EFFECT OF CULTIVATION PRACTICES ON SOIL PHYSICAL PROPERTIES AND TEMPORAL SHADE ON PHOTOSYNTHESIS OF CREEPING BENTGRASS USED FOR GOLF GREENS

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Abstract: Organic matter accumulation and soil compaction is a major concern for turfgrass managers, causing an increase in the softness of the surface, decreased water infiltration rate, and increased surface water retention. The ideal cultivation practice is one, which improves soil physical properties of the green while minimizing injury to the playing surface. Shade is another common challenge for putting green management. Shaded areas may be weak and more easily damaged from mechanical or foot injury. In order to maintain healthy turf, understanding how above ground and below ground environmental factors influence the plant is important. Therefore, the objective of this research was to evaluate the effect of cultivation practices and temporal shade on creeping bentgrass used for golf greens. The longevity and duration of two novel cultivation practices [air injection cultivation (AIC) or sand injection cultivation (SIC)] alone or in combination with conventional hollow tine cultivation (HTC) was evaluated in field studies at the Oklahoma State University Turfgrass Research Center and at six golf courses in central Oklahoma. Seasonal variability of several soil physical properties and turf quality was recorded regardless of cultivation treatment. Summer measurements had a higher infiltration rate, softer playing surface, and reduced ball roll distance compared to fall and spring measurements. Compared with the untreated control, HTC reduced surface firmness by 5% at 28 days after cultivation event (DACE), increased infiltration by 88% at 28 DACE, reduced ball roll distance by 6% up to 14 DACE, and reduced normalize difference vegetation index (NDVI) by 10% up to 14 DACE. The AIC and SIC had no consistent effect on any soil physical properties. Timing of shade did not affect the net carbon assimilation rate. Shoot dry weight was lower in morning shade compared to the non-shaded control and afternoon shade treatments. Results suggest novel cultivation practices were not as effective as conventional hollow tine cultivation in managing soil physical properties. Use of novel cultivation practices should be used in combination with, as opposed to in place of, conventional hollow tine cultivation. For shade management, there is evidence reducing the amount of morning shade may be more critical than doing so for afternoon shade. These studies contribute to the current knowledge regarding creeping bentgrass management in the transition zone.

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CHAPTER I

LITERATURE REVIEW

Management of creeping bentgrass [*Agrostis stolonifera* L.] in the transition zone can be a major challenge for golf course superintendents. Soil compaction, lack of soil aeration, and excessive organic matter are major problems associated with creeping bentgrass management. Shade is another common factor that can be detrimental to turfgrasses growth and development. This chapter reviews the pertinent literature regarding putting green cultivation strategies and shade management of creeping bentgrass. Subsequent chapters describe one case study and three experiments investigating aspects of creeping bentgrass putting green management in Oklahoma.

Root Zone Soil Physical Properties

The ideal soil for turfgrass root growth and development must be able to retain water and nutrients, allow air-exchange, drain quickly, and resist soil compaction. Soil structure, soil texture, and organic matter content determine water holding capacity, permeability, and soil workability that promote plant growth and development (Bigelow and Soldat, 2013). Sand is the largest soil particle and is associated with high macroporosity and correspondingly high air-filled porosity, permeability, and drainage

Clay is the smallest soil particle and is associated with increased microporosity and correspondingly high capillary-filled porosity and poor permeability and drainage. The United States Golf Association (USGA) recommendation for ideal putting green root zone soil has a total porosity of 35-55% with 15-30% air-filled porosity and 15-25% capillary filled porosity (USGA, 2004).

Golf course putting greens established in sand-based root zone mixtures have many advantages such as traffic tolerance, resistance to compaction, and higher permeability and higher infiltration rates (Gibbs et al., 2001). However, the performance of sand-based root zones can be diminished over time. Soil physical properties that change with time and use include reduced soil porosity, reduced gas exchange rate, reduced infiltration rate, increased root zone bulk density and water retention, and altered pore size distribution (Schmid, 2014). High bulk density, for a given soil texture, is an indicator of low soil porosity and soil compaction which restricts root growth and makes the playing surface firm (Turgeon, 1999). The USGA recommendation for the ideal bulk density of sand-based putting greens ranges between 1.2 g cm^{-3} to 1.6 g cm^{-3}, with an optimum level of 1.4 g cm^{-3} (McCarty, 2001). Plant root growth is restricted if bulk density exceeds 1.55 g cm^{-3} on clay loam, 1.65 g cm^{-3} on silt loam, and 1.80 g cm^{-3} on a fine sandy loam (Bowen, 1981). Cultivation practices that improve soil structure typically reduce the bulk density. In most cases, these improvements are only temporary and repeated cultivation is needed to sustain plant growth (Gibbs et al., 2001).

Surface smoothness and firmness affects the playability of putting green. A soft surface holds a ball near the point of impact whereas firm surface result in unpredictable movement of ball. (Bigelow et al., 2007; Zontek, 2008). Surface firmness is affected by many factors including soil moisture, thatch and organic matter, and bulk density. A strong negative correlation between soil moisture and surface firmness has been found (Linde et al., 2011; Young et al., 2017). In contrast, a positive correlation has been reported between soil bulk density and surface firmness (Dest et al., 2005; McNitt and Landshoot, 2003).

Firm and fast playing conditions can be achieved through increased mowing frequency and rolling (McCarty, 2001). However, daily rolling has been reported to cause greater ball mark injury compared to not rolling (Young et al., 2017). Golf ball mark recovery time was also longer for greens that received high rolling frequency and foot traffic (Young et al., 2017). It was speculated that increased wear from rolling and foot traffic increased recovery time for golf ball marks injury (Young et al., 2017). Murphy et al. (2003) observed a similar result of delayed ball mark recovery when wear and compaction were combined compared to compaction alone.

Previous studies reported hollow tine cultivation (HTC) softened the surface compared to verticutting, air injection cultivation (AIC), and sand injection cultivation (SIC) (Bunnell et al. 2001; Dickson et al., 2017; McCarty et al., 2007; Rowland et al, 2009). Increasing the number of core aerification events from one to three on a 10-yr-old ‘TifEagle’ bermudagrass reported reducing bulk density and surface hardiness (Atkinson et al., 2012). Furthermore, reducing the frequency of cultivation without reducing the surface area impacted improved turf quality but did not improve soil physical properties (Atkinson et al., 2012). Rowland et al. (2009) evaluated cultural practice impact on 8-yr-old ultradwarf bermudagrass and observed that verticutting provided a firmer surface than the core aeration.

The plant available water within a soil depends on soil structure, porosity, and organic matter content. The USGA minimum recommendation for saturated hydraulic conductivity is 15.2 cm h^{-1} (USGA, 2004). The slow infiltration rates of most putting greens over time is due to buildup of surface organic matter (OM) and sealing by fine particles including those used for topdressing (Carrow, 1998; O 'Brien and Hartwiger, 2003). Approximately 5% OM is sufficient to significantly clog micropores of most of the sand (Carrow, 1998).

Organic Matter and Thatch layer

Dead and decaying plant tissues add organic residue on the soil surface. Organic matter greater than 3-4% is considered to have negative effects on putting green performance (Carrow, 2003). Organic matter causes the plugging of soil macropores, which decreases water infiltration rates and increases surface water retention (Hurto et al., 1980). Excess surface water increases the moisture content in the root zone, which decreases gas exchange between the soil and atmosphere (Carrow, 1998 and 2003; Hurto et al., 1980; Murphy et al., 1993).

The surface layer of OM can be separated into either thatch or mat. Thatch is the layer of dead and partially decomposed plant tissues (Decker, 1974) whereas mat is the layer in which thatch becomes mixed with topdressing sand (Williams and McCarty, 2005). A thin thatch-mat layer is considered to be beneficial on putting green as it provides resilience to the turf, receives golf shots, increase tolerance to heavy equipment, and acts as a buffer for the moderation of soil temperature (Dernoeden et al., 2012; Moeller and Lowe, 2016). However, a thick and dense thatch-mat layer reduces the environmental tolerance of turfgrass making it liable to heat stress in the summer, promote disease, harbor insect pests, and make the surface more susceptible to scalping. Therefore, the management of greens to reduce thatch-mat layer is essential for maintaining smooth, healthier, and firm greens.

Soil compaction and organic matter accumulation have detrimental effect on playability and plant health. Though it is difficult to physically remove organic matter, it can be managed by coring, verticutting, and proper use of fertilizers and water (Dernoeden, 2012; McCarty et al., 2007). Coring, verticutting, and sand topdressing incorporate sand in the OM layer resulting in dilution of OM, which creates better growing conditions for roots and soil microorganisms (Carrow, 1998; Fu et al., 2009). Coring involves the physical penetration of turf surface and removing of compacted soil and organic matter along with cores. The holes created as a result of these practices provide multiple channels for gas exchange and water infiltration.

The main objective of cultivation practices is to either remove or dilute thatch and mat, reduce soil compaction, or improve surface properties for playability and plant health (Baldwin et al., 2006; Sorokovsky et al., 2007; Turgeon, 1999). Despite these beneficial outcomes for long-term plant health and playability, cultivation also results in temporary negative outcomes including disturbance of the putting surface, slower ball rolls, and greater sensitivity to other stresses.

History of Cultivation Practices

Cultivation in the turfgrass industry refers to a mechanical disturbance of soil surface to modify the physical properties of root zone mixtures. The earliest form of turf cultivation is called forking, which involves the penetration of turf with a pitchfork to improve infiltration (Turgeon and Fidanza, 2017). Over time, the practice of physical penetration of the turfgrass surface expanded to spiking, slicing, verticutting, HTC, STC, water injection cultivation (WIC), AIC, and SIC (Turgeon and Fidanza, 2017). Spiking and venting create small openings on the soil surface that provide multiple channels for infiltration and gas exchange (Fontanier et al., 2011). A slicer is a spike with larger knives for deeper penetration.

In the late 1940's, three cultivators were commercially introduced (Turgeon and Fidanza, 2017). The first machine used rotating drills to remove soil as it penetrated the turf. Although it was effective in creating holes and removing compacted soil, it was slow for use. Later in the 1990's, a similar concept called the drill and fill cultivator emerged (Gross, 2012). This cultivator created deep holes using long drill bits while simultaneously filling the holes with dry sand. The second invention of this period was the West Point Aerifier (West Point Products Corp., West Point, PA) developed by Tom Mascaro (Kauffman, 1999; Sheppard, 1957; Turgeon and Fidanza, 2017). This device pulled soil cores by inserting disk-mounted, half-rounded, open spoons. The cores were either removed or broken up with a drag mat and incorporated in the soil. The third innovation was designed with hollow tines mounted on a drum. The tines were inserted into the turf and cores were removed as the drum rotated (Turgeon and Fidanza, 2017). Improvements were made to this last machine, resulting in the replacement of the rotating drums with a vertical motion that limited the turf damage. This is now typically referred to as coring or core cultivation or HTC (Turgeon and Fidanza, 2017).

Vertical mowing or verticutting is another aerification technique that uses vertical knives mounted on a horizontal rotating shaft. The first vertical mower was developed by Tom Mascaro in 1955 (Turgeon and Fidanza, 2017). Shallow vertical mowing reduces the grain in putting greens whereas the deep verticutting alleviates the soil compaction and also promotes air and water movement through turf surface. In the 1980s, the Verti-drain unit (Redexim World, Netherland) was commercially introduced. The Verti-drain is using to break deep compaction layers using small diameter long tine (Turgeon and Fidanza, 2017). Water injection cultivation (WIC) developed by Toto Company in 1990 is cultivation equipment that improves infiltration and alleviates soil compaction without disturbing the turfgrass surface. Water injection cultivation shoots pressurized water into the ground without disturbing the surface. The pressurized stream causes the loosening of the soil through which air, water, and nutrients move to the turfgrass root system. Several other new cultivation technologies including SIC and AIC have been developed in recent years that have minimum surface disruption. Sand injection cultivation is a process in which a high-pressure water creates a hole in the root zone and sand is drawn into the root zone by a vacuum created by the water blast. This process is accomplished using the DryJect (DryJect Inc., Hatboro, PA). The DryJect machine can aerate, amend, and top-dress in one pass which eliminates the need of a crew to drag or remove cores and also allow a smooth surface that is ready to play immediately after treatment. The channels filled with amendments help to develop new deep roots. Air injection cultivation injects high pressurized compressed air to the depth of 15 to 30 cm. Air injection is applied using the Air2G2 (GT Airinject Inc., Jacksonville, FL). The pressurized air is speculated to relieve the compaction immediately, increases porosity allowing for better infiltration rate, and increases turf cushioning. Greens can be immediately played after AIC as it has no surface disruption and does not interfere with ball roll (Dickson et al., 2017).

Traditional Aerification

Cultivation practices such as core aerification, spiking, slicing, and verticutting followed by topdressing are used to maintain desirable root zone physical properties and reduce organic matter build up. Verticutting and HTC with adequate frequency and aggressiveness reduce the net accumulation of OM (Landreth et al. 2008; McCarty et al. 2007; Murphy et al. 1993). These cultivation practices cause surface disruption which affects the playability. (Dickson et al., 2017; McCarty et al. 2007).

Murphy and Rieke (1990) compared the effect of HTC and STC on ‘Penneagle’ creeping bentgrass [*Agrostis stolonifera* L.] green grown on a loamy sand soil in Michigan. Hollow tine cultivation increased the macro porosity compared to STC and an untreated control. The HTC also had 49 and 21% greater saturated water conductivity and air porosity than STC. The loosening effect of soil surface was a short term for STC compared to HTC. The author concluded frequent application of STC is required to manage soil compaction. However, the frequent application of STC resulted in the development of a cultivation pan.

Bunnell et al. (2001) investigated the effect of summer cultivation on gas exchange, water infiltration, soil hardness, and turf quality on 2-yr-old ‘Crenshaw’ and ‘Penn A-1’ creeping bentgrass research greens in South Carolina, U.S.A. The cultivation treatments applied were HTC, STC, deep hollow and solid tine, WIC, star tine, and needle tine. Summer cultivation treatments improved gas exchange, surface firmness, and water infiltration up to 30 days after treatment. Deep hollow tine (1.6 cm diameter and 20 cm deep tine), hollow tine (1.6 cm diameter and 9 cm deep tine), needle tine (0.75 cm diameter and 13 cm deep tine), and star tine (1.75 cm diameter and 9 cm deep tine) reduced surface hardness by 10-20% and soil CO_2 by 20-30%. Hollow tine cultivation increased the infiltration rate by 60%. However, a decrease in turf quality was observed with hollow tine, deep hollow tine, and solid tine.

Sorokovsky et al. (2007) studied the effect of HTC on soil physical properties of 'Providence' creeping bentgrass putting greens on Lower Fraser Valley of British Columbia. Core aerified plots had lower soil volumetric water content and a higher infiltration rate than the untreated control. The effect of HTC lasted only for one month. No significant difference in soil OM, root weight density, and soil bulk density was observed. The authors concluded that HTC impacting 5% of the surface area was not sufficient to affect soil properties except volumetric water content and infiltration rates.

