

Table 1.32. Volumetric water content (measured at a 0–38 mm depth with time domain reflectometry) response to sand size and topdressing rate on a 'Greenwich' velvet bentgrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2013.

Main Effects	16-May	17-Jun	28-Jun	10-Jul	22-Jul	8-Aug	16-Aug	20-Sep
	---------------	---------------	---------------	m^3 m^{-3}	---------------	---------------	---------------	---------------
Sand Size								
Medium-coarse	0.296	0.338	0.406	0.406	0.303	0.296	0.269	0.287
Medium-fine	0.315	0.346	0.421	0.422	0.326	0.334	0.277	0.309
Topdressing Rate†								
0.15 L m^{-2}	0.316	0.355	0.425	0.422	0.325	0.319	0.280	0.311
0.30 L m^{-2}	0.296	0.330	0.403	0.407	0.303	0.311	0.266	0.284
No Sand	0.342	0.389	0.461	0.444	0.370	0.342	0.303	0.341
$LSD_{0.05}$	0.030	0.025	0.026	0.023	0.053	0.066	0.034	0.016
ANOVA	---------------	---------------	---------------	$p > F$	---------------	---------------	---------------	---------------
No Sand vs Sand	*	**	**	*	*	NS‡	NS	***
Sand Size	NS	NS	NS	NS	NS	NS	NS	**
Topdressing Rate	NS	*	NS	NS	NS	NS	NS	**
Size x Rate	NS	NS	NS	NS	NS	NS	NS	NS
CV%	6.4	4.8	4.1	3.6	11.0	13.9	8.3	3.6

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Topdressing was applied every two weeks from May to September with the total amount of 2.1 and 4.2 L m^{-2} in 2013.
‡ NS, not significant.

Table 1.33. Steady-state infiltration rate measured with the mini disk infiltrometer and saturated hydraulic conductivity as affected by sand size and topdressing rate. Data were analyzed using natural log transformation.

	Steady-state infiltration rate						
Main Effects	–5.5 cm	–3.5 cm	–2.5 cm	–1.5 cm	–0.5 cm	K_{sat}	α
	---------------------------- cm d^{-1} ---------------------------						
Sand Size							
Medium-coarse	17	37	83	217	656	788	1.1
Medium-fine	17	28	93	251	594	575	0.9
Topdressing Rate†							
0.15 L m^{-2}	16	34	109	265	624	580	0.8
0.30 L m^{-2}	18	31	71	205	624	781	1.1
No Sand	19	31	63	128	405	443	1.0
ANOVA	-------------------------------- $p > F$ -----------------------------						
No Sand vs Sand	NS‡	NS	NS	0.054§	*	*	NS
Sand Size	NS	NS	NS	NS	NS	NS	NS
Topdressing Rate	NS	NS	NS	NS	NS	NS	NS
Size x Rate	NS	NS	NS	NS	NS	NS	NS
CV%	12.1	12.0	10.0	7.7	3.3	4.4	23.8

* Significant at the 0.05 probability level.

† Topdressing was applied every two weeks from June to September in 2011 and from May to September in 2012 and 2013.

‡ NS, not significant.

§ Probability level ≤ 0.1.

CHAPTER 2. Topdressing Sand Size Distribution Effect on Anthracnose Disease Severity, Turf Quality and Surface Characteristics of Annual Bluegrass Putting Green Turf

ABSTRACT

The sand size can impact the ability to incorporate topdressing into the turf canopy and thatch; unincorporated sand on putting greens interferes with mowing and play. This 3-yr field trial was initiated in 2011 to determine the effects of sand size on anthracnose disease (caused by *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman), turf quality, sand incorporation, and surface characteristics of annual bluegrass [*Poa annua* L. f. *reptans* (Hausskn) T. Koyama] putting green. Treatments included a non-topdressed control and topdressing every two weeks at 0.15 L m^{-2} during the summer with medium-coarse, medium, or medium-fine sand. Plots were arranged in a randomized complete block design with four replications. Turf responses to topdressing were not immediate; however, as sand accumulated in the turf canopy in 2012 and 2013, topdressed plots typically had lower anthracnose severity and better turf quality than the non-topdressed turf. Additionally, topdressing with medium and medium-fine sands produced equivalent or better turf quality and lower disease severity than plots topdressed with medium-coarse sand. As expected, topdressing with medium-coarse sand was more difficult to incorporate compared to the medium and medium-fine sands, resulting in greater amount of sand collected with mower clippings. Surprisingly, sand treatments reduced surface hardness measured with a 2.25- and 0.5-kg Clegg Impact Soil Tester (CIST) at a standard height (46- and 30-cm, respectively) on 50% and 21% of observations throughout the entire study, respectively, compared to the non-topdressed

control. Differences in surface hardness among sand treatments were subtle and inconsistent. In contrast, the 0.5-kg CIST dropped from a shorter height (10 cm) detected an increase in hardness on topdressed plots on 32% of the observation dates. The impact energy generated by the hammer falling from 10 cm is much less than from 30 cm, thus reflecting hardness of the surface rather than deeper in the soil profile. Similarly, topdressing decreased penetration depth suggesting increased surface strength as measured with a depth measuring penetrometer compared to non-topdressed control on all rating dates. Volumetric water content (VWC) at the 0- to 38-mm depth zone was greater in control plots than topdressed plots on 34% of observation dates. Very few and inconsistent differences in VWC were found among sand size treatments. The lack of short-term negative effects of medium and medium-fine sands on measured parameters suggests that further research is warranted to determine if they should be recommended for topdressing golf course putting greens.

INTRODUCTION

Anthracnose, caused by the fungus *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman, is a major disease of cool-season turfgrasses throughout the world (Browning et al., 1999; Crouch and Beirn, 2009; Crouch and Clarke, 2012; Landschoot and Hoyland, 1995; Mann and Newell, 2005; Smiley et al., 2005; Vargas, 2005). Anthracnose is particularly severe on annual bluegrass [*Poa annua* L. f. *reptans* (Hausskn) T. Koyama] putting greens (Browning et al., 1999; Crouch and Clarke, 2012; Mann and Newell, 2005; Smiley et al., 2005). Infection on annual bluegrass can occur almost any time of the year, but hot humid weather is most conducive to disease development (Smith et al., 1989; Vargas, 2005). Summer stresses often shorten turfgrass roots and weaken plants. Stressed and weakened plants are more susceptible to anthracnose than healthy and well-maintained turf (Landschoot and Hoyland, 1995; Murphy et al., 2012; Smiley et al., 2005; Sprague and Evaul, 1930; Vargas, 2005).

Increased nitrogen fertility, mowing height, soil water, and topdressing have been shown to decrease anthracnose severity (Hempfling et al., 2015; Inguagiato et al., 2008, 2009, 2012, 2013; Roberts et al., 2011; Roberts and Murphy, 2014). In particular, long-term sand topdressing programs can improve turf quality and suppress the severity of anthracnose on annual bluegrass putting green turf (Hempfling et al., 2015; Inguagiato et al., 2012, 2013; Roberts and Murphy, 2014). Topdressing with sand weekly at 0.3 L m^{-2} or every two weeks at 0.6 L m^{-2} during the summer can substantially reduce anthracnose severity (Inguagiato et al., 2012). Although the actual mechanism is unknown, sand topdressing may suppress anthracnose disease by burying infecting tissues or diluting the inoculum in the thatch/mat layer (Madison et al., 1974; Sprague and Evaul, 1930). Sand topdressing may also reduce anthracnose severity indirectly. Topdressing buries and protects crowns and leaf sheaths, thereby enhancing plant vigor. This can result in larger, deeper, and healthier crowns (Inguagiato et al., 2012). Moreover, topdressing firms and smooths the putting green surface of the green effectively raising the cutting height by better supporting mowers (Inguagiato et al., 2012); higher mowing has been shown to reduce anthracnose severity on annual bluegrass putting green turf (Inguagiato et al., 2009).

Although effective at reducing anthracnose, the relatively heavy summer topdressing rates (0.3 L m^{-2} weekly and 0.6 L m^{-2} every two weeks) used by Inguagiato et al. (2012) and Roberts and Murphy (2014) may interfere with mowing and putting quality. Wear on mower reels and bedknives can be substantial when topdressing is not fully incorporated into the turf canopy and daily mowing removes sand particles (Foy, 1999; Murphy, 2012; Vavrek, 1995). Sand contamination of clippings will also interfere with the measurement of clipping yield and the assessment of nutrient uptake on putting green turf (Johnston et al., 2005; Kreuser et al., 2011). The interruption to play and excessive wear on mowers discourages golf course superintendents from routinely implementing topdressing during the growing season.

Recently, some golf courses have adopted the use of finer (medium-fine) sands to improve the incorporation of topdressing sand (Murphy, 2012; Pippin, 2010). Topdressing with sand that contains predominately medium (0.25–0.50 mm) and fine (0.15–0.25 mm) particles has the benefits of easier incorporation and less interference to mowing and play. Coarse (0.5–1.0 mm) and very coarse (1.0–2.0 mm) sand particles are more likely to remain on turf surface, whereas finer sized sand particles more easily filter into the turf canopy (Stier and Hollman, 2003; Taylor, 1986). However, excess fine sand in the root zone of a putting green can reduce air-filled porosity and saturated hydraulic conductivity (Ksat) compared to the use coarse or coarse-medium sand (Murphy et al., 2001). Thus finer sand used for topdressing may potentially reduce water infiltration and increase surface water retention.

There has been very limited research on the use of medium-fine sand for topdressing turf. Henderson and Miller (2010) reported that fairway turf topdressed with finer sands had greater surface strength than coarse sands. Additionally, the finer sand tended to retain more water in the top 5 cm of the root zone (Henderson et al., 2010). Moeller (2008) reported that core aeration twice a year and topdressing with a medium-fine sand (finer than the underlying root zone) resulted in an increase of fine sand (0.15–0.25 mm) at the 0–5.7 cm root zone depth. However, medium-fine sand did not impede turfgrass performance and, in fact, turf color was sometimes improved likely due to greater water retention (Moeller, 2008). Because of the potential for detrimental effects, research is needed to investigate the effects of medium-fine sand on the performance characteristics of turf before it can be recommended for use on golf courses. The objectives of this research were to determine effect of sand particle size distribution on anthracnose disease severity, turfgrass quality and color, efficiency of incorporation, surface hardness and surface water retention of annual bluegrass putting green turf.

MATERIALS AND METHODS

Research Methodology

A three-year field study was initiated in mid-June 2011 on annual bluegrass turf grown on a Nixon sandy loam (fine-loamy, mixed, mesic Typic Hapludaults) and maintained as a putting green at the Rutgers Hort. Farm No. 2 in North Brunswick, NJ. The annual bluegrass turf was developed from the soil seed bank as well as seed introduced in 1998 from soil cores collected from Plainfield Country Club, Plainfield, NJ (Samaranayake et al., 2008). A monostand of annual bluegrass was established in September 2002 as described by Inguagiato et al. (2009). The topdressings treatments in this trial were a non-topdressed control and three sand sizes (Table 2.1), replicated four times in a randomized complete block design. A medium-coarse sand ("310" U.S. Silica, Co., Mauricetown, NJ), medium sand [coarse sand removed from medium-coarse sand with a #35 (500-µm) sieve], and medium-fine sand ("Drier 50" U.S. Silica, Co., Mauricetown, NJ) (Table 2.1) were applied at 0.15 L m^{-2} every two weeks from 26 July to 29 Aug. 2011, 19 June to 11 Oct. 2012 and 18 June to 3 Oct. 2013. Additional applications were applied in spring and autumn at 0.3 L m^{-2} on 11 July 2011, 23 May 2012, 5 June 2012, 16 Nov. 2012, 20 May 2013, 4 June 2013 and 14 Nov. 2013; and at 0.6 L m^{-2} on 13 June 2011, 27 June 2011, 21 Oct. 2011, 4 Nov. 2011, 10 Apr. 2012, 24 Apr. 2012, 17 Oct. 2012, 10 Apr. 2013, 24 Apr. 2013 and 29 Oct. 2013. The annual total of sand applied was 3.5 L m^{-2} in 2011, and 3.9 L m^{-2} in 2012 and 2013. Sand was measured for each treatment and applied with drop spreader (model SS-2, The Scotts Company, Marysville, OH) and incorporated immediately after topdressing with a stiff-bristled brush (Harper Brush Works, Inc., Fairfield, IA). Sand topdressing was never applied as a broadcast application to the entire study.

General Field Maintenance

Turf was mowed 6 d wk^{-1} with clippings collected during the growing season with a triplex greens mower (model 3150, Toro Co., Bloomington, MN) at a bench-setting of 2.8 mm. Plots were rolled 3 to 5 times a week with a smooth pavement roller (1.7 metric ton tandem vibratory roller, Model RD11A, Wacker Neuson, Germany) to smooth the surface and simulate traffic. Overhead irrigation and hand watering were applied to obtain moderately dry and uniform soil water content similar to a golf course setting. Water-soluble nitrogen sources were applied every two weeks at 4.9 kg ha^{-1} from April to August in 2011, 2012 and 2013 with the total of 53.7 kg ha^{-1} using urea, potassium nitrate, calcium nitrate or ammonium nitrate. To promote disease recovery, 18.3 kg ha^{-1} of N was applied on 19 Mar. 2012; 188 kg ha^{-1} and 96 kg ha^{-1} of N were applied 17 Aug. to 26 Oct. 2011 and 28 Aug. to 21 Nov. 2012, respectively. The mat layer pH was 5.4, 6.2 and 6.4 and the underlying soil pH was 6.1, 5.9 and 6.0 in 2011, 2012 and 2013, respectively. Dolomitic limestone was applied at 61 kg ha^{-1} on 24 Sept. 2011. Gypsum ($CaSO_4 \cdot 2H_2O$) was applied at 634 kg ha^{-1} on 29 June 2012. The trial was fertilized with 10.7, 22.6 and 12.6 kg ha^{-1} of P, and 204, 158 and 182 kg ha^{-1} of K in 2011, 2012 and 2013, respectively, based on soil test recommendations common for putting greens in the northeastern United States. Ethephon [(2-chloroethyl)phosphonic acid] was applied three times at 14 d intervals at 3.8 kg a.i. ha^{-1} from March to April in 2011, 2012 and 2013 to suppress seedheads. 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 22 Mar. to 26 Oct. 2011, 15 Mar. to 12 Nov. 2012 and 15 Mar. to 21 Nov. 2013 for vegetative growth suppression as is the standard management practice for annual bluegrass putting green turf in the northeastern United States. Dollar spot was preventatively controlled every 14 d from April to August each year with alternating applications of vinclozolin [3-(3,5-dichlorophenyl)-5-ethenyl-5-methyl-2,4-oxazolidinedione] and boscalid {3-pyridinecarboximide, 2-chloro-N-[4'chloro(1,1'-biphenyl)yl]} at 1.5 and 0.4 kg a.i. ha^{-1}, respectively. Azoxystrobin [methyl (E)-2-{2-[6-(2-cyanophenoxy) pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate] and flutolanil {N-[3-(1-methylethoxy)phenyl]-2-(trifluoromethyl)benzamide} were applied alternatively on a 14 d schedule from April through August at 0.6 kg a.i. ha^{-1} and 6.4 kg a.i. ha^{-1}, respectively, to control brown patch and summer patch diseases. These fungicides have been shown in previous studies on this site not to affect anthracnose (Clarke et al., 2006; Towers et al., 2003). Annual bluegrass weevils were controlled with bifenthrin {[2-methyl(1,1'-biphenyl)-3-yl]methyl 3-[2- chloro-3,3,3-trifluoro-1-propenyl]-2,2-dimethyl-cyclopropanecarboxylate} applied at 0.14 and 0.29 kg a.i. ha^{-1} on 21 Aug. 2011 and 30 June 2013, respectively, chlorantraniliprole {3-Bromo-N-[4-chloro-2-methyl-6-[(methylamino)carbonyl]phenyl]-1-(3-chloro-2-pyridinyl)-1H-pyrazole-5-carboxamide} applied at 0.18 kg a.i. ha^{-1} on 3 May 2011 and 0.12 kg a.i. ha^{-1} on 18 Apr. 2012 and 1 May 2013, and indoxacarb {(S)-methyl 7-chloro-2,5-dihydro-2-[[(methoxycarbonyl)[4(trifluoromethoxy)phenyl]amino]-carbonyl]indeno[1,2-ae][1,3,4]oxadiazine-4a-(3H)-carboxylate} applied at 0.25 kg a.i. ha^{-1} on 23 June 2012. Mancozeb (coordination of zinc ion and manganese ethylene bisdithiocarbamate), which has a limited effect on anthracnose, was applied at 15.3 kg a.i. ha^{-1} on 23 May 2012 and 2 July 2013 and 19.5 kg a.i. ha^{-1} on 19 Aug. 2012 to suppress algae (cyanobacteria).

Chlorothalonil (tetrachloroisophthalonitrile) at 12.6 kg a.i. ha^{-1}, fosetyl-Al (O-ethyl phosphonate) at 9.8 kg a.i. ha^{-1}, tebuconazole (α-[2-(4-chlorophenyl)ethyl]-α-(1,1-dimethylethyl)-1H-1,2,4-triazole-1-ethanol) at 0.7 kg a.i. ha^{-1}, or polyoxin D zinc salt (1:1) {Zinc 5-[[2-amino-5-O-(aminocarbonyl)-2-deoxy-L-xylonoyl]amino]-1-(5-carboxy-3,4-dihydro-2,4-dioxo-1(2H)-pyrimidinyl)-1,5-dideoxy-ß-D-allofuranuronate}at 0.3 kg a.i. ha^{-1} was applied every 14 d from 13 Aug. to 26 Oct. 2011 to arrest the anthracnose epiphytotic and promote turf recovery. In 2012, anthracnose was suppressed with chlorothalonil at 16.1 kg a.i. ha^{-1} on 17 August, and then every 8–12 d from 24 August to 5 October at 12.6 kg a.i. ha^{-1} and 10.1 kg a.i. ha^{-1} on 5 November. In 2013, chlorothalonil was applied alone at 12.6 kg a.i. ha^{-1} on 9 August, 16 August, 3 September, 21 September and at 8.1 kg a.i. ha^{-1} on 18 October, and in a tank mixture with tebuconazole at 8.1 kg a.i. ha^{-1} and 0.7 kg a.i. ha^{-1}, respectively, on 2 October. Metconazole was applied at 0.6 kg a.i. ha^{-1} on 30 Aug. 2013 to provide additional suppression of anthracnose and dollar spot.

Data Collection

Disease Severity

Anthracnose severity was visually assessed five times from 24 June to 16 Aug. 2011 (Table 2.2), six times from 27 June to 25 Sept. 2012 (Table 2.3), and seven times from 14 June to 17 Sept. 2013 (Table 2.4) using a line intercept-grid count method described by Inguagiato et al. (2008).

Turf Quality and Color

Visual evaluation of turf quality was assessed based on plant density, uniformity and disease severity on a 1–9 scale, where 9 represented the best turf quality and 5 was the minimum acceptable quality. Turf quality was rated six times from 24 June to 4 Nov.

2011 (Table 2.6), nine times from 3 Apr. to 25 Sept. 2012 (Table 2.7), and nine times from 10 Apr. to 17 Sept. 2013 (Table 2.8). Color was not included as a component of turf quality. Turf color was rated visually on a scale of 1–9, where 9 represented the darkest green color and 5 was the lowest acceptable color, five times from 24 June to 16 Aug. 2011 (Table 2.9), nine times from 3 Apr. to 25 Sept. 2012 (Table 2.10), and six times from 10 Apr. to 7 Aug. 2013 (Table 2.11).

Sand Incorporation

The completeness of sand incorporation after topdressing was assessed visually on a 1 to 9 scale, where 9 represented complete incorporation of sand into the turf canopy and 5 represented a visible but acceptable quantity of sand remaining (unincorporated) on top of the canopy. Visual sand incorporation was evaluated once on 4 Nov. 2011 (Table 2.12), five times from 11 Apr. to 26 Sept. 2012 (Table 2.12), and eight times from 10 Apr. to 3 Oct. 2013 (Table 2.13). To quantify unincorporated sand, clippings were occasionally collected the day after topdressing with a walk behind mower (Toro Greensmaster® 1000, Bloomington, MN) at bench-setting of 3.4 mm equivalent to daily mowing with a triplex greens mower (model 3150, Toro Co., Bloomington, MN) at bench-setting of 2.8 mm. Clippings were collected five times from 14 June to 23 Aug. 2011, four times from 11 Apr. to 1 Aug. 2012, and three times from 25 Apr. to 19 June 2013 (Table 2.14). Clipping samples were dried at 55°C for 72 h and combusted in a muffle furnace at 600°C for 4 h. Sand was separated from ash using 106 µm sieve and weighed as described by Johnston et al. (2005).

Surface Hardness and Strength

A 2.25- and 0.5-kg Clegg Impact Soil Tester (Models 95049 and 95048A, respectively, Lafayette Company, Lafayette, IN) was used to measure surface hardness. The maximum deceleration of a single drop of the 2.25- or 0.5-kg hammer from a height of 46- or 30-cm, respectively, was recorded 4 times per plot. Maximum deceleration was recorded in gravities (g_{max}) and the four measurements for each plot were averaged before statistical analysis. The 0.5-kg hammer was dropped similarly from 10- and 20-cm heights. Surface hardness was evaluated with a 2.25-kg hammer 14 times from 8 June to 11 Oct. 2011 (Table 2.15), 11 times from 2 Apr. to 13 Aug. 2012 (Table 2.16), and seven times from 7 May to 12 Sept. 2013 (Table 3.17); with a 0.5-kg hammer nine times from 18 July to 11 Oct. 2011 (Table 2.18), 13 times from 2 Apr. to 13 Aug. 2012 (Table 2.19) and seven times from 7 May to 20 Sept. 2013 (Table 2.21). Evaluation was also made with a 0.5-kg hammer released from a reduced height of 20 cm on 19 July 2011 (Table 2.18), 4 Apr. and 16 Apr. 2012 (Table 2.20) as well as from a reduced height of 10 cm once on 19 July 2011 (Table 2.18), 14 times from 4 Apr. to 13 Aug. 2012 (Table 2.20) and seven times from 7 May to 20 Sept. 2013 (Table 2.21).

In 2012, a depth-measuring micrometer (F2750-1 Wisdom 2700 Electronic Indicator 65847, The L.S. Starrett Company, Athol, MA) was modified to function as a shallow depth measuring penetrometer to assess surface strength. A flat metal base was mounted to the micrometer to serve as standing base and zero reference for the upper height of the turf canopy. This penetrometer measures the penetration depth of the 4.5-mm diameter probe with an applied pressure of 262 kPa. The shorter penetration depth, the greater surface strength (resistance to penetration). The average of eight depth measurements taken per plot was used for statistical analysis. Surface strength was evaluated with penetrometer 11 times from 14 May to 13 Aug. 2012 (Table 2.22) and five times from 17 June to 20 Sept. 2013 (Table 2.23).

Volumetric Water Content and Algae

Volumetric water content (VWC) was measured simultaneously with surface hardness and strength with time domain reflectometry (Field Scout TDR 300 model, Spectrum Technologies, Inc., Plainfield, IL) equipped with 38 mm probes. The average of four VWC measurements taken per plot was used for statistical analysis. Algae incidence was rated visually on 2 July and 13 Aug. 2013 (Table 2.27) after heavy rainfalls on a 1 to 9 scale, where 9 represented absence of algae and 5 is the minimum acceptable algae infestation.

Data Analysis

Data were subjected to analysis of variance using the General Linear Model procedure in the Statistical Analysis System software v. 9.3 (SAS Institute Inc., Cary, NC), and orthogonal contrasts were performed to compare treatments at the 0.05 probability level.

RESULTS

Disease Severity

Anthracnose was first observed in late-June 2011 as natural infestation and developed slowly before dramatically increasing to the peak disease severity (55%–74%) on 5 August (Table 2.2). Disease severity decreased slightly to 55%–67% turf area infested on 16 Aug. 2011 (Table 2.2). In 2012, disease developed on 27 June and gradually increased to 26%–44% turf area infested on 6 August (Table 2.3). Disease was initially observed in mid-June 2013 and progressed gradually before rapidly increasing to a maximum of 54%–71% turf area infested on 7 Aug. 2013 (Table 2.4). Accordingly, area under the disease progress curve (AUDPC) in 2012 was much lower than 2011 and 2013 (Table 2.5).

Disease severity reported as AUDPC was not different among treatment in 2011 (Table 2.5). Regardless of sand sizes, all topdressing treatments reduced anthracnose disease calculated as AUDPC in 2012 and 2013 (Table 2.5). Disease severity was low (< 18%) and similar among all treatments on the first three evaluation dates in 2011 (Table 2.2). However, on the last observation dates, plots treated with medium-fine sand had 12% less disease than medium sand treated plots on 16 Aug. 2011 (Table 2.2). All sand treatments suppressed disease compared to the non-topdressed plots on all rating dates in 2012 (Table 2.3). Varying sand size of topdressing did not affect disease severity in 2012 (Table 2.3). Topdressing treatments suppressed disease on 7 of 8 rating dates in 2013 (Table 2.4). Finer sands produced equivalent or better disease suppression on 2 of 7 dates compared to the medium-coarse sand in 2013 (Table 2.4). Plots topdressed with medium-fine sand had less anthracnose disease than plots topdressed with medium sand on one observation (26 July) in 2013 (Table 2.4).

Turfgrass Quality and Color

Turf quality was not substantially different among treatments in 2011 (Table 2.6). However, the turf quality pooled over all the topdressing treatments was significantly better than the non-topdressed control on 7 of 9 dates in 2012 and all dates in 2013 (Tables 2.7 and 2.8). Varying sand size did not affect turf quality in 2012 (Table 2.7). Finer sands were more effective in improving turf quality compared to the medium-coarse sand on 23 Aug. 2013 (Table 2.8).

Differences in color were not apparent among treatments in 2011 (Table 2.9). Sand topdressing improved turf color in 2012, except for the initial rating date on 3 April and on 11 July (Table 2.10), and on 3 of 6 dates in 2013 (Table 2.11). Varying sand size did not affect turf color in any year of the study (Tables 2.9, 2.10 and 2.11).

Sand Incorporation

Finer sands incorporated better into the turf canopy than medium-coarse sand on 10 of 14 observation dates during 2011, 2012 and 2013 (Tables 2.12 and 2.13). Medium-fine sand incorporated better than medium sand on 5 of 14 dates during 2011, 2012 and 2013 (Tables 2.12 and 2.13). The level of medium-fine sand incorporation was acceptable (≥ 5) on 12 of 14 dates during the study compared to 11 dates for medium sand and 9 dates for medium-coarse sand.

Consistent with visual observations, significantly less sand was removed with the clippings from plots topdressed with finer sands compared to plots treated with medium-coarse sand on 6 of 12 dates in 2011, 2012 and 2013 (Table 2.14). The quantity of sand collected in the clippings from medium-fine sand treated plots was lower than medium sand treated plots on 2 of 12 dates. Only a small quantity of sand particles (less than 1 g m^{-2}) was collected from non-topdressed treatments, which was due to contamination from adjacent sand treated plots during mowing. The quantity of sand removed by the mower on plots receiving medium-coarse sand on 20 June 2012 may have been slightly reduced because the sand was finer than what described in Table 2.1 due to segregation during storage and handling resulting in about 20% less coarse particles and more medium particles (0.5–0.25 mm). Clippings collected on 18 July 2012 were contaminated with gypsum (CaSO4·2H2O) applied on 29 June 2012. Both dates will not be further discussed.

Surface Hardness and Strength

Surprisingly, all sand treatments reduced surface hardness measured with a 2.25-kg hammer on 29%, 45%, and 100% of the rating dates in 2011, 2012 and 2013, respectively (Tables 2.15, 2.16 and 2.17). Plots treated with both finer sands had greater surface hardness than those treated with medium-coarse sand on 10 July 2013 (Table 2.17).

The pooled surface hardness of all topdressing treatments measured with the 0.5-kg hammer at the standard height of 30 cm did not statistically differ from non-topdressed in 2011 (Table 2.18). However, surface hardness at this height was decreased on 3 of 13 and 3 of 7 observations in 2012 and 2013, respectively, and increased on 16 May 2013 (Tables 2.19 and 2.21). Subtle differences in surface hardness (2 of 29) among sand sizes were inconsistent (Table 2.18). Plots topdressed with medium-coarse sand was firmer than plots topdressed with finer sands on 11 October 2011, and plots topdressed with medium sand was firmer than plots topdressed with medium-fine sand on 8 Aug. 2011 (Table 2.18).

Surface hardness measured with the 0.5-kg hammer dropped from a height of 10 cm increased on sand topdressed plots on 7 of 22 dates and decreased hardness on one date in 2011, 2012 and 2013 (Tables 2.18, 2.20 and 2.21).

All sand treatments decreased penetration depth (increased surface strength) on all rating dates in 2012 and 2013 compared to non-topdressed plots (Tables 2.22 and 2.23). Within the sand treatments, topdressing with finer sands was more effective at decreasing penetration depth on 2 of 11 dates compared to medium-coarse sand in 2012 (Table 2.22); medium-fine sand plots had shorter penetration depth than medium sand plots on 1 of 5 dates in 2013 (Table 2.23).

Volumetric Water Content and Algae

All plots treated with sand had significantly lower volumetric water content (VWC) than non-topdressed plots on 13 of 38 rating dates in 2011, 2012 and 2013 (Tables 2.24a, 2.24b, 2.25a, 2.25b and 2.26). Plots topdressed with medium-coarse sand had lower VWC than plots topdressed with finer sands on 2 dates and greater VWC on one date in 2011 (Tables 2.24a and 2.24b). Medium-fine sand plots had a greater VWC than medium sand plots on 2 dates in 2012 (Tables 2.25a and 2.25b). Regardless of sand sizes, all the sands reduced algae equally compared to non-topdressed control (Table 2.27).