McCarty et al. (2007) evaluated the effectiveness of various combinations of cultural practice followed by topdressing for managing thatch-mat levels on a 3-yr old sand-based 'A-1'creeping bentgrass putting green in South Carolina. Treatments applied were two levels of topdressing applied either twice monthly at 0.6 mm or once monthly at 1.2 mm from March through October, two vertical mowing treatments applied at a depth of 6.4 mm and 19.1 mm, grooming applied twice weekly at a depth of 3 mm with 6.4 mm spaced blade, and HTC applied using 16 mm diameter tine at a depth of 76 mm. A combination of HTC, verticutting, and grooming decreased OM content by 19% whereas topdressing alone did not manage OM content. All treatments that were combined with HTC reduced surface hardness by 9% and increased water infiltration by 127 to 168% compared to untreated control. Vertical mowing decreased ball roll distance by 6% up to 7 DAT, and HTC reduced ball roll distance by 5 to 8% up to 14 DAT compared to topdressing.

Rowland et al. (2009) studied the effect of cultural practice for controlling OM and their effects on soil physical properties and performance of an 8-yr-old sand-based ultradwarf bermudagrass research green with ‘Champion Dwarf’ and ‘TifEagle’ cultivars in Florida. Treatments applied were HTC (1, 2 or 3 times per year), verticutting (3 times per year), STC (5 times per year), and untreated control. Hollow tine cultivation impacted 7.7%, 15.45%, and 23.1% of the surface area with 1, 2, and 3 times application, respectively, using 1.6 cm diameter and 7.6 cm deep tine spaced at 5.1 cm. Solid tine cultivation impacted 15.7% surface area using 1.0 cm diameter and 7.6 cm deep tine spaced at 5.1 cm. Verticutting impacted 46.8% surface area using 0.2 cm tine spaced at 1.3 cm at a depth of 2.5 cm. Organic matter decreased throughout the study period, but there were no significant differences among cultural practices. The HTC treatment (3 times per year) increased saturated hydraulic conductivity, reduced volumetric water content, and increased localized dry spot. Although verticutting did not reduce soil organic matter, it provided the firmest turf with reduced mower scalping, localized dry spot, and increased root weights.

Landreth et al. (2008) evaluated the impact of aggressive verticutting and core aerification on organic matter management and turf recovery on 1-yr-old sand-based ‘Penn G-2’ creeping bentgrass green in Arkansas, U.S.A. Verticutting was applied at a tine depth of 2.5 cm using 1, 2, and 3 mm wide blade. Core aerification was applied using 0.6 cm and 1 3 cm diameter and of 3.8 cm and 5 cm deep tine with a spacing of 3.2 x 3.8 cm or 5 x 6.4 cm. Aggressive verticutting removed more OM than core aerification, but the recovery rate was slow. The recovery rate was faster for small diameter tine than larger tine. However, tine spacing did not affect the recovery time. Closely spaced small tine can be used to remove more OM without delaying recovery.

Atkinson et al. (2012) evaluated the effect of core aerification frequency, area impacted, and topdressing on turf quality and soil physical properties of a 10-yr-old USGA specified TifEagle ultradwarf bermudagrass research putting green in Clemson, South Carolina. Two years of study were conducted impacting 15% and 25% surface area through one, two, or three aerification events per year. Turf quality decline for up to 4 weeks after each aerification event. Increasing the frequency of aerification evets from one to three reduced decreased bulk density, surface hardness, and organic matter. Although reducing the frequency of aerification event while maintaining the same surface area impact improve turf quality but it did not improve soil physical properties.

Schmid et al. (2014) studied the effect of HTC, STC, and venting cultivation in managing OM and water infiltration of USGA specified Providence creeping bentgrass putting greens at the University of Nebraska-Lincoln John Seaton Anderson Turfgrass Research Facility, NE. Hollow tine cultivation and STC were applied with 1.27 cm diameter and 11.43 cm deep tine spaced at 5 cm. The HTC impacted 5.9% of surface area whereas STC and quad needle tine treatment impacted 4.9% surface area. Venting treatments were applied with PlanetAir, Hydroject, bayonet tine, or needle tine. Bayonet and PlanetAir impacted 2.1% of the surface area using 1.7 cm wide and 0.25 cm thick blade spaced at 5 cm. Tine and venting type impacted infiltration rates. Both HTC and STC had greater water infiltration rates than non-treated control. Hydroject and quad needle tine increased infiltration rates compared with PlanetAir, bayonet-tine, and non-venting. Cultivation practices had no impact on managing OM management, which the authors speculate was due to the low surface area impacted by all treatments. To prevent excessive organic matter accumulation, it is suggested to impact 15-20% of the surface area (Bevard, 2011; Hartwiger and O'Brien, 2001).

Alternative Aerification

Alternative aerification practices such as WIC, SIC, and AIC offer a less invasive approach for managing soil physical properties. These new cultivation practices improve infiltration and drainage, reduce soil compaction with minimum surface disruption (Craft et al., 2016; Dickson et al., 2017; Green et al., 2001). Water injection cultivation (WIC) was reported to increase the infiltration rate with minimum surface disruption (Green et al. 2001; Murphy and Rieke, 1994). In an experiment conducted by Murphy and Rieke (1994) on 5-yr- old 'Penncross' creeping bentgrass greens grown on modified loamy sand, WIC was equal or superior to hollow tine cultivation in reducing bulk density, and increasing porosity and saturated hydraulic conductivity in 0 to 76 mm depth root zone. Murphy and Rieke also observed WIC was able to alter soil physical properties deeper in the soil compared to HTC.

Green et al. (2001) evaluated the effects of WIC, and STC on 18-yr-old annual bluegrass (*Poa annua* L.) putting greens grown on USGA specification modified root zone greens at Industry Hills Golf Course, City of Industry, California. Water injection cultivation was better than the control and equal or superior to solid tine in increasing infiltration rate. Treatments had no significant effects on bulk density, soil oxygen diffusion rate, air porosity, and root weight density.

Karcher and Rieke (2005) studied the effect of WIC and HTC on mixing the topdressing sand layer with underlying native soil on Penncross creeping bentgrass in

Michigan. The treatments included WIC (applied weekly, biweekly, and monthly), and HTC (applied in spring and fall). After two years of treatment weekly application of WIC resulted in less sand in the topdressing layer. However, the soil layer mixing was only limited to 2.5 cm. Cultivation practice did not significantly decrease or change the bulk density. It was reported that WIC reduced the turf quality throughout the study and caused more damage during stress. The author concluded that during stressful conditions WIC should not be applied more frequently than biweekly and should only be used to supplement, but not to replace HTC to manage surface OM.

Fontanier et al. (2011) studied the effect of venting aeration in comparison to small diameter STC and HTC on thatch-mat accumulation, turf quality, saturated hydraulic conductivity, and soil volumetric water content of hybrid bermudagrass that has not been cultivated for 5 yrs. The study was conducted on an 11-yr-old sand-based green in College Station, TX and consisted of TifEagle, 'Tifdwarf', and 'Mini-Verde' cultivars. Venting aerations were applied monthly, biweekly, and weekly impacting 7.4-9.5%, 14.7-18.9%, and 29.4-37.8% surface area impacted annually. Hollow tine cultivation and STC were applied every three weeks impacting 14.0-16.8% surface area annually. Cultivation practices including venting and small diameter core aeration did not reduce thatch accumulation compared to untreated control. Although an individual venting event had a negligible impact on the playing surface, frequent venting reduced the turf quality and hydraulic conductivity and increased surface soil volumetric water content. The result from this study suggests that venting alone may not be effective in thatch management, but could be best utilized in combination with other cultural practices.

Craft et al. (2016) investigated the best combination of SIC with HTC to improve soil physical properties with minimal surface disruption. The study was conducted on ‘MS Supreme’ ultradwarf bermudagrass practice putting green established on a USGA specified root zone in Starkville, MS. The treatments included HTC (1.3 cm and 0.6 cm diameter tine), SIC (5 times per year), and a combination of HTC and SIC. They reported that HTC (1.3 cm) had a 76% higher infiltration rate than HTC (0.6 cm tine) + SIC. Although HTC (1.3 cm tine) was most effective in improving soil physical properties, it also had the slowest percentage recovery. The HTC 0.6 + SCI treatment had minimal surface disruption but could not provide the same improvement to soil physical properties as HTC 1.3 cm. The author concluded that SIC would be best used in combination with HTC to improve soil physical properties. Sand injection and HTC 0.6 cm would be the best combination as it improves soil physical properties with minimum surface disruption.

Dickson et al. (2015) tested the effectiveness of an air injection cultivation to reduce surface hardness and increase the porosity of compacted silt loam soil of bermudagrass athletic fields at the University of Tennessee, TN. Air injections were applied once every 15 days or once every 30 days from July through August 2014. Surface hardness was decreased immediately after treatment. Surface hardness was found to decrease by 21% and the porosity increased by 17% in the top 5 cm soil for both air injection treatments. There was no difference in percent green cover immediately after treatment. The result demonstrates that AIC decreases surface hardness and increases the total porosity of native soil athletic fields with minimum surface disruption.

Dickson et al. (2017) conducted two field study in Knoxville, TN, and Elizabethtown to investigated the effect of AIC, SIC, STC, HTC, and untreated control on 7-yr-old A-1creeping bentgrass greens established over a USGA specified root zone. Immediately after treatment AIC did not reduce green turfgrass cover compared to untreated control. The HTC treatment resulted in the largest reduction (16%) in green cover, while SIC and STC resulted in 9% and 8% reduction in green cover compared to the untreated control. The AIC treated plot had the firmest surface, whereas HTC had the softest surface among all the cultivation plots. The positive correlation (0.97) was observed between the green coverage and surface firmness, which indicates that more surface disruption after cultivation leads to a softer surface. Air injection treatment increased ball roll distance compared to control and other cultivation treatments. Decreased ball roll distance on HTC and STC plot was due to surface disruption and remaining topdressing sand on the turf surface. A positive correlation of 0.63 was observed between the ball roll distance and surface firmness. There was no difference in bulk density among treatment. The results indicate that AIC and SIC have less impact on surface playability of putting greens than HTC and STC.

Traditional aerification practice often reduce the playing quality of the putting surface resulting in a temporary closure and loss of revenue. In addition to this, most practices require extra labor, equipment, and materials to do work. Periodically, new cultivation technologies such as WIC, SIC, and AIC have emerged for managing soil physical conditions of putting greens with less invasive approaches. Although the initial cost of new technology is high, the benefit of sustained revenue after a cultivation event could justify the expense if the efficacy of the practice is known.

A considerable amount of research has been done to examine the timing, depth, spacing, and frequency of conventional aerification (Bunnell et al., 2001; McCarty et al., 2007; Rowland et al., 2009; Sorokovsky et al., 2007). Although there is a significant interest of superintendents on new less disruptive cultivation events, enough information in not available in the literature comparing new technology with traditional methods. Uncertainty remains for optimum timing and frequency of application, the longevity of the effects, and how these practices could be used to complement conventional top dressing and cultivations methods. Currently, there is no quantitative information published comparing AIC and SIC. Information is lacking on the magnitude and duration of effect from AIC or SIC. There is limited research done on AIC and SIC systems with regards to impacts on soil physical properties. The study that has been conducted only compares the short-term impact of AIC. Currently there is no published information on seasonal variability of soil physical properties of golf course putting green. No study has been done to compare the effectiveness of cultivation practices (AIC, SIC, and HTC) applied in spring, summer, and fall season. These technologies should be evaluated through scientific research to verify their efficacy and develop best management practices.

Effect of Temporal Shade

Shade can be detrimental to turfgrass growth, development, and quality. The most common and obvious effect of shading is the reduction in light intensity which limits energy available for photosynthesis. In the United States, it is estimated that 25% of the turfgrass area are under shade condition (Beard, 1973). Grasses under shade are usually taller and have lower dry weights and thinner stems (Dudeck and Peacock, 1992). Shade stress also affects the physiology of turfgrasses such as pigment concentration (Possingham, 1980; Wilkinson and Beard, 1975) and carbohydrates reserve (Bunnell et al., 2005). Shade provided by trees, shrubs, and buildings often reduces air circulation and increases relative humidity resulting in a microclimate conducive to disease development (Bell and Danneberger, 1999).

Creeping bentgrass has good shade tolerance in comparison to many other turfgrasses (Turgeon, 1991). However, low mowing heights typical of putting greens reduces the residual leaf area available for photosynthesis and thus making plants more sensitive to shade stress. On golf courses, due to the orientation of trees and other structures, shade is rarely constant and instead fluctuates throughout the day. Some areas may be shaded for a partial day whereas others may be continuously under shade. Bell and Danneberger (1999) reported no difference in turf color, density, and total nonstructural carbohydrates of creeping bentgrass exposed to morning shade, afternoon shade, or full sun. In contrast, a recent study conducted on ‘007’ creeping bentgrass greens in Arkansas demonstrated that afternoon shade was more detrimental to turfgrass quality than morning shade (Russell et al., 2019). Afternoon shade was also reported to be more detrimental to TifEagle bermudagrass [*Cynodon dactylon* (L.) Pers x *C. transvaalensis* Burtt-Davy] (Bunnell et al., 2005) and seashore paspalum [*Paspalum vaginatum* Swartz] (Jiang et al., 2003).

Field observations suggest that morning shaded areas decline more readily than those areas shaded in the afternoon (Freeman, 2012). This has been attributed in part to the leaf surface remaining wet with dew for many hours thus exacerbating disease pressure (Bell and Danneberger, 1999). Despite this, the results of most field studies investigating temporal shade have either been inconclusive or concluded afternoon shade as more detrimental. These studies have focused on evaluating turfgrass quality and biomass. However, there has been no published work quantifying more basic aspects of creeping bentgrass response to temporal shade.

Research Goal and Objectives

The ultimate goal of this project was to study the effect of air injection cultivation (AIC) and sand injection cultivation (SIC) alone or in combination with hollow tine cultivation (HTC) on soil physical properties of creeping bentgrass putting greens and to study the effect of morning and afternoon shade on creeping bentgrass performance.

The objectives of this research are:

1. To determine the magnitude and duration of effect from AIC, SIC, and HTC cultivation on surface firmness, infiltration rate, and surface disturbance of a sand-based creeping bentgrass putting green.
2. To evaluate the effect of AIC and SIC based programs on seasonal playing quality and soil physical properties of creeping bentgrass putting green.
3. To quantify the effect of AIC on soil oxygen content of a sand-based root zone.
4. To evaluate the effect of morning and afternoon shade on creeping bentgrass photosynthesis.

Testable hypothesis

1. Air Injection and SIC will have equal or superior infiltration rates and firmer soil surface compared to HTC.

2. Novel cultivation practice will have minimum surface disruption and have no impact on ball roll compared to HTC.
3. Air Injection will increase the soil oxygen content of a sand-based root zone compared to control.

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CHAPTER II

FIELD ASSESSMENT OF SOIL PHYSICAL PROPERTIES IN PUTTING GREENS AT SIX GOLF COURSES IN CENTRAL OKLAHOMA

Abstract

Managing soil organic matter and root zone moisture of sand-based putting greens is critical to the long-term health of turfgrass. Soil compaction and accumulation of organic layers near the root zone surface reduce infiltration rates, influence surface firmness, inhibit deep rooting, and negatively affect playability. Cultivation practices including core aerification are commonly used to improve or maintain soil physical conditions. However, core aerification is disruptive to the playing surface and results in temporary loss of revenue. Less disruptive technologies should be evaluated through scientific research to verify their efficacy and longevity of response. The objective of this study was to evaluate the soil physical properties of Oklahoma golf courses using various methods of cultivation. This research was conducted on six different golf courses in central Oklahoma from 2017 to 2018. Cultivation methods used at these locations included air injection cultivation (AIC), sand injection cultivation (SIC), hollow tine cultivation (HTC), and solid tine cultivation (STC). The parameters evaluated were sand particle size distribution, infiltration rate, volumetric water content, surface firmness, and ball roll. Results showed HTC and STC significantly increased infiltration rate and

reduced firmness whereas AIC and SIC had no impact on infiltration rate or surface firmness. Cultivation treatment had no effect on volumetric water content. Seasonal variability of soil physical properties was observed regardless of cultivation treatment. Summer measurement had a higher infiltration rate, softer playing surface, and reduced ball roll distance compared to fall and spring measurements. Results suggest AIC and SIC alone may not be effective for improving infiltration and managing soil physical properties.

Introduction

Creeping bentgrass [*Agrostis stolonifera* L.] and ultradwarf bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burt Davy] are the most prevalent turfgrass species used on putting greens, with bermudagrass being predominant in warm and humid regions and creeping bentgrass in the cooler regions of the United States (Hartwiger and O'Brien, 2006). In the transition zone, both creeping bentgrass and ultradwarf bermudagrass are used as putting green turf. Both of these species can produce thatch rapidly, which negatively affects the putting green performance and playability (Carrow, 1998; Fontanier et al, 2011; McCarty et al., 2007). Thatch is the layer of dead and partially decomposed plant tissues (Decker, 1974) whereas mat is the layer in which thatch becomes mixed with topdressing sand (Williams and McCarty, 2005). A thin thatch-mat layer is considered to be beneficial on putting green as it provides resilience to the turf, receives golf shots, increase tolerance to heavy equipment, and acts as a buffer for the moderation of soil temperature (Dernoeden et al., 2012; Moeller and Lowe, 2016). However, a thick thatch-mat layer reduces the stress tolerance of turfgrass, making plants more susceptible to heat, disease, insects, and mower injury associated with scalping (Dernoeden et al., 2012; Moeller and Lowe, 2016).

The United States Golf Association (USGA) recommends a specific sand-based root zone mixture for putting greens designed to have improved air and water permeability, drainage, and resistance to compaction. However, these properties of sand-based root zone diminish over time. Soil physical properties that change as putting greens mature include increased bulk density, reduced infiltration rate, and reduced soil oxygen diffusion (Murphy et al., 1993). These changes in soil physical properties are associated with compaction due to foot and mechanical traffic and blocking of soil pore space by organic matter and fine soil particles. The management of greens to reduce thatch-mat layer and soil compaction is essential for maintaining smooth, healthy, and firm greens.

Recommended cultivation frequency and timing depend on a number of factors including climate, frequency of play, cultivar, and nutrient management. Increased facility usage typically results in more aerification needed to reduce compaction. Core aerification is an effective practice to remove soil organic matter and to improve soil physical properties (Atkinson et al., 2012; Craft eta l., 2016; Rowland et al., 2009). Although core aerification improves soil properties, it can be disruptive to the putting surface (Craft et al., 2016; Dickson et al., 2017). Alternative cultivation practices such as air injection (AIC) and sand injection (SIC) have been increasingly used due to their minimal surface disruption (Craft et al., 2016; Dickson et al., 2017). Although the use of new cultivation practice is increasing, there is a lack of information comparing its effect with traditional core cultivation.

Soil moisture content, surface firmness, and infiltration of greens can change throughout the season. In order to efficiently use traditional or alternative cultivation methods, superintendents require information on these seasonal changes in soil physical properties. Therefore, the objectives of this study were to assess the soil physical properties of putting greens in central Oklahoma varying in cultivation management programs and quantify the seasonal variability in soil physical properties.

Materials and Methods

This study was conducted at six golf courses in central Oklahoma (Table 1). All putting greens in the study had been established on sand-based root zones. All cultural management decisions were made by the cooperating superintendents. This included irrigation, fertility, mowing, and nutrient management which typically resulted in a visually healthy playing surface at each location.

Cultivation events described in Table 1 were applied in spring 2017 and 2018. All aerification events were applied by golf course personnel or the relevant contractor with equipment settings based on typical local practices. Air injection cultivation was applied using the Air2G2 (GT Airinject Inc., Jacksonville, FL). The AIC equipment was operated at an injection burst pressure of 345 kPa through a 23-cm-long-tine and a tine insertion pressure of 345 kPa on 60 x 60 cm spacing. Sand injection cultivation was accomplished using the DryJect (DryJect Inc., Hatboro, PA) on 7.6 x 5 cm spacing at 10.5 cm tine depth. Hollow tine cultivation (HTC) and solid tine cultivation (STC) was applied using a Pro Core 648 (The Toro Company, Bloomington, MN). The setting for HTC was 5 x 5 cm spacing using 1.6 cm outside diameter and 6.4 cm deep tine. The STC was applied at 7.6 x 7.6 cm spacing using a 2 cm diameter tine at a tine depth of 11.75 cm. When HTC or STC was applied, sand was top-dressed and brushed into the holes. The specification of topdressing sand is listed in Table 3.

Two greens were selected at each golf course based on the accessibility and preference of the cooperating superintendent. Each green was then evaluated at three zones (experimental units) representing the front, middle, and back of the green. Measurements of infiltration rate, surface firmness, volumetric water content, and ball roll distance were made immediately before selected cultivation events and subsequently at 3, 7, and 28 days after cultivation event (DACE). These cultivation events were performed in the spring of each year. Each site was also evaluated once during summer and fall to estimate seasonal variability of soil physical properties.

Infiltration rates were measured using a double-ring infiltrometer (15 and 30 cm rings) and falling head technique (Fontanier et al., 2011; Gregory et al., 2005). The rings were inserted approximately 5 cm below the soil surface. Water was added to the top of both rings. The infiltration rate was measured as the decrease in water level within the inner ring after ten minutes. The process was repeated until two consecutive readings were the same.

Surface firmness was measured using a handheld firmness meter (Field Scout TruFirm, Spectrum Technologies, Inc. Aurora, IL) (Dickson et al., 2017). Firmness was assessed as the depth of golf ball impact into the putting green surface at nine points along a 90 x 90 cm grid and averaged to obtain a single value for each experimental unit.

Soil volumetric water content (VWC) was measured using a FieldScout time domain reflectometer (TDR 300) soil probe (Spectrum Technologies, Inc.). The mean

VWC of 3.8 cm and 7.6 cm depth was collected at nine points along 90 x 90 cm grid and averaged to obtain a single value for each experimental unit.

Ball roll distance (BRD) was measured using a USGA Stimpmeter (Gaussoin et al., 1995: United States Golf Association, 2009). Three balls were rolled in one direction and rerolled in the opposite direction. The distance for the six rolls was averaged to obtain a single value for each experimental unit.

In addition, nine 2-cm diameter root zone samples were randomly collected from each green before a cultivation event. The thatch layer and actively growing roots were removed from the samples, and particle size distribution was measured on the remaining soil.

Statistical Design and Data

The study was first analyzed as a completely randomized design with three replications (zones within each green). The treatment, time (DACE), and treatment × time interaction effects were evaluated using a repeated measures analysis in the GLIMMIX procedure (SAS version 9.3; SAS Institute Inc., NC) with data pooled across locations and greens within locations. Subsequently, data were re-analyzed using the GLIMMIX procedure to evaluate the effects of location, season, and the location × season interaction on measured parameters. Means were compared using Fisher's protected least significant difference (LSD). All tests were performed at a significance level of $p \leq 0.05$.

Results and Discussion

Cultivation Effects

Particle Size Distribution

Root zone and topdressing sand particle size distributions varied among golf courses but was not affected by the age of the green (Tables 2 and 3). Infiltration rate was higher for the golf courses that have higher very coarse and coarse sand particles and lower fine sand, silt and clay compared to golf courses that have higher fine sand, silt, and clay and lower very coarse and coarse sand particles. These findings are not surprising and prior research has shown a similar reduction in infiltration due to the accumulation of silt and clay particles in root zone (Lewis et al., 2010).

Volumetric Water Content

Cultivation practice had a minimal effect on VWC at either the 3.8 cm or 12 cm depth (Table 5). At the 3.8 cm depth, HTC increased VWC at 3 and 7 but not 28 DACE, and the SIC treatment increased VWC at 3, 7, and 28 DACE. The increase in VWC could be influenced by a number of factors including increased water holding capacity of the soil after cultivation. However, the most likely cause for increased VWC immediately after cultivation is increased water inputs typically applied to settle sand into the canopy, prevent plant tissue damage, and encourage recovery. Furthermore, the SIC process itself introduces a substantial amount of water to create channels for sand. In the present study, AIC and STC had no effect on VWC. Craft et al. (2016) reported no difference in VWC between HTC (0.6 cm tine) and the control, whereas HTC with a larger diameter (1.3 cm tine) reduced VWC compared to control. Rowland et al. (2009) also reported that VWC of HTC applied 1 or 3 times per year and STC applied 5 times per year was not different than the control. The temporal and spatial variability in soil moisture content likely contributes to the inconsistent findings both within this study and those conducted at research stations.

Surface Firmness

Hollow tine cultivation reduced surface firmness up to 28 DACE (Table 6). In contrast, STC reduced surface firmness for only 3 DACE. These findings are in agreement with McCarty et al. (2007) and Murphy et al. (1993) who reported that creeping bentgrass putting greens treated with HTC had reduced surface firmness compared with STC and control.

Surface firmness was not affected by SIC, while there was a small decrease in firmness for AIC at 7 DACE (Table 6). Craft et al. (2016) reported that an ultradwarf bermudagrass treated with SIC had no difference in surface firmness compared to control. However, Dickson et al. (2017) reported a decrease in surface firmness immediately after either SIC or AIC in a creeping bentgrass green. Soil VWC is often related to surface firmness, which likely explains much of the effects seen for HTC (Linde et al., 2011). However, it is somewhat surprising that SIC would increase VWC but not reduce firmness. These findings reinforce that HTC is an effective form of mitigating compaction whereas SIC may not be as effective for that goal. Reduced surface firmness can be desired for cushioning ball bounce (McCarty et al., 2007). The surface firmness affects the golf ball mark severity and recovery. Young et al. (2017) observed ball mark severity was small with deep ball mark under soft condition. The golf ball mark recovery was slow when low mowing height combine with daily roll and traffic. In contrast, Nemitz et al. (2008) reported increased ball mark injury and longer recovery time under soft condition.

Infiltration Rate

The HTC and STC events increased infiltration rate compared to baseline values at 7 and 28 DACE, respectively (Table 6). In contrast, neither AIC nor SIC affected infiltration rates. Core cultivation (HTC or STC) has routinely been reported to increase infiltration rate compared to a control (Schmid et al., 2014; Sorokovsky et al., 2007). Key factors influencing the relative effect of cultivation on infiltration have included channel diameter and depth, particularly if the channel does not completely pass through the thatch-mat layer (Craft et al., 2016; Fontanier et al., 2011). Further, cultivation techniques which combine aeration with OM removal are likely to enhance infiltration over those that only accomplish one goal (Fontanier et al., 2011; Hurto et al., 1980). Furthermore, cultivation techniques that require frequent application to manage soil compaction have been reported to lead to development of a hardpan over time (Fontanier et al, 2011; Murphy et al., 1993).

Turf Quality

Turf quality was reduced by HTC and STC events up to 3 and 7 DACE, respectively (Table 7). In contrast, neither SIC nor AIC events affected TQ within the measurement period. These findings are in agreement with AIC and SIC equipment manufacturer guidelines and research by Dickson et al. (2017) who reported HTC reduced green cover by 16%, whereas SIC reduced cover by only 9% immediately after cultivation events. Changes to tine spacing and diameter can be made to reduce the immediate impact on TQ with corresponding reductions in surface area impacted.

Ball Roll Distance

Ball roll distance was reduced by HTC up to 28 DACE, presumably due to a decline in the smoothness of the surface (Table 7). Previous research has reported a decrease in ball roll distance after core cultivation (Dickson et al., 2017; McCarty et al., 2007). In contrast, AIC has increased ball roll distance at 3 DACE, and SIC showed no consistent effect on ball roll distance. These findings are in agreements with Dickson et al. (2017) who reported increased ball roll immediately after AIC, similar ball roll after SIC, and reduce ball roll distance after HTC and STC compared to control.

Season Effects

For each measured parameter, the season main effect and its interaction with location were significant (Table 4). At the 3.8 cm depth, four golf courses out of six had higher VWC in summer measurement than in spring and fall (Table 8). Presumably, this occurred due to frequent irrigation cycles commonly used to overcome summer heat stress. Similarly, VWC at the 12 cm depth showed a strong main effect indicating higher values during summer than other seasons. The greater VWC in summer corresponded to softer playing surface in summer compared to spring and fall measurements at five of six locations (Table 9). Furthermore, weakened root systems and tall mowing heights typical of creeping bentgrass putting greens during summer likely influenced firmness measurements.

Each location had infiltration rates greater than the USGA's recommended minimum of 15 cm h^{-1} throughout the study except for Stillwater Country Club (SWCC) in summer and fall and Gaillardia Country Club (GCC) in fall. Three locations had a lower infiltration rate in fall than in summer or spring (Table 9). For the present study, factors which may have influenced infiltration rate could include antecedent soil moisture content, soil chemical properties, soil texture, and surface compaction. Infiltration rate is reported to be affected by organic matter build up (Baker et al., 1999; Baker, 2004) and organic matter layering (Curtis and Pulis, 2001). Organic matter can retain or repel water (Gaussoin et al., 2013) which may affect the infiltration rate. The methodology used should have mitigated the effect of antecedent soil moisture content, thus differences in infiltration are likely due to one or more of the other factors. Although most locations incorporated a fall aerification event (usually in September or October), surface compaction is a likely causal agent as indicated by surface firmness data. What is surprising is that fall and spring had similar surface firmness, and thus some other factor may also be contributing to the differences in infiltration between fall and spring.

Four golf courses out of six had lower turf quality in spring compared to summer or fall, largely due to discoloration and reduced uniformity typical of cool temperatures (Table 10). Four locations demonstrated lower ball roll distance in summer than fall, while three locations similarly showed lower ball roll distance for summer than spring. The ball roll distance in fall was equal or greater than in spring for each location except for Stillwater Country Club. The reduced ball roll distance in summer is unsurprising and corresponds well to the greater VWC and softer conditions.

Conclusion

Results indicate core cultivation was most effective at increasing the infiltration rate and reducing surface firmness. Although core cultivation was able to change soil physical properties, the impact was short term. These findings suggest that more than one application of cultivation practices impacting more surface area is more likely necessary for long-term improvement of soil physical properties of putting greens. Future research should examine how these cultivation practices could be best utilized to improve soil physical properties with minimum impact on playing surface. Additional study should evaluate the long-term benefit of new cultivation practice in managing the organic matter.