DISCUSSION

Topdressing did not suppress disease nor improve turf quality or color in the first year of the trial. However, topdressing reduced anthracnose severity and improved overall performance of annual bluegrass regardless of sand size the last two years of this study. Inguagiato et al. (2012) also reported a lag in disease suppression from topdressing on annual bluegrass putting green turf suggesting that sufficient sand accumulation within the turf canopy and thatch is necessary to suppress disease and improve turf quality. Improvements in root zone properties from topdressing have not been immediately recognized in other turf research studies. Topdressing creeping bentgrass putting greens reduced thatch accumulation only in the last three years of a six-year study (Callahan et al., 1998), and increased water infiltration only occurred in the second year of another two-year topdressing study (McCarty et al., 2005). In our trial, negative effects of medium-fine and medium sand topdressing on turf quality, surface hardness and strength, and VWC were not observed.

Coarse (0.5–1.0 mm) and very coarse (1.0–2.0 mm) sand particles are more likely to be collected with mower clippings than particles less than 0.5 mm in diameter (Stier and Hollman, 2003; Taylor, 1986). Taylor (1986) also reported that finer sands were easier to incorporate resulting in less sand collected with mower clippings. The medium-coarse sand in the current study contained 31% of particles larger than 0.5 mm in diameter whereas the medium-fine and medium sands did not contain coarse particles. This would explain why topdressing with medium-coarse sand was more difficult to incorporate compared to the medium and medium-fine sands.

Numerous studies have reported sand topdressing improved turf performance (Henderson and Miller, 2010; Inguagiato et al., 2012; Madison et al., 1974; Rieke et al., 1988; Whitlark et al., 2001). Sand topdressing improved physical structure of the surface thatch layer and reduced puffiness, therefore reducing mower scalping (McCarty et al., 2007; White and Dickens, 1984). Once a substantial thatch layer develops in a turf, it serves a greater role than soil as the plant holding matrix and growth medium (Hurto et al., 1980). Because, within a matter of a few years turfgrass roots will be growing within a layer of topdressing rather than the original root zone when topdressing is practiced regularly (Cooper, 2004). Topdressing has been shown to be one of the most effective practices for managing thatch (Barton et al., 2009; Beard, 1973; Carrow et al., 1987; Engel and Alderfer, 1967; Thompson and Ward, 1966). Others reported benefits from topdressing include protection from winter desiccation and better spring recovery (Christians et al., 1985; Piper and Oakley, 1917).

Topdressing with medium-coarse, medium or medium-fine sand significantly reduced disease severity after 2011. Inguagiato et al. (2012) interpreted larger and elongated sheaths and deeper crowns of annual bluegrass tillers in topdressed plots as an indication of enhanced plant vigor resulting in a decrease in anthracnose severity. The firmness and smooth surface created by routine topdressing provides better support for mowers which effectively raises the cutting height (Inguagiato et al., 2012); anthracnose has been shown to be less severe at higher (3.2- and 3.6-mm) than lower (2.8-mm) mowing height (Inguagiato et al., 2009). Topdressing may also bury infested plant tissue or dilute the inoculum in the thatch (Madison et al., 1974; Sprague and Evaul, 1930) resulting in less disease. Previous to the work of Inguagiato et al. (2012), topdressing was suspected of enhancing the severity of anthracnose through increased abrasion and wounding, especially during the summer when heat and drought stresses could further weaken turf. However, summer topdressing did not increase anthracnose severity in our study; in other studies with medium-coarse sand, a small and brief increase in disease was observed early in the first year when crowns were not buried and protected by sufficient topdressing layer (Hempfling, 2013; Inguagiato et al., 2012, 2013; Roberts and Murphy, 2014). Therefore, golf course superintendents who maintain turfs with a history of severe anthracnose should consider more aggressive (greater cumulative quantities) topdressing programs without being concerned about intensifying this disease.

All sands were applied at the same rate; however, medium-fine sand was better incorporated into the turf canopy resulting in substantially less sand removed by mowing compared to medium-coarse sand. This process overtime could contribute to a lower quantity of sand accumulated in the root zone of medium-coarse sand treated plots compared to medium or medium-fine sand treated plots. This may explain why finer sands occasionally had less disease, better turf quality and turf color than medium-coarse sand in the last year of the study. Additionally, improved turf establishment and turf color have been speculated to be the result of greater water retention associated with medium-fine sands compared to medium-coarse sand (Moeller, 2008; Murphy et al., 2001; Neylan and Robinson, 1997). Despite the occasional and subtle increase in VWC (< 0.03 m^3 m^{-3}) in plots receiving medium-fine compared to medium or medium-coarse sand, few differences in VWC between the three sand sizes were observed in this trial.

Sand topdressing is expected to increase surface firmness through the bridging of sand particles within the turf canopy and the surface layer of accumulating thatch

(Inguagiato et al., 2012; Li et al., 2009). Espevig et al. (2012) observed that increasing topdressing rate from 0.5 to 1 L m^{-2} every two weeks (totaling 7 to 14 L m^{-2} annually) increased surface hardness of velvet bentgrass turf maintained as a putting green. Kauffman et al. (2011) found that topdressing applied every two weeks at 0.4 L m^{-2} incorporated by brushing increased surface hardness on ultradwarf bermudagrass [*Cynodon dactylon* (L.) × *C. transvaalensis* Burtt Davy] putting greens measured with a 2.25-kg hammer. However, soil water content was not reported in both studies. Contrary to expectations, results from our study indicated that sand topdressing decreased surface hardness with increased frequency from 2011 to 2013 measured with a 2.25-kg hammer (Tables 2.15, 2.16 and 2.17). It is possible that the soil underneath the thatch layer of non-topdressed plots was more compacted by routine traffic from a pavement roller than on topdressed plots, but further research is need to validate this hypnosis. Surface hardness of topdressed plots measured with a 0.5-kg hammer often did not differ from that of non-topdressed in our study similar to reports of Barton et al. (2009) and McCarty et al. (2005) with 2.25-kg hammer. When differences were observed with 0.5-kg hammer, they often supported results measured with a 2.25-kg hammer, except for one observation (16 May 2013) where topdressing increased surface hardness probably by decreasing soil water content compared to non-topdressed.

Measurement taken with either the 2.25- and 0.5-kg hammer may be more representative of hardness deeper in the soil profile than within the topdressing layer at the surface. Both 2.25- and 0.5-kg hammers detected differences in soil compaction, but surface conditions such as cutting heights and presence of verdure or thatch affecting hardness were only detected with the 0.5-kg hammer (Rogers and Waddington, 1989, 1992). Gibbs et al. (2000) concluded that a single drop of the 0.5-kg hammer best represented immediate surface firmness on golf putting greens. The 2.25-kg hammer is typically recommended for detecting hardness (compaction) deeper in the profile, because the impact energy produced by the 0.5-kg hammer is lower than that produced by the 2.25-kg hammer (Rogers and Waddington, 1990b).

Hardness responses measured with the 0.5-kg hammer in our study dropped from a reduced height (10 cm) contradicted those obtained using the standard drop height (30 cm) and the 2.25-kg hammer. The impact energy generated by a 0.5-kg hammer falling from 10 cm is much less than from 30 cm or from a 2.25-kg hammer. The deceleration from a 10 cm drop height is probably affected more by the impact absorption characteristics of the upper surface of the turf (thatch and topdressing) than when the hammer is released from 20- or 30-cm. McClements and Baker (1994) used 30- and 55-cm drop heights with a 0.5-kg hammer to measure the hardness of natural turf hockey pitches, and concluded that results from the 55 cm drop height better represented players' evaluation of the surface for running; varying drop heights is also described as custom protocol in the CIST user's manual.

The depth measuring penetrometer documented shorter penetration depth suggesting greater surface strength on topdressed plots compared to non-topdressed controls on all evaluation dates. This effect was consistent with measurements of hardness using the 0.5-kg hammer dropped from a reduced height. In another study, although the thatch of the non-topdressed plots was very easily compressed and spongy, a self-recording penetrometer (Mathieu and Toogood, 1958) indicated a softer top 2.5 cm layer as topdressing frequency increased; Murphy (1983) speculated that topdressing played a part in alleviating soil compaction. Occasionally, finer sands in the current study were more effective in increasing surface strength than medium-coarse sand, which agrees with the findings of Henderson and Miller (2010).

Results from our study indicated that sand topdressing reduced water retention under wet conditions thereby contributing to algae suppression. Topdressing was also observed to reduce the incidence of surface ponding (Baker and Canaway, 1990). Many have reported a negative association between surface hardness and moisture content (Linde et al., 2011; McClements and Baker, 1994; McNitt and Landschoot, 2001; Rogers and Waddington, 1989; Rogers and Waddington, 1990a; Rogers and Waddington, 1992). However, this relationship was not clear in our study, Stowell et al. (2009) also did not find a relationship between surface hardness and moisture content and attributed the lack of correlation to sand topdressing. Soil water content is known to have little effect on surface hardness of root zones with high sand content (Baker, 1991; Li et al., 2009; McNitt and Landschoot, 2003), but water content can greatly influence hardness of root zones with high soil content (Baker, 1991). A fairway topdressing study indicated the coarser the sand the less water was retained in the upper 5 cm profile (Henderson et al., 2010). Moreover, higher VWC at the 0–5.7 cm depth from frequent topdressing with medium-fine sand was observed on a creeping bentgrass putting green by Moeller (2008); however, this effect could have been strongly affected by core cultivation. In our study, sand sizes occasionally affected VWC at the 0–3.8 cm depth but results varied.

Once sufficient sand accumulated within the turf canopy and thatch, routine topdressing suppressed disease and improved overall performance of annual bluegrass putting green turf in our study. Medium and medium-fine sands reduced anthracnose disease but usually did not significantly differ from medium-coarse sand. The lack of short-term negative effects of medium and medium-fine sands on measured parameters suggests that further research is warranted. The use of finer sands could have a significant impact on putting green management. Less disruption to the putting surface, even at higher topdressing rate of finer sands, would likely encourage superintendents to apply topdressing at greater quantity during the summer resulting in less anthracnose and better playing conditions.

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Table 2.1. Particle size distribution of sands used for topdressing.

	Particle Size (mm)					
	Very Coarse	Coarse	Medium	Fine	Very Fine	
Sand Size	2–1	1–0.5	0.5–0.25	0.25–0.15	0.15–0.05	<0.05
	--------------------------------- % (by weight) ---------------------------------					
Medium-coarse	0.07	31.27	65.05	3.32	0.27	0.01
Medium†	0	0.93	90.88	7.67	0.47	0.03
Medium-fine	0.03	0.25	72.38	24.40	2.92	0.03

† Sand created by sieving medium-coarse sand through #35 sieve (500-µm screen) to remove coarse sand particles.

Table 2.2. Anthracnose severity response on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2011.

Sand Size	24-Jun	7-Jul	16-Jul	5-Aug	16-Aug
	-------------------Turf Area Infested (%)---------------				
None	2.2	4.9	13.3	74.3	64.7
Medium-coarse (MC)	2.6	6.3	17.1	61.7	56.9
Medium-fine (MF)	2.0	4.2	12.2	55.1	55.1
Medium (M)	2.2	3.5	13.8	68.8	67.1
Orthogonal Contrasts	------------------------- $p > F$ --------------------------				
No Sand vs All Sands	NS†	NS	NS	NS	NS
MC vs All Finer Sands	NS	NS	NS	NS	NS
MF vs M	NS	NS	NS	NS	*
CV, %	50.7	70.0	33.3	17.9	11.9

* Significant at the 0.05 probability level.

† NS, not significant.

Table 2.3. Anthracnose severity response on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2012.

Sand Size	27-Jun	11-Jul	27-Jul	6-Aug	20-Aug†	25-Sep†
	Turf Area Infested (%)					
None	4.1	10.3	33.8	44.0	69.1	28.9
Medium-coarse (MC)	1.0	3.5	20.1	29.4	49.8	14.0
Medium-fine (MF)	0.5	4.2	17.0	27.2	50.2	14.8
Medium (M)	2.0	4.0	17.7	26.0	52.4	16.4
Orthogonal Contrasts	$p > F$					
No Sand vs All Sands	**	**	**	**	**	***
MC vs All Finer Sands	NS‡	NS	NS	NS	NS	NS
MF vs M	NS	NS	NS	NS	NS	NS
CV, %	82.3	51.4	30.4	19.1	14.5	22.4

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Data were taken after curative anthracnose chemical control was applied.

‡ NS, not significant.

Table 2.4. Anthracnose severity response on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2013.

Sand Size	14-Jun	8-Jul	15-Jul	26-Jul	7-Aug	23-Aug[†]	17-Sep[†]
	---------------------------Turf Area Infested (%)--------------------------						
None	11.6	21.6	36.4	42.6	71.2	25.5	13.9
Medium-coarse (MC)	3.4	19.5	27.5	37.8	64.7	23.4	11.7
Medium-fine (MF)	1.6	10.4	18.5	27.7	53.8	16.3	8.2
Medium (M)	2.9	16.1	23.1	35.7	60.3	19.3	9.1
Orthogonal Contrasts	---------------------------------- $p > F$ ----------------------------------						
No Sand vs All Sands	***	NS	*	*	**	**	*
MC vs All Finer Sands	NS[‡]	NS	NS	NS	*	*	NS
MF vs M	NS	NS	NS	*	NS	NS	NS
CV, %	35.6	34.9	31.2	13.9	8.0	13.4	29.9

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Data were taken after curative anthracnose chemical control was applied.
‡ NS, not significant.

Table 2.5. Anthracnose severity response reported as area under the disease progress curve (AUDPC) on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2011, 2012 and 2013.

Sand Size	2011	2012	2013
	---------------AUDPC------------		
None	1768.5	841.8	1719.2
Medium-coarse (MC)	1603.9	466.9	1413.6
Medium-fine (MF)	1393.7	423.8	988.6
Medium (M)	1688.2	434.3	1265.5
Orthogonal Contrasts	------------ $p > F$ -------------		
No Sand vs All Sands	NS†	***	**
MC vs All Finer Sands	NS	NS	NS
MF vs M	NS	NS	NS
CV, %	17.4	24.3	17.2

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† NS, not significant.

Table 2.6. Turf quality response on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2011.

Sand Size	24-Jun	7-Jul	16-Jul	5-Aug	16-Aug	4-Nov[†]
	------------------------------ 1–9 scale[‡] ------------------------------					
None	8.8	8.0	7.5	5.1	5.9	6.8
Medium-coarse (MC)	8.5	8.0	7.3	5.9	6.0	7.1
Medium-fine (MF)	8.8	7.8	7.3	5.8	6.1	7.4
Medium (M)	8.5	8.0	7.0	5.3	5.5	7.1
Orthogonal Contrasts	-------------------------------- $p > F$ --------------------------------					
No Sand vs All Sands	NS[§]	NS	NS	NS	NS	NS
MC vs All Finer Sands	NS	NS	NS	NS	NS	NS
MF vs M	NS	NS	NS	NS	NS	NS
CV, %	3.3	7.9	6.5	13.6	10.0	5.3

[†] Data were taken after curative anthracnose chemical control was applied.
[‡] Nine(9) = excellent turf, 6 = acceptable, 1 = dead or necrotic turf.
[§] NS, not significant.

Table 2.7. Turf quality response on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2012.

Sand Size	3-Apr	30-May	15-Jun	25-Jun	11-Jul	27-Jul	6-Aug	20-Aug†	25-Sep†
	----------	----------	----------	----------	1–9 scale‡	----------	----------	----------	----------
None	7.4	7.8	7.6	7.5	6.9	5.9	4.9	3.6	5.3
Medium-coarse (MC)	8.0	8.3	7.9	8.1	8.0	7.4	6.5	6.3	6.9
Medium-fine (MF)	7.8	8.3	8.1	8.0	7.9	7.6	6.8	6.3	6.9
Medium (M)	7.6	8.1	8.1	8.3	8.1	7.5	6.8	6.0	6.8
Orthogonal Contrasts	----------	----------	----------	----------	*p* > *F*	----------	----------	----------	----------
No Sand vs All Sands	NS§	NS	*	**	***	**	***	***	**
MC vs All Finer Sands	NS	NS	NS	NS	NS	NS	NS	NS	NS
MF vs M	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV, %	6.2	4.4	3.1	3.3	4.4	8.5	9.1	11.9	9.8

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Data were taken after curative anthracnose chemical control was applied.
‡ Nine(9) = excellent turf, 6 = acceptable, 1 = dead or necrotic turf.
§ NS, not significant.

Table 2.8. Turf quality response on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2013.

Sand Size	10-Apr	31-May	14-Jun	8-Jul	15-Jul	26-Jul	7-Aug	23-Aug†	17-Sep†
	-- 1–9 scale‡ --								
None	4.8	6.8	5.5	5.3	4.8	3.8	3.8	4.8	5.0
Medium-coarse (MC)	7.3	8.4	7.5	6.5	6.0	4.3	4.8	5.5	6.8
Medium-fine (MF)	7.5	8.3	7.8	7.5	7.5	5.5	5.8	7.0	6.8
Medium (M)	7.3	7.9	7.5	7.0	6.8	4.8	5.3	6.5	6.8
Orthogonal Contrasts	-- $p > F$ --								
No Sand vs All Sands	***	***	***	**	**	*	*	**	**
MC vs All Finer Sands	NS§	NS	NS	NS	NS	NS	NS	**	NS
MF vs M	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV, %	11.6	6.5	5.1	13.5	16.4	18.0	16.4	9.8	13.0

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Data were taken after curative anthracnose chemical control was applied.
‡ Nine(9) = excellent turf, 6 = acceptable, 1 = dead or necrotic turf.
§ NS, not significant.

Table 2.9. Turf color response on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2011.

Sand Size	24-Jun	7-Jul	16-Jul	5-Aug	16-Aug
	---------------------- 1–9 scale† ----------------------				
None	8.3	7.3	6.8	6.5	6.6
Medium-coarse (MC)	8.5	7.3	6.8	6.9	7.0
Medium-fine (MF)	8.5	7.3	6.8	6.9	6.9
Medium (M)	8.5	7.3	6.5	6.9	6.6
Orthogonal Contrasts	------------------------- $p > F$ -------------------------				
No Sand vs All Sands	NS‡	NS	NS	NS	NS
MC vs All Finer Sands	NS	NS	NS	NS	NS
MF vs M	NS	NS	NS	NS	NS
CV, %	6.3	9.8	10.0	9.1	6.3

† Nine(9) = darkest green, 6 = acceptable, 1 = dead or necrotic turf.

‡ NS, not significant.

Table 2.10. Turf color response on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2012.

Sand Size	3-Apr	30-May	15-Jun	25-Jun	11-Jul	27-Jul	6-Aug	20-Aug[†]	25-Sep[†]
	------------------------------ 1–9 scale[‡] ------------------------------								
None	7.9	7.6	7.6	7.5	7.1	6.1	5.4	3.4	5.5
Medium-coarse (MC)	8.0	8.4	8.3	8.1	7.6	7.8	6.9	5.6	7.0
Medium-fine (MF)	7.9	8.3	8.0	8.0	7.8	7.6	7.0	5.4	7.0
Medium (M)	7.9	8.3	8.3	8.1	7.6	7.6	7.1	5.0	6.5
Orthogonal Contrasts	------------------------------ $p > F$ ------------------------------								
No Sand vs All Sands	NS[§]	**	*	*	NS	***	**	***	*
MC vs All Finer Sands	NS	NS	NS	NS	NS	NS	NS	NS	NS
MF vs M	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV, %	5.6	4.1	4.9	4.3	5.7	5.2	9.5	14.4	11.5

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Data were taken after curative anthracnose chemical control was applied.
‡ Nine(9) = darkest green, 6 = acceptable, 1 = dead or necrotic turf.
§ NS, not significant.

Table 2.11. Turf color response on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2013.

Sand Size	10-Apr	14-Jun	8-Jul	15-Jul	26-Jul	7-Aug
	---------------------- 1–9 scale† ----------------------					
None	6.1	5.6	6.3	5.3	3.8	4.8
Medium-coarse (MC)	7.6	7.6	6.8	6.3	3.8	4.5
Medium-fine (MF)	8.1	7.9	7.5	7.5	4.8	6.3
Medium (M)	7.9	7.8	7.5	6.8	4.3	5.5
Orthogonal Contrasts	------------------------ *p* > *F* --------------------------					
No Sand vs All Sands	**	***	NS	*	NS	NS
MC vs All Finer Sands	NS‡	NS	NS	NS	NS	NS
MF vs M	NS	NS	NS	NS	NS	NS
CV, %	11.4	6.8	11.2	13.8	28.9	20.1

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Nine(9) = darkest green, 6 = acceptable, 1 = dead or necrotic turf.
‡ NS, not significant.

Table 2.12. Sand incorporation response on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2011 and 2012.

	2011	2012				
	4-Nov	11-Apr	25-Apr	20-Jun	11-Jul	26-Sep
Sand Size	0 DAT†	1 DAT	1 DAT	1 DAT	8 DAT	0 DAT
	------------------------------ 1–9 scale‡ ------------------------------					
None	9.0	9.0	9.0	9.0	9.0	9.0
Medium-coarse (MC)	7.3	6.3	6.6	7.9	6.6	2.0
Medium-fine (MF)	7.3	7.6	7.9	8.3	7.1	4.8
Medium (M)	7.8	7.3	6.6	8.0	7.0	3.3
Orthogonal Contrasts	-------------------------------- $p > F$ --------------------------------					
No Sand vs All Sands	***	***	***	**	***	***
MC vs All Finer Sands	NS§	**	NS	NS	NS	***
MF vs M	NS	NS	**	NS	NS	**
CV, %	6.1	6.7	6.8	4.3	6.4	9.9

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Number of days after topdressing (DAT), 0 = ratings were taken on the same day after topdressing.

‡ Nine (9) represents no sand visible at turf surface, and 5 represents the minimally acceptable rating.

§ NS, not significant.

Table 2.13. Sand incorporation response on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2013.

Sand Size	10-Apr 0 DAT†	24-Apr 0 DAT	4-Jun 0 DAT	5-Jun 0 DAT	5-Jul 0 DAT	7-Jul 0 DAT	15-Jul 0 DAT	3-Oct 0 DAT
	1–9 scale‡							
None	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
Medium-coarse (MC)	3.0	4.0	4.9	5.4	6.0	7.8	5.3	4.8
Medium-fine (MF)	4.5	5.3	6.0	7.0	7.5	9.0	6.8	6.3
Medium (M)	4.3	4.6	5.3	5.9	7.0	9.0	6.3	5.5
Orthogonal Contrasts	$p > F$							
No Sand vs All Sands	***	***	***	***	***	*	***	***
MC vs All Finer Sands	***	***	**	**	*	***	***	**
MF vs M	NS§	*	*	**	NS	NS	NS	NS
CV, %	8.0	5.5	5.3	7.0	8.8	2.9	5.0	7.8

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Number of days after topdressing (DAT), 0 = ratings were taken on the same day after topdressing.
‡ Nine (9) represents no sand visible at turf surface, and 5 represents the minimally acceptable rating.
§ NS, not significant.

Table 2.14. Sand removed by mowing as influenced by sand size from an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2011, 2012 and 2013.

	2011					2012				2013		
Sand Size	14-Jun	28-Jun	12-Jul	9-Aug	23-Aug	11-Apr	20-Jun†	18-Jul‡	1-Aug	25-Apr	5-Jun	19-Jun
	------------------ $g\ m^{-2}$ ------------------											
None	0.4	0.4	0.4	0.5	0.3	0.0	0.1	2.1	0.8	0.2	0.7	0.1
Medium-coarse (MC)	42.9	28.3	11.4	13.3	9.5	3.0	2.5	25.1	32.3	12.0	49.0	12.3
Medium-fine (MF)	33.3	16.9	6.7	5.6	3.6	1.1	1.6	19.6	14.4	7.9	20.2	5.4
Medium (M)	33.4	23.8	10.0	10.8	5.0	2.3	2.1	21.0	17.8	7.8	38.2	6.5
Orthogonal Contrasts	------------------ $p > F$ ------------------											
No Sand vs All Sands	***	***	**	**	***	***	***	***	***	**	***	***
MC vs All Finer Sands	NS§	NS	NS	*	***	***	NS	NS	***	NS	*	**
MF vs M	NS	NS	NS	NS	NS	**	NS	NS	NS	NS	*	NS
CV, %	32.1	36.0	46.6	45.2	35.3	24.4	38.1	22.7	22.6	57.1	36.8	42.8

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The medium-coarse sand used on those dates was accidentally finer than it usually was.
‡ Clippings were contaminated with gypsum ($CaSO_4 \cdot 2H_2O$) applied on 29 June 2012.
§ NS, not significant.

Table 2.15. Surface hardness response measured with 2.25 kg Clegg Impact Soil Tester on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2011.

Sand Size	8 Jun	13 Jun	20 Jun	27 Jun	5 Jul	11 Jul	18 Jul	28 Jul	8 Aug	22 Aug	29 Aug	5 Sep	19 Sep	11 Oct
	Surface hardness (g_{max})													
None	79	67	69	74	69	72	71	78	77	59	60	61	60	70
Medium-coarse (MC)	76	65	66	74	64	71	67	75	75	58	58	62	61	70
Medium-fine (MF)	78	67	65	74	65	70	68	74	73	57	59	61	58	67
Medium (M)	77	65	66	73	64	68	67	72	72	55	57	58	58	67
Orthogonal Contrasts	$p > F$													
No Sand vs All Sands	NS[†]	NS	*	NS	**	NS	NS	**	*	NS	NS	NS	NS	NS
MC vs All Finer Sands	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
MF vs M	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV, %	2.7	3.8	2.7	3.4	2.4	3.9	5.3	2.9	2.9	4.1	3.0	4.8	4.0	4.6

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

[†] NS, not significant.

Table 2.16. Surface hardness response measured with 2.25 kg Clegg Impact Soil Tester on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2012.

Sand Size	2-Apr	14-May	11-Jun	26-Jun	2-Jul	9-Jul	16-Jul	25-Jul	30-Jul	6-Aug	13-Aug
	---------- Surface hardness (g_{max}) ----------										
None	62	64	57	67	72	82	64	83	65	66	73
Medium-coarse (MC)	60	62	51	64	72	78	61	77	60	63	72
Medium-fine (MF)	60	61	52	63	70	79	60	74	58	61	68
Medium (M)	61	61	53	62	74	78	61	75	59	62	70
Orthogonal Contrasts	---------- $p > F$ ----------										
No Sand vs All Sands	NS†	NS	*	*	NS	NS	NS	***	**	*	NS
MC vs All Finer Sands	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
MF vs M	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV, %	4.6	4.5	5.1	3.8	4.0	3.7	5.6	3.1	3.8	3.7	4.3

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† NS, not significant.

Table 2.17. Surface hardness response measured with 2.25 kg Clegg Impact Soil Tester on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2013.

Sand Size	7-May	16-May	17-Jun	27-Jun	10-Jul	8-Aug	20-Sep
	------------------------ Surface hardness (g_{max}) ------------------------						
None	66	66	57	60	78	65	70
Medium-coarse (MC)	60	61	51	55	72	60	66
Medium-fine (MF)	61	59	50	54	74	60	65
Medium (M)	60	62	52	55	76	59	63
<u>Orthogonal Contrasts</u>	------------------------------------ *p* > F ----------------------------------						
No Sand vs All Sands	***	**	**	***	**	**	**
MC vs All Finer Sands	NS[†]	NS	NS	NS	**	NS	NS
MF vs M	NS	NS	NS	NS	NS	NS	NS
CV, %	3.1	3.5	4.9	3.2	2.1	4.3	4.3

** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
[†] NS, not significant.

Table 2.18. Surface hardness response measured with 0.5 kg Clegg Impact Soil Tester on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2011.

	30 cm†									20 cm‡	10 cm§
Sand Size	18-Jul	19-Jul	28-Jul	8-Aug	22-Aug	29-Aug	5-Sep	19-Sep	11-Oct	19-Jul	19-Jul
	---- Surface hardness (g_{max}) ----										
None	85	95	97	90	73	75	86	75	90	67	40
Medium-coarse (MC)	81	89	96	91	69	73	86	77	96	64	39
Medium-fine (MF)	84	90	95	89	72	71	86	75	90	65	42
Medium (M)	81	91	94	95	71	70	85	75	88	68	41
<u>Orthogonal Contrasts</u>	---- $p > F$ ----										
No Sand vs All Sands	NS¶	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
MC vs All Finer Sands	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS
MF vs M	NS	NS	NS	**	NS	NS	NS	NS	NS	NS	NS
CV, %	5.0	5.5	3.3	2.4	4.4	4.1	5.2	5.0	5.1	7.8	8.6

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† The hammer of 0.5 kg CIST was released from the standard height of 30 cm above ground
‡ The hammer of 0.5 kg CIST was released from a reduced height of 20 cm above ground.
§ The hammer of 0.5 kg CIST was released from a reduced height of 10 cm above ground.
¶ NS, not significant.

Table 2.19. Surface hardness response measured with 0.5 kg Clegg Impact Soil Tester released from the standard height of 30 cm on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2012.

Sand Size	2-Apr	4-Apr	16-Apr	14-May	11-Jun	26-Jun	2-Jul	9-Jul	16-Jul	25-Jul	30-Jul	6-Aug	13-Aug
	-- Surface hardness (g_{max}) --												
None	66	67	76	70	66	77	87	98	76	102	76	79	94
Medium-coarse (MC)	67	71	82	72	64	75	88	97	73	102	72	76	90
Medium-fine (MF)	68	69	82	71	65	78	85	101	71	99	69	73	89
Medium (M)	66	68	80	72	67	74	89	94	72	98	72	74	91
Orthogonal Contrasts	-- $p > F$ --												
No Sand vs All Sands	NS†	NS	NS	NS	NS	NS	NS	NS	*	NS	*	*	NS
MC vs All Finer Sands	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
MF vs M	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV, %	6.0	3.1	6.4	4.3	3.7	4.1	7.2	5.8	3.0	3.9	4.7	3.3	4.5

* Significant at the 0.05 probability level.

† NS, not significant.

Table 2.20. Surface hardness response measured with 0.5 kg Clegg Impact Soil Tester released from the reduced height of 20- and 10-cm on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2012.

	20 cm†		10 cm‡													
Sand Size	4 Apr	16 Apr	4 Apr	16 Apr	16 May	18 May	11 Jun	15 Jun	26 Jun	2 Jul	9 Jul	16 Jul	25 Jul	30 Jul	6 Aug	13 Aug
	------ Surface hardness (g_{max}) ------															
None	51	56	31	37	28	32	31	32	32	38	41	37	47	36	34	43
Medium-coarse (MC)	54	64	35	40	31	37	33	34	35	40	41	35	45	33	35	43
Medium-fine (MF)	50	64	34	41	30	35	34	35	35	41	44	34	45	33	32	44
Medium (M)	51	64	36	41	30	35	33	35	34	42	41	33	46	34	35	46
Orthogonal Contrasts	------ p > F ------															
No Sand vs All Sands	NS§	**	*	**	*	*	NS	*	*	NS	NS	*	NS	NS	NS	NS
MC vs All Finer Sands	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
MF vs M	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	**	NS
CV, %	5.7	6.7	8.0	4.8	4.9	5.7	4.7	6.3	7.0	7.7	6.4	5.9	8.0	6.4	2.9	9.4

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† The hammer of 0.5 kg CIST was released from a reduced height of 20 cm above ground.
‡ The hammer of 0.5 kg CIST was released from a reduced height of 10 cm above ground.
§ NS, not significant.

Table 2.21. Surface hardness response measured with 0.5 kg Clegg Impact Soil Tester on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2013.

	30 cm[†]							10 cm[‡]						
Sand Size	7 May	16 May	17 Jun	27 Jun	10 Jul	8 Aug	20 Sep	7 May	16 May	17 Jun	27 Jun	10 Jul	8 Aug	20 Sep
	Surface hardness (g_{max})													
None	71	71	72	76	97	92	104	36	30	34	38	39	40	47
Medium-coarse (MC)	77	78	65	73	94	84	98	36	35	35	41	41	40	48
Medium-fine (MF)	66	75	65	76	96	84	97	35	35	33	39	41	40	47
Medium (M)	78	76	68	74	98	85	95	37	34	33	38	40	40	45
Orthogonal Contrasts	p > F													
No Sand vs All Sands	NS[§]	*	*	NS	NS	**	*	NS	***	NS	NS	NS	NS	NS
MC vs All Finer Sands	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
MF vs M	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV, %	14.8	5.7	5.0	2.9	3.9	4.0	4.4	6.3	4.6	8.0	5.1	3.8	4.8	5.8

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The hammer of 0.5 kg CIST was released from the standard height of 30 cm above ground
‡ The hammer of 0.5 kg CIST was released from a reduced height of 10 cm above ground.
§ NS, not significant.

Table 2.22. Penetration depth response on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2012.

	Penetrometer†										
Sand Size	14-May	11-Jun	15-Jun	26-Jun	2-Jul	9-Jul	16-Jul	25-Jul	30-Jul	6-Aug	13-Aug
	---mm‡---										
None	5.03	4.28	4.62	4.88	4.90	4.49	5.31	3.85	4.26	4.64	3.66
Medium-coarse (MC)	4.39	3.38	3.88	4.25	4.17	3.93	4.82	3.36	3.82	4.48	3.42
Medium-fine (MF)	4.45	3.29	3.70	4.30	4.27	3.94	4.83	3.30	3.64	4.27	3.46
Medium (M)	4.42	3.36	3.76	4.32	4.09	3.98	4.70	3.34	3.71	4.23	3.28
Orthogonal Contrasts	-- *p* > *F* --										
No Sand vs All Sands	***	***	***	**	***	***	**	**	***	**	**
MC vs All Finer Sands	NS§	NS	NS	NS	NS	NS	NS	NS	*	*	NS
MF vs M	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV, %	4.1	4.3	3.6	5.7	5.0	2.3	3.9	5.5	2.6	3.5	4.1

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† An electronic indicator was modified and stabilized by adding a flat metal base to function as a penetrometer.
‡ Distance the indicator tip penetrated into the turf canopy.
§ NS, not significant.

Table 2.23. Penetration depth response on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2013.

	Penetrometer†				
Sand Size	17-Jun	27-Jun	10-Jul	8-Aug	20-Sep
	--------------------------------mm‡--------------------------------				
None	5.92	5.12	4.88	4.33	3.81
Medium-coarse (MC)	5.07	4.25	4.27	3.68	3.21
Medium-fine (MF)	5.07	4.09	4.34	3.77	3.18
Medium (M)	4.86	4.22	4.35	3.70	3.37
Orthogonal Contrasts	------------------------------ $p > F$ ------------------------------				
No Sand vs All Sands	***	***	***	**	***
MC vs All Finer Sands	NS§	NS	NS	NS	NS
MF vs M	NS	NS	NS	NS	*
CV, %	4.9	2.3	6.2	5.8	3.4

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† An electronic indicator was modified and stabilized by adding a flat metal base to function as a penetrometer.
‡ Distance the indicator tip penetrated into the turf canopy.
§ NS, not significant.

Table 2.24a. Volumetric water content (measured at a 0–38 mm depth with time domain reflectometry) response on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ from 8 June to 28 July 2011.

Sand Size	8-Jun	13-Jun	20-Jun	27-Jun	5-Jul	11-Jul	18-Jul	19-Jul	28-Jul
	---------- m^3 m^{-3} ----------								
None	0.279	0.368	0.306	0.270	0.330	0.271	0.313	0.243	0.213
Medium-coarse (MC)	0.301	0.356	0.296	0.259	0.325	0.270	0.321	0.256	0.219
Medium-fine (MF)	0.267	0.363	0.311	0.263	0.324	0.273	0.322	0.238	0.218
Medium (M)	0.279	0.372	0.309	0.261	0.319	0.272	0.321	0.248	0.225
Orthogonal Contrasts	---------- $p > F$ ----------								
No Sand vs All Sands	NS[†]	NS	NS	NS	NS	NS	NS	NS	NS
MC vs All Finer Sands	*	NS	*	NS	NS	NS	NS	NS	NS
MF vs M	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV, %	6.4	3.0	2.8	5.4	2.7	5.9	5.2	8.6	5.7

* Significant at the 0.05 probability level.

† NS, not significant.

Table 2.24b. Volumetric water content (measured at a 0–38 mm depth with time domain reflectometry) response on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ from 8 Aug. to 11 Oct. 2011.

Sand Size	8-Aug	22-Aug	29-Aug	5-Sep	19-Sep	11-Oct
	---------------------------------- m^3 m^{-3} --------------------------------					
None	0.212	0.321	0.305	0.311	0.331	0.278
Medium-coarse (MC)	0.213	0.305	0.295	0.296	0.322	0.254
Medium-fine (MF)	0.220	0.323	0.300	0.311	0.327	0.260
Medium (M)	0.222	0.320	0.306	0.312	0.324	0.276
Orthogonal Contrasts	--------------------------------- $p > F$ ---------------------------------					
No Sand vs All Sands	NS[†]	NS	NS	NS	NS	NS
MC vs All Finer Sands	NS	**	NS	NS	NS	NS
MF vs M	NS	NS	NS	NS	NS	NS
CV, %	4.4	2.6	3.6	5.1	3.9	6.1

** Significant at the 0.01 probability level.

† NS, not significant.

Table 2.25a. Volumetric water content (measured at a 0–38 mm depth with time domain reflectometry) response on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ from 2 Apr. to 26 June 2012.

Sand Size	2-Apr	4-Apr	16-Apr	14-May	16-May	18-May	11-Jun	15-Jun	26-Jun
	----------	----------	----------	----------	$m^3 m^{-3}$	----------	----------	----------	----------
None	0.346	0.327	0.220	0.351	0.492	0.400	0.485	0.412	0.347
Medium-coarse (MC)	0.332	0.313	0.212	0.319	0.458	0.354	0.457	0.378	0.308
Medium-fine (MF)	0.335	0.309	0.212	0.314	0.467	0.372	0.462	0.385	0.305
Medium (M)	0.326	0.308	0.207	0.325	0.451	0.349	0.464	0.381	0.313
Orthogonal Contrasts	----------	----------	----------	----------	$p > F$	----------	----------	----------	----------
No Sand vs All Sands	NS[†]	NS	NS	**	***	**	**	*	**
MC vs All Finer Sands	NS	NS	NS	NS	NS	NS	NS	NS	NS
MF vs M	NS	NS	NS	NS	*	NS	NS	NS	NS
CV, %	6.4	7.8	9.3	4.4	2.1	5.5	2.5	5.5	6.2

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† NS, not significant.

Table 2.25b. Volumetric water content (measured at a 0–38 mm depth with time domain reflectometry) response on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ from 2 July to 13 Aug. 2012.

Sand Size	2-Jul	9-Jul	16-Jul	25-Jul	30-Jul	6-Aug	13-Aug
	------------------------------------ m^3 m^{-3} ------------------------------------						
None	0.313	0.292	0.529	0.255	0.381	0.388	0.307
Medium-coarse (MC)	0.267	0.264	0.473	0.231	0.345	0.351	0.274
Medium-fine (MF)	0.293	0.247	0.487	0.253	0.370	0.357	0.297
Medium (M)	0.250	0.262	0.481	0.235	0.344	0.340	0.271
Orthogonal Contrasts	------------------------------------ $p > F$ ------------------------------------						
No Sand vs All Sands	*	**	***	NS[†]	*	**	NS
MC vs All Finer Sands	NS	NS	NS	NS	NS	NS	NS
MF vs M	NS	NS	NS	NS	*	NS	NS
CV, %	11.6	5.6	3.1	6.5	4.3	4.5	8.9

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† NS, not significant.

Table 2.26. Volumetric water content (measured at a 0–38 mm depth with time domain reflectometry) response on an annual bluegrass turf mowed at 2.8 mm and topdressed with three sand sizes in North Brunswick, NJ during 2013.

Sand Size	7-May	16-May	17-Jun	27-Jun	10-Jul	8-Aug	20-Sep
	------------	------------	------------	$m^3\ m^{-3}$	------------	------------	------------
None	0.363	0.362	0.469	0.442	0.321	0.315	0.306
Medium-coarse (MC)	0.347	0.327	0.430	0.415	0.305	0.293	0.288
Medium-fine (MF)	0.357	0.337	0.459	0.430	0.293	0.312	0.293
Medium (M)	0.345	0.326	0.431	0.412	0.289	0.292	0.295
Orthogonal Contrasts	------------	------------	------------	*p > F*	------------	------------	------------
No Sand vs All Sands	NS†	**	*	NS	NS	NS	NS
MC vs All Finer Sands	NS	NS	NS	NS	NS	NS	NS
MF vs M	NS	NS	NS	NS	NS	NS	NS
CV, %	4.8	4.6	4.4	4.7	7.5	6.1	5.4

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

† NS, not significant.

Table 2.27. Algae incidence after heavy rainfall as influenced by topdressing sand size on an annual bluegrass putting green turf mowed at 2.8 mm in North Brunswick, NJ during 2013.

Sand Size	2-Jul	13-Aug
	----- 1–9 scale† ----	
None	5.1	3.3
Medium-coarse (MC)	8.8	6.5
Medium-fine (MF)	8.1	5.3
Medium (M)	7.8	5.8
Orthogonal Contrasts	------- *p* > *F* ------	
No Sand vs All Sands	***	**
MC vs All Finer Sands	NS‡	NS
MF vs M	NS	NS
CV, %	13.1	19.9

** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Nine(9) = free of algae, 5 = acceptable, 1 = covered completely with algae.
‡ NS, not significant.

CHAPTER 3. Sand Topdressing Programming Effects on Anthracnose Disease of Annual Bluegrass Putting Green Turf

ABSTRACT

Sand topdressing applied to annual bluegrass (*Poa annua* L. f. *reptans* [Hauskins] T. Koyama) putting green turf during the spring and summer can reduce the severity of anthracnose caused by *Colletotrichum cereale* Manns. However, the effects of topdressing during autumn on this disease are not well understood. A 3-yr field study was initiated in autumn 2010 to evaluate the effect of autumn, spring and summer topdressing with medium-coarse sand on anthracnose severity of annual bluegrass turf mowed at 2.8 mm. This trial was arranged as a 3 x 3 x 3 factorial in a randomized complete block design with four replications. Autumn and spring topdressing were applied at rates of 0, 1.2, or 2.4 L m^{-2}. Summer topdressing was applied every two weeks at 0, 0.075 or 0.15 L m^{-2} for a total of eight applications. In general, greater topdressing rates provided better disease suppression. Spring topdressing rate effect accounted for more of the variation (10%, 37% and 18% in 2011, 2012 and 2013, respectively) in disease response (measured as area under disease progress curve) than autumn and summer topdressing. Spring topdressing also provided the most consistent and long-term disease suppression throughout the growing season. Autumn topdressing reduced disease only in the early-season each year and summer topdressing occasionally reduced disease only in the late-season suggesting that low topdressing rates in the summer were insufficient to suppress anthracnose disease. Interactions among autumn, spring, and summer topdressing were not observed for disease severity. In addition, Cate-Nelson model identified a critical annual sand quantity of 2.4 L m^{-2} to maximize disease suppression in both 2011 and

2012. Linear-plateau model determined that 4.2 and 4.8 L m^{-2} of sand was needed annually to maximize disease suppression in 2011 and 2012, respectively. In 2013, there was a poor fit of the disease response to the Cate-Nelson model and a critical value was not observed for linear-plateau model. The reduction in anthracnose severity due to topdressing contributed to enhanced turf quality. Increasing the rate of spring topdressing was more effective at improving turf quality compared to autumn and summer topdressing; summer topdressing had the least impact on turf quality. Increasing autumn and spring topdressing rate decreased soil water content in the 0- to 38-mm soil profile on 85% and 69% of the observation dates, respectively, whereas increasing summer rate decreased soil water content on only 8% of the observations. Both autumn and spring topdressing often reduced surface hardness measured with the 2.25-kg Clegg Impact Soil Tester hammer, however results contradicted those measured with the 0.5-kg hammer or estimates of surface strength made with a depth measuring penetrometer. Both spring and autumn topdressing were more effective than summer topdressing at decreasing organic matter (OM) concentration and increasing mat layer depth probably because the summer rates were too low to have a large impact on surface root zone physical properties. Additionally, increasing autumn topdressing rate was slightly more effective than increasing spring topdressing rate at reducing OM concentration. Increasing the rate of spring topdressing was more effective at reducing anthracnose severity than autumn topdressing, while autumn topdressing slightly more effective at decreasing surface soil water content of annual bluegrass putting green turf than spring topdressing. The summer topdressing rates (0.075 or 0.15 L m^{-2} applied every two weeks) evaluated in this research, which readily incorporated into the turf, were too low to consistently reduce disease and improve turf performance.

INTRODUCTION

Anthracnose, caused by *Colletotrichum cereale* Manns sensu lato Crouch, Clarke, and Hillman (Crouch et al., 2006), is a major disease of cool-season turfgrasses throughout the world (Browning et al., 1999; Crouch and Beirn, 2009; Crouch and Clarke, 2012; Landschoot and Hoyland, 1995; Mann and Newell, 2005; Smiley et al., 2005; Vargas, 2005). Over sixty percent of the golf course superintendents surveyed across the United States and Canada, and over seventy percent surveyed in England and Ireland reported anthracnose as a problem on putting greens (Inguagiato, 2012; Mann and Newell, 2005). This disease is particularly detrimental on annual bluegrass [*Poa annua* L. f. *reptans* (Hausskn) T. Koyama] putting greens (Smiley et al., 2005; Vargas, 2005). Disease symptoms appear initially as yellow or bronze leaves. As the disease progresses, the turf thins in irregular spots or patches as a result of the death of tillers and crowns (Smiley et al., 2005). Although little is known about the infection process of *C. cereale*, excess water or high humidity in the leaf canopy is thought to enhance anthracnose severity by favoring spore release or germination (Agrios, 2005; Smiley et al., 2005). Infection can take place in the cool weather (10–25°C); however, hot (29–35°C) humid weather favors disease outbreaks (Smiley et al., 2005; Smith et al., 1989; Vargas, 2005). When high temperature stress is combined with other stresses, such as drought stress, plant defense against anthracnose disease can fail, causing serious turf damage (Landschoot and Hoyland, 1995; Smiley et al., 2005; Sprague and Evaul, 1930; Vargas, 2005).

Applying a thin layer of sand to a turf is widely practiced by golf course superintendents to dilute thatch and smooth the surface (Beard, 1973). However, sand topdressing can also be an expensive and laborious practice. A traditional topdressing program typically includes applying large quantities (4–6 L m^{-2}) of sand in the spring and autumn after core aeration. Topdressing frequently during the summer can be expensive, laborious, interrupt play, and interfere with mowing equipment. Therefore, it is more practical and less disruptive to topdress frequently at low rates to match the growth of the grass to maintain turf quality and playability during the summer. When sand is applied at higher rates, it can be difficult to incorporate into the turf canopy and thatch (Hempfling et al., 2015; Murphy, 2012). Excessive brushing used to incorporate sand can cause abrasion to leaf blades or crowns (Foy, 1999). Moreover, sand applications on golf course putting greens can interfere with maintenance and play when it is not fully incorporated. Numerous reports indicate that sand is often present in mower clippings after topdressing is applied frequently (Johnston et al., 2005; Kauffman et al., 2011; Kreuser et al., 2011; Stier and Hollman, 2003; Taylor, 1986). Stier and Hollman (2003) found that routine mowing collected more sand when topdressing was applied monthly at 0.4 L m^{-2} than every two weeks at 0.2 L m^{-2}, suggesting greater sand removal under heavier and less frequent topdressing programs. Sand removed during mowing can cause excessive wear on cutting edges of the blades (Foy, 1999; Murphy, 2012; Vavrek, 1995).

Many research reports have documented the benefits of topdressing including reducing organic matter (Barton et al., 2009; Carrow et al., 1987; Engel and Alderfer, 1967; Espevig et al., 2012; McCarty et al., 2007; Rieke et al., 1988b), improving surface firmness and decreasing soil water content (Henderson and Miller, 2010), protection from winter desiccation and better spring recovery after sand topdressing in late autumn (Christians et al., 1985). Recently, sand topdressing was reported to suppress anthracnose on annual bluegrass putting green turfs (Hempfling et al., 2015; Inguagiato et al., 2012, 2013; Roberts and Murphy, 2014). Sand topdressing applied weekly at 0.3 L m^{-2} or every two weeks at 0.6 L m^{-2} during the summer can substantially reduce anthracnose severity (Inguagiato et al., 2012). However, these relatively heavy topdressing rates on putting greens during the summer may be impractical due to poor incorporation and disruption to play, and are therefore less likely to be adopted by golf course superintendents. In a subsequent study, increasing summer topdressing rate (0, 0.075, 0.15, 0.3 and 0.6 L m^{-2} applied every two weeks) produced a linear decrease in disease severity during the first year and a quadratic decrease in the subsequent year (Hempfling et al., 2015). They also found that increased spring topdressing rates (0, 1.2 and 2.4 L m^{-2}) produced greater linear disease suppression and interacted with summer topdressing, suggesting that a low-rate summer topdressing program should be done in conjunction with heavier spring topdressing rates to enhance disease suppression with topdressing. As recommended by many researchers, heavy topdressing (~6 L m^{-2}) in late autumn can protect turf from winter desiccation and improve spring recovery (Christians et al., 1985; Vavrek, 1995). However, the effects of autumn topdressing on anthracnose disease are currently not known.

In addition to topdressing timing, the cumulative amount of sand applied to turf may affect the degree of anthracnose suppression. Frequent ultra-light (< 0.15 L m^{-2}) topdressing every 7–14 days with sand, also known as dusting, is a common practice in the golf industry; however, the cumulative rate of sand applied in this manner may not be great enough to reduce disease severity or keep pace with thatch (organic matter) accumulation (Vavrek, 2007). Inguagiato et al. (2012) reported that a high topdressing rate (1.2 L m^{-2}) applied at longer intervals (21 to 42 d) provided similar anthracnose suppression as lower rates (0.3 to 0.6 L m^{-2}) applied at shorter intervals (7 to 14 d), although it took longer in the first year for this effect to occur. This suggests that the cumulative quantity of sand applied may be more important for reducing anthracnose than the rate or interval between applications. Other studies have shown that increasing the quantity of sand applied annually, either by increasing the frequency or rate of topdressing, also benefits turf performance. Henderson and Miller (2009) observed an increase in turf color, quality and cover as monthly topdressing rate increased. White and Dickens (1984) concluded that topdressing four times with a total of 16.0 L m^{-2} of mortar sand per year reduced thatch accumulation more than a single topdressing at 6.4 L m^{-2}. Similarly, Callahan et al. (1998) reported that sand topdressing six times for an annual total of 21.0 L m^{-2} or three times for a total of 10.5 L m^{-2} reduced the depth of thatch compared with no topdressing, with the greater quantity of topdressing providing a greater thatch reduction. Although, in general, increasing the total quantity of topdressing sand applied each year provides better turf quality and performance, the cumulative amount of sand required for optimum anthracnose suppression on annual bluegrass putting green turf has not been determined.

The objectives of this study were to i) evaluate the impact of autumn topdressing rate on anthracnose severity of annual bluegrass turf; ii) determine if autumn topdressing interacts with the effect of either spring or summer topdressing; and iii) develop models to predict the disease response based on the annual cumulative quantity of applied topdressing sand.

MATERIALS AND METHODS

General Field Maintenance

A three-year field study was initiated in autumn 2010 on annual bluegrass turf grown on a Nixon sandy loam (fine-loamy, mixed, mesic Typic Hapludaults) and maintained as a putting green at the Rutgers University Hort. Farm No. 2 in North Brunswick, NJ. The annual bluegrass turf was developed from the soil seed bank as well as seed introduced in 1998 from soil cores collected from Plainfield Country Club, Plainfield, NJ (Samaranayake et al., 2008). A monostand of annual bluegrass was established in September 2002 as described by Inguagiato et al. (2009). The mat layer pH was 5.4, 6.2 and 6.4 and the underlying soil pH was 6.1, 5.9 and 6.0 in 2011, 2012 and 2013, respectively. Dolomitic limestone was applied at 61 kg ha^{-1} on 24 Sept. 2011. Gypsum ($CaSO_4 \cdot 2H_2O$) was applied at 634 kg ha^{-1} on 29 June 2012. The trial was fertilized with 10.7, 22.6 and 12.6 kg ha^{-1} of P, and 204, 158 and 182 kg ha^{-1} of K in 2011, 2012 and 2013, respectively, based on soil test recommendations common for putting greens in the northeastern United States. Water-soluble nitrogen sources (urea, potassium nitrate, calcium nitrate or ammonium nitrate) were applied every two weeks at 4.9 kg ha^{-1} of N from April to August 2011, 2012 and 2013 totaling 53.7 kg ha^{-1} of N each year. To promote turf recovery from disease, 188 kg ha^{-1} and 96 kg ha^{-1} of N were applied 17 Aug. to 26 Oct. 2011 and 28 Aug. to 21 Nov. 2012, respectively, and 18.3 kg ha^{-1} of N was applied on 19 Mar. 2012. Turf was mowed 6 d wk^{-1} with clippings collected during the growing season with a triplex greens mower (model 3150, Toro Co., Bloomington, MN) at a bench-setting of 2.8 mm. Plots were rolled 1 to 2 times a week with a smooth pavement roller (1.7 metric ton tandem vibratory roller, Model RD11A, Wacker Neuson, Germany) to simulate traffic stress. Overhead irrigation and hand watering were applied to maintain moderately dry and uniform soil water content similar to a golf course putting green. Ethephon [(2-chloroethyl)phosphonic acid] was applied three times at 14 d intervals at 3.8 kg a.i. ha^{-1} from March to April in 2011, 2012 and 2013 to suppress seedheads. 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 22 Mar. to 26 Oct. 2011, 15 Mar. to 12 Nov. 2012 and 15 Mar. to 21 Nov. 2013 to simulate standard practices for vegetative growth suppression on annual bluegrass putting green turf in the northeastern United States. Sand topdressing was not applied as a broadcast application to the study.

Dollar spot (*Sclerotinia homoeocarpa*) was preventatively controlled each year from April to August by alternating 14 d schedules of vinclozolin [3-(3,5-dichlorophenyl)-5-ethenyl-5-methyl-2,4- oxazolidinedione] and boscalid {3-pyridinecarboximide, 2-chloro-N-[4'chloro(1,1'- biphenyl)yl]} at 1.5 and 0.4 kg a.i. ha^{-1}, respectively. Azoxystrobin [methyl (E)-2-{2-[6-(2-cyanophenoxy) pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate] and flutolanil {N-[3-(1-methylethoxy)phenyl]-2-(trifluoromethyl)benzamide} were alternated on a 14 d schedule from April through August at 0.6 kg a.i. ha^{-1} and 6.4 kg a.i. ha^{-1}, respectively to control brown patch and summer patch diseases. These fungicides have been shown in previous studies at this location not to affect anthracnose (Clarke et al., 2006; Towers et al., 2003). Annual bluegrass weevils were controlled with bifenthrin {[2-methyl(1,1'-biphenyl)-3-yl]methyl 3-[2- chloro-3,3,3-trifluoro-1-propenyl]-2,2-dimethyl-cyclopropanecarboxylate} applied at 0.14 and 0.29 kg a.i. ha^{-1} on 21 Aug. 2011 and 30 June 2013, respectively, chlorantraniliprole {3-Bromo-N-[4-chloro-2-methyl-6-[(methylamino)carbonyl]phenyl]-1-(3-chloro-2-pyridinyl)-1H-pyrazole-5-carboxamide} applied at 0.18 kg a.i. ha^{-1} on 3 May 2011 and 0.12 kg a.i. ha^{-1} on 18 Apr. 2012 and 1 May 2013, and indoxacarb {(S)-methyl 7-chloro-2,5-dihydro-2-[[(methoxycarbonyl)[4(trifluoromethoxy)phenyl]amino]-carbonyl]indeno[1,2-e][1,3,4]oxadiazine-4a-(3H)-carboxylate} applied at 0.25 kg a.i. ha^{-1} on 23 June 2012. Mancozeb (coordination of zinc ion and manganese ethylene bisdithiocarbamate), which had previously been shown not to affect anthracnose in this location (Clarke et al., 2006; Towers et al., 2003), was applied at 15.3 kg a.i. ha^{-1} on 23 May 2012 and 2 July 2013, and 19.5 kg a.i. ha^{-1} on 19 Aug. 2012 to suppress algae (*Cyanobacteria*).

Chlorothalonil (tetrachloroisophthalonitrile) at 12.6 kg a.i. ha^{-1}, fosetyl-Al (O-ethyl phosphonate) at 9.8 kg a.i. ha^{-1}, tebuconazole (α-[2-(4-chlorophenyl)ethyl]-α-(1,1-dimethylethyl)-1H-1,2,4-triazole-1-ethanol) at 0.7 kg a.i. ha^{-1}, or polyoxin D zinc salt (1:1) {Zinc 5-[[2-amino-5-O-(aminocarbonyl)-2-deoxy-L-xylonoyl]amino]-1-(5-carboxy-3,4-dihydro-2,4-dioxo-1(2H)-pyrimidinyl)-1,5-dideoxy-ß-D-allofuranuronate}at 0.3 kg a.i. ha^{-1} was applied every 14 d from 13 Aug. to 26 Oct. 2011 to arrest the anthracnose epiphytotic and promote turf recovery. In 2012, anthracnose was suppressed with applications of chlorothalonil at 12.6 kg a.i. ha^{-1} every 8–12 d from 24 August to 5 October and one application at 10.1 kg a.i. ha^{-1} on 5 November. In 2013, anthracnose was controlled with chlorothalonil at 12.6 kg a.i. ha^{-1} on 3 and 21 September, and at 8.1 kg a.i. ha^{-1} on 18 October and in a tank-mixture with tebuconazole at 0.7 kg a.i. ha^{-1} on 2 October. Metconazole was applied on 30 Aug. 2013 at 0.6 kg a.i. ha^{-1} to provide additional suppression of anthracnose and dollar spot.

Research Methodology

This trial was designed as a 3 x 3 x 3 factorial arranged in a randomized complete block design with four replications. The factors were autumn, spring, and summer topdressing with sand. Autumn topdressing was applied as two split applications at rates of 0, 1.2, and 2.4 L m^{-2} on 22 Oct. and 9 Nov. 2010, 21 Oct. and 4 Nov. 2011, and 18 Oct. and 6 Nov. 2012. Spring topdressing was applied at rates of 0, 1.2, and 2.4 L m^{-2} using two split applications on 21 Apr. and 5 May 2011, 20 Apr. and 4 May 2012, and 20 Apr. and 3 May 2013. Summer topdressing was applied every two weeks at 0, 0.075, and 0.15 L m^{-2} of sand from 7 June to 13 Sept. 2011, 8 June to 14 Sept. 2012 and 12 June to 13 Sept. 2013. The medium-coarse, sub-angular silica sand ("310" U.S. Silica, Co., Mauricetown, NJ) used in this study had a particle distribution (Table 3.1) conforming to USGA recommendations (United States Golf Association Green Section Staff, 2004). Sand was applied with drop spreader (model SS-2, The Scotts Company, Marysville, OH) and immediately incorporated into the turf canopy with a stiff-bristled brush (Harper Brush Works, Inc., Fairfield, IA). Turf was not mowed for 2 to 3 days after autumn and spring topdressing to reduce removal of sand by mowers. Core cultivation was not performed to avoid potential confounding effects of de-compaction and organic matter removal.