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Table 1. Description of six case study sites used to evaluate cultivation event and seasonal effects on soil physical properties of golf course putting greens in central Oklahoma.

Location†	Green No.	Cultivation Type‡	Cultivar	Green Age	Spacing	Tine Diameter	Tine Depth	Event Date
				yr	cm	cm	cm	
BGC	12	Air Injection	G2	17	60 x 60			10 July 2017
	12	Sand Injection	G2	17	7.6 x 5			27 Mar. 2018
	Practice	Air Injection	G2	9	60 x 60			10 July 2017
	Practice	Air Injection	G2	9	60 x 60			4 June 2018
BRGG	10	Sand Injection	007	3	7.6 x 5			28 Feb. 2017
	14	Sand Injection	007	3	7.6 x 5			28 Feb. 2017
GCC	Practice (1)	Air Injection	A4	21	60 x 60			17 Mar. 2017
	Practice (1)	Sand Injection	A4	21	7.6 x 5			10 Apr. 2018
	Practice (2)	Air Injection	A4	21	60 x 60			17 Mar. 2017
GCE	18	Sand Injection	007	3	7.6 x 5			27 Feb. 2017
	10	Sand Injection	SR1020	10	7.6 x 5			27 Feb. 2017
LMGC	13	Sand Injection	SR1020	19	7.6 x 5			1 Mar. 2017
	9	Sand Injection	SR1020	19	7.6 x 5			1 Mar. 2017
	13	Solid Tine	SR1020	19	7.6 x 7.6	2	10.2	7 May 2018
	18	Solid Tine	SR1020	19	7.6 x 7.6	2	10.2	7 May 2018
SCC	12	Hollow Tine	L93	17	5 x 5	1.6	6.4	12 Mar. 2017
	6	Hollow Tine	L93	17	5 x 5	1.6	6.4	12 Mar. 2017
	12	Solid Tine	L93	17	7.6 x 7.6	2	10.2	9 Mar. 2018
	6	Solid Tine	L93	17	7.6 x 7.6	2	10.2	9 Mar. 2018

†BGC = Belmar Golf Club; BRGG = Buffalo Rock Golf and Gun; GCE = Golf Course of Edmond; GCC = Gaillardia Country Club; LMGC= Lakeside Memorial Golf Course; SCC = Stillwater Country Club.

‡ Air injection cultivation = Air2G2; GT Airinject Inc., Jacksonville, FL; hollow tine cultivation = Pro Core 648; The Toro Company, Bloomington, MN; sand injection cultivation = DryJect; DryJect Inc., Hatboro, PA); solid tine cultivation = Pro Core 648; The Toro Company, Bloomington, MN.

Table 2. Particle size distribution of root zone sand from selected putting greens at six golf courses studied in central Oklahoma.

Golf course[†]	Green No.	Fine Gravel[‡] (>2.0 mm)	Very Coarse (1.0-2.0 mm)	Coarse (0.5-1.0 mm)	Medium (0.25-0.5 mm)	Fine (0.15-0.25 mm)	Very Fine (0.05-0.15 mm)	Silt + Clay (<0.05 mm)
		--------------------	--------------------	--------------------	%	--------------------	--------------------	--------------------
BCC	12	0.23 f[§]	13.04 a	34.46 ab	42.35 de	8.83 f	0.92 e	0.16 d
BCC	Practice	0.81 cde	6.23 de	24.85 de	50.42 c	16.28 c	1.18 e	0.24 cd
BRGC	10	0.87 cd	8.00 bc	35.13 ab	43.04 de	11.72 de	1.04 e	0.20 d
BRGC	14	1.82 a	11.74 a	37.77 a	36.17 f	9.59 ef	2.23 b	0.68 a
GCC	Practice (1)	0.60 def	5.68 de	31.36 bc	45.27 d	13.24 d	3.44 a	0.40 b
GCC	Practice (2)	1.37 ab	8.70 b	38.33 a	39.74 e	9.38 f	2.14 bc	0.33 bc
GCE	10	0.30 f	5.40 de	29.43 c	44.89 d	16.66 c	2.38 b	0.77 a
GCE	18	1.11 bc	6.64 cd	28.03 cd	44.00 d	17.64 bc	2.35 b	0.23 cd
LMGC	9	0.77 cde	4.12 e	21.95 ef	54.18 bc	17.17 c	1.47 d	0.33 bc
LMGC	13	0.84 cde	4.85 e	23.22 ef	53.18 bc	16.03 c	1.61 d	0.27 cd
SCC	6	0.40 ef	2.38 f	17.07 g	58.16 a	19.98 a	1.68 d	0.34 bc
SCC	12	0.38 ef	2.34 f	20.38 fg	55.14 ab	19.68 ab	1.82 cd	0.26 cd

[†]BGC = Belmar Golf Club; BRGG = Buffalo Rock Golf and Gun; GCE = Golf Course of Edmond; GCC = Gaillardia Country Club; LMGC= Lakeside Memorial Golf Course; SCC = Stillwater Country Club.

[‡] Particle size was classified based on USDA textural classification system (USDA,1951). Particle size were separated by passing soil samples through U.S. standard sieve mesh (No. 10, No. 18, No. 35. No. 60, No. 100, and No. 270).

[§]Means within each column followed by the same letter are not significantly different at the p = 0.05 significance level.

Table 3. Particle size distribution of top dressing sand used at six golf courses studied in central Oklahoma.

Golf course[†]	Fine Gravel[‡] (>2.0 mm)	Very Coarse (1.0-2.0 mm)	Coarse (0.5-1.0 mm)	Medium (0.25-0.5 mm)	Fine (0.15-0.25 mm)	Very Fine (0.05-0.15 mm)
	-------------------------	-------------------------	----------------------%	-------------------------	-------------------------	
BGC	20.05 b[§]	23.37 c	38.41 c	14.05 c	3.19 bc	0.94 a
BRGG	09.65 d	36.91 b	43.48 b	07.00 d	2.34 dc	0.60 b
GCC	27.21 a	36.63 b	28.61 d	05.54 d	1.76 d	0.30 c
GCE	14.79 c	49.93 a	27.02 d	6.32 d	1.81 d	0.15 c
LMGC	13.92 c	20.38 c	41.53 c	19.51 b	4.15 ab	0.51 b
SCC	01.57 e	16.90 d	50.43 d	25.80 a	4.40 a	0.90 a

[†]BGC = Belmar Golf Club; BRGG = Buffalo Rock Golf and Gun; GCE = Golf Course of Edmond; GCC = Gaillardia Country Club; LMGC= Lakeside Memorial Golf Course; SCC = Stillwater Country Club.

[‡] Particle size was classified based on USDA textural classification system (USDA, 1951). Particle size were separated by passing soil samples through U.S. standard sieve mesh (No. 10, No. 18, No. 35. No. 60, No. 100, and No. 270).

[§]Means within each column followed by the same letter are not significantly different at the p = 0.05 significance level

Table 4. Analysis of variance for volumetric water content (VWC), surface firmness, infiltration rate, ball roll distance (BRD), and turf quality for treatment and seasonal measurement at six golf courses in central Oklahoma.

		VWC					
Effect	df	3.8 cm depth	12 cm depth	Firmness	Infiltration	BRD	Turf quality
			Treatment effect				
Treatment	3	**	NS	NS[†]	NS	*	*
DACE	3	***	NS	***	***	***	***
Treatment*DACE	9	***	NS	***	**	*	*
			Seasonal effect				
Location	5	NS	NS	***	NS	***	NS
Season	2	***	***	***	***	***	***
Location*Season	10	*	***	***	***	*	*

*, **, *** significant at $p = 0.05$, 0.01, and 0.001, respectively.
†NS, not significant at $p = 0.05$ the level.

Table 5. Volumetric water content VWC at 3.8 cm and 12 cm depth before cultivation events 3, 7, and 28 days after cultivation event (DACE) on creeping bentgrass putting greens at six golf courses in central Oklahoma.

	Volumetric water content[†]							
	3.8 cm depth				12 cm depth			
DACE	AIC[‡]	HTC	SIC	STC	AIC	HTC	SIC	STC
	--				%--			
0	26.4 a[§]	28.7 b	12.3 c	30.1 a	18.9 a	22.5 a	19.4 a	22.6 a
3	25.6 a	32.7 a	21.7 b	30.2 a	18.9 a	26.8 a	19.2 a	22.1 a
7	25.6 a	32.5 a	26.0 a	32.4 a	17.7 a	26.8 a	20.7 a	23.0 a
28	24.2 a	30.2 ab	27.0 a	30.9 a	18.7 a	24.6 a	21.7 a	21.9 a

[†]Volumetric water content was measured using handheld soil moisture meter (FieldScout TDR 300, Spectrum Technologies, Inc. Plainfield, IL) in nine randomly selected points across a grid and then averaged to get overall surface firmness of each individual plot.

[‡] AIC = air injection cultivation (Air2G2; GT Airinject Inc., Jacksonville, FL); HTC = hollow tine cultivation (Pro Core 648; The Toro Company, Bloomington, MN); SIC = sand injection cultivation (DryJect; DryJect Inc., Hatboro, PA); STC = solid tine cultivation (Pro Core 648; The Toro Company, Bloomington, MN).

[§]Means within each column followed by the same letter are not significantly different at the $p = 0.05$ significance level.

Table 6. Surface firmness (depth of penetration) and infiltration rate collected before cultivation events 3, 7, and 28 days after cultivation event (DACE) on creeping bentgrass putting greens at six golf courses in central Oklahoma.

	Surface firmness (depth of penetration)†				Infiltration rate‡			
DACE	AIC§	HTC	SIC	STC	AIC	HTC	SIC	STC
	--------------- cm---------------				--------------- cm h^{-1}---------------			
0	-0.94 a¶	-0.87 a	-0.98 a	-1.14 a	52.5 a	11.7 c	32.2 a	27.9 b
3	-0.96 a	-1.05 c	-0.97 a	-1.22 b	55.2 a	25.7 ab	29.3 ab	42.5 a
7	-1.00 b	-1.04 c	-0.95 a	-1.07 a	59.1 a	34.0 a	29.0 ab	45.3 a
28	-0.92 a	-0.96 b	-0.98 a	-1.05 a	48.6 a	16.7 bc	24.4 b	38.3 a

†Surface firmness (depth of penetration) was measured using a handheld firmness meter (Field Scout TruFirm; Spectrum Technologies, Inc. Aurora, IL) which records the penetration depth of a falling plunger as it hits a surface. Firmness was measured following single drop of the plunger in nine point across a grid and then averaged to get overall surface firmness of each individual plot. Firmness values are presented as negative values indicating depth below the horizon.

‡Infiltration rate was measured using a double-ring infiltrometer (15 and 30 cm rings) and falling head technique. Infiltration rate was recorded as the decrease in water within the inner ring after ten minutes.

§ AIC = air injection cultivation (Air2G2; GT Airinject Inc., Jacksonville, FL); HTC = hollow tine cultivation (Pro Core 648; The Toro Company, Bloomington, MN); SIC = sand injection cultivation (DryJect; DryJect Inc., Hatboro, PA); STC = solid tine cultivation (Pro Core 648; The Toro Company, Bloomington, MN).

¶Means within each column followed by the same letter are not significantly different at the $p = 0.05$ significance level.

Table 7. Ball roll distance and turf quality before cultivation events 3, 7, and 28 days after cultivation event (DACE) on creeping bentgrass putting greens at six golf courses in central Oklahoma.

	Ball roll distance†				Turf quality‡			
DACE	AIC§	HTC	SIC	STC	AIC	HTC	SIC	STC
	--------------- cm---------------				--------------- 1-9---------------			
0	317.7 b¶	308.5 a	304.3a	284.0 a	7.0 a	6.0 b	6.5 a	7.0 a
3	352.0 a	249.2 b	316.8 a	255.7 b	7.0 a	5.0 c	5.9 b	6.0 b
7	309.8 b	241.4 b	303.7 a	254.9 b	7.3 a	5.5 c	6.5 a	6.5 ab
28	293.2 b	225.4 b	279.9 b	255.8 b	7.0 a	7.0 a	7.0 a	7.0 a

†Ball roll distance was measured using a USGA Stimpmeter. Three balls were rolled in two directions and the average distance traveled by balls was measured.

‡Turf quality measured in a scale of 1-9 (9 = ideal healthy condition; 6= minimally acceptable quality; 1= brown dead leaf).

§ AIC = air injection cultivation (Air2G2; GT Airinject Inc., Jacksonville, FL); HTC = hollow tine cultivation (Pro Core 648; The Toro Company, Bloomington, MN); SIC = sand injection cultivation (DryJect; DryJect Inc., Hatboro, PA); STC = solid tine cultivation (Pro Core 648; The Toro Company, Bloomington, MN).

¶Means within each column followed by the same letter are not significantly different at the $p = 0.05$ significance level.

Table 8.Volumetric water content at 3.8 cm and 12 cm depth collected in spring, summer, and fall month on creeping bentgrass putting greens at six golf courses in central Oklahoma.

	Volumetric Water Content‡					
	3.8 cm depth			12 cm depth		
Location†	Spring§	Summer	Fall	Spring	Summer	Fall
	--		%	--		
BGC	27.4 a¶	29.6 a	26.8 a	18.8 a	20.0 a	18.6 a
BRGG	13.1 b	37.1 a	34.0 a	22.6 a	25.1 a	21.0 a
GCC	24.6 b	33.0 a	26.0 b	19.4 b	26.6 a	19.8 b
GCE		29.5 a	27.0 a	16.7 a	19.1 a	17.4 a
LMGC	21.0 b	30.3 a	29.1 a	19.9 a	20.3 a	20.4 a
SCC	29.7 b	35.6 a	30.0 ab	23.3 a	24.2 a	21.3 a

†BGC = Belmar Golf Club; BRGG = Buffalo Rock Golf and Gun; GCC = Gaillardia Country Club; GCE = Golf Course of Edmond; LMGC = Lakeside Memorial Golf Course; SCC = Stillwater Country Club.

‡Volumetric water content was measured using handheld soil moisture meter (FieldScout TDR 300, Spectrum Technologies, Inc. Plainfield, IL) in nine randomly selected points across a grid and then averaged to get overall surface firmness of each individual plot.

§Spring measurements were taken in March; summer measurements were taken in July; and fall measurements were taken in November 2017 and 2018.

¶Means with in each row under same location and same parameter followed by the same letter are not significantly different at the p = 0.05 significance level.

Table 9. Surface firmness and infiltration rate collected in spring, summer, and fall month on creeping bentgrass putting greens at six golf courses in central Oklahoma.

Location†	Surface firmness‡			Infiltration rate§		
	Spring¶	Summer	Fall	Spring	Summer	Fall
	--------------- cm---------------			--------------- $cm\ h^{-1}$ ---------------		
BGC	-1.00 a#	-1.04 a	-0.96 a	61.1 a	64.5 a	27.7 b
BRGG	-1.04 a	-1.27 b	-1.21 b	40.2 a	18.5 a	27.0 a
GCC	-0.83 a	-1.09 b	-0.95 a	30.5 a	36.9 a	14.4 b
GCE	-0.82 a	-1.12 b	-0.95 a	32.0 a	43.0 a	24.3 a
LMGC	-1.25 a	-1.35 b	-1.29 a	30.2 ab	43.2 a	19.7 b
SCC	-1.01 a	-1.21 b	-1.02 a	19.4 a	13.3 a	16.5 a

†BGC = Belmar Golf Club; BRGG = Buffalo Rock Golf and Gun; GCC = Gaillardia Country Club; GCE = Golf Course of Edmond; LMGC = Lakeside Memorial Golf Course; SCC = Stillwater Country Club.

‡ Surface firmness was measured using a handheld firmness meter (Field Scout TruFirm; Spectrum Technologies, Inc. Aurora, IL) which records the penetration depth of a falling plunger as it hits a surface. Firmness was measured following single drop of the plunger in nine point across a grid and then averaged to get overall surface firmness of each individual plot. Firmness values are presented as negative values indicating depth below the horizon.

§Infiltration rate was measured using a double-ring infiltrometer (15 and 30 cm rings) and falling head technique. Infiltration rate was recorded as the decrease in water within the inner ring after ten minutes.

¶Spring measurements were taken in March; summer measurements were taken in July; and fall measurements were taken in November 2017 and 2018.

#Means with in each row under same location and same parameter followed by the same letter are not significantly different at the $p = 0.05$ significance level.

Table 10. Ball roll distance and turf quality collected in spring, summer, and fall month on creeping bentgrass putting greens at six golf courses in central Oklahoma.

Location†	Ball roll distance‡			Turf quality§		
	Spring¶	Summer	Fall	Spring	Summer	Fall
	--------------- cm---------------			--------------- 1-9---------------		
BGC	304.7 b#	281.4 b	355.3 a	7.25 a	7.5 a	7.0 a
BRGG	276.6 a	218.7 b	317.4 a	6.0 b	7.0 a	7.0 a
GCC	363.6 a	295.4 b	375.2 a	6.7 b	7.6 a	7.9 a
GCE	282.2 b	279.9 b	361.5 a	6.0 b	7.5 a	7.0 a
LMGC	259.1 a	254.4 a	275.1 a	7.0 a	7.5 a	7.0 a
SCC	317.0 a	260.0 b	267.2 b	6.5 b	7.0 ab	7.5 a

†BGC = Belmar Golf Club; BRGG = Buffalo Rock Golf and Gun; GCC = Gaillardia Country Club; GCE = Golf Course of Edmond; LMGC = Lakeside Memorial Golf Course; SCC = Stillwater Country Club.

‡ Ball roll distance was measured using a 35 cm long modified USGA Stimpmeter. Three balls were rolled in two directions and the average distance traveled by balls was measured.

§Turf quality measured in a scale of 1-9 (9 = ideal healthy condition; 6= minimally acceptable quality; 1= brown dead leaf).

¶Spring measurements were taken in March; summer measurements were taken in July; and fall measurements were taken in November 2017 and 2018.

#Means with in each row under same location and same parameter followed by the same letter are not significantly different at the $p = 0.05$ significance level

CHAPTER III

EFFECT OF A SINGLE APPLICATION OF AIR INJECTION OR SAND INJECTION CULTIVATION ON SOIL PHYSICAL PROPERTIES OF A CREEPING BENTGRASS PUTTING GREEN

Abstract

Cultural practices including core aerification are commonly used to improve soil physical conditions of putting greens. However, core aerification is disruptive and causes substantial damage to the playing surface and loss of revenue for the golf course. Less invasive cultivation techniques are available, but less is known about their relative performance. The objective of this study was to assess the efficacy and longevity of air injection cultivation (AIC), sand injection cultivation (SIC), and hollow tine cultivation (HTC) on managing soil physical properties of putting greens. A field study was conducted at the Oklahoma State University Turfgrass Research Center in Stillwater, Oklahoma, on a creeping bentgrass [*Agrostis stolonifera* L. 'Penncross'] green from September 2017 to September 2019. The two factors cultivation type and timing of application were arranged in a split-plot, randomized complete block design with four replications. Cultivation type was defined as either AIC, SIC, or HTC, and each was applied in spring, summer, and fall. Compared with the untreated control, HTC reduced

surface firmness by 5% at 28 days after cultivation event (DACE), increased infiltration by 87% at 28 DACE, reduced ball roll distance by 6% up to 14 DACE, and reduced normalize difference vegetation index (NDVI) by10% up to 14 DACE. The AIC and SIC had no significant effect on any soil physical properties compared to the control. Results suggest that a single application of AIC or SIC may not be effective in managing soil physical properties.

Introduction

Sand based root zones have high permeability and infiltration rates, high gas exchange rates, and resistance to soil compaction, which are ideal conditions for putting green health and playability. However, these conditions diminish over time due to accumulation of organic matter and development of thatch-mat layers (Carrow, 2003; Fontanier et al., 2011). Excessive thatch has a negative impact on soil physical and biological properties such as reduced infiltration rate, increased localized dry spot, reduced tolerance to temperature stress, increased surface compaction, and increased disease and pest problems (Dernoeden et al., 2012; McCarty et al., 2007; Moeller and Lowe, 2016).

Mechanical cultivation practices such as core aerification, vertical mowing, and topdressing are commonly used to manage soil organic matter or compaction. Core aerification is typically considered the most effective method for physical removal of organic matter, reducing compaction, increasing infiltration rates, and increasing surface aeration and rooting. However, core aerification can reduce the aesthetic and functional aspects of a putting green temporarily causing reduced revenue or distaste within the course membership. Less disruptive cultivation practices such as sand injection (SIC) and air injection (AIC) are becoming popular which offer a less invasive approach to managing soil physical properties. Previous research has shown that summer cultivation with water injection and needle tine improved gas exchange, surface firmness, and water infiltration but did not reduce turf quality (Bunnell et al., 2001). Increasing the number of core aerification events from one to three while impacting the same amount of surface area per year was reported to reduce bulk density, surface hardiness and thatch-mat organic matter (Atkinson et al., 2012). In contrast, reducing frequency of cultivation events but maintaining the same surface area impact per year did not improve soil physical properties but improve the turf quality (Atkinson et al., 2012).

Alternative aerification practices such as venting, water injection cultivation (WIC), SIC, and AIC offer a less invasive approach for managing soil physical properties. These new cultivation practices have been reported to increase infiltration and drainage or reduce soil compaction with minimal surface disruption (Craft et al., 2016; Dickson et al., 2017; Green et al., 2001). Water injection cultivation (WIC) has in multiple studies been shown to increase the infiltration rate compared to a control (Green et al. 2001; Murphy and Rieke, 1994). Fontanier et al. (2011) studied the effect of venting cultivation and reported that venting aeration had minimal surface disruption but did not improve infiltration rate or reduce organic matter. Schmid et al. (2014) reported venting such as WIC and needle tine are effective at improving infiltration but not effective at reducing organic matter. A considerable amount of study has been conducted to compare the impact of traditional cultivation practices timing, depth, spacing, and frequency on soil physical properties (Bunnell et al., 2001; McCarty et al., 2007; Sorokovsky et al.

2007; Rowland et al., 2009) while less research has conducted to compare the effect of alternative cultivation practices (e.g., AIC and SIC).

Although there is significant interest in new cultivation technology, there is a lack of unbiased information on efficacy of novel cultivation practices, especially AIC and SIC cultivation. Therefore, the objective of this research was to evaluate the efficacy and longevity of single applications of AIC and SIC applied at different times of a year.

Materials and Methods

Field research was conducted from September 2017 to September 2019 at the Oklahoma State University Turfgrass Research Center in Stillwater, Oklahoma, on a creeping bentgrass [*Agrostis stolonifera* L. 'Penncross'] green constructed on a sand-based root zone. The green was mowed daily during the growing season at 3.9 mm with clippings removed. Slow release granular fertilizer was applied monthly to achieve annual rates of 293 kg ha^{-1} N, 100 kg ha^{-1} P, and 202 kg ha^{-1} K. Topdressing was applied biweekly with a spinner-type spreader (Quick pass 300, Tyro-crop, McGrath road Rosedale, B.C. Canada) during the growing season at a rate of 4.9 m^3 ha^{-1} using a locally available kiln-dried sand (Mohawk Materials, Tulsa, OK) that met USGA specifications for root zones. A wetting agent (Aquicare™, Winfield solution, LLC, St. Paul, MN) was applied monthly from June to August each year at a rate of 19 L ha^{-1} in accordance with typical practices to reduce localized dry spot. The experiment station standard fungicide and insecticide program were applied to prevent common diseases and insects. A combination of bensulide (5.25%) and oxadiazon (1.31%) (Goosegrass/Crabgrass Control, The Andersons Inc., Maumee, OH) was applied at 109 kg ha^{-1} rate in late winter to control annual grassy weeds.

The factors were arranged as a split-plot randomized complete block design with four replications. The whole main plot was cultivation type which included single applications of air injection cultivation (AIC), sand injection cultivation (SIC), hollow tine cultivation (HTC), or non-treated control. The subplot was season of application. Plots measured 1.8 x 2.0 m. The first cultivation events were applied in October 2017. Air injection cultivation was applied using the Air2G2 (GT Airinject Inc., Jacksonville, FL). The AIC equipment was operated at an injection burst pressure of 345 kPa through a 23-cm-long-tine and a tine insertion pressure of 345 kPa on 60 x 6 cm spacing. Sand injection cultivation was accomplished using the DryJect (DryJect Inc., Hatboro, PA) on 7.6 x 5 cm spacing at 10.5 cm tine depth. Hollow tine cultivation was applied using a walk behind aerifier (Pro Core 648, The Toro Company, Bloomington, MN) equipped with 1.3 cm outside diameter and 6.4 cm long tines set at a 5 x 5 cm spacing. Sand used for SIC and HTC was the same material previously described for topdressing.

Treatment effects were assessed by measuring infiltration rate, surface firmness, volumetric water content, ball roll distance, organic matter content, bulk density, normalized difference vegetation index (NDVI). Measurements were made within 24-hr prior to a cultivation event, and subsequent measurements were conducted 7 days, 14 days, 21 days, and 28 days, after the cultivation event (DACE).

Infiltration rates were measured using a double-ring infiltrometer (15 and 30 cm rings) and falling head technique (Fontanier et al., 2011; Gregory et al., 2005). The rings were inserted approximately 5 cm into the soil surface. Water was added to the top of both rings. Infiltration rate was recorded as the decrease in water within the inner ring after ten minutes. The process was repeated until two consecutive readings were the same.

Surface firmness was measured using a handheld firmness meter (Field Scout TruFirm; Spectrum Technologies, Inc. Aurora, IL) which records the penetration depth of a falling plunger as it hits a surface (Craft et al., 2016; Dickson et al., 2017). Firmness was measured following the single drop of the plunger on nine points across a grid and averaged within each plot for subsequent analyses.

Volumetric water content was measured using a handheld soil moisture meter (FieldScout TDR 300, Spectrum Technologies, Inc. Plainfield, IL) and the 7.6 cm probes. The VWC was measured from nine randomly selected points across a grid and then averaged within each plot before subsequent analyses.

Soil bulk density was measured shortly before each cultivation event, immediately after cultivation event, and one week after the cultivation event. A standard 15 cm soil probe was used to remove a 5 cm diameter core, the upper 1 cm of thatch and verdure were removed from the sample, and remaining core oven dried for 48 h at 105 ^{o}C. Bulk density was calculated by dividing dry soil core mass by the total soil core volume.

Ball roll distance was measured using a 35 cm long modified USGA Stimpmeter (Gaussoin et al., 1995; United States Golf Association, 2009). Three balls were rolled in two directions and the average distance traveled by balls was measured. The distance for the six rolls were averaged to obtain a single value for each experimental unit.

Organic matter content was determined by the loss on ignition method (Atkinson et al., 2012; Snyder and Cisar, 2000). A standard soil probe was used to remove a 5 cm diameter core to a depth of 5 cm. Shoots and roots were removed from the sample, and the remaining materials oven-dried for 48 h at 105 ^oC. After measuring the weight dry soil samples were placed in a muffle furnace for 3 h at 550 ^oC. Weight of ashed sample was measured after bringing to room temperature. Soil organic matter content was calculated as the difference between dry weight and ashed weight on a percentage basis.

The percent recovery from a cultivation event was estimated visually on a scale of 0 to 100% (100%=holes fully recovered) (Craft et al., 2016). Recovery was rated 7, 14, 21, and 28 days after cultivation event. Normalized difference vegetation index (NDVI) was measured using a hand-held reflectance meter (Trimble Navigation Inc. Sunnyvale, CA). Measurements were made every week after cultivation event as a single pass across the middle of the plots.

Statistical Analysis

The cultivation type, timing, and their interaction were evaluated using a repeated measures analysis with the GLIMMIX procedure in Statistical Analysis of Variance (Version 9.4; SAS Institute Inc. Cary, NC). Tukey-Kramer multiple-comparison procedure was used when effects were significant ($P \leq 0.05$). Since all cultivation events were applied by outside vendors and scheduling them for the same day was often difficult, not all events were on the same day or in some cases in the same week. Thus, each cultivation type (AIC, SIC, HTC) was analyzed separately in comparison to a control plot measured on the same date.

Results and Discussion

The treatment by season and the three-way interaction effects were not significant for any parameter except for visual recovery in SIC (Table 3). Thus results are presented for the treatment by DACE interaction.

Canopy Loss and Recovery from Event

Air injection cultivation maintained similar NDVI and visual coverage as the control at 7, 14, 21, and 28 DACE (Table 4). The SIC and HTC treatments decreased NDVI compared to the control up to 7 and 14 DACE, respectively. At 7, 14 and 21 DACE, HTC had 53%, 69% and 87% recovery, respectively, whereas SIC had 62%, 78%, and 92% recovery, respectively. By 28 DACE, both HTC and SIC had a greater than 95% recovery. The slow recovery for HTC is unsurprising due to the larger surface area impacted compared to SIC. In a similar study, Dickson et al. (2017) reported HTC resulted in a 16% reduction in green coverage, while SIC resulted in a 9% reduction in green coverage immediately after cultivation event.

Ball Roll Distance

Ball roll distance was reduced by HTC at 7 and 14 DAT compared with the non-cultivated control (Table 4). By 21 DAT, there was no detectable difference in ball roll distance compared to control. McCarty et al. (2007) similarly reported a reduction in ball roll up to 14 DAT after HTC. Ball roll distance was not affected by AIC or SIC. Dickson et al. (2017) similarly reported that ball roll distance on SIC was similar to a non-treated control, while HTC reduced ball roll compared with the non-treated control. The reduced injury and unaffected ball roll distance associated with AIC and SIC suggest each has potential to sustain revenues for golf facilities concerned about the disruption associated with HTC.