Data Collection and Analysis

Anthracnose severity was assessed seven times from 21 June to 11 Aug. 2011, eight times from 7 June to 19 Sept. 2012 and seven times from 14 June to 20 Sept. 2013 using a line intercept-grid count method described by Inguagiato et al. (2008). Disease severity data for each year were transformed to area under disease progress curve (AUDPC) using the formula:

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

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.

AUDPC values were plotted against cumulative topdressing sand quantities applied in each year of the study. Each data point represents the mean of four replications for the AUDPC response of any treatment combination (3 × 3 × 3). The various treatment combinations from the 3 × 3 × 3 factorial randomized complete block design provided a wide range of annual cumulative sand quantities. Model analysis was used to determine a critical value of total sand needed annually for the optimum disease suppression response for each year of the study. The Cate-Nelson method (Cate and Nelson, 1971) was used to partition AUDPC data into two classes: i) a large disease response to cumulative topdressing sand quantity class and ii) a small or no disease response to the cumulative topdressing sand quantity class. The critical levels for Cate-Nelson model were determined using the GLM procedure in SAS statistical software (SAS Institute Inc, 2013) by maximizing the sum of squares for this model. Additionally, a linear or linear-plateau and a quadratic or quadratic-plateau model were used to describe the relationship between disease severity and cumulative quantities of sand applied using the NLIN procedure in SAS (SAS Institute Inc, 2013).

Visual evaluation of turf quality was based on plant density, uniformity and disease severity on a 1 to 9 scale, where 9 represented the best turf quality and 5 was the minimum acceptable quality. Color was not included as a component of turf quality. Turf color was rated visually on a scale of 1 to 9, where 9 represented the darkest green color and 5 was an acceptable color. Turfgrass color was also evaluated using a CM1600 Chlorophyll Meter (Spectrum Technologies. Inc., Plainfield, IL) placed at 85 cm above ground to confirm visual color ratings. The average of four readings was recorded for each plot on 15 July and 19 Sept. 2013. The handheld device sensed light at wavelengths of 700 nm and 840 nm to estimate the quantity of chlorophyll in leaves. The completeness of sand incorporation was assessed visually daily after topdressing on 20 Apr., 3 May, 21 June and 13 Sept. 2013 until sand was incorporated completely into the canopy, and once on 12 June 2013, on a 1 to 9 scale, 9 represented complete incorporation of sand into the turf canopy and 5 represented a visible but acceptable quantity of sand remaining (unincorporated) on the canopy. Algae incidence was rated 2 July, 13 Aug., 23 Aug. and 3 Sept. 2013 after heavy rainfalls on a 1 to 9 scale, where 9 represented absence of algae and 5 is the minimum acceptable algae infestation.

Surface hardness was measured on 1 July, 15 July and 26 Sept. 2011, 7 June and 28 June 2012, and 22 May and 25 June 2013 with the 2.25-kg Clegg Impact Soil Tester (Model 95049, Lafayette Company, Lafayette, IN). Additionally, the 0.5-kg Clegg Impact Soil Tester (Model 95048A, Lafayette Company, Lafayette, IN) was used on 15 July and 26 Sept. 2011, 7 June and 28 June 2012, and 4 June and 25 June 2013 to measure hardness. The maximum deceleration of a single drop of the 2.25- or 0.5-kg hammer from a standard height of 46- or 30-cm, respectively, was recorded three times per plot in 2011 and four times per plot in 2012 and 2013. Maximum deceleration was recorded in gravities (g_{max}) and measurements for each plot were averaged before statistical analysis. In addition, the 0.5-kg hammer was dropped four times per plot from a 10 cm height on 4 and 25 June 2013.

Surface strength was evaluated with a modified depth-measuring micrometer (F2750-1 Wisdom 2700 Electronic Indicator 65847, The L.S. Starrett Company, Athol, MA) on 29 May and 28 June 2012, 22 May and 24 June 2013. This penetrometer measures the penetration depth of the 4.5-mm diameter probe with an applied pressure of 262 kPa. Therefore, a shorter penetration depth indicates a greater surface strength, and *vice versa*. The average of eight depth measurements taken per plot was used for statistical analysis.

Volumetric water content (VWC) was measured simultaneously when surface hardness or surface strength was determined with the Clegg Impact Soil Tester or penetrometer, respectively, in all three years of the study, and independently on 7 Aug. 2012, 23 Aug. 2013 and 23 Sept. 2013 at the 0- to 38-mm depth with time domain reflectometry (Field Scout TDR 300 model, Spectrum Technologies, Inc., Plainfield, IL). Three measurements of VWC per plot were taken in 2011 and four measurements per plot were taken in 2012 and 2013, and the average of VWC measurements taken per plot was used for statistical analysis.

Samples of the mat layer (an organic layer intermixed with topdressing sand) that had developed in response to topdressing treatments were taken at the conclusion of this study. Four 32-mm diameter (approximately 70-mm deep) cores were collected from each plot from replication 1 on 26 September and replications 2, 3 and 4 on 27 Sept. 2013. A distinct thick sand layer (40–60 mm) in the soil profile from a previous field renovation (heavy topdressing and core aeration) in 2008 was observed to be consistent across the entire field and were used as reference to measure mat layer depth (Fig. A.4). After the renovation, the field was managed using a routine sand topdressing program which was insufficient to prevent the development of an excessive thatch layer prior to this study. Mat layer samples were separated at interface of the heavy sand layer and the thatch layer (as shown in Fig. A.4). The depth of the mat layer was measured at three equidistant points on each core. Verdure was removed from each core and organic matter content was determined using the loss on ignition at 360°C (ASTM Standard F1647-02a) for 12 h.

All data were subjected to analysis of variance using the General Linear Model procedure in the Statistical Analysis System software v. 9.3 (SAS Institute Inc., Cary, NC) and means were separated by Fisher's protected least significant difference at the 0.05 probability level. The amount of variation attributable to ANOVA sources (factors) was determined by analysis of the sum of squares.

Results and Discussion

Disease Severity

Symptoms of anthracnose developed naturally each year. Anthracnose was first observed on 21 June in 2011 and progressed gradually to a maximum of 64% turf area infested by 11 August (Table 3.2). Disease severity was low (1% to 6%) in June 2012, developed slowly through July, and increased dramatically up to 50%–64% by 21 August (Table 3.3). Initial symptoms in 2013 were observed on 14 June; severity increased to a maximum of 64% on 4 August before slightly decreasing to 56%–59% on 17 August (Table 3.4).

Spring topdressing rate had the greatest effect on anthracnose severity in all 3 years, accounting for 10%, 37%, and 18% of the experimental variation when reported as the area under the disease progress curve (AUDPC) in 2011, 2012 and 2013, respectively (Table 3.5). In general, greater spring topdressing rates provided better suppression of anthracnose severity and this effect was consistent throughout each year of the study (Tables 3.2, 3.3 and 3.4), expect for early in 2012 (7 June) when disease severity was low (< 2%) and not uniform (coefficient of variation of 100.7%), and late in 2013 (17 August) when disease severity was high. Increasing spring topdressing rate reduced disease linearly on 19 of 20 dates over the trial period (Tables 3.2, 3.3 and 3.4).

Autumn topdressing rate had the second greatest effect on anthracnose severity; disease typically was reduced early but not later each year. Disease was not responsive to autumn topdressing by early August 2011, late August 2012, and early July 2013 (Tables 3.2, 3.3 and 3.4). Increasing autumn topdressing rate suppressed disease linearly on 5 of 7, 6 of 7 and 1 of 6 dates in 2011, 2012 and 2013, respectively (Tables 3.2, 3.3 and 3.4).

Summer topdressing only reduced disease severity from late July through September 2012, accounting for 8% to 15% of the variation in disease response (Table 3.3). Topdressing applied every two weeks in the summer produced a linear disease response (reduction) on 4 of 7 dates in 2012 (Table 3.3).

Sand topdressing may suppress anthracnose directly by affecting the pathogen or indirectly by improving the plant health. Topdressing can bury dead/infested plants and dilute the inoculum in the thatch (Madison et al., 1974; Sprague and Evaul, 1930). Additionally, sand topdressing may reduce anthracnose severity indirectly by providing a better growing medium for turfgrass, and burying and protecting crowns and leaf sheaths. Larger, elongated sheaths and deeper crowns of annual bluegrass were observed in plots topdressed with sand compared to non-topdressed plots (Inguagiato et al., 2012). Moreover, increased firmness and smoothness of the surface created by topdressing provides better support for mowers which can effectively raise the cutting height (Inguagiato et al., 2012); higher mowing has been shown to reduce anthracnose severity on annual bluegrass putting green turf (Inguagiato et al., 2009).

Autumn topdressing reduced disease severity early in the season and spring topdressing continued to suppress disease throughout the season; as the autumn and spring topdressing weakened in the end of the season, summer topdressing could have an effect on anthracnose disease when adequate sand accumulated in the canopy. Since the epidemiology of *C. cereale* remains poorly understood, the most effective time to bury or dilute the inoculum with topdressing for anthracnose suppression is not clear. The onset of anthracnose symptoms often occurs during hot humid weather (summer months). It seems logical to expect that the effect of autumn topdressing would be reduced later in the season, because autumn topdressing was applied more than three months before the disease epiphytotic developed the following year in this study. Alternatively, spring topdressing filled the turf canopy just prior to the disease outbreak and summer stresses, which improves plant health and effectively raises the cutting height. Spring topdressing produced a strong and consistent reduction in anthracnose disease, which corroborates the work of Hempfling et al. (2015). Topdressing improves plant health and results in stronger defense against anthracnose but a delay response should be expected. Thus, topdressing applied after disease emergence in the summer may not be effective until adequate sand accumulated in the canopy.

Greater topdressing rate was generally more effective in reducing disease severity compared to non-topdressed turf. Summer topdressing had a lesser effect than autumn and spring topdressing presumably because the quantity of topdressing applied in the summer was half of that applied in the autumn or spring. Inguagiato et al. (2012) reported anthracnose was suppressed by summer topdressing applied every two weeks at 0.3 and 0.6 L m^{-2}, but these rates were four times greater than the summer rates used in our study. According to Hempfling et al. (2015), topdressing in the spring decreased the summer topdressing needed to reduce anthracnose disease; however, even under high spring topdressing (2.4 L m^{-2}), summer topdressing applied every two weeks at 0.3 L m^{-2} was needed to maximize disease suppression. Thus, the summer topdressing rates of 0.075 and 0.15 L m^{-2} applied every two weeks in our study were probably too low to have a consistent effect in reducing the severity of anthracnose.

Inguagiato et al. (2012) suggested that the cumulative quantity of sand applied to annual bluegrass might be important for anthracnose suppression. Since no interactions were observed among the main effects for the anthracnose response in this study, disease data for the autumn, spring and summer topdressing rates were pooled to evaluate the effect of cumulative sand quantity on this disease. Additionally, the various treatment combinations from the 3 × 3 × 3 factorial design provided a wide range of annual cumulative sand quantities, and were therefore more informative than the main effects.

The AUDPC response in 2011 and 2012 was similar; however, this response differed from the response identified in 2013. In 2011 and 2012, both the Cate-Nelson (Fig. 3.1) and linear-plateau models (Fig. 3.2) identified a critical level where the probability of any further AUDPC response to additional topdressing sand would be unlikely. The Cate-Nelson model divided the data into a relatively large response group and a small or no response group and suggested a critical value of 2.4 L m^{-2} with R^2 of 0.58 and 0.50 in 2011 and 2012, respectively (Fig. 3.1). The linear-plateau model suggested that increasing the cumulative quantity of topdressing linearly decreased anthracnose AUDPC up to a sand quantity of 4.2 and 4.8 L m^{-2} in 2011 and 2012, respectively, after which the relationship plateaued and further increases in topdressing did not affect disease severity (Fig. 3.2). These disease responses were described relatively well by linear-plateau model in 2011 and 2012 with $p < 0.001$ and R^2 of 0.72 and 0.61, respectively.

However, in 2013, a plateau response was not reached; instead a linear relationship indicated that increasing sand quantity within the range (0 to 5.55 L m^{-2}) evaluated in this study reduced AUDPC, but the R^2 of 0.23 was low (Fig. 3.2). Whereas, the Cate-Nelson model identified a low critical level (0.975 L m^{-2}) in 2013 with a low R^2 of 0.20 (Fig. 3.1), but the disease response in the two groups was similar. Unlike in 2011 and 2012, spring topdressing was the only factor that contributed to significant reduction of anthracnose severity in 2013 (Table 3.5). Therefore, the suppression of disease in response to increasing cumulative sand quantities was weaker in 2013 compared to 2011 and 2012; and disease response was not plateaued indicated that the cumulative sand quantities were not enough to achieve optimum disease reduction in 2013 (Fig. 3.2). Additionally, the amount of N and K applied in autumn 2012 to recover from anthracnose damage that season was much lower than the amount of N and K applied in autumn 2011 for anthracnose recovery and the disease in 2013 is higher than 2011 and 2012 (data not shown). Research has shown that N and K are critical for annual bluegrass growth and suppression of anthracnose disease (Hempfling et al., 2014; Inguagiato et al., 2008; Schmid et al., 2013; Uddin et al., 2006). The weaker plants and higher disease pressure might have required greater cumulative sand to achieve maximum disease suppression in 2013.

The AUDPC response was also explained by the quadratic model (Fig. 3.3). Within the 0–6 L m^{-2} cumulative sand range we studied, the plateau from the quadratic-plateau model was not reached in any year of the study, indicating that increasing sand quantity was beneficial for disease suppression. However, the derivatives of the estimated quadratic equation were less negative as the cumulative quantity of sand applied increased, suggesting that the benefit of increasing sand declined as cumulative sand quantity increased. However, the disease response beyond our sand quantity range remains unknown. The topdressing rates used in this study are commonly used in the golf industry for annual bluegrass putting greens. Considering topdressing is such a costly practice and is disruptive to play, turf managers would unlikely apply quantities of sand beyond the highest annual rate (6 L m^{-2}) used in our study on annual bluegrass putting greens.

Critical values estimated by the Cate-Nelson model were lower than linear-plateau model in both 2011 and 2012; and the plateau portion of the quadratic-plateau model was beyond our sand quantity range in all three years. Similarly, in soil fertility studies, the lowest to highest critical levels were often produced in the order of Cate-Nelson, linear-plateau, and quadratic-plateau models (Collins and Allinson, 2004; Geng et al., 2014; Mangiafico and Guillard, 2006). Critical values from the Cate-Nelson method are often lower because data are portioned into high and reduced response classes, whereas the plateau models identify the critical level beyond which no response is expected. The linear-plateau model provides an abrupt endpoint to the plateau, whereas the quadratic-plateau model continues to model the diminishing effect with the curvature until the plateau is reached; therefore, the quadratic-plateau model typically produces a higher critical level than the linear-plateau model. Geng et al. (2014) suggested that the higher critical value identified with the quadratic-plateau model may be statistically significant, but it may not always be important from a practical standpoint. In our study, the critical cumulative sand quantity estimated by the Cate-Nelson and linear-plateau models ranged from 2.4 to 4.8 L m^{-2} in 2011 and 2012, and the critical value was not reached in 2013. Targeting the higher end of critical range (4.8 L m^{-2}) for the cumulative quantity of topdressing sand applied would ensure maximum disease suppression and is practical for topdressing annual bluegrass putting green turf.

Previous to the work of Inguagiato et al. (2012), topdressing was suspected of enhancing the severity of anthracnose through increased abrasion and wounding, especially during the summer when heat and drought stresses could further weaken turf. However, summer topdressing did not increase anthracnose severity in our study; in other studies, a small and brief increase in disease was observed early in the first year when crowns were not buried and protected by sufficient topdressing layer (Hempfling, 2013; Inguagiato et al., 2012, 2013; Roberts and Murphy, 2014). Therefore, golf course superintendents who maintain turfs with a history of severe anthracnose should consider more aggressive (greater cumulative quantities) topdressing programs without being concerned about intensifying this disease.

Turfgrass Quality

Main Effects

Spring topdressing rate had the greatest effect on turfgrass quality; increasing the rate produced a linear improvement in turf quality on all observation dates in 2011, 2012 and 2013 (Tables 3.6, 3.7 and 3.8a). Autumn topdressing rate had the next greatest impact on turf quality and produced linear increases in quality early in the seasons of 2011 (21 June to 29 July) and 2012 (15 June to 8 August) (Tables 3.6 and 3.7). In addition to the early season increase in quality in 2013 (17 April to 14 June), autumn topdressing rate also had a late season effect on 3 and 19 August and during recovery on 20 September and 19 November (Tables 3.8a and 3.8b). Autumn topdressing rate had an adverse effect on turf quality in late season and during recovery in 2013; topdressed plots had lower quality than plots that received no autumn topdressing (Tables 3.8a and 3.8b).

Increasing summer topdressing rate did not affect turf quality in 2011 but improved (linearly) turf quality later in the season of 2012 (27 July to 22 August) and twice in 2013 (17 April and 31 May) (Tables 3.7 and 3.8a). Summer topdressing rate also consistently improved turf quality linearly during recovery (after curative fungicide applications) on 29 Sept. 2011, 20 Sept. 2012, and 20 Sept. and 19 Nov. 2013 (Tables 3.6, 3.7 and 3.8b). Increasing summer topdressing rates produced a subtle decrease in turf quality on 8 July 2013 (Table 3.8a); however, this effect did not occur at any other time during the trial and therefore was considered a random effect.

Interactions

Turf quality was affected by the interaction of autumn and spring topdressing on two dates during the trial: 22 July 2011 and 27 July 2012 (Table 3.9). On 22 July 2011, turf quality was improved by increasing spring topdressing when autumn topdressing was applied at 0 or 1.2 L m^{-2}; similarly, turf quality was improved by increasing autumn topdressing when 0 or 1.2 L m^{-2} of spring topdressing was applied (Table 3.9). On 27 July 2012, spring topdressing improved (linear response) turf quality only when autumn topdressing was applied at 0 or 2.4 L m^{-2}; autumn topdressing improve turf quality with quadratic and linear response when 0 and 1.2 L m^{-2} of spring topdressing was applied, respectively (Table 3.9).

Spring topdressing interacted with summer topdressing rate twice on 8 Aug. and 20 Sept. 2012 (Table 3.10). Increasing summer topdressing rate increased turf quality at the 0 and 1.2 L m^{-2} of spring topdressing; increasing spring topdressing rate increased turf quality at the 0 and 0.075 L m^{-2} of summer topdressing (Table 3.10). Thus, the rate response of summer or spring topdressing was not evident at the highest level of spring or summer topdressing, respectively (Table 3.10).

A three-way interaction was observed on 19 Nov. 2013 during recovery, which explained more variation than any other source (13%, data not shown) (Table 3.8b).

Although the main effect of autumn topdressing suggested that increasing the rate linearly decreased quality on that date, the interaction indicated this decrease in quality only occurred under the combination of no (0 L m^{-2}) summer topdressing and 1.2 L m^{-2} of spring topdressing (Table A.1). It is not clear whether this interaction is meaningful but it may suggest that topdressing during the spring and autumn without summer topdressing could have negative effects. Other researchers have expressed concerns about potential problems due to alternating layers from topdressing programs that include only spring and autumn applications (Rieke et al., 1988a, b).

Turfgrass quality was mainly affected by anthracnose disease during the 3-yr trial and therefore agreed with disease ratings. Additionally, interactions were only occasionally observed. When a spring by summer topdressing rate interaction occurred, the highest level of one reduced the rate response of the other. Hempfling et al. (2015) observed similar spring by summer topdressing interaction in disease response and concluded that spring topdressing could reduce the quantity of summer topdressing needed for maximum disease suppression. Similarly, higher level (2.4 L m^{-2}) of autumn topdressing occasionally weakened the rate response of spring topdressing.

Autumn topdressing appeared to have a subtle negative effect on turf quality towards the end of the last season when disease was so high that all plots had unacceptable quality ratings (< 5). Each year, fungicides were sprayed and large quantities (110 to 190 kg ha^{-1}) of N was applied from late summer to autumn to arrest disease, promote recovery and bring the field to a desirable condition before the disease epiphytotic in the subsequent year. Large amount of sand applied in autumn buried and protected crowns but may also have served as barrier above thatch preventing fungicides from reaching crowns.

Additionally, the significant three-way interaction occurred during recovery indicating that autumn topdressing rate response was affected by spring and summer topdressing, and only reduced turf quality under some levels of spring and summer topdressing. One example, autumn topdressing did not decrease turf quality on 19 Nov. 2013 except when spring and summer topdressing were applied at 1.2 and 0 L m^{-2}, respectively (Table A.1). The mat layer sampling and evaluation at the end of the trial revealed that alternate sand and thatch layers were associated with treatment combinations that high rate of sand was applied in autumn but not in spring and summer. Ledeboer and Skogley (1967) reported that thatch layer could restrict roots from extending into soil underneath. Although, distinct thatch layers in between topdressing layers were observed, root counts data were not taken in our study.

Turfgrass Color

Anthracnose reduced turf color as well as turf quality. Changes in disease severity and turf quality were generally reflected in turf color; plots with less anthracnose were healthier and had more vivid green color.

Increasing the rate of spring topdressing resulted in a linear improvement in turf color on 18 of 21 dates in 2011, 2012 and 2013 (Tables 3.11, 3.12 and 3.13). Spring topdressing did not significantly improve color on one initial rating on 17 Apr. 2013 before the spring application was made in that year, and one early season observation on 30 May 2012 (Tables 3.12 and 3.13).

Turf color had a positive linear response to increased autumn topdressing rate early in the season from 21 June to 5 Aug. 2011, 18 June to 8 Aug. 2012 and 17 Apr. 2013 (Tables 3.11, 3.12 and 3.13). This color response generally followed the trend of turf quality ratings. However, by 15 July 2013, increased autumn topdressing rate produced a linear reduction in turf color (Table 3.13). The negative color response to autumn topdressing occurred two weeks earlier than the decline in turf quality in 2013.

A quadratic summer topdressing rate response was observed on 21 June 2011 (Table 3.11) before initiation of summer treatments likely due to initial non-uniformity in disease development that affected color, and was therefore considered a random effect. Increased turf color due to summer topdressing first occurred on 5 Aug. 2011 (Table 3.11). A consistent summer topdressing rate effect was observed from 18 June 2012 through 17 Apr. 2013, which suggested that increasing topdressing rate improved turf color (Tables 3.12 and 3.13). A subtle negative linear color response to increased summer topdressing was observed once on 9 July 2013 and did not occur again during the trial (Table 3.13).

Summer topdressing interacted with spring topdressing on 27 July, 8 Aug. and 21 Sept. 2012 (Table 3.14). Increasing summer topdressing rate on these dates was effective at improving turf color under the 0 or 1.2 L m^{-2} spring topdressing levels but not under the 2.4 L m^{-2} rate, which suggested that high level of spring topdressing could mask the effect of summer topdressing (Table 3.14). Increasing spring topdressing rate improved turf color on 27 July and 8 Aug. 2012 only when no summer topdressing was applied, but enhanced turf color at the 0 or 0.075 L m^{-2} summer rates on 21 Sept. 2012 (Table 3.14). A summer by autumn rate interaction occurred on the first rating (21 June 2011) before initiation of summer treatments likely due to non-uniformity in initial disease development affecting color (Table 3.11). An autumn by spring by summer topdressing rate interaction was evident on 13 July 2012 and 20 Sept. 2013 (Tables A.3 and A.4). The autumn main effect occurred on 20 Sept. 2013 indicated that a linear decrease in color occurred as the autumn topdressing rate increased (Table 3.13). Interestingly, the three-way interaction on the same date indicated that this response to autumn topdressing was not evident under each combination of summer and spring topdressing (Table A.4). Comparison of interaction means did not reveal any pattern of response to treatments on 13 July 2012 (Table A.3); therefore there was no meaningful interpretation of this three-way interaction. Chlorophyll measurements confirmed visual color ratings on 15 July and 19 Sept. 2013 (Table A.5).

Sand Incorporation

Topdressing rate significantly affected the ability to incorporate sand into the turf canopy. Greater topdressing rates resulted in more remnant sand particles remaining on the turf surface and extended the time required for sand to dissipate from the turf surface. Spring topdressing applied at 1.2 L m^{-2} on 20 April and 3 May 2013 required no more than one day for sand to incorporate into turf canopy, resulting in no unacceptable interference to visual quality, mowing and playability (Table 3.15). When applied at 2.4 L m^{-2} on the same dates, spring topdressing required approximately four days for sand to dissipate from the turf surface and provide a minimally acceptable putting surface cleanness and smoothness (Table 3.15 and Fig. 3.4). Early summer topdressing applications of sand on 12 and 21 June 2013 incorporated immediately into all turf plots (Table A.8). As sand accumulated in the thatch and turf canopy throughout the season, plots receiving the highest summer rate (0.15 L m^{-2}) at the last summer application on 13 Sept. 2013 exhibited a slight delay in incorporation (Table A.11); these plots required no more than one day for incorporation to be acceptable (Table 3.15). Inguagiato et al. (2012) used much greater quantity of summer topdressing (0.3 and 0.6 L m^{-2} applied every two weeks) than in our study, and they indicated that their rates exceeded what is typically applied in the turf industry (< 0.3 L m^{-2} per application). Hempfling et al. (2015) reported poor incorporation of summer topdressing at 0.3 and 0.6 L m^{-2} which exceeded the rate of biomass (canopy and thatch) development; whereas, when they used the same summer topdressing rates as our study (0.075 and 0.15 L m^{-2} applied every two weeks), sand was readily incorporated into the turf. The autumn, spring and summer rates evaluated in our study are more typically used in the golf industry and have not been reported to be disruptive to play or mowing on putting greens.

Volumetric Water Content and Algae

Increasing topdressing rate in our study generally decreased soil volumetric water content (VWC), which agrees with the results of another topdressing trial on a creeping bentgrass fairway (Henderson et al., 2010). The response was more evident when soil VWC was high (Tables 3.16 and 3.17). When soil VWC was relatively low on 1 and 15 July 2011, the linear response to autumn, spring or summer topdressing rate did not occur (Table 3.16). Autumn topdressing had a greater influence on soil VWC than spring or summer topdressing; a significant linear response to autumn topdressing occurred on 11 of 13 observation dates throughout 3-yr study and accounted for more of the variation in this response than spring or summer topdressing factor (Tables 3.16 and 3.17). Increasing spring topdressing rate reduced soil VWC linearly on 9 of 13 dates in 2011, 2012 and

2013 (Tables 3.16 and 3.17). Increased summer topdressing rate produced a quadratic reduction in VWC on 23 Aug. 2013; the lowest VWC occurred on plots receiving 0.075 L m^{-2} of sand every two weeks (Table 3.17). This response was inconsistent with other rating dates and only explained a small amount of the variation (6%) (Table 3.17), and was therefore considered a random effect.

An interaction between spring and summer topdressing was evident on 29 May 2012, and accounted for 4% of the variation in the VWC response (Table 3.16). Increasing spring topdressing rate linearly decreased VWC but not under the highest level of summer topdressing; similarly, increased summer topdressing rate did not reduce VWC only under the highest spring topdressing rate (Table 3.18). The three-way interaction of autumn, spring and summer topdressing rate was observed on 22 May and 4 June 2013 (Table 3.17), but did not indicate a consistent or clear response pattern (Tables A.12 and A.13).

Unlike autumn and spring topdressing, summer topdressing did not affect VWC except on 23 Aug. 2013 (quadratic response). Summer topdressing was applied as eight applications each year on a two-week interval totaling 0, 0.6 and 1.2 L m^{-2}. Summer totals spread out over three months were half the quantities of sand applied in autumn or spring. Thus, the lower summer topdressing rates were less likely to have an effect on soil VWC.

Algae emerged naturally due to excessive wetness in the turf canopy after heavy rainfall. As expected, since sand topdressing reduced surface water content during wet conditions, the incidence of algae observed in 2013 was reduced by the application of sand. In general, increasing topdressing rate significantly reduced algae (Table 3.19).

Increasing autumn topdressing rate had the greatest impact on the algal response: significantly reducing algae linearly on every rating date in 2013 (Table 3.19). Increased spring or summer topdressing also produced a linear decrease in the incidence of algae on 2 of 4 observations (Table 3.19). An autumn and spring rate interaction effect was observed on 13 Aug. 2013 (Table 3.19). Increasing the autumn rate linearly reduced algae only when spring topdressing was applied at 2.4 L m^{-2}; whereas, increasing the spring topdressing rate reduced algae at both the 1.2 and 2.4 L m^{-2} levels of autumn topdressing (Table 3.20). Thus, this interaction indicated that combining autumn and spring topdressing was more effective in reducing algae than increasing autumn or spring rate alone in the absence of the other factor.