Surface Firmness

Hollow tine cultivation reduced surface firmness up to 28 DACE compared with the non-cultivated control (Table 5). At 28 DACE, HTC had a 5% softer surface compared to non-cultivated control. Several studies have evaluated the HTC impact on surface firmness and found similar results as reported in this study (Craft at al., 2016; McCarty et al. 2007; Murphy et al. 1993). Bunnell et al. (2001) observed a reduction in surface firmness after core aerification compared to control and water injection cultivation in a creeping bentgrass green. Dickson et al. (2017) reported a reduction in surface firmness immediately after AIC, SIC, HTC, and STC events compared to non-cultivated control. Craft et al. (2016) reported that HTC reduced the surface firmness up to 28 DACE compared to non-cultivated control, whereas SIC applied 5 times per year did not impact the surface firmness compared to the control. Surface firmness reduction with HTC is attributed to greater surface area disruption, core removal and greater surface fracture (Bunnell et al., 2001). Holes created after HTC provide additional space for collapsing the side walls which likely contributes to the playing surface becoming soft (Murphy and Rieke, 1994)

Infiltration Rate

Compared with the control, the only cultivation type that improved infiltration rate was HTC. At 28 DACE, HTC had an 87% higher infiltration rate than the non-cultivated control (Table 5). The holes created by HTC provide vertical channels near the surface and thus increased infiltration. It has been widely reported that HTC provides a greater infiltration rate compared with a non-cultivated control (Craft et al., 2016; Fontanier et al., 2011; McCarty et al., 2007; Rowland et al., 2009; Schmid et al., 2014; Sorokovsky et al., 2007). McCarty et al. (2007) measured infiltration to be 157% higher after core aerification when compared with a non-treated control, whereas Bunnell et al. (2011) reported a 37 to 58% increase in infiltration rate after core cultivation.

Infiltration rate of AIC and SIC was not different from control. Craft et al. (2016) also reported that SIC applied 5 times per year did not improve the infiltration rate compared to non-treated control. This lack of effect is possibly due to a relatively small area of impact and no alleviation of surface compaction. Craft et al. (2016) speculated that the greater rate of infiltration rate for the HTC was due to greater surface area impact and removal of soil cores. Similarly, Schmid (2014) also observed higher infiltration rate for venting cultivation that impacted higher surface area compared to other venting cultivation and non-cultivated control.

Volumetric Water Content (VWC)

At 7.6 cm depth, no significant interaction effect of treatment and DACE were observed for volumetric water content (Table 6). Similar results were reported by Rowland et al (2009) on bermudagrass greens. The reason for no difference in VWC after cultivation treatment might be due the good drainage of the green before treatment. The control plots averaged an infiltration rate between 25 and 38 cm h^{-1}. This infiltration rate is greater than two golf courses studied in chapter 2.

Organic Matter (OM)

Organic matter ranged from 2.29 to 2.44% in the upper 6.3 cm, but none of the cultivation events reduced organic matter compared to control (Table 6). Schmid et al.

(2004) reported OM of 2.08% to 3.40% on 10-yrs old and 1.59% to 2.48% on 7-yrs-old ‘Providence’ creeping bentgrass green at upper 7.6 cm. Similar to the present study, Sorokovsky et al. (2007) and Craft et al. (2016) reported HTC did not reduce OM compared to control. In a two-year field study conducted on a ‘Providence’ creeping bentgrass putting greens, Schmid et al. (2014) also did not observed reduction in OM after HTC, STC, and venting compared to control. McCarty et al. (2007) did not observe a decrease in OM concentration even after four HTC events. Atkinson et al. (2012) reported reduction in OM concentration with increasing the number of HTC from one to three per year. Similarly, Rowland et al. (2009) also reported that HTC two times per year and HTC three times per year reduced an OM compared to the non-treated control. The lack of any cultivation treatment effect on OM content in the present study may be attributed to the small surface area of impact, the duration of the experiment, and sampling methodology. Furthermore, the regular topdressing sand applied to all plots including control might also have contributed to the inability to detect a difference in OM. The USGA recommends impacting 15 to 20% of the surface area yearly to manage thatch-mat and soil OM (O’Brien and Hartwiger, 2003). In contrast, HTC and SIC events applied in the present study only impacted 4.9 and 3.3% surface area, respectively Clearly changes in OM content are difficult to detect unless a substantial area of the green is impacted.

Bulk Density

Immediately after cultivation, AIC and HTC reduced bulk density compared to control. By 7 DACE, a decreased in bulk density was not observed for either treatment (Table 6). No change in bulk density was observed for SIC. Dickson et al. (2015)

reported AIC decreased bulk density of a compacted native soil bermudagrass athletic fields. Craft et al. (2016) and Dickson et al. (2017) reported no change in soil bulk density after cultivation events including HTC, SIC, or AIC. Murphy and Rieke (1994) reported bulk density was reduced after water injection and HTC. In contrast, Green et al. (2001) did not observe reduction in bulk density after STC or water injection cultivation on annual bluegrass putting green. Atkinson et al. (2012) observed bulk density decreased with increase in surface area impacted and frequency of cultivation events. Previous researchers have observed and concluded that the improvement of bulk density might be short-lived, difficult to detect, and long-term study is needed to modify the existing soil texture that would result in bulk density differences (Green et al., 2001; Lee, 1998; Murphy and Rieke 1994; Robert, 1975).

Conclusion

The HTC was the best cultivation practice for increasing infiltration rate and reducing compaction. Under the conditions encountered in this study, a single application of AIC and SIC was not able to influence infiltration rate, surface firmness, or soil moisture content. None of the cultivation practices reduced organic matter.

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Table 1. Detailed list of cultivation programs (treatments) with specification and timings of air injection cultivation (AIC), sand injection cultivation (SIC), and hollow-tine cultivation (HTC) applied to a creeping bentgrass putting green in Stillwater, Oklahoma.

Treatment†	Spacing	Depth‡	Tine size	Surface area impacted	Aerification timing					
					Fall		Spring		Summer	
	-------------cm-------------			%	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Control	-	-	-	-	-	-	-	-	-	-
AIC	60 x 60	23		-	25 Sept.	11 Oct.	16 March	18 March	9 June	30 May
HTC	5 x 5	5	1.3	4.9	2 Oct.	24 Sept.	16 March	20 March	9 June	30 May
SIC	7.6 x 5	8.8	1.3	3.3	2 Oct.	24 Sept.	19 April	20 March		

† AIC = air injection cultivation (Air2G2; GT Airinject Inc., Jacksonville, FL); HTC = hollow tine cultivation (Pro Core 648; The Toro Company, Bloomington, MN); SIC = sand injection cultivation (DryJect; DryJect Inc., Hatboro, PA). Treatments were applied from September 2017 to May 2019.

‡ Depth represent tine depth for AIC and HTC and average penetration depth for SIC.

Table 2. Particle size distribution of root zone mixtures and topdressing sand applied during the study to a creeping bentgrass putting green in Stillwater, Oklahoma.

Golf course	Fine Gravel[†] (>2.0 mm)	Very coarse (1.0-2.0 mm)	Coarse (0.5-1.0 mm)	Medium (0.25-0.5 mm)	Fine (0.15-0.25 mm)	Very Fine (0.05-0.15 mm)	Silt+ Clay (<0.05 mm)
		--%--					
Root zone mixture	3.16	18.88	31.17	33.62	9.91	2.67	0.58
Top dressing sand	-	33.05	35.93	25.42	4.59	0.84	0.16

[†]Particle size was classified based on USDA textural classification system (USDA, 1951). Particle size were separated by passing soil samples through U.S. standard sieve mesh (No. 10, No. 18, No. 35. No. 60, No. 100, and No. 270).

Table 3. Analysis of variance for the effect of cultivation treatment (TRT), season, and days after cultivation event (DACE) on soil volumetric water content (VWC), surface firmness, infiltration rate, ball roll distance (BRD), normalized difference vegetation index (NDVI), and visual recovery of creeping bentgrass putting receiving air injection cultivation (AIC), sand injection cultivation (SIC), and hollow-tine cultivation (HTC) events in spring, summer and fall in Stillwater, Oklahoma.

Effect	df	VWC	Firmness	Infiltration	BRD	NDVI	Recovery
			Control vs AIC				
TRT	1	NS†	NS	NS	NS	NS	NS
Season	2	***	***	***	**	***	NS
TRT*Season	2	NS	NS	NS	NS	NS	NS
DACE	4	***	***	*	NS	***	NS
TRT*DACE	4	NS	NS	NS	NS	NS	NS
Season*DACE	8	***	***	**	**	***	NS
TRT*Season*DACE	8	NS	NS	NS	NS	NS	NS
			Control vs HTC				
TRT	1	NS	**	*	*	***	***
Season	2	***	*	***	**	***	*
TRT*Season	2	NS	NS	NS	NS	NS	NS
DACE	4	***	***	***	***	***	***
TRT*DACE	4	NS	***	***	***	***	***
Season*DACE	8	***	**	*	***	***	NS
TRT*Season*DACE	8	NS	NS	NS	NS	NS	NS
			Control vs SIC				
TRT	1	NS	NS	NS	NS	NS	***
Season	1	NS	NS	***	*	NS	**
TRT*Season	1	NS	NS	NS	NS	NS	**
DACE	4	*	NS	**	NS	NS	***
TRT*DACE	4	NS	NS	NS	NS	**	***
Season*DACE	4	***	*	*	*	***	NS

*, **, *** significant at $p = 0.05$, 0.01, and 0.001, respectively. † NS, not significant at 0.05 the level.

Table 4. Effect of cultivation type on normalized difference vegetation index (NDVI), recovery percentage and, ball roll distance (BRD) at 0, 7, 14, 21, and 28 days after cultivation event (DACE) on a creeping bentgrass putting green in Stillwater, Oklahoma.

	NDVI‡					Recovery percentage§			Ball roll distance¶				
Treatment†	0 DACE	7 DACE	14 DACE	21 DACE	28 DACE	7 DACE	14 DACE	21 DACE	0 DACE	7 DACE	14 DACE	21 DACE	28 DACE
	-------------------- 0-1--------------------					--------------- 1-100------------			-------------------cm-------------------				
						Control vs AIC							
Control	0.74 a#	0.75 a	0.76 a	0.74	0.75 a	100 a	100 a	100 a	262.4 a	256.1 a	259.5 a	253.9 a	254.1 a
AIC	0.73 a	0.75 a	0.75	0.73	0.75 a	100 a	100 a	100 a	267.0 a	258.4 a	256.6 a	251.2 a	257.5 a
						Control vs HTC							
Control	0.75 a	0.74 a	0.76 a	0.76 a	0.75 a	100 a	100 a	100 a	263.3 a	259.6 a	259.7 a	257.7 a	257.8 a
HTC	0.74 a	0.61 b	0.68 b	0.72 a	0.73 a	53 b	69 b	87 b	272.0 a	240.1 b	243.5 b	250.5 a	252.8 a
						Control vs SIC							
Control	0.75 a	0.77 a	0.75 a	0.74 a	0.73 a	100 a	100 a	100 a	258.8 a	263.8 a	264.5 a	259.8 a	267.5 a
SIC	0.73 a	0.72 b	0.73 a	0.72 a	0.74 a	62 b	78 b	92 b	256.0 a	257.8 a	257.2 a	257.0 a	269.1 a

†AIC = air injection cultivation (Air2G2; GT Airinject Inc., Jacksonville, FL); HTC = hollow tine cultivation (Pro Core 648; The Toro Company, Bloomington, MN); SIC = sand injection cultivation (DryJect; DryJect Inc., Hatboro, PA).

‡Normalized difference vegetation index (NDVI) was measured using a hand-held reflectance meter (Trimble Navigation Inc. Sunnyvale, CA). Measurements were made every week after cultivation event as a single pass across the middle of the plots.

§Recovery percentage was measured on a scale of 0 to 100% (100%= full coverage).

¶Ball roll distance was measured using a 35 cm long modified USGA Stimpmeter. Three balls were rolled in two directions and the average distance traveled by balls was measured.

#Means followed by same letters within each column are not significantly different at $p = 0.05$ significance level.

Table 5. Effect of cultivation type on surface firmness and infiltration rate at 0, 7, 14, 21, and 28 days after cultivation event (DACE) on a creeping bentgrass putting green in Stillwater, Oklahoma.

	Surface firmness(depth of penetration)[‡]					Infiltration rate [§]				
Treatment[†]	0 DACE	7 DACE	14 DACE	21 DACE	28 DACE	0 DACE	7 DACE	14 DACE	21 DACE	28 DACE
	--------------------cm--------------------					--------------------cm h^{-1}--------------------				
					Control vs AIC					
Control	-1.19 a[¶]	-1.16 a	-1.17 a	-1.16 a	-1.18 a	36.7 a	33.4 a	37.8 a	29.7 a	27.7 a
AIC	-1.21 a	-1.17 a	-1.19 a	-1.18 a	-1.19 a	38.0 a	36.0 a	39.8 a	36.1 a	35.5 a
					Control vs AIC					
Control	-1.18 a	-1.17 a	-1.17 a	-1.16 a	-1.16 a	36.1 a	35.5 b	38.6 b	28.0 b	25.3 b
HTC	-1.19 a	-1.28 b	-1.27 b	-1.23 b	-1.22 b	36.7 a	54.0 a	54.3 a	45.4 a	47.2 a
					Control vs SIC					
Control	-1.16 a	-1.17 a	-1.16 a	-1.16 a	-1.18 a	35.8 a	36.6 a	32.4 a	26.2 a	25.1 a
SIC	-1.17 a	-1.20 a	-1.17 a	-1.18 a	-1.18 a	38.8 a	35.3 a	37.2 a	34.9 a	30.7 a

[†]AIC = air injection cultivation (Air2G2; GT Airinject Inc., Jacksonville, FL); HTC = hollow tine cultivation (Pro Core 648; The Toro Company, Bloomington, MN); SIC = sand injection cultivation (DryJect; DryJect Inc., Hatboro, PA).

[‡] Surface firmness was measured using a handheld firmness meter (Field Scout TruFirm; Spectrum Technologies, Inc. Aurora, IL) which records the penetration depth of a falling plunger as it hits a surface. Firmness was measured following single drop of the plunger in nine point across a grid and then averaged to get overall surface firmness of each individual plot. Firmness values are presented as negative values indicating depth below the horizon.

[§] Infiltration rate was measured using a double-ring infiltrometer (15 and 30 cm rings) and falling head technique. Infiltration rate was recorded as the decrease in water within the inner ring after ten minutes.

[¶]Means followed by same letters within each column are not significantly different at $p = 0.05$ significance level.

Table 6. Effect of cultivation type on volumetric water content at 7.6 cm depth, organic matter and bulk density at 0, 7, 14, 21, and 28 days after cultivation event (DACE) on a creeping bentgrass putting green in Stillwater, Oklahoma.

Treatment†	Volumetric water content (7.6 cm depth)‡					Organic Matter§		Bulk Density¶		
	0 DACE	7 DACE	14 DACE	21 DACE	28 DACE	Initial	Final	0 DACE	1 DACE	7 DACE
	--------------------%--------------------					---------%---------		-----------g cm^{-3}-----------		
					Control vs AIC					
Control	25.7 a#	24.9 a	25.2 a	26.0 a	26.2 a	2.43 a	2.32 a	1.69 a	1.70 a	1.70 a
AIC	26.6 a	24.9 a	24.8 a	25.0 a	26.30 a	2.40 a	2.29 a	1.69 a	1.66 b	1.69 a
					Control vs HTC					
Control	24.7 a	25.1 a	24.7 a	26.1 a	26.7 a	2.42 a	2.34 a	1.69 a	1.70 a	1.70 a
HTC	23.8 a	22.7 a	21.9 a	24.1 a	24.2 a	2.30 a	2.32 a	1.69 a	1.65 b	1.70 a
					Control vs SIC					
Control	23.3 a	25.8 a	27.1 a	28.0 a	28.9 a	2.51 a	2.21 a	1.70 a	1.70 a	1.69 a
SCI	22.9 a	26.4 a	26.6 a	28.0 a	28.8 a	2.44 a	2.28 a	1.70 a	1.69 a	1.70 a

†AIC = air injection cultivation (Air2G2; GT Airinject Inc., Jacksonville, FL); HTC = hollow tine cultivation (Pro Core 648; The Toro Company, Bloomington, MN); SIC = sand injection cultivation (DryJect; DryJect Inc., Hatboro, PA).

‡ Volumetric water content was measured using handheld soil moisture meter (FieldScout TDR 300, Spectrum Technologies, Inc. Plainfield, IL) in nine randomly selected points across a grid and then averaged to get overall surface firmness of each individual plot.

§ Organic matter content was determined by the loss on ignition method.

¶ Soil bulk density was measured shortly before each cultivation event, immediately after cultivation event, and one week after the cultivation event. A standard 15 cm soil probe was used to remove a 5 cm diameter core, the upper 1 cm of thatch and verdure were removed from the sample, and remaining core oven dried for 48 h at 105 °C.

#Means followed by same letters within each column are not significantly different at $p = 0.05$ significance level.

CHAPTER IV

EVALUATION OF SELECTED CULTIVATION PROGRAMS FOR MANAGEMENT OF CREEPING BENTGRASS PUTTING GREENS

Abstract

Cultivation is a common practice performed by golf course superintendents on putting greens to improve soil physical properties and reduce organic matter. Surface disruption after cultivation is a major concern of golf course superintendents. Although less invasive cultivation is available and commonly practiced, there is little research examining the effect of less invasive novel cultivation. This study was conducted to investigate the effect of air injection cultivation (AIC) and sand injection cultivation (SIC) alone or in combination with hollow tine cultivation (HTC) on soil moisture content, surface firmness, water infiltration rate, organic matter content, and soil oxygen. A two-year study was conducted on a sand-based research putting green located at the Oklahoma State University Turfgrass Research Center in Stillwater, OK. Hollow tine cultivation alone or in combination with AIC or SIC reduced soil moisture content, reduced surface firmness, and increased infiltration rates. However, normalized difference vegetation index and ball roll distance were reduced at 7 days after HTC. Novel cultivation alone (SIC or AIC) did not affect soil physical properties compared to

the control. Air injection cultivation did not increase soil oxygen concentration compared to the control at 10.2 cm depth. Results suggest annual cultivation programs should not rely strictly on SIC or AIC but these novel practices can be useful supplements to HTC.

Introduction

Cultivation is a common mechanical practice that involves soil disturbance to various degrees without destroying the turfgrass surface to improve soil physical properties and turfgrass performance. The main objective of cultivation is to remove thatch-mat and organic matter or improve soil physical properties for plant growth. The effect of cultivation practice includes increased air-soil gas exchange, reduced soil compaction, increased infiltration rate, reduced water runoff and puddling, improved fertilizer uptake, and stronger turfgrass roots (Baldwin, 2006; Sorokovsky et al. 2007; Turgeon, 1999).

Hollow tine cultivation (HTC) has often been reported to soften the turf surface, even in comparison to other cultivation practices such as verticutting, air injection cultivation (AIC) and sand injection cultivation (SIC) (Bunnell et al. 2001; Craft et al., 2016; Dickson et al., 2017; McCarty et al., 2007; Rowland et al, 2009). Rowland et al. (2009) compared verticutting to HTC and solid tine cultivation (STC) and observed that verticutting provided a firmer surface than either tine cultivation. Cultivation events that include core cultivation typically increase the infiltration rate (Craft et al., 2016; McCarty et al., 2007, Rowland et al., 2009). These effects on infiltration rate can last up to one month after treatment (Bunnell et al., 2001; Sorokovsky et al., 2007). Core cultivation can also reduce soil volumetric water content (VWC) of the upper root zone (Craft et al., 2016; Rowland et al., 2009; Sorokovsky et al., 2007).

Although core cultivation and verticutting can effectively manage thatch and/or soil physical properties, each is reported to have temporary reductions in turf quality that can be unacceptably slow to recover (Atkinson et al., 2012; Bunnell et al., 2001; Craft et al., 2016; Dickson et al., 2017). In a study conducted on a 10-yr-old 'TifEagle' bermudagrass [*Cyanodon dactylon* (L.) Pers. X C. *transvaalensis* Burtt Davy] research putting green in Clemson, SC, turf quality declined for up to 4 weeks after each core cultivation treatment regardless of cultivation frequency or surface area impacted (Atkinson et al., 2012). In another study, conducted on a 7-yrs-old 'A-1' creeping bentgrass [*Agrostis stolonifera* L.] in Knoxville, TN and Elizabethtown, KY, HTC resulted in an immediate 16% reduction in green coverage whereas SIC resulted in a 9% reduction (Dickson et al., 2017). In several instances, decreases in ball roll distance were reported after core cultivation, verticutting, or topdressing (Atkinson et al., 2012; Dickson et al., 2017; McCarty et al., 2007). Increasing demand for high-quality conditions year-round requires a less destructive and fast recovering method of cultivation.

Combining alternative aerification practices such as spiking, slicing, water injection cultivation (WIC) and SIC cultivation with core cultivation are becoming popular (Craft et al., 2016; Fontanier et al., 2011; Karcher and Rieke, 2005; McCarty et al., 2007). McCarty et al. (2007) studied a 3-year-old USGA specification creeping bentgrass putting greens at Clemson University in Clemson, SC, to compare various combinations of verticutting, core aeration, grooming and topdressing. The only treatment that controlled organic matter content was a combination of core cultivation, verticutting (6.4 and 19.1 mm deep), and grooming (3 mm deep and 6.4 mm apart).

Previous researchers have suggested that new technologies should be used in combination with conventional cultivation practices (Craft et al., 2016; Fontanier et al., 2011; Karcher and Rieke, 2005). Karcher and Rieke (2005) concluded that WIC should only be used to supplement, but not to replace HTC to manage surface organic matter. For putting greens having a substantial organic layer, venting cultivation alone was not effective in reducing thatch or improving water infiltration but could be best utilized in combination with other cultural practices to achieve these goals (Fontanier et al., 2011). The United States Golf Association Green Section has similarly recommended against using SIC to replace core aeration or verticutting (Moeller and Lowe, 2016).

Compacted soil with limited soil water infiltration and percolation limit gas exchange. Reduction of oxygen concentration in soil affects the respiration rate of plant roots and microorganisms. Movement of oxygen in the soil mainly occurs by diffusion. The rate of oxygen diffusion in the soil is affected by soil physical properties such as texture, structures, and pore size and its distribution. Compaction of soil due to foot and mechanical traffic modifies the soil structures, which decreases the air-filled pore space, increases the soil bulk density, and decreases the oxygen diffusion rate to the level unfavorable for plant growth (Neira, 2015). There is a close relationship between oxygen diffusion rates, air-filled porosity, and bulk density (Liu, 2004). The root zone soil moisture also plays a role in controlling the oxygen exchange rate. A decrease in oxygen diffusion rate with profile depth is observed due to an increase in soil moisture at a lower profile (Van Wijk, 1980). Mechanical cultivation like coring, slicing, spiking, and forking is commonly used to improve the anaerobic condition of the greens. Previous research has demonstrated variation in soil aeration status with different cultivation practices

(Bunnell et al., 2001; Carrow 2003; Engle and Alderfer 1976; Green et al, 2001; Rieke and Murphy, 1989)

A considerable amount of research has been done to examine the effect of venting, WIC, and SIC (Craft et al., 2016; Fontanier et al., 2011; Karcher and Rieke, 2005). Although there is a significant interest of superintendents on new cultivation technology, researchers have suggested the use of novel cultivation in combination with conventional cultivation. There is little research examining the effect of a combination of new cultivation practice and conventional HTC. Uncertainty remains for how these practices could be used to complement conventional top dressing and cultivations methods. Currently, there is no quantitative information regarding how it can be incorporated with traditional equipment. These technologies should be evaluated through scientific research to verify their efficacy and develop best management practices. Therefore, the objective of this research was to evaluate the effectiveness of combining novel cultivation and conventional cultivation for improving soil physical properties such as VWC, surface firmness, infiltration rates, and controlling organic matter.

Materials and Methods

A two-year field study was conducted from September 2017 to September 2019 on a creeping bentgrass [*Agrostis stolonifera* L. 'Penncross'] green grown in a sand-based root zone mixture at the Oklahoma State University Turfgrass Research Center in Stillwater, Oklahoma. The putting green was maintained at a height of 3.9 mm using a triplex mower with clippings removed after each mowing. The green was fertilized with slow-release granular fertilizer to achieve the annual rate to 293 kg ha^{-1} N, 100 kg ha^{-1} P, and 202 kg ha^{-1} K. Topdressing was applied biweekly with a spinner-type spreader

(Quick pass 300, Tyro-crop, McGrath road Rosedale, B.C. Canada) during the growing season at a rate of 4.9 m^3 ha^{-1} using a locally available kiln-dried material (Mohawk Materials, Tulsa) that met USGA specifications for putting green root zones. A wetting agent (Aquicare™, Winfield solution, LLC, St. Paul, MN) was applied monthly from June to August each year at a rate of 19 L ha^{-1} to reduce the localized dry spot. The experiment station standard fungicide and insecticide program were used on a preventative and curative basis. A combination of bensulide (5.25% a.i) and oxadiazon (1.31% a.i) (Goosegrass/Crabgrass Control, The Andersons Inc., Maumee, OH) was applied at 109 kg ha^{-1} rate in late winter to control annual grassy weeds.

The experiment was designed to compare the effects of two novel cultivation practices (NCP) alone or combined with conventional cultivation practice (CCP) on soil physical properties. The experiment was conducted as a randomized complete block design with four replications of each of eight treatments. The plot size was 1.8 x 2.5 m. Treatments included AIC, SIC (Fall), SIC (Spring), HTC, AIC + HTC, SIC (Fall) + HTC, SIC (Spring) + HTC, and a control (Table 1). All equipment settings were selected based on typical local practices. Air injection cultivation was applied using the Air2G2 (GT Airinject Inc., Jacksonville, FL) set for an injection burst pressure of 345 kPa through 23-cm-long-tine and a tine insertion pressure of 345 kPa on 60 x 60 cm spacing. Sand injection cultivation was accomplished using the DryJect (DryJect Inc., Hatboro, PA) on 7.6 x 5 cm spacing at 10.5 cm tine depth. Hollow tine cultivation was applied using a walk behind aerifier (Pro Core 648, The Toro Company, Bloomington, MN) equipped with 1.3 cm outside diameter and 6.4 cm long tines set at a 5 x 5 cm spacing. Sand used to fill holes for SIC and HTC was the same material previously described for topdressing.

Treatment effects were assessed by measuring infiltration rate, surface firmness, volumetric water content, ball roll distance, organic matter content, and bulk density. Measurements were made within 24-hr before cultivation treatment and subsequent measurements were conducted at 1, 2, 3, and 4 weeks after treatment (WAT), and then monthly thereafter (Table 2).

Infiltration rates were measured using a double ring infiltrometer and falling head technique (Fontanier et al., 2011). The outer ring measure 30 cm and the inner ring measures 15 cm in diameter. Infiltrometer was placed at the center of each plot and inserted approximately 5 cm into the soil surface. Water was added until it reaches the top of both rings. Infiltration rates were recorded as the decrease in the inner ring after 10 minutes. Measurements were repeated until the two consecutive readings were the same.

Surface firmness was measured using a handheld firmness meter (Field Scout TruFirm; Spectrum Technologies, Inc. Aurora, IL) which records the penetration depth of a falling plunger as it hits a surface (Craft et al., 2016; Dickson et al., 2017). Firmness was measured following the single drop of the plunger on nine points across a grid and averaged within each plot for subsequent analyses.

Volumetric water content (VWC) was measured using a handheld soil moisture meter (FieldScout TDR300 Spectrum Technologies, Inc.) and the 7.6 cm probes. The VWC was measured from nine randomly selected points across a grid and then averaged within each plot before subsequent analyses.

Ball roll distance (BRD) was measured using a modified USGA Stimpmeter (Gaussoin et al., 1995; United States Golf Association, 2009). Three balls were rolled from a 35 cm long Stimpmeter in two directions and the average distance traveled by balls was measured.

Normalized difference vegetation index (NDVI) was measured using a handheld NDVI meter (Trimble Navigation Inc. Sunnyvale, CA). Measurements were made within 24 h before cultivation treatment and subsequent measurements were conducted at 1, 2, 3, and 4 weeks after treatment (WAT), and then monthly thereafter as a single pass across the middle of the plots.

Organic matter (OM) content was determined by the loss on ignition method (Atkinson et al., 2012; Snyder and Cisar, 2000). A soil core of 5 cm was removed to the depth of 5 cm using a standard soil probe. Shoots and roots were removed from the sample, and the remaining sample oven-dried for 48 h at 105 °C, allowed to cool to room temperature and weighed. Dried soil samples were then placed in a muffle furnace for 3 h at 550 °C. The weight of the ashed sample was measured after bringing to room temperature. The difference between dry and ashed weights was assume to be organic matter.

The gaseous oxygen content of the soil in AIC and control plots was measured using a soil oxygen sensor (SO-110, Apogee Instruments, Inc., Logan, Utah) fitted with a diffusing head. The sensor was installed vertically with the sensor opening pointed down in accordance with manufacturer recommendations. A single sensor was installed at the 10.2 cm depth in each control and AIC plot. An additional sensor was installed at the 22.8 cm depth in each AIC plot. The voltage output from the sensor was converted to the percentage of oxygen (Eq. 1) by multiplying by manufacturer calibration factors and then subtracting the offset:

$$\text{Oxygen (\%)} = CF.\ mV_M - \text{Offset} \qquad \text{Eq. 1}$$

where CF is calibration factor, mV_M is voltage output (mV) and Offset is derived by multiplying CF by mVo (Eq. 2)

$$CF = \frac{20.95\ \%}{mVc - mVo} \qquad \text{Eq. 2}$$

mVc is sensor voltage output [mV] during calibration and mVo is sensor voltage output [mV] under zero oxygen (0 kPa O2). mVc was measured in well-ventilated area. mVo was estimated to be 3.0 mV and used same for all sensor as recommended by apogee Instrument.

Statistical Analysis

The experiment was analyzed as a randomized complete block design having four replications of each treatment. The treatments were arranged as a four by two factor design representing NCP (AIC, SIC (fall), SIC (spring), control) and CCP (HTC or control). Data were averaged across each year and analysis of variance was performed to evaluate main and interaction effects of the two factors with the GLIMMIX procedure in Statistical Analysis System (Version 9.3; SAS Inc., Cary, NC). All tests were performed at a significance of 0.05. Data collected over two years were pooled (Table 3). To also evaluate the immediate response of each treatment, measurements taken 7 days after NCP were analyzed separately following similar methods.