Surface Hardness and Strength

Surface hardness measured with the 2.25-kg hammer responded to spring topdressing more than autumn or summer topdressing rate. Increasing spring topdressing produced linear and quadratic reductions in surface hardness on five dates and one date, respectively, out of seven observation dates over the 3-yr study (Tables 3.21, 3.22 and 3.23). Increased autumn topdressing rate reduced surface hardness linearly on 5 of 7 observations (Tables 3.21, 3.22 and 3.23). Summer topdressing reduced surface hardness linearly as the rate increased on 1 of 7 observation dates (Tables 3.21, 3.22 and 3.23). Interactions between autumn and spring topdressing occurred twice during the study (Tables 3.22 and 3.23). On 28 June 2012, increasing autumn topdressing rates reduced surface hardness linearly when no spring topdressing was applied; whereas, increasing spring topdressing rate reduced surface hardness with a linear and a quadratic response at the 0 and 2.4 L m^{-2} levels of autumn topdressing, respectively (Table 3.24). On 22 May

2013, the linear decrease in surface hardness as a result of increased spring topdressing rate diminished as the rate of autumn topdressing increased; no response to spring topdressing rate was evident at the highest level of autumn topdressing. Additionally, a quadratic decrease in surface hardness occurred in response to increased autumn topdressing rate only in the absence of spring topdressing (Table 3.24).

The 0.5-kg hammer released from 30 cm (standard height) occasionally detected surface hardness responses to the spring topdressing rate, but the responses were inconsistent (Tables 3.21, 3.22 and 3.23). A significant quadratic response occurred on 15 July 2011 and 4 June 2013, which indicated that spring topdressing at 1.2 L m^{-2} resulted the greater surface hardness than at 0 or 2.4 L m^{-2} (Tables 3.21 and 3.23). The response occurred on 15 July 2011 might be associated with the quadratic response detected on the same date for VWC; where plots receiving 1.2 L m^{-2} of spring topdressing had the lowest water content and the greatest hardness (Table 3.16). However, the quadratic response on 4 June 2013 could not be explained by water content. A linear rate response observed on 26 Sept. 2011, which indicated that increasing spring topdressing reduced surface hardness (Table 3.21). Increased autumn topdressing rate linearly increased surface hardness once on 28 June 2012, and there was no summer topdressing main effect on surface hardness as measured by the 0.5-kg hammer. An autumn by summer topdressing rate interaction was evident on 4 June 2013 (Table 3.23). On this date, a linear increase in surface hardness occurred in response to increased summer topdressing rate when autumn topdressing was applied at 2.4 L m^{-2}, indicating that summer topdressing increased surface hardness only when the greatest level of autumn topdressing was applied (Table 3.25).

Many have reported a negative relationship between surface hardness and soil water content (Linde et al., 2011; McClements and Baker, 1994; McNitt and Landschoot, 2001; Rogers and Waddington, 1989; Rogers and Waddington, 1990a; Rogers and Waddington, 1992). This relationship was occasionally observed in our study on 15 July 2011, 28 June 2012 with the 0.5-kg hammer released from the 30 cm height and 25 June 2013 with 0.5-kg hammer released from a 10 cm height. Soil water content is known to have less of an effect on surface hardness of sand dominated root zones compared to soil dominated root zones where water content can greatly influence hardness (Baker, 1991). Stowell et al. (2009) speculated that sand topdressing could reduce the effect of soil water content on hardness of putting greens because of the substantial amount of sand that accumulates at the surface of a root zone from topdressing.

Contrary to our findings with the 2.25-kg Clegg Impact Soil Tester, it has been reported that sand topdressing can increase surface hardness. Espevig et al. (2012) observed that increasing topdressing rate from 0.5 to 1.0 L m^{-2} every two weeks (totaling 7 to 14 L m^{-2} annually) increased surface hardness of velvet bentgrass turf maintained as a putting green. Kauffman et al. (2011) reported that topdressing applied every two weeks at 0.4 L m^{-2} incorporated by brushing increased surface hardness measured with a 2.25-kg hammer compared to the non-topdressed control on ultradwarf bermudagrass [*Cynodon dactylon* (L.) × *C. transvaalensis* Burtt Davy] putting green turf. However, soil water content was not reported in either study. Additionally, their topdressing rates were much greater than those applied in our annual bluegrass trial, thus the quantity of topdressing in our study may not have been sufficient to increase surface hardness when measured with the 2.25-kg hammer. However, the highest summer topdressing rate of

0.15 L m^{-2} applied every two weeks in our study, similar to that used by Stier and Hollman (2003), is a more typical rate used by turf managers for cool season turfgrasses and thus may better reflect the relationship between topdressing and surface hardness on commercial golf courses.

Both the 2.25- and 0.5-kg Clegg Impact Soil Testers may be more representative of hardness deeper in the soil profile than within the topdressing layer at the surface. Baker and Canaway (1992) reported that increasing sand topdressing rate increased surface hardness (0.5-kg hammer) of a sports field in wet conditions, but decreased surface hardness in dry conditions. They speculated that the soil underneath rather than the topdressing layer determined the surface hardness under dry conditions. However, water content was not observed to consistently affect the surface hardness response to topdressing rate in our study. The Clegg Impact Soil Tester originally was developed for testing road base compaction (Clegg, 1976); subsequent uses in turfgrass systems have not always been effective at detecting differences in hardness due to topdressing treatments (Barton et al., 2009; McCarty et al., 2005). Gibbs et al. (2000) concluded that immediate surface firmness on golf putting greens was best represented by a single drop of the 0.5-kg hammer and recommended the 2.25-kg hammer for detecting soil hardness from deeper in the profile. Although both the 2.25- and 0.5-kg hammers have detected soil compaction in turfgrass systems; however, the variation in surface conditions such as cutting heights and presence of verdure or thatch affecting hardness was only detected by the 0.5-kg hammer (Rogers and Waddington, 1989, 1992). Murphy (1983) interpreted the lower penetrometer ratings (softer soil surface) from topdressing treatments as that topdressing alleviated soil compaction rather than it decreased firmness. Therefore, similarly data obtained from the Clegg Impact Soil Testers in our study suggested that soil underneath the thatch layer of non-topdressed plots was more compacted than soil underneath the mat layer of topdressed plots, presumably caused by traffic (from the pavement roller). However, further research is needed to validate this speculation.

A reduced drop height of 10 cm with the 0.5-kg hammer detected a linear increase in surface strength as autumn or spring topdressing rate increased on 25 June 2013 (Table 3.23). Although observations were limited, results contradicted hardness measured with the 0.5- and 2.25-kg hammer using the standard drop height (Table 3.23). The different results generated by the Clegg Impact Soil Testers presumably related to the impact energy that was generated by the free falling hammer. The impact energy produced by the 2.25-kg hammer is greater than that produced by 0.5-kg hammer (Rogers and Waddington, 1990b), and better reflected soil hardness deeper in the profile (Gibbs et al., 2000). The impact energy generated by the hammer falling from 10 cm is much less than from 30 cm. Thus, a 10 cm drop height with the 0.5-kg hammer may better represent the impact absorption characteristics of the turf surface. McClements and Baker (1994) used 30- and 55-cm drop heights with the 0.5-kg hammer to measure the hardness of natural turf hockey pitches and concluded that the 55 cm drop height better represented players' evaluation of the surface for running. Varying drop height was described as custom protocol in the Clegg Impact Soil Tester user's manual.

Penetrometer data indicated that increasing topdressing rate generally decreased penetration depth reflecting an increase in surface strength. This linear response to spring topdressing was consistently highly significant ($p < 0.001$) on all dates (Table 3.26). The linear decrease in penetration depth response to increased autumn rate also occurred on every observation but accounted for a much smaller percentage of the variation of the model than the spring rate: 5% to 18% vs 49% to 77% of the variation, respectively (Table 3.26). The linear decrease in penetration depth in response to increasing summer topdressing rate was evident on 3 of 4 dates, accounting for only 3% to 14% of the variation (Table 3.26).

Similar to our findings, Henderson and Miller (2010) observed a linear increase in soil penetration resistance (measured with a proving ring penetrometer) as monthly topdressing rates increased (0, 1.2, 2.4 and 3.6 L m^{-2}) over two years of a creeping bentgrass fairway topdressing study. Murphy (1983) reported that increasing topdressing frequency and thus annual topdressing rate (0, 2.3, 3.2, 10.8 and 18.2 L m^{-2}) decreased soil firmness at the 2.5 cm surface layer of creeping bentgrass putting green turf as measured with a different penetrometer (a self recording penetrometer). He also observed that the thatch of the non-topdressed plots was spongy and very easily compressed. Therefore, Murphy (1983) interpreted the penetrometer results as suggesting that topdressing alleviated soil compaction rather than reduced firmness.

Organic Matter Production

Topdressing reduces organic matter (OM) content by diluting thatch and forming a mat layer (McCarty et al., 2007; McCarty et al., 2005; Rieke et al., 1988a; Stier and Hollman, 2003; Vavrek, 1995; White and Dickens, 1984). Organic matter production was measured as both mat layer depth and OM content (weight loss-on-ignition) at the conclusion of our study to allow adequate accumulation of sand. Other studies have indicated that topdressing effects on OM content required more than two years of treatment to be measureable (McCarty et al., 2007; McCarty et al., 2005).

Increasing topdressing rate significantly increased mat layer depth and reduced OM content regardless of season. Autumn and spring topdressing rate effects explained the most variation in mat layer depth (37% and 47%, respectively) and OM content (42% and 33%, respectively) responses (Tables 3.27 and 3.29). Summer topdressing explained 10% and 3% of the variation in mat layer depth and OM content responses, respectively (Tables 3.27 and 3.29). Autumn interacted with spring topdressing and accounted for 1% and 8% of the variation in mat layer depth and OM content responses, respectively (Tables 3.27 and 3.29). The three-way interaction only explained 1% and 2% of the variation in mat layer depth and OM content responses, respectively (Tables 3.27 and 3.29). Summer topdressing interacted with either autumn or spring topdressing and each interaction only accounted for 2% of the variation in OM content response (Table 3.29).

Spring topdressing rate explained the most variation (47%) in mat depth (Table 3.27). Increasing spring topdressing rate linearly increased mat layer depth (Table 3.27). Whereas, increasing rate of autumn topdressing significantly increased mat layer depth with a quadratic response (Table 3.27). This quadratic response indicated that a dramatic increase in mat layer depth occurred when autumn topdressing rate increased from 0 to 1.2 L m^{-2}; however, increasing topdressing rate to 2.4 L m^{-2} resulted in a relatively small increase in mat depth (Table 3.28). The spring by autumn topdressing interaction indicated that the quadratic response to autumn topdressing only occurred when spring topdressing was not applied. Summer topdressing linearly increased mat depth as rate increased and accounted for 10% of the variation (Table 3.27). The three-way interaction among autumn, spring and summer topdressing rate (1% of the variation) indicated that under the absence of summer topdressing, the interaction of autumn and spring rates was more dramatic (Tables 3.27 and A.14).

Autumn topdressing had greatest effect on OM content. Increasing either autumn or spring topdressing rate reduced OM content with a quadratic response (Table 3.29). OM content decreased 22 g kg^{-1} when autumn topdressing rate increased from 0 to 1.2 L m^{-2}; however, increasing the autumn topdressing rate from 1.2 to 2.4 L m^{-2} resulted in a relatively small decrease (12 g kg^{-1}) in OM content (Table 3.29). Spring topdressing had a lesser effect on OM: increasing the rate from 0 to 1.2 L m^{-2} and 1.2 to 2.4 L m^{-2} decreased the OM content 20 and 10 g kg^{-1}, respectively (Table 3.29). Summer topdressing linearly reduced OM content as topdressing rate increased and accounted for 5% of the variation (Table 3.29). The three-way interaction indicated that autumn topdressing rate had a strong effect on the spring and summer rate responses. Under the greatest rate (2.4 L m^{-2}) of autumn topdressing, the summer rate response was significant only under the 2.4 L m^{-2} of spring topdressing (Table 3.30). Under the 0 and 1.2 L m^{-2} levels of autumn topdressing, summer topdressing rate response was weakened as spring topdressing increased (Table 3.30). Spring topdressing produced a quadratic reduction in OM content in the absence of autumn and summer topdressing; increasing the spring rate from 0 to 1.2 L m^{-2} produced a dramatic decrease in OM content while the increase from 1.2 to 2.4 L m^{-2} produced a smaller decrease in OM content (Table 3.30). This quadratic response of OM content to spring topdressing rate faded as autumn or summer topdressing increased (Table 3.30).

Sand topdressing in spring and autumn or frequently (every three or six weeks) throughout the year was reported to increase mat layer depth and decrease OM content of creeping bentgrass putting green turf; but responses did not differ among topdressing programs (Rieke et al., 1988a, b). In our study, spring topdressing was slightly more effective than autumn topdressing on increasing mat layer depth, whereas, autumn topdressing was more effective at reducing OM content. Increasing autumn or spring topdressing increased mat layer depth 6 or 7 mm, and decreased OM content 34 or 30 g kg^{-1}, respectively (Tables 3.27 and 3.29). The small difference in mat layer responses could due to growth (crowns, stolons, and roots). Healthy and actively growing plants produce more thatch and contribute to greater mat layer depth. Spring topdressing was more effective at simulating growth and improving the overall health of annual bluegrass (less anthracnose disease, higher quality and color) than other factors. Consequently, autumn topdressing treatments presumably with lower organic matter would be more responsive to dilution with the same quantities of sand as spring topdressing. Summer topdressing was less effective at increasing mat layer depth and reducing OM content than autumn or spring topdressing because the total quantity of summer topdressing applied was half as much as the autumn or spring topdressing.

Autumn topdressing had the greatest effect on reducing OM content, which may explain why it also had the greatest impact on decreasing VWC in our study. Turf with high organic content is known to retain excessive water (Hurto et al., 1980). Research also has suggested an increase in cation exchange capacity and available water as organic content increases (McCoy, 1998). The combined effects of reduced VWC and OM due to increased autumn topdressing rate presumably contributed to the small decrease in color that we observed in late 2013, however the mechanism for this response remains unknown.

CONCLUSIONS

Topdressing rate played an important role in the management of anthracnose disease; generally greater topdressing rates provided better suppression of disease severity. Autumn topdressing suppressed anthracnose disease early in the season whereas spring topdressing typically reduced disease severity throughout the season, as the autumn and spring topdressing weakened in the end of the season, summer topdressing could have an effect on anthracnose disease when adequate sand accumulated in the canopy. Spring topdressing produced the greatest reduction in disease severity throughout the study. Summer topdressing applied the lowest quantity of sand and occasionally reduced disease severity late in the growing season. This suggested that the summer rates used in our study were marginally effective for anthracnose disease suppression. Modeling the disease response indicated that an annual cumulative sand quantity range of 2.4 to 4.8 L m^{-2} applied as topdressing was needed to optimize disease suppression in 2011 and 2012. However, there was a poor fit of the disease response to the Cate-Nelson model and a critical value was not observed for linear-plateau model in 2013. In addition, topdressing positively affected root zone physical properties. Increasing rates of topdressing decreased organic matter concentration and surface water retention. Autumn topdressing was slightly more effective at reducing OM concentration than spring topdressing, whereas both spring and autumn topdressing were more effective than summer topdressing at reducing OM concentration and increasing mat layer depth probably because summer rates were relatively low compared to the rates applied in autumn and spring. Increasing the rate of autumn and spring topdressing can reduce anthracnose severity, maintain acceptable turfgrass performance and improve soil physical properties of annual bluegrass putting green turf. Although, summer topdressing applied every two weeks at either 0.075 or 0.15 L m^{-2} was readily incorporated into the turf, those rates were too low to effectively reduce disease and improve turf performance.

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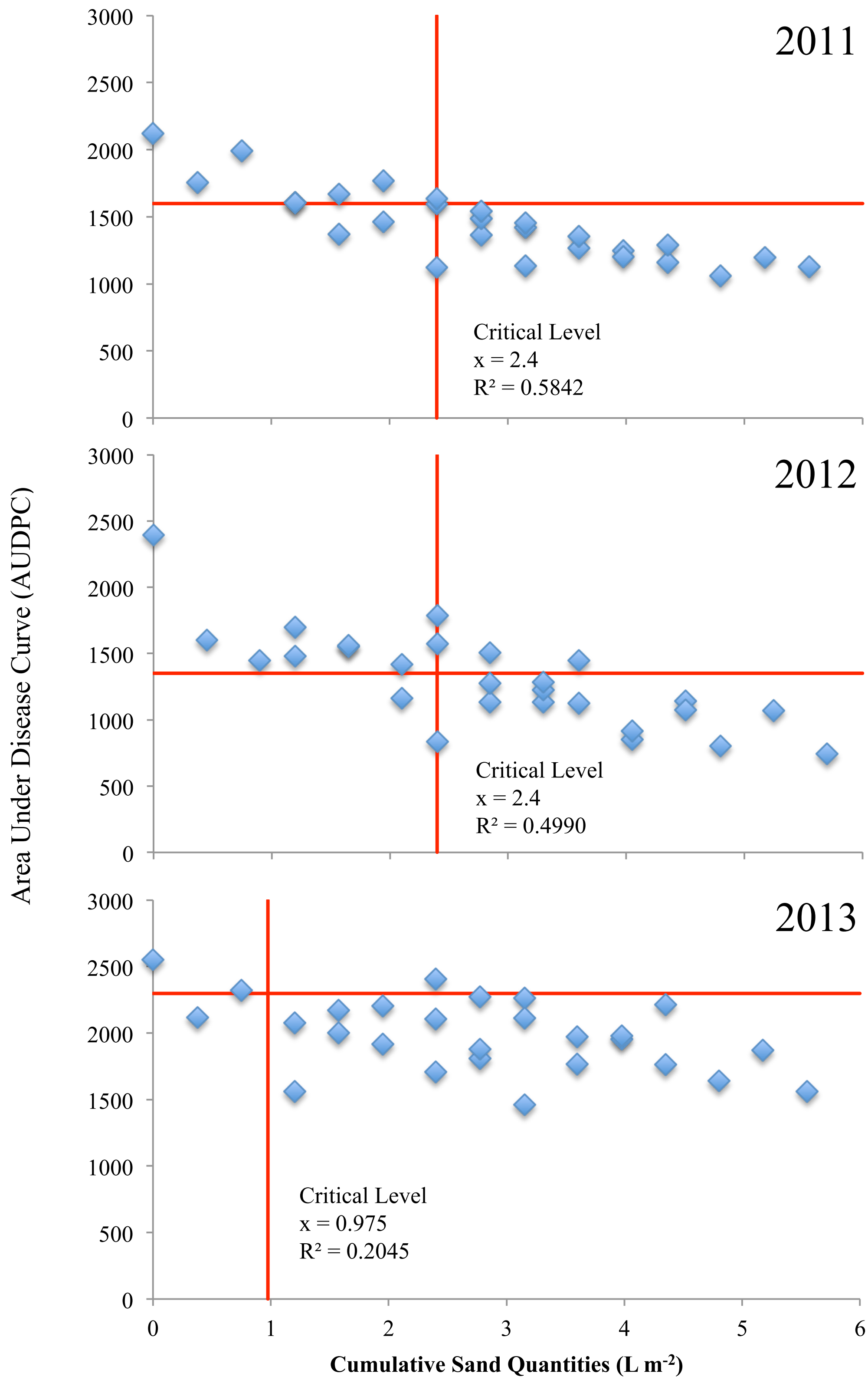


Figure 3.1. Anthracnose severity response reported as area under the disease progress curve (AUDPC) to cumulative topdressing sand quantities explained by Cate-Nelson model on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2011, 2012 and 2013.

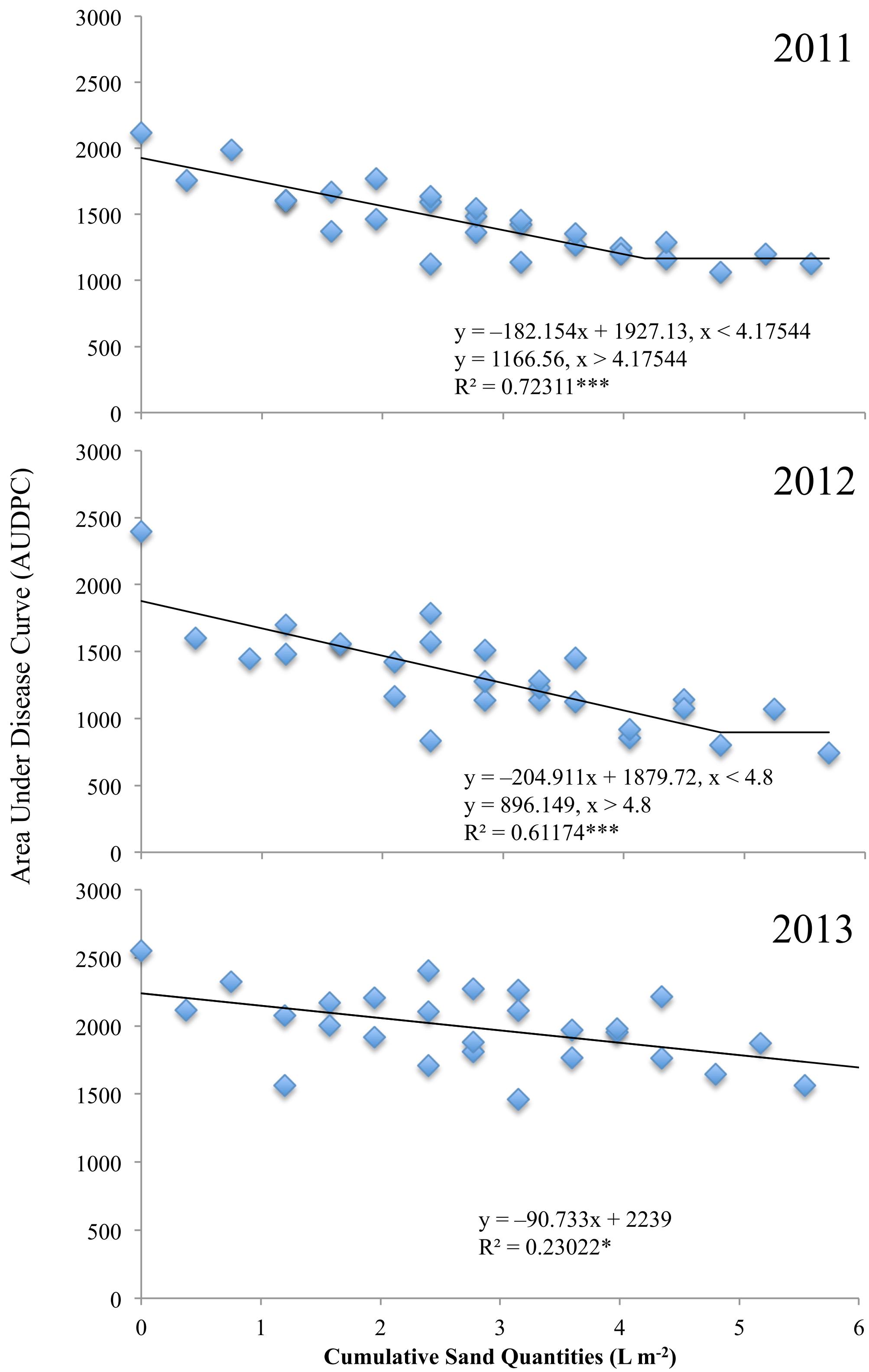


Figure 3.2. Anthracnose severity response reported as area under the disease progress curve (AUDPC) to cumulative topdressing sand quantities explained by linear or linear-plateau model on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2011, 2012 and 2013. The * and *** indicate significance at the 0.05 and 0.001 probability level, respectively.

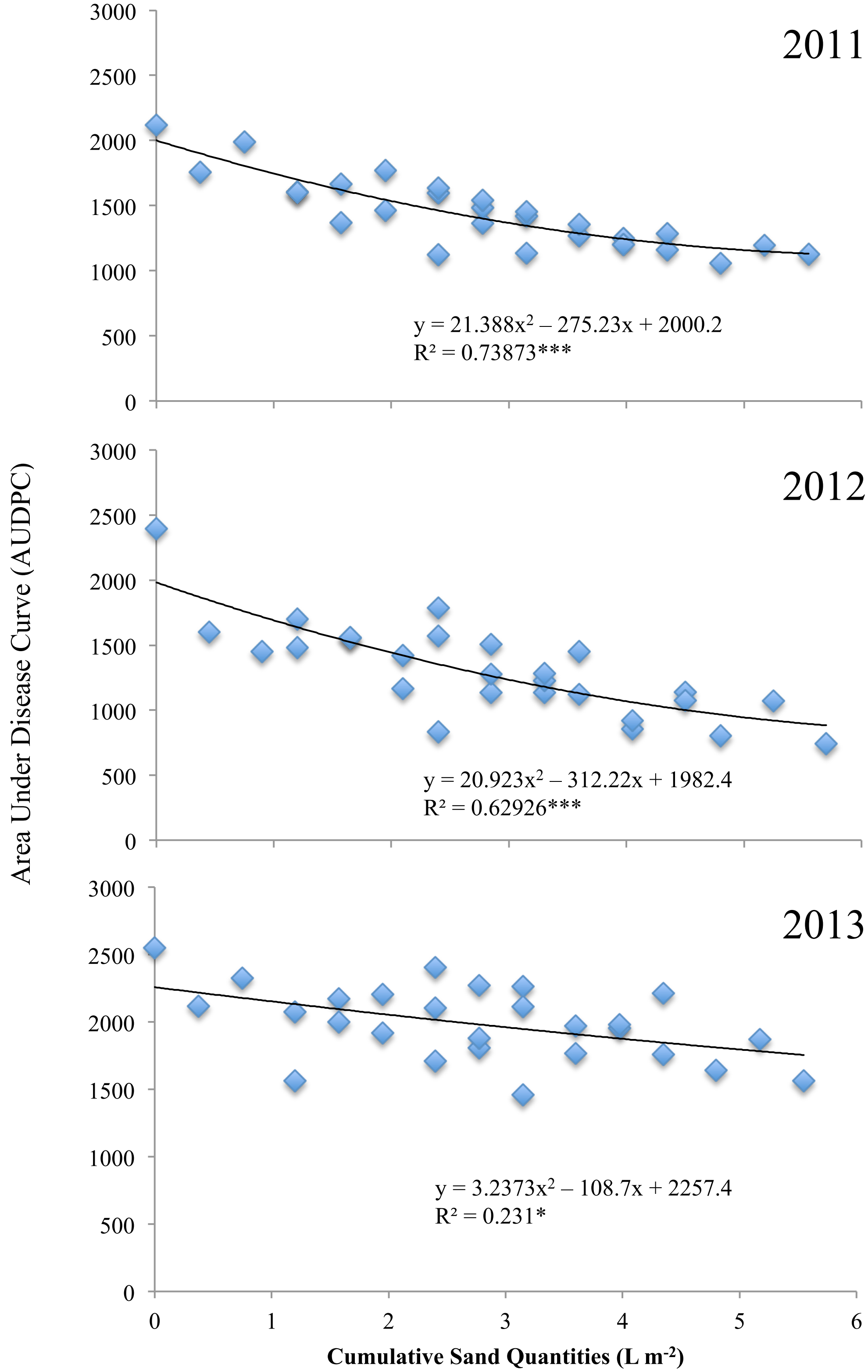
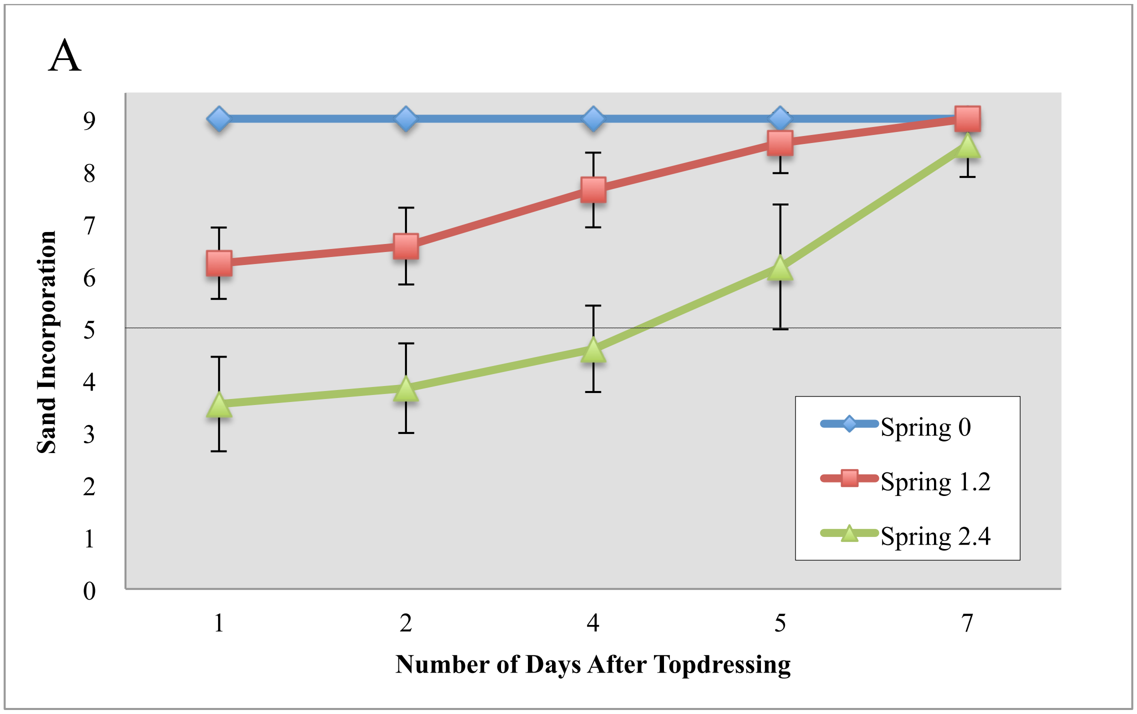


Figure 3.3. Anthracnose severity response reported as area under the disease progress curve (AUDPC) to cumulative topdressing sand quantities explained by quadratic model on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2011, 2012 and 2013. The * and *** indicate significance at the 0.05 and 0.001 probability level, respectively.



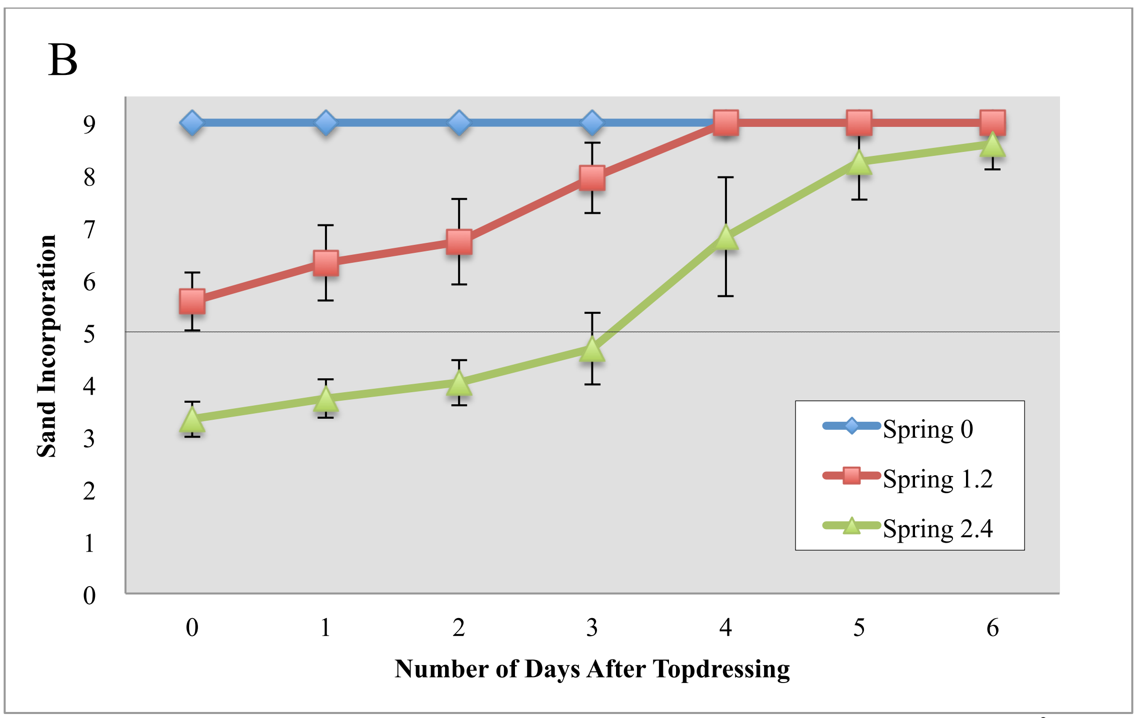


Figure 3.4. Sand incorporation response to spring topdressing rate of 0, 1.2 and 2.4 L m^{-2} applied as two split applications on 20 April (A) and 3 May 2013 (B) on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ. Nine (9) represents no sand visible at turf surface, and 5 represents the minimally acceptable rating.

Table 3.1. Particle size distribution of sand used for topdressing.

Particle Size (mm)					
Very Coarse	Coarse	Medium	Fine	Very Fine	
2–1	1–0.5	0.5–0.25	0.25–0.15	0.15–0.05	<0.05
---------------------------------- % (by weight) ----------------------------------					
0.07	31.27	65.05	3.32	0.27	0.01

Table 3.2. Anthracnose severity response to autumn, spring and summer topdressing rate on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2011.

Season	Rate	21-Jun	4-Jul	11-Jul	20-Jul	28-Jul	4-Aug	11-Aug
	L m^{-2}	----------------------------Turf Area Infested (%)-----------------------						
Autumn†	0	7	10	22	29	49	60	61
Autumn	1.2	7	8	17	25	45	58	62
Autumn	2.4	5	7	15	23	41	54	58
Spring‡	0	8	11	26	33	51	63	64
Spring	1.2	6	8	16	26	47	59	62
Spring	2.4	5	6	13	19	38	50	56
Summer§	0	6	9	19	26	46	60	63
Summer	0.075	6	9	18	25	45	58	60
Summer	0.15	6	8	18	27	45	55	59
ANOVA		----------------------------------- *p > F* -----------------------------------						
Autumn Rate (A)		***(16%)¶	***(6%)	**(5%)	*(2%)	*(3%)	NS#	NS
Linear		***	***	***	**	**	NS	NS
Quadratic		NS	NS	NS	NS	NS	NS	NS
Spring Rate (Sp)		***(33%)	***(12%)	***(16%)	***(12%)	***(8%)	***(6%)	**(2%)
Linear		***	***	***	***	***	***	***
Quadratic		NS	NS	NS	NS	NS	NS	NS
Summer Rate (S)		NS	NS	NS	NS	NS	NS	NS
Linear		NS	NS	NS	NS	NS	NS	NS
Quadratic		NS	NS	NS	NS	NS	NS	NS
A x Sp		NS	NS	NS	NS	NS	NS	NS
A x S		NS	NS	NS	NS	NS	NS	NS
Sp x S		NS	NS	NS	NS	NS	NS	NS
A x Sp x S		NS	NS	NS	NS	NS	NS	NS
CV, %		39.6	42.0	47.4	37.9	26.1	21.1	16.2

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 22 Oct. and 9 Nov. 2010.
‡ The total spring topdressing rate was applied as two split applications on 21 Apr. and 5 May 2011.
§ Summer topdressing rate was applied every two weeks from 7 June to 13 Sept. 2011.
¶ Numbers in parentheses are the percentage of variation calculated as the sum of squares of each factor divided by model sum of squares.
\# NS, not significant.

Table 3.3. Anthracnose severity response to autumn, spring and summer topdressing rate on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2012.

Season	Rate	7 Jun	17 Jun	27 Jun	12 Jul	25 Jul	7 Aug	21 Aug	19 Sep[¶]
	$L\ m^{-2}$	---Turf Area Infested (%)---							
Autumn[†]	0	2	3	6	14	21	36	59	21
Autumn	1.2	1	2	3	11	19	33	59	20
Autumn	2.4	1	2	3	8	13	30	56	21
Spring[‡]	0	2	3	5	13	21	38	64	25
Spring	1.2	1	2	4	12	20	35	60	21
Spring	2.4	1	1	2	6	12	25	50	17
Summer[§]	0	2	2	4	12	20	37	64	25
Summer	0.075	1	2	4	10	17	33	58	20
Summer	0.15	1	2	4	9	16	29	53	17
ANOVA		--- $p > F$ ---							
Autumn Rate (A)		0.09[#]	**(13%)[††]	***(27%)	***(20%)	***(17%)	0.10	NS[‡‡]	NS
Linear		*	**	***	***	***	*	NS	NS
Quadratic		NS	NS	NS	NS	NS	NS	NS	NS
Spring Rate (Sp)		0.07	**(11%)	***(20%)	***(33%)	***(33%)	***(35%)	***(32%)	***(24%)
Linear		*	**	***	***	***	***	***	***
Quadratic		NS	NS	NS	*	0.06	NS	NS	NS
Summer Rate (S)		NS	NS	NS	0.09	*(8%)	*(10%)	**(15%)	***(22%)
Linear		NS	NS	NS	*	*	**	***	***
Quadratic		0.08	NS	NS	NS	NS	NS	NS	NS
A x Sp		NS	NS	NS	NS	NS	NS	NS	NS
A x S		NS	NS	NS	NS	NS	NS	NS	NS
Sp x S		NS	NS	NS	NS	0.09	0.07	NS	NS
A x Sp x S		NS	NS	NS	NS	NS	NS	NS	NS
CV, %		100.7	85.5	68.7	49.0	46.5	34.0	20.1	36.4

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† The total autumn topdressing rate was applied as two split applications on 21 Oct. and 4 Nov. 2011.

‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 4 May 2012.

§ Summer topdressing rate was applied every two weeks from 8 June to 14 Sept. 2012.

¶ Data were taken after curative anthracnose chemical control.

\# Probability level ≤ 0.1.

†† Numbers in parentheses are the percentage of variation calculated as the sum of squares of each factor divided by model sum of squares.

‡‡ NS, not significant.

Table 3.4. Anthracnose severity response to autumn, spring and summer topdressing rate on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2013.

Season	Rate	14-Jun	3-Jul	9-Jul	17-Jul	4-Aug	17-Aug	20-Sep[¶]
	L m^{-2}	----------------------Turf Area Infested (%)----------------------						
Autumn[†]	0	7	11	19	26	58	56	12
Autumn	1.2	5	12	20	28	61	58	14
Autumn	2.4	5	11	20	26	62	59	16
Spring[‡]	0	7	14	26	34	64	59	15
Spring	1.2	5	12	19	27	60	58	14
Spring	2.4	3	8	14	20	57	56	14
Summer[§]	0	5	11	19	27	61	59	15
Summer	0.075	6	11	19	27	61	58	15
Summer	0.15	5	12	21	27	60	56	12
ANOVA		-------------------------------- *p* > *F* -------------------------------						
Autumn Rate (A)		*(6%)[#]	NS[††]	NS	NS	NS	NS	*(7%)
Linear		*	NS	NS	NS	0.08[‡‡]	0.09	**
Quadratic		NS	NS	NS	NS	NS	NS	NS
Spring Rate (Sp)		***(17%)	***(18%)	***(32%)	***(26%)	**(5%)	NS	NS
Linear		***	***	***	***	***	NS	NS
Quadratic		NS	NS	NS	NS	NS	NS	NS
Summer Rate (S)		NS	NS	NS	NS	NS	NS	**(9%)
Linear		NS	NS	NS	NS	NS	NS	**
Quadratic		NS	NS	NS	NS	NS	NS	NS
A x Sp		NS	NS	NS	NS	NS	NS	NS
A x S		NS	NS	NS	NS	NS	NS	NS
Sp x S		NS	NS	NS	NS	0.09	NS	NS
A x Sp x S		NS	NS	NS	NS	NS	NS	NS
CV, %		62.6	52.2	36.8	37.1	14.2	15.5	35.7

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.
‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.
§ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.
¶ Data were taken after curative anthracnose chemical control.
\# Numbers in parentheses are the percentage of variation calculated as the sum of squares of each factor divided by model sum of squares.
†† NS, not significant.
‡‡ Probability level ≤ 0.1.

Table 3.5. Anthracnose severity response reported as the area under the disease progress curve (AUDPC) to autumn, spring and summer topdressing rate on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2011, 2012 and 2013.

Season	Rate	2011	2012	2013
	$L\ m^{-2}$	---------------- AUPDC -------------		
Autumn†	0	1580	1469	1919
Autumn	1.2	1435	1316	1999
Autumn	2.4	1318	1132	1982
Spring‡	0	1693	1531	2229
Spring	1.2	1453	1404	1967
Spring	2.4	1187	982	1705
Summer§	0	1484	1460	1955
Summer	0.075	1425	1275	1985
Summer	0.15	1423	1181	1960
ANOVA		--------------- $p > F$ ----------------		
Autumn Rate (A)		**(3%)¶	**(13%)	NS#
Linear		***	***	NS
Quadratic		NS	NS	NS
Spring Rate (Sp)		***(10%)	***(37%)	***(18%)
Linear		***	***	***
Quadratic		NS	NS	NS
Summer Rate (S)		NS	*(9%)	NS
Linear		NS	**	NS
Quadratic		NS	NS	NS
A x Sp		NS	NS	NS
A x S		NS	NS	NS
Sp x S		NS	0.07††	NS
A x Sp x S		NS	NS	NS
CV, %		22.0	29.6	20.6

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† The total autumn topdressing rate was applied as two split applications on 22 Oct., 9 Nov. 2010; 21 Oct., 4 Nov. 2011 and 18 Oct., 6 Nov. 2012.

‡ The total spring topdressing rate was applied as two split applications on 21 Apr., 5 May 2011; 20 Apr., 4 May 2012 and 20 Apr., 3 May 2013.

§ Summer topdressing rate was applied every two weeks from 7 June to 13 Sept. 2011, 8 June to 14 Sept. 2012 and 12 June to 13 Sept. 2013.

¶ Numbers in parentheses are the percentage of variation calculated as the sum of squares of each factor divided by model sum of squares.

NS, not significant.

†† Probability level ≤ 0.1.

Table 3.6. Turf quality response to autumn, spring and summer topdressing rate on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2011.

Season	Rate	21 Jun	5 Jul	13 Jul	22 Jul	29 Jul	5 Aug	12 Aug	29 Sep[¶]
	$L\ m^{-2}$	------------------	------------------	------------------	1–9 scale[#]	------------------	------------------	------------------	------------------
Autumn[†]	0	7.4	7.4	7.0	6.8	6.8	5.8	5.7	6.4
Autumn	1.2	7.6	7.7	7.1	7.2	7.1	5.8	5.6	6.2
Autumn	2.4	7.7	7.9	7.5	7.3	7.4	6.1	5.8	6.3
Spring[‡]	0	7.4	7.4	6.8	6.7	6.6	5.6	5.3	6.0
Spring	1.2	7.5	7.6	7.1	7.0	7.1	5.8	5.6	6.2
Spring	2.4	7.8	8.1	7.6	7.6	7.6	6.4	6.1	6.6
Summer[§]	0	7.6	7.7	7.1	7.1	7.0	5.8	5.5	6.1
Summer	0.075	7.5	7.7	7.2	7.2	7.1	6.0	5.8	6.2
Summer	0.15	7.6	7.7	7.3	7.0	7.1	6.0	5.7	6.5
ANOVA		------------------	------------------	------------------	$p > F$	------------------	------------------	------------------	------------------
Autumn Rate (A)		*	***	**	***	**	NS[††]	NS	NS
Linear		*	***	***	***	***	NS	NS	NS
Quadratic		NS	NS	NS	NS	NS	NS	NS	NS
Spring Rate (Sp)		**	***	***	***	***	***	***	***
Linear		**	***	***	***	***	***	***	***
Quadratic		NS	*	NS	NS	NS	NS	NS	NS
Summer Rate (S)		NS	NS	NS	NS	NS	NS	NS	*
Linear		NS	NS	NS	NS	NS	NS	NS	**
Quadratic		NS	NS	NS	NS	NS	NS	NS	NS
A x Sp		NS	NS	NS	*	NS	NS	NS	NS
A x S		NS	NS	NS	NS	NS	NS	NS	NS
Sp x S		NS	NS	NS	NS	NS	NS	NS	NS
A x Sp x S		NS	NS	NS	NS	NS	NS	NS	NS
CV, %		7.5	6.4	8.0	8.7	9.4	12.3	13.5	9.5

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 22 Oct. and 9 Nov. 2010.
‡ The total spring topdressing rate was applied as two split applications on 21 Apr. and 5 May 2011.
§ Summer topdressing rate was applied every two weeks from 7 June to 13 Sept. 2011.
¶ Data were taken after curative anthracnose chemical control.
# 9 = best turf quality, 5 = acceptable, 1 = dead or necrotic turf.
†† NS, not significant.

Table 3.7. Turf quality response to autumn, spring and summer topdressing rate on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2012.

Season	Rate	2 Apr	30 May	15 Jun	27 Jun	13 Jul	27 Jul	8 Aug	22 Aug	20 Sep¶
	L m^{-2}	---------------------------------- 1–9 scale# --------------------------------								
Autumn†	0	8.0	7.7	7.6	7.5	7.4	7.0	6.2	4.8	6.5
Autumn	1.2	7.8	7.8	7.9	7.8	7.7	7.2	6.5	4.8	6.6
Autumn	2.4	8.0	7.8	8.0	7.9	8.1	7.5	6.9	5.1	6.6
Spring‡	0	7.7	7.6	7.7	7.5	7.3	6.9	6.0	4.2	6.2
Spring	1.2	7.9	7.8	7.8	7.8	7.6	7.1	6.4	4.8	6.5
Spring	2.4	8.2	7.9	8.0	8.0	8.3	7.7	7.1	5.7	7.1
Summer§	0	7.8	7.7	7.7	7.7	7.6	7.0	6.2	4.4	6.2
Summer	0.075	8.0	7.8	7.9	7.8	7.8	7.2	6.6	4.9	6.6
Summer	0.15	8.0	7.8	7.9	7.7	7.9	7.5	6.8	5.3	7.0
ANOVA		------------------------------------ $p > F$ ----------------------------------								
Autumn Rate (A)		NS††	NS	**	**	***	***	***	NS	NS
Linear		NS	NS	***	***	***	***	***	NS	NS
Quadratic		0.09‡‡	NS	NS	NS	NS	NS	NS	NS	NS
Spring Rate (Sp)		**	0.07	**	***	***	***	***	***	***
Linear		***	*	**	***	***	***	***	***	***
Quadratic		NS	NS	NS	NS	0.08	*	NS	NS	NS
Summer Rate (S)		NS	NS	NS	NS	0.06	**	***	**	***
Linear		0.08	NS	NS	NS	*	***	***	**	***
Quadratic		NS	NS	NS	NS	NS	NS	NS	NS	NS
A x Sp		0.05	NS	NS	NS	NS	*	NS	NS	NS
A x S		NS	NS	NS	NS	NS	NS	NS	NS	NS
Sp x S		NS	NS	NS	NS	NS	NS	**	0.05	*
A x Sp x S		NS	NS	NS	NS	NS	NS	NS	NS	NS
CV, %		7.0	6.4	6.2	5.7	7.7	7.9	9.7	22.9	9.1

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 21 Oct. and 4 Nov. 2011.
‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 4 May 2012.
§ Summer topdressing rate was applied every two weeks from 8 June to 14 Sept. 2012.
¶ Data were taken after curative anthracnose chemical control.
# 9 = best turf quality, 5 = acceptable, 1 = dead or necrotic turf.
†† NS, not significant.
‡‡ Probability level ≤ 0.1.

Table 3.8a. Turf quality response to autumn, spring and summer topdressing rate on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ from 17 Apr. to 19 Aug. 2013.

Season	Rate	17 Apr	31 May	14 Jun	4 Jul	8 Jul	19 Jul	3 Aug	19 Aug
	$L\ m^{-2}$	---------- 1–9 scale¶ ----------							
Autumn†	0	7.4	7.7	7.3	7.2	6.7	6.3	4.7	4.3
Autumn	1.2	7.9	8.0	7.6	7.3	6.8	6.2	4.2	3.8
Autumn	2.4	7.9	8.0	7.6	7.5	6.9	6.3	4.3	3.8
Spring‡	0	7.6	7.8	7.2	6.9	6.0	5.6	4.1	3.7
Spring	1.2	7.6	7.8	7.5	7.3	6.8	6.2	4.4	4.0
Spring	2.4	7.9	8.0	7.8	7.8	7.5	7.0	4.8	4.2
Summer§	0	7.5	7.8	7.6	7.3	7.0	6.2	4.2	3.8
Summer	0.075	7.8	7.9	7.5	7.4	6.9	6.2	4.4	4.0
Summer	0.15	7.9	8.0	7.5	7.3	6.4	6.4	4.5	4.2
ANOVA		---------- $p > F$ ----------							
Autumn Rate (A)		**	*	*	NS#	NS	NS	*	**
Linear		**	*	**	NS	NS	NS	*	**
Quadratic		0.09††	NS	NS	NS	NS	NS	0.10	NS
Spring Rate (Sp)		0.06	0.07	***	***	***	***	***	*
Linear		*	*	***	***	***	***	***	**
Quadratic		NS	NS	NS	NS	NS	NS	NS	NS
Summer Rate (S)		**	0.08	NS	NS	*	NS	0.10	0.10
Linear		**	*	NS	NS	**	NS	NS	*
Quadratic		NS	NS	NS	NS	NS	NS	NS	NS
A x Sp		NS	NS	NS	NS	NS	NS	NS	NS
A x S		NS	NS	NS	NS	NS	NS	NS	NS
Sp x S		NS	NS	NS	NS	NS	NS	NS	NS
A x Sp x S		NS	NS	NS	NS	NS	NS	NS	NS
CV, %		7.9	5.8	6.1	8.1	12.8	11.9	17.6	19.3

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.
‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.
§ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.
¶ 9 = best turf quality, 5 = acceptable, 1 = dead or necrotic turf.
# NS, not significant.
†† Probability level ≤ 0.1.

Table 3.8b. Turf quality response to autumn, spring and summer topdressing rate on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ on 20 Sept. and 19 Nov. 2013.

Season	Rate	20 Sep††	19 Nov††
	L m^{-2}	--- 1–9 scale¶ ---	
Autumn†	0	7.3	7.6
Autumn	1.2	6.6	7.3
Autumn	2.4	6.3	7.0
Spring‡	0	6.8	7.0
Spring	1.2	6.7	7.3
Spring	2.4	6.7	7.6
Summer§	0	6.4	7.0
Summer	0.075	6.6	7.3
Summer	0.15	7.1	7.5
ANOVA		----- $p > F$ -----	
Autumn Rate (A)		***	**
Linear		***	**
Quadratic		NS#	NS
Spring Rate (Sp)		NS	**
Linear		NS	**
Quadratic		NS	NS
Summer Rate (S)		**	*
Linear		**	*
Quadratic		NS	NS
A x Sp		NS	NS
A x S		NS	NS
Sp x S		NS	NS
A x Sp x S		0.06‡‡	*
CV, %		14.1	10.6

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.
‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.
§ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.
¶ 9 = best turf quality, 5 = acceptable, 1 = dead or necrotic turf.
# NS, not significant.
†† Data were taken after curative anthracnose chemical control.
‡‡ Probability level ≤ 0.1.

Table 3.9. Turf quality response to the interaction of autumn and spring topdressing rate on an annual bluegrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2011 and 2012.

	22 July 2011					27 July 2012				
	Autumn Rate†					Autumn Rate				
Spring Rate‡	0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}			0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}		
L m^{-2}	1–9 scale§			Linear	Quadratic	1–9 scale			Linear	Quadratic
0	6.0	7.0	7.1	***	NS¶	6.5	7.2	7.0	*	*
1.2	6.7	6.9	7.3	*	NS	6.9	6.8	7.5	*	NS
2.4	7.5	7.6	7.6	NS	NS	7.6	7.5	8.0	NS	NS
Linear	***	*	NS			***	NS	***		
Quadratic	NS	NS	NS			NS	*	NS		

* Significant at the 0.05 probability level.

*** Significant at the 0.001 probability level.

† The total autumn topdressing rate was applied as two split applications on 22 Oct. and 9 Nov. 2010, 21 Oct. and 4 Nov. 2011.

‡ The total spring topdressing rate was applied as two split applications on 21 Apr. and 5 May 2011, 20 Apr. and 4 May 2012.

§ 9 = best turf quality, 5 = acceptable, 1 = dead or necrotic turf.

¶ NS, not significant.

Table 3.10. Turf quality response to the interaction of spring and summer topdressing rate on an annual bluegrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2012.

	8 August 2012					20 September 2012				
	Spring Rate[†]					Spring Rate				
Summer Rate[‡]	0 $L\ m^{-2}$	1.2 $L\ m^{-2}$	2.4 $L\ m^{-2}$			0 $L\ m^{-2}$	1.2 $L\ m^{-2}$	2.4 $L\ m^{-2}$		
$L\ m^{-2}$		1–9 scale[§]		Linear	Quadratic		1–9 scale		Linear	Quadratic
0	5.4	5.9	7.2	***	*	5.6	5.8	7.0	***	**
0.075	6.1	6.6	7.0	**	NS[¶]	6.1	6.7	7.0	**	NS
0.15	6.5	6.7	7.1	NS	NS	6.8	7.1	7.3	NS	NS
Linear	***	**	NS			**	***	NS		
Quadratic	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.

† The total spring topdressing rate was applied as two split applications on 20 Apr. and 4 May 2012.

‡ Summer topdressing rate was applied every two weeks from 8 June to 14 Sept. 2012.

§ 9 = best turf quality, 5 = acceptable, 1 = dead or necrotic turf.

¶ NS, not significant.

Table 3.11. Turf color response to autumn, spring and summer topdressing rate on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2011.

Season	Rate	21 Jun	5 Jul	13 Jul	22 Jul	29 Jul	5 Aug	12 Aug	29 Sep¶
	$L\ m^{-2}$	----------	----------	----------	1–9 scale#	----------	----------	----------	----------
Autumn†	0	7.4	7.3	7.1	7.0	6.7	5.5	5.5	6.7
Autumn	1.2	7.5	7.4	7.3	7.2	6.8	5.7	5.7	6.7
Autumn	2.4	7.8	7.7	7.7	7.4	7.2	5.8	5.9	6.6
Spring‡	0	7.4	7.1	7.1	6.7	6.4	5.3	5.3	6.7
Spring	1.2	7.4	7.5	7.3	7.3	6.9	5.6	5.7	6.7
Spring	2.4	7.8	7.8	7.8	7.7	7.4	6.1	6.1	6.7
Summer§	0	7.6	7.6	7.3	7.3	6.8	5.4	5.5	6.6
Summer	0.075	7.4	7.4	7.4	7.2	6.9	5.8	5.9	6.8
Summer	0.15	7.7	7.4	7.4	7.1	7.0	5.8	5.8	6.7
ANOVA		----------	----------	----------	----------	$p > F$	----------	----------	----------
Autumn Rate (A)		**	*	***	*	**	NS††	NS	NS
Linear		**	**	***	*	**	*	NS	NS
Quadratic		NS	NS	NS	NS	NS	NS	NS	NS
Spring Rate (Sp)		**	***	***	***	***	***	***	NS
Linear		**	***	***	***	***	***	***	NS
Quadratic		NS	NS	NS	NS	NS	NS	NS	NS
Summer Rate (S)		*	NS	NS	NS	NS	*	NS	NS
Linear		NS	NS	NS	NS	NS	*	NS	NS
Quadratic		*	NS	NS	NS	NS	NS	NS	NS
A x Sp		NS	NS	NS	NS	NS	NS	NS	NS
A x S		*	NS	NS	NS	NS	NS	NS	NS
Sp x S		NS	NS	NS	NS	NS	NS	NS	NS
A x Sp x S		NS	NS	NS	NS	NS	NS	NS	NS
CV, %		6.6	9.2	8.1	9.6	9.8	12.2	14.1	10.0

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 22 Oct. and 9 Nov. 2010.
‡ The total spring topdressing rate was applied as two split applications on 21 Apr. and 5 May 2011.
§ Summer topdressing rate was applied every two weeks from 7 June to 13 Sept. 2011.
¶ Data were taken after curative anthracnose chemical control.
\# 9 = darkest green, 5 = acceptable, 1 = dead or necrotic turf.
†† NS, not significant.

Table 3.12. Turf color response to autumn, spring and summer topdressing rate on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2012.

Season	Rate	3 Apr	30 May	18 Jun	27 Jun	13 Jul	27 Jul	8 Aug	22 Aug	21 Sep¶
	L m^{-2}	1–9 scale#								
Autumn†	0	7.7	7.8	7.7	7.6	7.5	7.2	6.1	4.2	6.7
Autumn	1.2	7.5	7.9	7.9	7.8	7.7	7.3	6.3	4.3	6.7
Autumn	2.4	7.5	7.9	8.0	7.9	8.0	7.6	6.6	4.4	6.8
Spring‡	0	7.4	7.8	7.7	7.6	7.4	7.1	6.0	3.7	6.4
Spring	1.2	7.6	7.9	7.8	7.8	7.6	7.1	6.2	4.1	6.6
Spring	2.4	7.8	8.0	8.0	8.0	8.2	7.8	6.9	5.0	7.2
Summer§	0	7.5	7.8	7.8	7.8	7.5	7.1	6.1	4.0	6.4
Summer	0.075	7.6	7.9	7.9	7.8	7.8	7.3	6.3	4.3	6.7
Summer	0.15	7.7	8.0	7.9	7.8	7.8	7.6	6.6	4.6	7.2
ANOVA		*p > F*								
Autumn Rate (A)		NS††	NS	*	**	**	*	0.06	NS	NS
Linear		0.09‡‡	NS	*	***	***	**	*	NS	NS
Quadratic		NS	NS	NS	NS	NS	NS	NS	NS	NS
Spring Rate (Sp)		**	NS	**	**	***	***	***	***	***
Linear		**	NS	**	***	***	***	***	***	***
Quadratic		NS	NS	NS	NS	NS	**	0.07	NS	NS
Summer Rate (S)		NS	NS	NS	NS	*	**	*	*	***
Linear		NS	NS	NS	NS	*	***	*	*	***
Quadratic		NS	NS	NS	NS	NS	NS	NS	NS	NS
A x Sp		NS	NS	NS	NS	NS	NS	NS	NS	NS
A x S		NS	0.06	NS	NS	NS	NS	NS	NS	NS
Sp x S		NS	NS	NS	NS	NS	**	**	0.09	**
A x Sp x S		NS	NS	NS	NS	*	NS	NS	NS	NS
CV, %		7.1	5.9	4.9	5.4	7.9	7.7	12.0	25.7	8.3

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 21 Oct. and 4 Nov. 2011.
‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 4 May 2012.
§ Summer topdressing rate was applied every two weeks from 8 June to 14 Sept. 2012.
¶ Data were taken after curative anthracnose chemical control.
\# 9 = darkest green, 5 = acceptable, 1 = dead or necrotic turf.
†† NS, not significant.
‡‡ Probability level ≤ 0.1.

Table 3.13. Turf color response to autumn, spring and summer topdressing rate on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2013.

Season	Rate	17 Apr	14 Jun	9 Jul	15 Jul	3 Aug	19 Aug	20 Sep¶
	$L\ m^{-2}$	--- 1–9 scale# ---						
Autumn†	0	7.6	7.3	7.0	6.9	5.1	3.6	7.3
Autumn	1.2	7.9	7.6	6.7	6.4	4.5	3.1	7.3
Autumn	2.4	7.9	7.5	6.7	6.4	4.0	2.9	6.9
Spring‡	0	7.7	7.2	6.0	5.9	4.3	3.0	7.1
Spring	1.2	7.8	7.5	6.8	6.6	4.6	3.2	7.2
Spring	2.4	7.9	7.8	7.6	7.2	4.8	3.4	7.1
Summer§	0	7.7	7.5	7.1	6.7	4.5	3.0	7.1
Summer	0.075	7.8	7.5	6.8	6.4	4.5	3.1	7.0
Summer	0.15	8.0	7.5	6.5	6.6	4.6	3.4	7.3
ANOVA		--- $p > F$ ---						
Autumn Rate (A)		*	0.06‡‡	NS	*	***	***	*
Linear		*	0.09	NS	*	***	***	**
Quadratic		NS††	0.09	NS	NS	NS	NS	NS
Spring Rate (Sp)		NS	***	***	***	0.07	0.07	NS
Linear		NS	***	***	***	*	*	NS
Quadratic		NS	NS	NS	NS	NS	NS	NS
Summer Rate (S)		*	NS	*	NS	NS	0.10	NS
Linear		**	NS	**	NS	NS	*	NS
Quadratic		NS	NS	NS	NS	NS	NS	NS
A x Sp		NS	0.06	NS	NS	NS	NS	NS
A x S		NS	NS	NS	NS	NS	NS	NS
Sp x S		NS	NS	NS	NS	NS	NS	NS
A x Sp x S		NS	NS	NS	NS	NS	0.07	*
CV, %		6.3	6.0	13.1	13.7	20.5	22.4	9.4

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.
‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.
§ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.
¶ 9 = darkest green, 5 = acceptable, 1 = dead or necrotic turf.
# Data were taken after curative anthracnose chemical control.
†† NS, not significant.
‡‡ Probability level ≤ 0.1.

Table 3.14. Turf color response to the interaction of spring and summer topdressing rate on an annual bluegrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2012.

	27 July 2012					8 August 2012					21 September 2012				
	Spring Rate†					Spring Rate					Spring Rate				
Summer Rate‡	0 $L\ m^{-2}$	1.2 $L\ m^{-2}$	2.4 $L\ m^{-2}$			0 $L\ m^{-2}$	1.2 $L\ m^{-2}$	2.4 $L\ m^{-2}$			0 $L\ m^{-2}$	1.2 $L\ m^{-2}$	2.4 $L\ m^{-2}$		
$L\ m^{-2}$	1–9 scale§			Linear	Quad.	1–9 scale			Linear	Quad.	1–9 scale			Linear	Quad.
0	6.6	6.8	8.0	***	**	5.4	5.7	7.2	***	*	5.9	6.0	7.2	***	**
0.075	7.3	7.3	7.5	NS¶	NS	6.1	6.3	6.6	NS	NS	6.3	6.7	7.1	***	NS
0.15	7.5	7.4	7.9	NS	NS	6.5	6.4	6.8	NS	NS	7.0	7.2	7.3	NS	NS
Linear	***	*	NS			**	*	NS			***	***	NS		
Quadratic	NS	NS	*			NS	NS	NS			NS	NS	NS		

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† The total spring topdressing rate was applied as two split applications on 20 Apr. and 4 May 2012.

‡ Summer topdressing rate was applied every two weeks from 8 June to 14 Sept. 2012.

§ 9 = darkest green, 5 = acceptable, 1 = dead or necrotic turf.

¶ NS, not significant.

Table 3.15. Number of days after spring and summer topdressing events to achieve an acceptable level of sand incorporation as affected by autumn, spring and summer topdressing rates on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2013.

Season	Rate	Spring 1st	Spring 2nd	Summer 8th[¶]
	L m^{-2}	-------------- days after topdressing -----------		
Autumn[†]	0	1.9	1.3	0.2
Autumn	1.2	1.7	1.3	0.2
Autumn	2.4	1.8	1.4	0.3
Spring[‡]	0	0.0	0.1	0.1
Spring	1.2	1.0	0.3	0.3
Spring	2.4	4.3	3.6	0.2
Summer[§]	0	1.8	1.3	0.0
Summer	0.075	1.8	1.4	0.0
Summer	0.15	1.8	1.3	0.6
ANOVA		--------------- $p > F$ -----------------		
Autumn Rate (A)		NS[#]	NS	NS
Linear		NS	NS	NS
Quadratic		NS	NS	NS
Spring Rate (Sp)		***	***	NS
Linear		***	***	NS
Quadratic		***	***	NS
Summer Rate (S)		NS	NS	***
Linear		NS	NS	***
Quadratic		NS	NS	***
A x Sp		NS	NS	NS
A x S		NS	NS	NS
Sp x S		NS	NS	NS
A x Sp x S		NS	NS	NS
CV, %		44.8	45.5	135.7

*** Significant at the 0.001 probability level.

† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.

‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.

§ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.

¶ The 8th summer topdressing was applied on 13 Sept. 2013.

NS, not significant.

Table 3.16. Soil volumetric water content (measured at the 0–38 mm depth with time domain reflectometry) response to autumn, spring and summer topdressing rate on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2011 and 2012.

		2011			2012			
Season	Rate	1-Jul	15-Jul	26-Sep	29-May	7-Jun	28-Jun	7-Aug
	L m^{-2}	--			m^3 m^{-3}			--
Autumn†	0	0.240	0.259	0.347	0.378	0.349	0.308	0.332
Autumn	1.2	0.227	0.250	0.337	0.351	0.332	0.291	0.317
Autumn	2.4	0.230	0.251	0.333	0.336	0.317	0.274	0.304
Spring‡	0	0.240	0.257	0.346	0.365	0.341	0.307	0.329
Spring	1.2	0.228	0.245	0.335	0.353	0.329	0.286	0.314
Spring	2.4	0.230	0.257	0.336	0.347	0.328	0.281	0.310
Summer§	0	0.235	0.255	0.341	0.358	0.335	0.293	0.321
Summer	0.075	0.233	0.250	0.339	0.355	0.332	0.294	0.318
Summer	0.15	0.230	0.254	0.337	0.353	0.331	0.286	0.313
<u>ANOVA</u>		--			*p > F*			--
Autumn Rate (A)		NS¶	NS	***(11%)#	***(49%)	***(34%)	***(17%)	***(21%)
Linear		NS	NS	***	***	***	***	***
Quadratic		NS	NS	NS	0.08	NS	NS	NS
Spring Rate (Sp)		NS	0.07††	*(7%)	***(9%)	**(7%)	***(11%)	***(11%)
Linear		NS	NS	*	***	**	***	***
Quadratic		NS	*	0.09	NS	NS	NS	NS
Summer Rate (S)		NS	NS	NS	NS	NS	NS	NS
Linear		NS	NS	NS	NS	NS	NS	0.09
Quadratic		NS	NS	NS	NS	NS	NS	NS
A x Sp		NS	0.08	NS	NS	NS	NS	NS
A x S		NS	NS	NS	NS	NS	NS	NS
Sp x S		0.07	NS	NS	*(4%)	NS	NS	NS
A x Sp x S		NS	NS	NS	NS	NS	NS	0.06
CV, %		11.6	10.4	4.8	4.5	5.3	9.0	6.2

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 22 Oct. and 9 Nov. 2010, 21 Oct. and 4 Nov. 2011.
‡ The total spring topdressing rate was applied as two split applications on 21 Apr. and 5 May 2011, 20 Apr. and 4 May 2012.
§ Summer topdressing rate was applied every two weeks from 7 June to 13 Sept. 2011 and 8 June to 14 Sept. 2012.
¶ NS, not significant.
# Numbers in parentheses are the percentage of variation calculated as the sum of squares of each factor divide by model sum of squares.
†† Probability level ≤ 0.1.

Table 3.17. Soil volumetric water content (measured at the 0–38 mm depth with time domain reflectometry) response to autumn, spring and summer topdressing rate on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2013.

Season	Rate	22-May	4-Jun	24-Jun	25-Jun	23-Aug	23-Sep
	L m^{-2}	--		m^3 m^{-3}		--	
Autumn[†]	0	0.345	0.443	0.292	0.304	0.335	0.339
Autumn	1.2	0.324	0.425	0.282	0.293	0.321	0.327
Autumn	2.4	0.311	0.417	0.269	0.280	0.313	0.314
Spring[‡]	0	0.340	0.437	0.280	0.294	0.329	0.335
Spring	1.2	0.325	0.429	0.281	0.293	0.323	0.326
Spring	2.4	0.315	0.419	0.283	0.291	0.318	0.318
Summer[§]	0	0.330	0.429	0.283	0.291	0.328	0.330
Summer	0.075	0.327	0.427	0.284	0.298	0.318	0.327
Summer	0.15	0.323	0.428	0.276	0.289	0.324	0.323
ANOVA		--		$p > F$		--	
Autumn Rate (A)		***(28%)[¶]	***(25%)	*(5%)	*(7%)	***(29%)	***(31%)
Linear		***	***	**	**	***	***
Quadratic		NS[#]	NS	NS	NS	NS	NS
Spring Rate (Sp)		***(16%)	***(13%)	NS	NS	**(8%)	***(14%)
Linear		***	***	NS	NS	***	***
Quadratic		NS	NS	NS	NS	NS	NS
Summer Rate (S)		NS	NS	NS	NS	**(6%)	NS
Linear		0.07[††]	NS	NS	NS	NS	NS
Quadratic		NS	NS	NS	NS	**	NS
A x Sp		NS	NS	NS	NS	NS	NS
A x S		NS	NS	NS	NS	NS	NS
Sp x S		0.07	NS	NS	NS	NS	NS
A x Sp x S		*(6%)	*(9%)	NS	NS	NS	NS
CV, %		4.9	3.6	11.6	12.1	4.0	4.2

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.
‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.
§ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.
¶ Numbers in parentheses are the percentage of variation calculated as the sum of squares of each factor divide by model sum of squares.
\# NS, not significant.
†† Probability level ≤ 0.1.

Table 3.18. Soil volumetric water content (measured at the 0–38 mm depth with time domain reflectometry) response to the interaction of spring and summer topdressing rate on 29 May 2012 on an annual bluegrass turf mowed daily at 2.8 mm in North Brunswick, NJ.

	Spring Rate†				
Summer Rate‡	0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}		
L m^{-2}	------- m^3 m^{-3} -------			Linear	Quadratic
0	0.373	0.358	0.344	***	NS§
0.075	0.365	0.355	0.344	**	NS
0.15	0.358	0.346	0.355	NS	NS
Linear	**	*	NS		
Quadratic	NS	NS	NS		

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total spring topdressing rate was applied as two split applications on 21 Apr. and 5 May 2011, 20 Apr. and 4 May 2012.
‡ Summer topdressing rate was applied every two weeks from 8 June to 14 Sept. 2012.
§ NS, not significant.

Table 3.19. Algae incidence after heavy rainfall as influenced by autumn, spring, summer sand topdressing rate on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2013.

Season	Rate	2-Jul	13-Aug	23-Aug	3-Sep
	L m^{-2}	---------------------- 1–9 scale[¶] ------------------			
Autumn[†]	0	5.0	4.5	4.2	1.8
Autumn	1.2	6.7	5.2	5.4	2.0
Autumn	2.4	8.0	5.8	5.6	2.8
Spring[‡]	0	5.9	4.5	4.8	2.1
Spring	1.2	6.4	5.0	5.0	1.8
Spring	2.4	7.5	6.0	5.3	2.7
Summer[§]	0	6.5	4.6	4.6	2.4
Summer	0.075	6.6	5.2	5.2	2.2
Summer	0.15	6.6	5.7a	5.4	2.1
ANOVA		----------------------- $p > F$ ----------------------			
Autumn Rate (A)		***	***	***	**
Linear		***	***	***	**
Quadratic		NS[#]	NS	0.05[††]	NS
Spring Rate (Sp)		***	***	0.06	*
Linear		***	***	NS	0.06
Quadratic		NS	NS	NS	0.06
Summer Rate (S)		NS	**	**	NS
Linear		NS	***	**	NS
Quadratic		NS	NS	NS	NS
A x Sp		NS	**	NS	NS
A x S		NS	NS	NS	NS
Sp x S		NS	NS	NS	NS
A x Sp x S		NS	NS	NS	NS
CV, %		18.7	22.6	21.7	63.6

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.
‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.
§ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.
¶ 9 = free of algae, 5 = acceptable, 1 = covered completely with algae.
# NS, not significant.
†† Probability level ≤ 0.1.

Table 3.20. Algae incidence response to the interaction of autumn and spring topdressing rate on 13 August 2013 on an annual bluegrass turf mowed daily at 2.8 mm in North Brunswick, NJ.

	Autumn Rate†				
Spring Rate‡	0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}		
L m^{-2}	------- 1–9 scale§ -------			Linear	Quadratic
0	4.3	4.3	4.8	NS ¶	NS
1.2	4.7	5.2	5.3	NS	NS
2.4	4.6	6.0	7.3	***	NS
Linear	NS	**	***		
Quadratic	NS	NS	NS		

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.

‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.

§ 9 = free of algae, 5 = acceptable, 1 = covered completely with algae.

¶ NS, not significant.

Table 3.21. Surface hardness response to autumn, spring and summer topdressing rate measured with a 2.25- and 0.5-kg Clegg Impact Soil Testers on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2011.

		2.25 kg hammer			0.5 kg hammer	
Season	Rate	1-Jul	15-Jul	26-Sep	15-Jul	26-Sep
	L m^{-2}	------------- Surface hardness (g_{max}) -------------				
Autumn†	0	77	72	52	88	74
Autumn	1.2	76	72	52	87	74
Autumn	2.4	74	71	52	87	74
Spring‡	0	76	72	52	87	75
Spring	1.2	76	73	52	89	74
Spring	2.4	74	70	52	86	73
Summer§	0	75	72	52	86	74
Summer	0.075	75	72	52	88	74
Summer	0.15	76	72	52	88	74
ANOVA		------------------------ $p > F$ ------------------------				
Autumn Rate (A)		**	0.09¶	NS#	NS	NS
Linear		**	*	NS	NS	NS
Quadratic		NS	NS	NS	NS	NS
Spring Rate (Sp)		*	***	NS	***	*
Linear		*	**	NS	*	**
Quadratic		0.06	*	NS	***	NS
Summer Rate (S)		NS	NS	NS	0.07	NS
Linear		NS	NS	NS	NS	NS
Quadratic		NS	NS	NS	NS	NS
A x Sp		NS	NS	NS	NS	NS
A x S		NS	NS	NS	NS	0.09
Sp x S		NS	0.08	NS	NS	NS
A x Sp x S		NS	NS	NS	NS	NS
CV, %		4.4	4.2	4.7	4.4	4.6

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 22 Oct. and 9 Nov. 2010.
‡ The total spring topdressing rate was applied as two split applications on 21 Apr. and 5 May 2011.
§ Summer topdressing rate was applied every two weeks from 7 June to 13 Sept. 2011.
¶ Probability level ≤ 0.1.
# NS, not significant.

Table 3.22. Surface hardness response to autumn, spring and summer topdressing rate measured with a 2.25- and 0.5-kg Clegg Impact Soil Testers on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2012.

		2.25 kg hammer		0.5 kg hammer	
Season	Rate	7-Jun	28-Jun	7-Jun	28-Jun
	L m^{-2}	------------- Surface hardness (g_{max}) -----------			
Autumn†	0	55	63	61	72
Autumn	1.2	54	63	61	73
Autumn	2.4	54	62	62	74
Spring‡	0	56	64	62	73
Spring	1.2	55	63	62	73
Spring	2.4	53	61	61	72
Summer§	0	55	63	62	73
Summer	0.075	55	63	62	73
Summer	0.15	54	62	61	72
ANOVA		---------------------- *p* > *F* ----------------------			
Autumn Rate (A)		NS¶	NS	NS	NS
Linear		NS	*	NS	*
Quadratic		NS	NS	NS	NS
Spring Rate (Sp)		***	***	NS	NS
Linear		***	***	NS	NS
Quadratic		NS	NS	NS	NS
Summer Rate (S)		NS	NS	NS	NS
Linear		NS	NS	NS	NS
Quadratic		NS	NS	NS	NS
A x Sp		NS	*	NS	NS
A x S		NS	NS	NS	NS
Sp x S		NS	NS	NS	NS
A x Sp x S		NS	NS	NS	NS
CV, %		5.7	4.3	6.3	5.5

* Significant at the 0.05 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 21 Oct. and 4 Nov. 2011.
‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 4 May 2012.
§ Summer topdressing rate was applied every two weeks from 8 June to 14 Sept. 2012.
¶ NS, not significant.

Table 3.23. Surface hardness response to autumn, spring and summer topdressing rate measured with a 2.25- and 0.5-kg Clegg Impact Soil Testers on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2013.

				0.5 kg hammer[¶]			
		2.25 kg hammer		30 cm		10 cm	
Season	Rate	22-May	25-Jun	4-Jun	25-Jun	4-Jun	25-Jun
	L m^{-2}	---------------- Surface hardness (g_{max}) ------------					
Autumn[†]	0	62	67	64	77	32	36
Autumn	1.2	60	65	63	76	31	37
Autumn	2.4	60	64	64	78	31	39
Spring[‡]	0	62	68	64	78	30	36
Spring	1.2	61	66	65	77	32	37
Spring	2.4	59	63	62	76	31	38
Summer[§]	0	61	66	64	77	31	37
Summer	0.075	61	65	63	77	32	37
Summer	0.15	60	65	64	77	31	38
ANOVA		------------------------- $p > F$ ------------------------					
Autumn Rate (A)		**	***	NS[#]	NS	NS	*
Linear		**	***	NS	NS	NS	**
Quadratic		NS	0.09[††]	NS	NS	NS	NS
Spring Rate (Sp)		***	***	*	NS	0.06	0.07
Linear		***	***	NS	0.07	NS	*
Quadratic		NS	NS	*	NS	*	NS
Summer Rate (S)		0.09	NS	NS	NS	NS	0.09
Linear		*	NS	NS	NS	NS	NS
Quadratic		NS	NS	NS	NS	0.06	NS
A x Sp		**	NS	NS	NS	NS	NS
A x S		NS	NS	**	NS	NS	NS
Sp x S		NS	NS	NS	NS	NS	NS
A x Sp x S		NS	NS	NS	NS	NS	NS
CV, %		10.8	5.6	6.0	7.3	10.4	10.2

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
[†] The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.
[‡] The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.
[§] Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.
[¶] The hammer of 0.5 kg hammer was released from the standard height of 30 cm above ground and a reduced height of 10 cm above ground.
[#] NS, not significant.
[††] Probability level ≤ 0.1.

Table 3.24. Surface hardness response to the interaction of autumn and spring topdressing rate measured with 2.25 kg Clegg Impact Soil Tester on an annual bluegrass turf mowed daily at 2.8 mm in North Brunswick, NJ during 2011 and 2012.

	28 June 2012					22 May 2013				
	Autumn Rate†					Autumn Rate				
Spring Rate‡	0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}			0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}		
L m^{-2}	Surface hardness (g_{max})			Linear	Quadratic	Surface hardness (g_{max})			Linear	Quadratic
0	66	62	63	*	NS§	65	61	61	***	*
1.2	63	64	63	NS	NS	62	60	60	NS	NS
2.4	61	62	60	NS	NS	59	59	60	NS	NS
Linear	*	NS	NS			***	*	NS		
Quadratic	NS	NS	*			NS	NS	NS		

* Significant at the 0.05 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 21 Oct. and 4 Nov. 2011, 18 Oct. and 6 Nov. 2012.
‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 4 May 2012, 20 Apr. and 3 May 2013.
§ NS, not significant.

Table 3.25. Surface hardness response to the interaction of autumn and summer topdressing rate measured with 0.5 kg Clegg Impact Soil Tester on 4 June 2013 on an annual bluegrass turf mowed daily at 2.8 mm in North Brunswick, NJ.

	Autumn Rate†				
Summer Rate‡	0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}		
L m^{-2}	Surface hardness (g_{max})			Linear	Quadratic
0	64	64	62	NS§	NS
0.075	62	64	63	NS	NS
0.15	66	61	67	NS	**
Linear	NS	NS	***		
Quadratic	NS	NS	NS		

** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.
‡ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.
§ NS, not significant.

Table 3.26. Penetration depth response to autumn, spring and summer topdressing rate on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2012 and 2013.

		Penetrometer¶			
		2012		2013	
Season	Rate	29-May	28-Jun	22-May	24-Jun
	L m^{-2}	---------------------mm#----------------------			
Autumn†	0	5.71	5.19	6.13	5.72
Autumn	1.2	5.65	5.15	5.97	5.61
Autumn	2.4	5.46	4.94	5.75	5.56
Spring‡	0	6.11	5.33	6.65	5.91
Spring	1.2	5.53	5.07	5.86	5.62
Spring	2.4	5.19	4.88	5.33	5.35
Summer§	0	5.70	5.19	5.96	5.75
Summer	0.075	5.60	5.07	5.89	5.64
Summer	0.15	5.52	5.02	6.00	5.49
ANOVA		-------------------- $p > F$ -------------------			
Autumn Rate (A)		**(6%)††	***(18%)	***(7%)	*(5%)
Linear		***	***	***	**
Quadratic		NS‡‡	*	NS	NS
Spring Rate (Sp)		***(77%)	***(49%)	***(87%)	***(64%)
Linear		***	***	***	***
Quadratic		NS	NS	*	NS
Summer Rate (S)		*(3%)	**(8%)	NS	***(14%)
Linear		*	***	NS	***
Quadratic		NS	NS	NS	NS
A x Sp		NS	NS	NS	NS
A x S		NS	NS	NS	NS
Sp x S		NS	NS	NS	NS
A x Sp x S		NS	NS	NS	NS
CV, %		5.4	4.2	5.2	4.3

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 21 Oct., 4 Nov. 2011 and 18 Oct., 6 Nov. 2012.
‡ The total spring topdressing rate was applied as two split applications on 20 Apr., 4 May 2012 and 20 Apr., 3 May 2013.
§ Summer topdressing rate was applied every two weeks from 8 June to 14 Sept. 2012 and 12 June to 13 Sept. 2013.
¶ An electronic indicator was modified and stabilized by adding a flat metal base to function as a penetrometer.
# Distance the indicator tip penetrated into the turf canopy.
†† Numbers in parentheses are the percentage of variation calculated as the sum of squares of each factor divide by model sum of squares.
‡‡ NS, not significant.

Table 3.27. Mat layer depth response to autumn, spring and summer topdressing rate measured at the conclusion of the study (27 Sept. 2013) on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ.

Season	Rate	27 Sept. 2013
	L m^{-2}	---- mm ----
Autumn†	0	19
Autumn	1.2	23
Autumn	2.4	25
Spring‡	0	19
Spring	1.2	22
Spring	2.4	26
Summer§	0	21
Summer	0.075	22
Summer	0.15	24
ANOVA		---- $p > F$ ----
Autumn Rate (A)		***(37%)¶
Linear		***
Quadratic		*
Spring Rate (Sp)		***(47%)
Linear		***
Quadratic		NS#
Summer Rate (S)		***(10%)
Linear		***
Quadratic		NS
A x Sp		*(1%)
A x S		NS
Sp x S		NS
A x Sp x S		*(1%)
CV, %		4.4

* Significant at the 0.05 probability level.

*** Significant at the 0.001 probability level.

† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.

‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.

§ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.

¶ Numbers in parentheses are the percentage of variation calculated as the sum of squares of each factor divide by model sum of squares.

\# NS, not significant.

Table 3.28. Response of mat layer depth to the interaction of autumn and spring topdressing rate on 27 Sept. 2013 on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ.

	Autumn Rate†,				
Spring Rate‡	0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}		
L m^{-2}		------- mm -------		Linear	Quadratic
0	15	20	22	***	**
1.2	19	22	26	***	NS§
2.4	23	26	29	***	NS
Linear	***	***	***		
Quadratic	NS	NS	NS		

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.

‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.

§ NS, not significant.

Table 3.29. Organic matter content response to autumn, spring and summer topdressing rate measured at the conclusion of the study (27 Sept. 2013) on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ.

Season	Rate	27 Sept. 2013
	L m^{-2}	---- g kg^{-1} ----
Autumn†	0	92
Autumn	1.2	70
Autumn	2.4	58
Spring‡	0	90
Spring	1.2	70
Spring	2.4	60
Summer§	0	80
Summer	0.075	73
Summer	0.15	68
ANOVA		---- $p > F$ ----
Autumn Rate (A)		***(42%)¶
Linear		***
Quadratic		***
Spring Rate (Sp)		***(33%)
Linear		***
Quadratic		***
Summer Rate (S)		***(5%)
Linear		***
Quadratic		NS#
A x Sp		***(8%)
A x S		***(2%)
Sp x S		***(2%)
A x Sp x S		***(2%)
CV, %		6.8

*** Significant at the 0.001 probability level.

† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.

‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.

§ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.

¶ Numbers in parentheses are the percentage of variation calculated as the sum of squares of each factor divide by model sum of squares.

NS, not significant.

Table 3.30. Organic matter content response to the interaction of autumn, spring and summer topdressing rate measured at the conclusion of the study (27 Sept. 2013) on an annual bluegrass turf mowed daily at 2.8 mm in North Brunswick, NJ.

	Autumn Rate† 0 L m^{-2}					Autumn Rate 1.2 L m^{-2}					Autumn Rate 2.4 L m^{-2}				
	Spring Rate‡					Spring Rate					Spring Rate				
Summer Rate§	0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}			0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}			0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}		
L m^{-2}		g kg^{-1}		Linear	Quad.		g kg^{-1}		Linear	Quad.		g kg^{-1}		Linear	Quad.
0	145	90	76	***	**	93	74	62	***	*	69	58	54	***	NS
0.075	113	88	72	***	NS¶	81	69	60	***	NS	68	57	51	**	NS
0.15	104	78	65	***	NS	75	65	56	**	NS	65	55	48	***	NS
Linear	***	**	*			***	**	*			NS	NS	*		
Quadratic	NS	NS	NS			NS	NS	NS			NS	NS	NS		

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.
‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.
§ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.
¶ NS, not significant.

APPENDIX

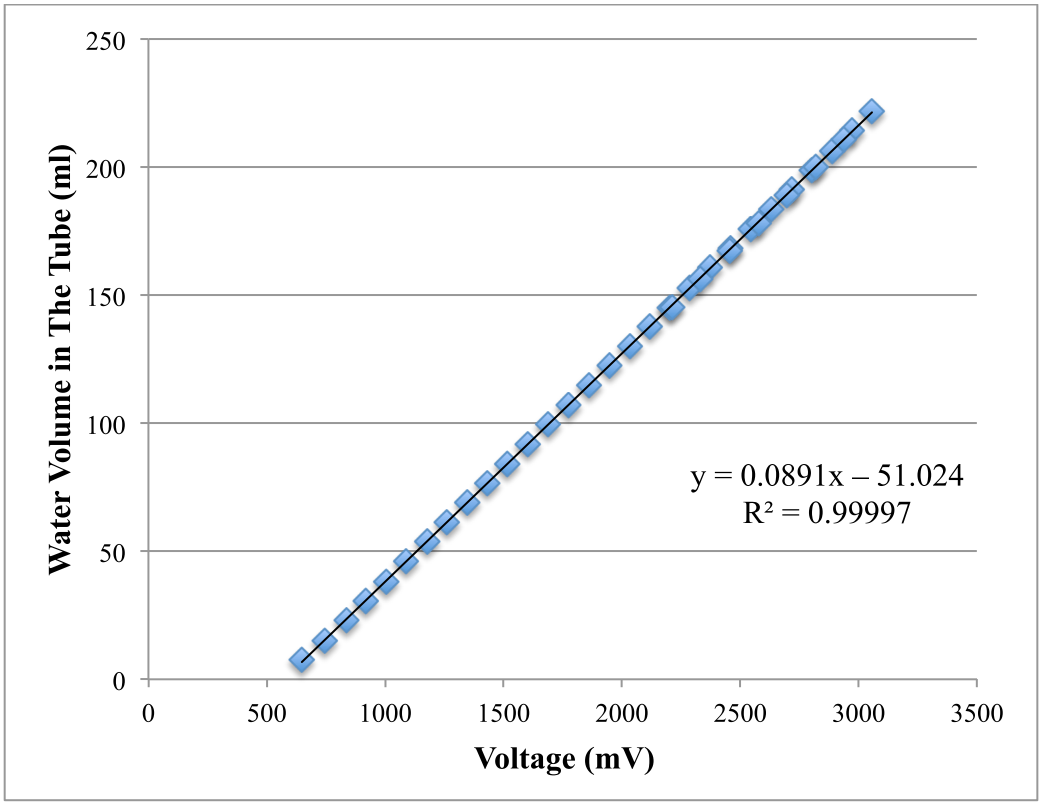


Figure A.1. Transducer calibration curve using transducer No. 4 as an example.

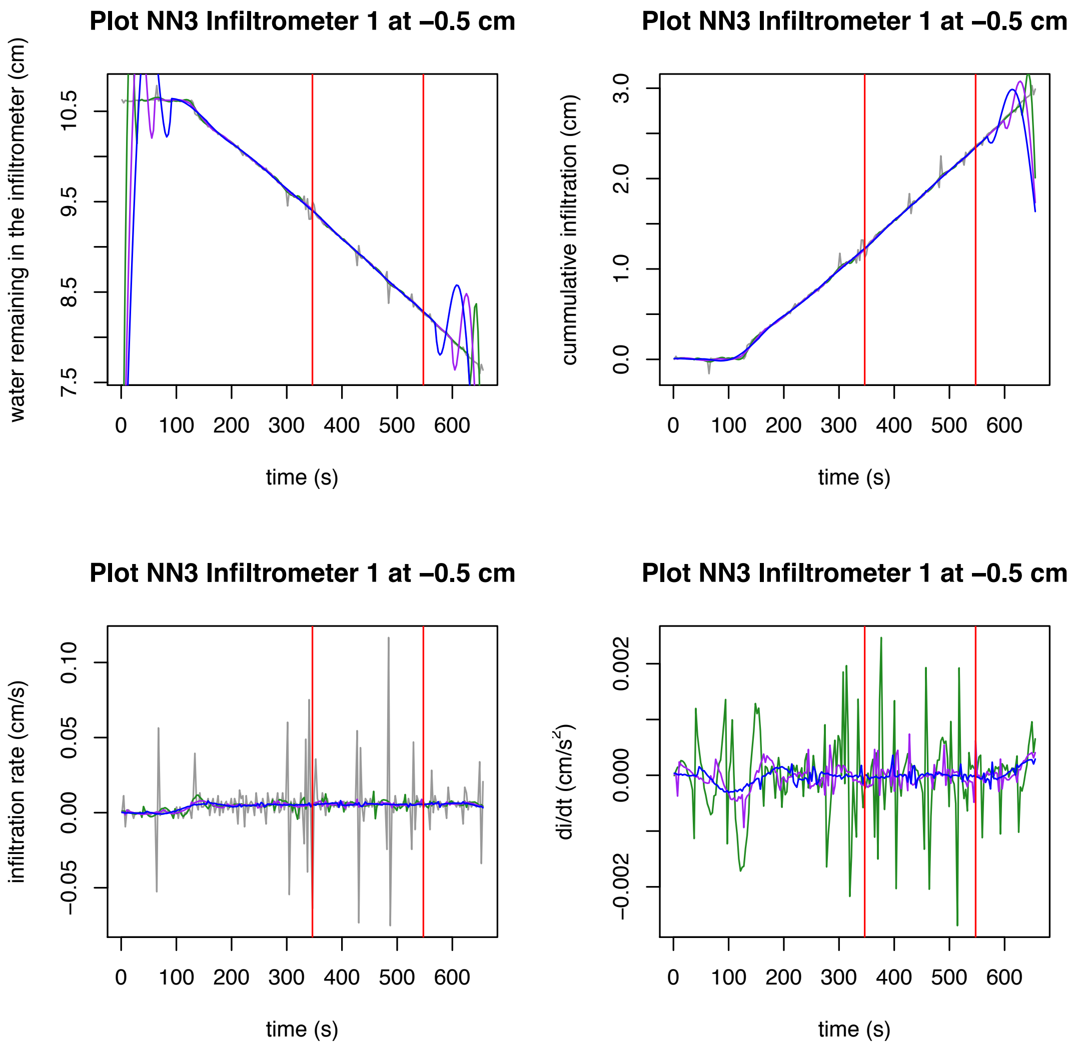


Figure A.2. Raw data smoothing and infiltration rate calculation in R-project using infiltrometer No.1 at –0.5 cm from the non-topdressed control in replication 3 as an example.

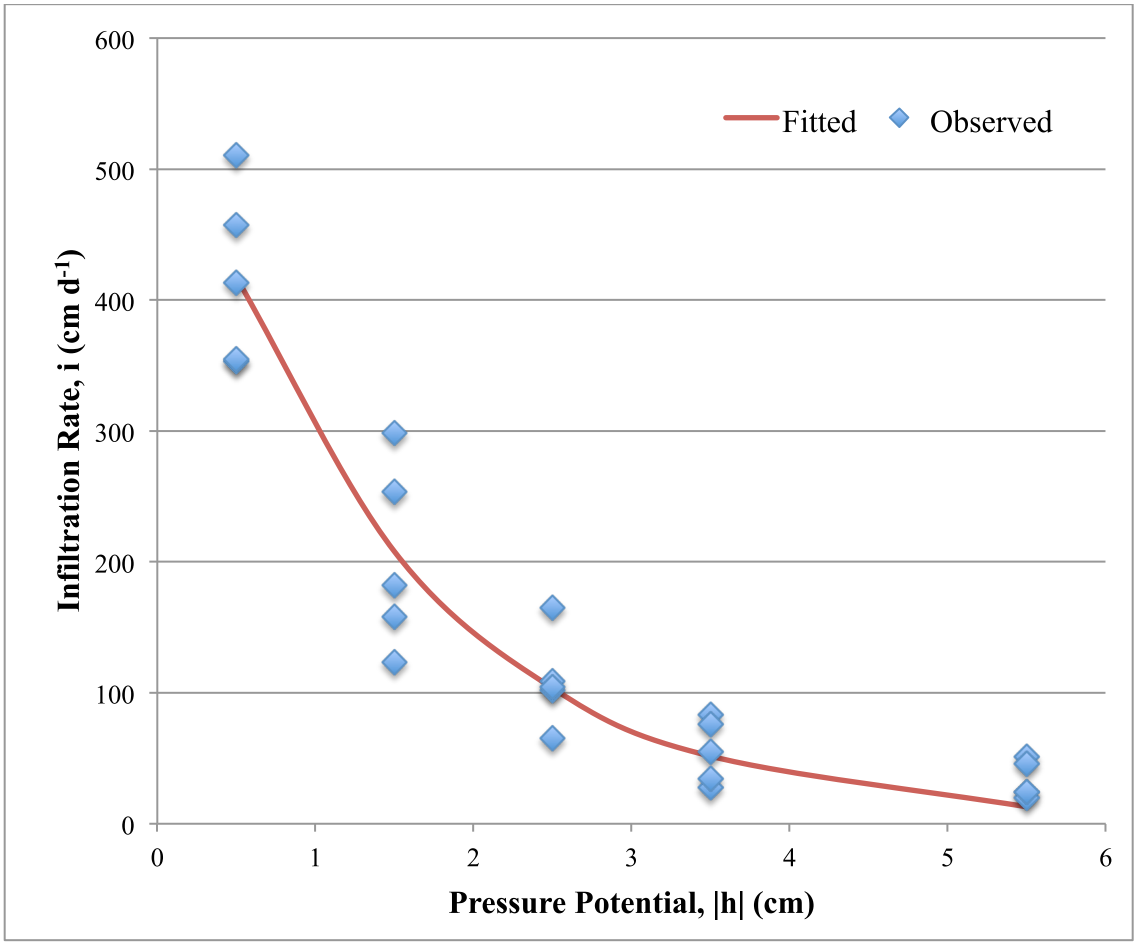


Figure A.3. Infiltration rate as a function of absolute value of pressure potential using the non-topdressed control in replication 1 as an example.

Figure A.4. Soil cores from an annual bluegrass putting green were separated from the distinct interface between thatch and sand layer indicated by the red arrow.

Table A.1. Turf quality response to the interaction of autumn, spring and summer topdressing rate on 19 Nov. 2013 on an annual bluegrass turf mowed daily at 2.8 mm in North Brunswick, NJ.

	Spring Rate† 0 L m^{-2}					Spring Rate 1.2 L m^{-2}					Spring Rate 2.4 L m^{-2}				
	Autumn Rate‡					Autumn Rate					Autumn Rate				
Summer Rate§	0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}			0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}			0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}		
L m^{-2}	1–9 scale¶			Linear	Quad.	1–9 scale			Linear	Quad.	1–9 scale			Linear	Quad.
0	6.3	6.5	6.8	NS#	NS	8.0	7.8	6.0	**	NS	7.8	7.3	7.0	NS	NS
0.075	7.8	7.0	6.8	NS	NS	7.3	7.0	7.3	NS	NS	7.8	7.5	7.3	NS	NS
0.15	7.8	7.5	6.5	NS	NS	7.8	7.0	7.3	NS	NS	8.0	7.8	8.0	NS	NS
Linear	NS	*	NS			NS	NS	**			NS	NS	NS		
Quadratic	NS	NS	NS			NS	NS	NS			NS	NS	NS		

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

† The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.

‡ The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.

§ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.

¶ 9 = best turf quality, 5 = acceptable, 1 = dead or necrotic turf.

NS, not significant.

Table A.2. Turf color response to the interaction of autumn and summer topdressing rate on 21 June 2011 on an annual bluegrass turf mowed daily at 2.8 mm in North Brunswick, NJ.

	Autumn Rate†				
Summer Rate‡	0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}		
L m^{-2}		1–9 scale§		Linear	Quadratic
0	7.4	7.6	7.8	NS¶	NS
0.075	7.1	7.6	7.5	*	NS
0.15	7.7	7.3	8.1	NS	**
Linear	NS	NS	NS		
Quadratic	**	NS	*		

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† The total autumn topdressing rate was applied as two split applications on 22 Oct. and 9 Nov. 2010.
‡ Summer topdressing rate was applied every two weeks from 7 June to 13 Sept. 2011.
§ 9 = darkest green, 5 = acceptable, 1 = dead or necrotic turf.
¶ NS, not significant.

Table A.3. Turf color response to the interaction of autumn, spring and summer topdressing rate on 13 July 2012 on an annual bluegrass turf mowed daily at 2.8 mm in North Brunswick, NJ.

	Summer Rate† 0 L m^{-2}					Summer Rate 0.075 L m^{-2}					Summer Rate 0.15 L m^{-2}				
	Spring Rate‡					Spring Rate					Spring Rate				
Autumn Rate§	0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}			0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}			0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}		
L m^{-2}	1–9 scale¶			Linear	Quad.	1–9 scale			Linear	Quad.	1–9 scale			Linear	Quad.
0	6.3	7.4	8.0	**	NS#	7.5	7.4	7.9	NS	NS	7.6	7.3	7.9	NS	NS
1.2	7.8	6.8	7.9	NS	*	7.4	7.6	8.3	NS	NS	7.6	8.1	8.3	NS	NS
2.4	7.1	7.9	8.6	*	NS	8.0	8.4	8.1	NS	NS	7.5	7.9	8.5	*	NS
Linear	NS	NS	*			NS	NS	NS			NS	NS	NS		
Quadratic	NS	NS	NS			NS	NS	NS			NS	NS	NS		

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

† Summer topdressing rate was applied every two weeks from 8 June to 14 Sept. 2012.

‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 4 May 2012.

§ The total autumn topdressing rate was applied as two split applications on 21 Oct. and 4 Nov. 2011.

¶ 9 = darkest green, 5 = acceptable, 1 = dead or necrotic turf.

NS, not significant.

Table A.4. Turf color response to the interaction of autumn, spring and summer topdressing rate on 20 Sept. 2013 on an annual bluegrass turf mowed daily at 2.8 mm in North Brunswick, NJ.

	Spring Rate† 0 L m^{-2}					Spring Rate 1.2 L m^{-2}					Spring Rate 2.4 L m^{-2}				
	Summer Rate‡					Summer Rate					Summer Rate				
Autumn Rate§	0 L m^{-2}	0.075 L m^{-2}	0.15 L m^{-2}			0 L m^{-2}	0.075 L m^{-2}	0.15 L m^{-2}			0 L m^{-2}	0.075 L m^{-2}	0.15 L m^{-2}		
L m^{-2}	1–9 scale¶			Linear	Quad.	1–9 scale			Linear	Quad.	1–9 scale			Linear	Quad.
0	7.0	7.5	7.3	NS#	NS	7.5	7.5	7.8	NS	NS	7.5	7.3	6.8	NS	NS
1.2	7.0	6.8	8.3	*	NS	7.8	7.3	7.0	NS	NS	6.8	7.0	7.5	NS	NS
2.4	7.0	6.8	6.8	NS	NS	6.5	6.8	7.0	NS	NS	7.0	6.5	7.8	*	**
Linear	NS	NS	NS			NS	NS	NS			NS	NS	NS		
Quadratic	NS	NS	*			NS	NS	NS			NS	NS	NS		

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

† The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.

‡ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.

§ The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.

¶ 9 = darkest green, 5 = acceptable, 1 = dead or necrotic turf.

NS, not significant.

Table A.5. Turf color response to autumn, spring and summer topdressing rate measured with chlorophyll meter on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ during 2013.

Season	Rate	15-Jul	19-Sep¶
	L m^{-2}	chlorophyll index value (0–999)	
Autumn†	0	198.2	200.6
Autumn	1.2	192.1	202.5
Autumn	2.4	188.7	197.2
Spring‡	0	185.6	201.8
Spring	1.2	192.5	199.2
Spring	2.4	201.0	199.3
Summer§	0	193.9	201.0
Summer	0.075	191.5	200.3
Summer	0.15	193.7	199.0
ANOVA		------------ $p > F$ -------------	
Autumn Rate (A)		**	0.05††
Linear		***	NS
Quadratic		NS#	0.06
Spring Rate (Sp)		***	NS
Linear		***	NS
Quadratic		NS	NS
Summer Rate (S)		NS	NS
Linear		NS	NS
Quadratic		NS	NS
A x Sp		NS	NS
A x S		NS	NS
Sp x S		NS	NS
A x Sp x S		NS	NS
CV, %		5.9	4.6

** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.
‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.
§ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.
¶ Data were taken after curative anthracnose chemical control.
# NS, not significant.
†† Probability level ≤ 0.1.

Table A.6. Sand incorporation response to autumn, spring and topdressing rate after the first spring topdressing event on 20 Apr. 2013 on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ.

Season	Rate	1 DAT¶	2 DAT	4 DAT	5 DAT	7 DAT
	$L\ m^{-2}$	----------------------------	----------------------------	1–9 scale#	----------------------------	----------------------------
Autumn†	0	6.1	6.3	6.9	7.8	8.8
Autumn	1.2	6.2	6.6	7.2	8.0	8.9
Autumn	2.4	6.3	6.6	7.1	7.9	8.9
Spring‡	0	9.0	9.0	9.0	9.0	9.0
Spring	1.2	6.2	6.6	7.6	8.5	9.0
Spring	2.4	3.5	3.8	4.6	6.2	8.5
Summer§	0	6.2	6.5	7.0	7.8	8.8
Summer	0.075	6.3	6.5	7.2	7.9	8.8
Summer	0.15	6.1	6.4	7.1	7.9	8.8
ANOVA		----------------------------	----------------------------	$p > F$	----------------------------	----------------------------
Autumn Rate (A)		NS††	0.10‡‡	NS	NS	NS
Linear		NS	0.07	NS	NS	NS
Quadratic		NS	NS	NS	NS	NS
Spring Rate (Sp)		***	***	***	***	***
Linear		***	***	***	***	***
Quadratic		NS	NS	***	***	***
Summer Rate (S)		NS	NS	NS	NS	NS
Linear		NS	NS	NS	NS	NS
Quadratic		NS	NS	NS	NS	NS
A x Sp		NS	NS	NS	NS	NS
A x S		NS	NS	NS	NS	NS
Sp x S		NS	NS	NS	NS	NS
A x Sp x S		NS	NS	NS	NS	NS
CV, %		9.1	9.3	8.8	8.8	4.0

*** Significant at the 0.001 probability level.

† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.

‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.

§ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.

¶ Days after topdressing.

9 represents no sand visible at turf surface, and 5 represents the minimally acceptable rating.

†† NS, not significant.

‡‡ Probability level ≤ 0.1.

Table A.7. Sand incorporation response to autumn, spring and topdressing rate after the second spring topdressing event on 3 May 2013 on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ.

Season	Rate	0 DAT¶	1 DAT	2 DAT	3 DAT	4 DAT	5 DAT	6 DAT
	$L\ m^{-2}$	---------- 1–9 scale# ----------						
Autumn†	0	6.0	6.3	6.5	7.3	8.3	8.8	8.9
Autumn	1.2	6.0	6.4	6.6	7.2	8.3	8.8	8.9
Autumn	2.4	5.9	6.3	6.6	7.2	8.2	8.7	8.8
Spring‡	0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
Spring	1.2	5.6	6.3	6.7	7.9	9.0	9.0	9.0
Spring	2.4	3.3	3.7	4.0	4.7	6.8	8.3	8.6
Summer§	0	5.9	6.3	6.5	7.2	8.2	8.7	8.9
Summer	0.075	6.0	6.4	6.6	7.2	8.3	8.8	8.9
Summer	0.15	5.9	6.4	6.6	7.2	8.3	8.8	8.9
ANOVA		---------- $p > F$ ----------						
Autumn Rate (A)		NS††	NS	NS	NS	NS	NS	NS
Linear		NS	NS	NS	NS	NS	NS	NS
Quadratic		NS	NS	NS	NS	NS	NS	NS
Spring Rate (Sp)		***	***	***	***	***	***	***
Linear		***	***	***	***	***	***	***
Quadratic		***	NS	0.07‡‡	***	***	***	**
Summer Rate (S)		NS	NS	NS	NS	NS	NS	NS
Linear		NS	NS	NS	NS	NS	NS	NS
Quadratic		NS	NS	NS	NS	NS	NS	NS
A x Sp		NS	NS	NS	NS	NS	NS	NS
A x S		NS	NS	NS	NS	NS	NS	NS
Sp x S		NS	NS	NS	NS	NS	NS	NS
A x Sp x S		NS	NS	NS	NS	NS	NS	NS
CV, %		6.6	7.5	8.4	8.2	8.4	5.0	3.4

** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.
‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.
§ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.
¶ Days after topdressing.
# 9 represents no sand visible at turf surface, and 5 represents the minimally acceptable rating.
†† NS, not significant.
‡‡ Probability level ≤ 0.1.

Table A.8. Sand incorporation response to autumn, spring and topdressing rate after summer topdressing events on 12 June and 21 June 2013 on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ.

		12-Jun	21-Jun			
Season	Rate	0 DAT¶	0 DAT	1 DAT	3 DAT	4 DAT
	L m^{-2}	------------------------ 1–9 scale# ------------------------				
Autumn†	0	8.2	8.0	8.3	8.6	8.9
Autumn	1.2	8.1	8.1	8.3	8.8	9.0
Autumn	2.4	8.3	8.1	8.3	8.8	9.0
Spring‡	0	8.1	7.9	8.1	8.7	9.0
Spring	1.2	8.3	8.0	8.3	8.8	8.9
Spring	2.4	8.2	8.2	8.4	8.8	9.0
Summer§	0	9.0	9.0	9.0	9.0	9.0
Summer	0.075	8.5	8.3	8.7	9.0	9.0
Summer	0.15	7.1	6.9	7.1	8.3	8.9
ANOVA		------------------------ $p > F$ ------------------------				
Autumn Rate (A)		NS††	NS	NS	**	NS
Linear		NS	NS	NS	**	NS
Quadratic		NS	NS	NS	NS	NS
Spring Rate (Sp)		NS	***	***	0.09‡‡	NS
Linear		NS	***	***	*	NS
Quadratic		NS	NS	NS	NS	0.07
Summer Rate (S)		***	***	***	***	**
Linear		***	***	***	***	**
Quadratic		***	***	***	***	NS
A x Sp		NS	NS	0.05	NS	NS
A x S		NS	*	*	***	NS
Sp x S		NS	*	*	*	NS
A x Sp x S		NS	NS	NS	NS	NS
CV, %		6.2	4.3	3.6	3.3	1.7

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.
‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.
§ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.
¶ Days after topdressing.
# 9 represents no sand visible at turf surface, and 5 represents the minimally acceptable rating.
†† NS, not significant.
‡‡ Probability level ≤ 0.1.

Table A.9. Sand incorporation response to the interaction of autumn and summer topdressing rate after a summer application on 21 June 2013 on an annual bluegrass turf mowed daily at 2.8 mm in North Brunswick, NJ.

	0 DAT§					1 DAT					3 DAT				
	Autumn Rate†					Autumn Rate					Autumn Rate				
Summer Rate‡	0 $L\ m^{-2}$	1.2 $L\ m^{-2}$	2.4 $L\ m^{-2}$			0 $L\ m^{-2}$	1.2 $L\ m^{-2}$	2.4 $L\ m^{-2}$			0 $L\ m^{-2}$	1.2 $L\ m^{-2}$	2.4 $L\ m^{-2}$		
$L\ m^{-2}$	1–9 scale¶			Linear	Quad.	1–9 scale			Linear	Quad.	1–9 scale			Linear	Quad.
0	9.0	9.0	9.0	NS#	NS	9.0	9.0	9.0	NS	NS	9.0	9.0	9.0	NS	NS
0.075	8.4	8.3	8.1	NS	NS	8.8	8.8	8.5	NS	NS	9.0	9.0	9.0	NS	NS
0.15	6.7	6.9	7.1	*	NS	7.0	7.1	7.3	*	NS	7.8	8.4	8.5	**	NS
Linear	***	***	***			***	***	***			***	***	***		
Quadratic	**	**	NS			***	***	***			***	*	*		

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.
‡ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.
§ Days after topdressing.
¶ 9 represents no sand visible at turf surface, and 5 represents the minimally acceptable rating.
# NS, not significant.

Table A.10. Sand incorporation response to the interaction of spring and summer topdressing rate after a summer application on 21 June 2013 on an annual bluegrass turf mowed daily at 2.8 mm in North Brunswick, NJ.

	0 DAT§					1 DAT					3 DAT				
	Spring Rate†					Spring Rate					Spring Rate				
Summer Rate‡	0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}			0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}			0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}		
L m^{-2}	1–9 scale¶			Linear	Quad.	1–9 scale			Linear	Quad.	1–9 scale			Linear	Quad.
0	9.0	9.0	9.0	NS#	NS	9.0	9.0	9.0	NS	NS	9.0	9.0	9.0	NS	NS
0.075	8.1	8.2	8.4	NS	NS	8.5	8.7	8.8	*	NS	9.0	9.0	9.0	NS	NS
0.15	6.5	6.9	7.3	***	NS	6.8	7.1	7.4	***	NS	8.0	8.3	8.5	*	NS
Linear	***	***	***			***	***	***			***	***	***		
Quadratic	*	*	*			***	***	***			***	***	*		

* Significant at the 0.05 probability level.
*** Significant at the 0.001 probability level.
† The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.
‡ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.
§ Days after topdressing.
¶ 9 represents no sand visible at turf surface, and 5 represents the minimally acceptable rating.
# NS, not significant.

Table A.11. Sand incorporation response to autumn, spring and topdressing rate after the last summer topdressing events on 13 Sept. 2013 on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ.

Season	Rate	0 DAT¶	1 DAT	2 DAT	3 DAT	4 DAT	5 DAT
	$L\ m^{-2}$	------------------------------ 1–9 scale# ------------------------------					
Autumn†	0	7.7	8.1	8.1	8.5	8.9	9.0
Autumn	1.2	7.6	7.9	8.0	8.4	8.9	9.0
Autumn	2.4	7.4	7.9	8.1	8.4	8.9	9.0
Spring‡	0	7.7	8.1	8.2	8.5	9.0	9.0
Spring	1.2	7.6	7.9	8.0	8.4	8.9	9.0
Spring	2.4	7.4	7.8	7.9	8.4	8.8	8.9
Summer§	0	9.0	9.0	9.0	9.0	9.0	9.0
Summer	0.075	8.3	8.7	8.9	8.9	9.0	9.0
Summer	0.15	5.3	6.1	6.3	7.4	8.7	8.9
ANOVA		-------------------------------- $p > F$ --------------------------------					
Autumn Rate (A)		*	NS††	NS	NS	NS	NS
Linear		*	NS	NS	NS	NS	NS
Quadratic		NS	NS	NS	NS	NS	NS
Spring Rate (Sp)		*	*	*	NS	NS	NS
Linear		*	**	*	0.06‡‡	0.10	0.08
Quadratic		NS	NS	NS	NS	NS	NS
Summer Rate (S)		***	***	***	***	***	NS
Linear		***	***	***	***	***	NS
Quadratic		***	***	***	***	*	NS
A x Sp		NS	NS	NS	NS	NS	NS
A x S		NS	NS	NS	NS	NS	NS
Sp x S		NS	NS	0.05	NS	NS	0.09
A x Sp x S		NS	NS	NS	NS	NS	NS
CV, %		7.4	6.1	5.9	4.4	3.9	1.5

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.
‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.
§ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.
¶ Days after topdressing.
# 9 represents no sand visible at turf surface, and 5 represents the minimally acceptable rating.
†† NS, not significant.
‡‡ Probability level ≤ 0.1.

Table A.12. Soil volumetric water content (measured at the 0–38 mm depth with time domain reflectometry) response to the interaction of autumn, spring and summer topdressing rate on 22 May 2013 on an annual bluegrass turf mowed daily at 2.8 mm in North Brunswick, NJ.

	Summer Rate† 0 L m^{-2}					Summer Rate 0.075 L m^{-2}					Summer Rate 0.15 L m^{-2}				
	Spring Rate‡					Spring Rate					Spring Rate				
Autumn Rate§	0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}			0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}			0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}		
L m^{-2}		m^3 m^{-3}		Linear	Quad.		m^3 m^{-3}		Linear	Quad.		m^3 m^{-3}		Linear	Quad.
0	0.359	0.357	0.336	NS¶	NS	0.357	0.339	0.336	*	NS	0.336	0.335	0.346	NS	NS
1.2	0.343	0.314	0.317	NS	NS	0.356	0.323	0.290	***	NS	0.328	0.326	0.319	NS	NS
2.4	0.325	0.320	0.298	*	NS	0.324	0.318	0.296	NS	NS	0.330	0.295	0.294	*	NS
Linear	*	**	**			NS	NS	*			NS	**	***		
Quadratic	NS	*	NS			NS	NS	NS			NS	NS	NS		

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.
‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.
§ The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.
¶ NS, not significant.

Table A.13. Soil volumetric water content (measured at the 0–38 mm depth with time domain reflectometry) response to the interaction of autumn, spring and summer topdressing rate on 4 June 2013 on an annual bluegrass turf mowed daily at 2.8 mm in North Brunswick, NJ.

	Summer Rate† 0 L m^{-2}					Summer Rate 0.075 L m^{-2}					Summer Rate 0.15 L m^{-2}				
	Spring Rate‡					Spring Rate					Spring Rate				
Autumn Rate§	0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}			0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}			0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}		
L m^{-2}		m^3 m^{-3}		Linear	Quad.		m^3 m^{-3}		Linear	Quad.		m^3 m^{-3}		Linear	Quad.
0	0.455	0.445	0.436	NS¶	NS	0.457	0.433	0.433	*	NS	0.455	0.438	0.432	*	NS
1.2	0.446	0.408	0.414	***	**	0.428	0.441	0.409	NS	NS	0.436	0.423	0.422	NS	NS
2.4	0.411	0.437	0.411	NS	*	0.420	0.424	0.404	NS	NS	0.430	0.409	0.409	NS	NS
Linear	**	NS	NS			*	NS	**			NS	*	NS		
Quadratic	NS	*	NS			NS	NS	NS			NS	NS	NS		

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.
‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.
§ The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.
¶ NS, not significant.

Table A.14. Mat layer depth response to the interaction of autumn, spring and summer topdressing rate measured at the conclusion of the study (27 Sept. 2013) on an annual bluegrass turf mowed daily at 2.8 mm in North Brunswick, NJ.

	Summer Rate† 0 L m^{-2}					Summer Rate 0.075 L m^{-2}					Summer Rate 0.15 L m^{-2}				
	Spring Rate‡					Spring Rate					Spring Rate				
Autumn Rate§	0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}			0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}			0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}		
L m^{-2}		mm		Linear	Quad.		mm		Linear	Quad.		mm		Linear	Quad.
0	12	18	22	***	NS¶	16	19	22	***	NS	17	21	25	***	NS
1.2	19	20	24	***	**	20	22	26	***	NS	21	25	28	***	NS
2.4	20	24	28	***	NS	22	25	28	***	NS	23	27	30	***	NS
Linear	***	***	***			***	***	***			***	***	**		
Quadratic	**	*	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.
† Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.
‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.
§ The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.
¶ NS, not significant

Table A.15. Response of organic matter content to the interaction of autumn and spring topdressing rate on 27 Sept. 2013 on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ.

	Autumn Rate†				
Spring Rate‡	0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}		
L m^{-2}	------- g kg^{-1} -------			Linear	Quadratic
0	121	83	67	***	***
1.2	86	69	57	***	NS§
2.4	71	59	51	***	NS
Linear	***	***	***		
Quadratic	***	NS	NS		

*** Significant at the 0.001 probability level.

† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.

‡ The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.

§ NS, not significant.

Table A.16. Response of organic matter content to the interaction of autumn and summer topdressing rate on 27 Sept. 2013 on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ.

	Autumn Rate†				
Summer Rate‡	0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}		
L m^{-2}	------- g kg^{-1} -------			Linear	Quadratic
0	104	76	60	***	*
0.075	91	70	58	***	**
0.15	82	65	56	***	*
Linear	***	***	*		
Quadratic	NS§	NS	NS		

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† The total autumn topdressing rate was applied as two split applications on 18 Oct. and 6 Nov. 2012.
‡ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.
§ NS, not significant.

Table A.17. Response of organic matter content to the interaction of spring and summer topdressing rate on 27 Sept. 2013 on an annual bluegrass turf mowed at 2.8 mm in North Brunswick, NJ.

	Spring Rate†				
Summer Rate‡	0 L m^{-2}	1.2 L m^{-2}	2.4 L m^{-2}		
L m^{-2}		------- g kg^{-1} -------		Linear	Quadratic
0	102	74	64	***	***
0.075	87	71	61	***	NS§
0.15	82	66	56	***	NS
Linear	***	***	***		
Quadratic	NS	NS	NS		

*** Significant at the 0.001 probability level.

† The total spring topdressing rate was applied as two split applications on 20 Apr. and 3 May 2013.

‡ Summer topdressing rate was applied every two weeks from 12 June to 13 Sept. 2013.

§ NS, not significant.