Oxygen data were averaged across each year and the main effect of treatment on soil oxygen was evaluated using analysis of variance with the GLIMMIX procedure in Statistical Analysis System (Version 9.3; SAS Inc., Cary, NC). All tests were performed at a significance of 0.05. To also evaluate the immediate response of treatment, soil oxygen data one day after treatment were analyzed separately (Table 7).

Results and Discussion

The main effect of NCP was not significant for any measured variable except for firmness. However, the main effect of CCP was significant for all parameters measured (Table 3). The two-way interaction effect was significant for VWC and infiltration rate but no other variables. Thus, VWC and infiltration rate data are presented as the interaction, while other variables are pooled across NCP to examine the CCP main effect.

Volumetric Water Content (VWC)

Treatments that included HTC had lower annual mean VWC compared to those that did not, with the exception of SIC (fall) alone which resulted in similar VWC as SIC (fall) + HTC (Table 4). Combining AIC or SIC with HTC did not provide additional reduction in VWC compared to HTC alone. Craft et al. (2016) reported HTC + SIC lowered VWC compared to control. The lower VWC in the combination treatment was attributed to HTC creating a surface hole, removing organic matter with soil core, and AIC creating a subsurface fracture through which water drain. Not only did NCP have limited effect on annual mean VWC, but even at 7 days after cultivation (Table 6), only the main effect of CCP was detectable.

Infiltration Rate

Treatments with HTC had faster infiltration than those that did not (Table 4). Infiltration rate for AIC or SIC alone was similar to the control (Table 4). Combining HTC with AIC increased infiltration rate over HTC alone. In contrast, incorporating SIC with HTC did not enhance infiltration rates over HTC alone. It has been widely reported that HTC increases infiltration rates (Craft et al., 2016; Fontanier et al., 2011; McCarty et al., 2007; Rowland et al., 2009; Schmid et al., 2007; Sorokovsky et al., 2007). McCarty et al. (2007) reported cultivation that incorporates HTC had increased infiltration rate compared to control, verticutting, and grooming. One explanation for no effect of AIC on infiltration rate is the minimum surface area impact. Schmid et al. (2007) reported venting treatment which has least surface area impact did not improve infiltration rate. Channels created by venting with minimum surface area impact can be sealed before infiltration could be measured (Fontanier et al., 2011). No change in infiltration rate after SIC may be associated with reduction in macropores, which may have been destroyed or compressed by high pressure sand injection.

Even at 7 DACE, NCP had no effect on infiltration rate (Table 6). Only the main effect of CCP was detectable. The larger channel created by HTC and the physical removal of OM likely contributed to the larger and longer-term effect on infiltration.

Surface Firmness

The main effect of NCP was not significant indicating firmness for AIC and SIC were similar to the control (Table 3). Investigation of the interaction suggested no differences among any treatment combinations (table 4). However, the CCP main effect was much larger and it indicated HTC decreased firmness compared to the control (Table 5).

At 7 DACE, only the main effect of CCP was observed. Similar to the present study, McCarty et al. (2007) and Murphy et al. (1993) reported that creeping bentgrass treated with HTC had reduced surface firmness compared with control. This is presumably due to the removal of cores creating less surface stability.

Ball Roll Distance (BRD)

The CCP main effect resulted in HTC having reduced BRD compared to the control (Table 5). It is widely reported that HTC can reduce ball roll distance during the recovery period but it is still surprising that this effect is detectable when aggregating measurements across an entire year (Dickson et al., 2017; McCarty et al., 2007). The lack of effect due to NCP for ball roll distance suggests minimal disturbance to the surface and fast recovery. Similar evidence was seen when examining data at 7 DACE. Specifically, ball roll distance for either AIC or SIC (fall or spring) was similar to control even at 7 DACE. McCarty et al. (2007), observed reduction in ball roll distance by core cultivation compared to control and topdressing itself at 7 DAT. Similarly, Dickson et al. (2017) reported that BRD on SIC were similar to a non-treated control, while HTC reduced ball roll compared with the non-treated control. In contrast to our result, Dickson et al. (2017) reported increases in BRD immediately after AIC compared to non-treated control.

Normalizes Difference Vegetation Index (NDVI)

The main effect of CCP resulted in lower NDVI values for HTC compared to the control (Table 5). This finding reinforces that HTC resulted in a large surface area impacted and slower recovery than AIC or SIC. At 7 DACE, the main effect of CCP again resulted in lower NDVI for HTC than the control. However, the main effect of NCP showed that SIC also had lower NDVI than AIC or the control. These results are not surprising and closely follow the surface area impacted of each treatment.

Organic Matter (OM)

Differences in OM concentration were not observed between AIC or SIC and non-treated control. In contrast, treatments that included HTC reduced OM. The USGA recommends impacting 15 to 20% of the surface area yearly to manage thatch-mat and soil OM (O'Brien and Hartwiger, 2003). In contrast, SIC applied in this study only impact 3.3% surface area. Although both SIC and HTC incorporated sand for dilution of the organic layer, HTC is the only treatment that involved removal of organic matter. Atkinson et al. (2012) reported that as the number of HTC events per year increased from one to three, OM concentration was reduced. Similarly, Rowland et al., (2009) also reported that HTC 2 times per year and HTC 3 times per year reduced an OM compared to the non-treated control.

Craft et al. (2016) did not observe differences in thatch-mat depth after SIC during a 2-yr study on an ultradwarf bermudagrass putting greens. Similar to thatch-mat layer, difference in OM concentration (average 5%) between treatments were not observed. The other reason for no detectable difference in OM might be the topdressing sand applied across all treatment which could have masked the effect of SIC and AIC. Beard (1973) suggested topdressing alone can be effective in controlling. Soil organic matter can be highly variable and these studies illustrate the challenge in detecting differences in field studies. More numerous or larger soil core sample may be required to detect changes in soil organic matter for short duration experiments.

Soil Oxygen

The annual average soil oxygen (O_2) concentration at 10.2 cm depth is 18.3% and at 22.8 cm depth is 17.1%. Similar to findings in our study, Brotherton (2011) observed the O_2 concentration of 17.6 to 20.9% in a creeping bentgrass green. The range of O_2 for optimum plant growth is 5 to 15% (Luxmooree et al., 1970; Barden et al., 1987). Regardless of cultivation, soil O_2 was adequate for turf growth at 10.2 cm depth. Previous research has also reported soil O_2 concentration above optimum range for turf growth regardless of cultivation practices (Barden et al., 1987; Brotherton, 2010; Green et al., 2001; Luxmooree et al., 1970). Green et al. (2001) observed cultivation had no effect on ODR. In contrast, Bunnell et al. (2001) reported soil oxygen levels were increased following conventional hollow tine treatment on 'Penn A-1' and 'Crenshaw' creeping bentgrass compared to control at 15 days after treatment. However, at the 20 cm depth, differences in oxygen concentration were not observed. Engle Alderfer (1967) also reported a 20% increase in ODR with spoon-type cultivation. Similar to our findings, Brotherton reported O_2 concentration above optimum range for turf growth during May to October. In contrast to our findings, Carrow (2003) reported low O_2 concentration levels at 3 cm depth under hot summer conditions. The lack of effect and overall high oxygen concentration in this green may be attributed to high drainage and air-filled porosity. The result might have been different if the study is conducted in compacted soil where gas exchange was limited.

At the 22.8 cm depth oxygen levels were lower than at 10.2 cm depth. Bunnell et al. (2001) reported a similar reduction in O_2 at the 22.2 cm depth compared to the 9 cm depth. A decrease in soil O_2 content with profile depth is attributed to an increase in soil moisture at a lower profile (Van Wijk, 1980). Soil O_2 concentration declined from March to August each year at each depth with a larger decline observed at the 22.8 cm depth (Figure 1 and 2).

Conclusion

Annual cultivation programs using AIC or SIC alone did not consistently influence VWC, surface firmness, or infiltration rate. Incorporation of HTC with AIC or SIC increased infiltration rate, reduced firmness, and VWC. Since novel cultivation itself was not effective in reducing VWC and surface firmness and increasing infiltration, result suggests a need for HTC in maintaining desirable soil physical properties. Incorporation of AIC with HTC showed evidence for further increases in infiltration rates compared to HTC alone. Although SIC showed minimal effect on any of the measured variables, combining SIC with HTC can provide similar benefits as HTC alone with the ability to increase the amount of sand incorporated into the thatch-mat layer. Continuing research is needed to further investigate the long-term benefit of combination of conventional and novel cultivation in managing soil organic matter, soil bulk density, and infiltration rate.

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Table 1. Detailed list of annual cultivation programs (treatments) with specification and timings of novel cultivation practices (NCP) including air injection cultivation (AIC) and sand injection cultivation (SIC) and conventional cultivation practices (CCP) including hollow-tine cultivation (HTC) applied to a creeping bentgrass putting green in Stillwater, Oklahoma.

NCP†	CCP	Spacing	Depth‡	Surface Area Impacted
		cm	cm	%
Control	Without HTC§			
AIC		60 x 60	23	
SIC Fall		7.6 x 5	8.8	3.3
SIC Spring				3.3
Control	HTC	5 x 5	5	4.9
			23	
AIC		5 x 5	5	4.9
SIC Fall		7.6 x 5	8.8	
		5 x 5	5	8.2
SIC Spring		7.6 x 5	8.8	
		5 x 5	5	8.2

†AIC = air injection cultivation (Air2G2; GT Airinject Inc., Jacksonville, FL); HTC = hollow tine cultivation (Pro Core 648; The Toro Company, Bloomington, MN); SIC = sand injection cultivation (DryJect; DryJect Inc., Hatboro, PA). Treatments were applied from September 2017 to May 2019.

‡Depth represent tine depth for AIC and HTC and average depth of penetration for SIC.

AIC applied 3 times per year in March, June, and September; SIC Fall applied 1 time per year in September; SIC spring applied 1 time per year in March; HTC applied 2 times per year in March and Spring.

§HTC treatment was applied approximately 1 week before SIC. 1.3 cm diameter tine was used for HTC.

Table 2. Particle size distribution of root zone mixtures and topdressing sand applied to a creeping bentgrass putting green in Stillwater, Oklahoma.

Golf course	Fine Gravel† (>2.0 mm)	Very Coarse (1.0-2.0 mm)	Coarse (0.5-1.0 mm)	Medium (0.25-0.5 mm)	Fine (0.15-0.25 mm)	Very Fine (0.05-0.15 mm)	Silt + Clay (<0.05 mm)
		--------------------	--------------------	----------%----------	--------------------	--------------------	
Root zone mixture	3.13	22.34	33.12	30.73	8.17	2.09	0.42
Top dressing sand	-	33.05	35.93	25.42	4.59	0.84	0.16

†Particle size was classified based on USDA textural classification system (USDA, 1951). Particle size were separated by passing soil samples through U.S. standard sieve mesh (No. 10, No. 18, No. 35. No. 60, No. 100, and No. 270).

Table 3. Summary analysis of variance table for the effect of novel cultivation practices (NCP) and conventional cultivation practices (CCP) on volumetric water content (VWC), surface firmness, infiltration rate, ball roll distance (BRD), and normalized difference vegetation index (NDVI) of a creeping bentgrass putting green in Stillwater, Oklahoma during the years 2017 to 2019.

Effect	DF	VWC	Infiltration	Firmness	BRD	NDVI	OM
			Annual Means				
NCP	3	NS[†]	NS	NS	NS	NS	NS
CCP	1	***	***	***	*	***	*
NCP × CCP	3	**	*	NS	NS	NS	NS
			7 Days after NCP				
NCP	3	NS	NS	NS	NS	***	
CCP	1	***	***	***	**	***	
NCP × CCP	3	NS	NS	NS	NS	NS	

*, **, *** significant at $p = 0.05$, 0.01, and 0.001, respectively.

† NS, not significant at $p = 0.05$ significance level.

Table 4. Interaction effect of novel cultivation practices (NCP) using air injection (AIC) or sand injection (SIC) and conventional cultivation practices (CCP) using hollow-tine core aerification (HTC) on annual mean volumetric water content (VWC) at 7.6 cm depth, surface firmness, infiltration rate, ball roll distance (BRD), normalized difference vegetation index (NDVI), and organic matter content (OM) on a creeping bentgrass putting green in Stillwater, Oklahoma.

NCP	CCP	VWC† 7.6 cm depth	Firmness‡	Infiltration§	BRD¶	NDVI#	OM††
		%	cm	cm h^{-1}	cm	0-1	%
Control	without HTC	22.4 a†††	-1.14 a	36.6 c	258.4 a	0.72 a	2.3 a
AIC		22.4 a	-1.14 a	37.4 c	259.1 a	0.72 a	2.2 a
SIC Fall		21.2 ab	-1.12 a	39.5 c	260.7 a	0.71 a	2.2 a
SIC Spring		21.5 ab	-1.14 a	39.7 c	256.2 a	0.71 a	2.2 a
Control	with HTC	19.6 c	-1.18 a	52.6 b	255.1 a	0.70 a	2.1 a
AIC		19.1 c	-1.16 a	58.3 a	255.8 a	0.70 a	2.1 a
SIC Fall		20.3 bc	-1.16 a	53.1 b	257.1 a	0.70 a	2.2 a
SIC Spring		19.6 c	-1.17 a	56.5 ab	254.2 a	0.70 a	2.1 a

†Volumetric water content was measured using handheld soil moisture meter (FieldScout TDR 300, Spectrum Technologies, Inc. Plainfield, IL) in nine randomly selected points across a grid and then averaged to get overall surface firmness of each individual plot.

‡Surface firmness was measured using a handheld firmness meter (Field Scout TruFirm; Spectrum Technologies, Inc. Aurora, IL) which records the penetration depth of a falling plunger as it hits a surface. Firmness was measured following single drop of the plunger in nine point across a grid and then averaged to get overall surface firmness of each individual plot. Firmness values are presented as negative values indicating depth below the horizon.

§Infiltration rate was measured using a double-ring infiltrometer (15 and 30 cm rings) and falling head technique. Infiltration rate was recorded as the decrease in water within the inner ring after ten minutes.

¶Ball roll distance was measured using a 35 cm long modified USGA Stimpmeter. Three balls were rolled in two directions and the average distance traveled by balls was measured.

#Normalized difference vegetation index (NDVI) was measured using a hand-held reflectance meter (Trimble Navigation Inc. Sunnyvale, CA). Measurements were made every week after cultivation event as a single pass across the middle of the plots.

††Organic matter content was determined by the loss on ignition method.

†††Means within each column followed by the same letter are not significantly different at the $p = 0.05$ significance level.

Table 5. Main effects of novel cultivation practices using air injection (AIC) or sand injection (SIC) and main effects of conventional cultivation practices using hollow-tine cultivation (HTC) on annual mean volumetric water content (VWC) at 7.6 cm depth, surface firmness, infiltration rate, ball roll distance (BRD), normalized difference vegetation index (NDVI), and organic matter content (OM) on a creeping bentgrass putting green in Stillwater, Oklahoma.

Treatment	VWC (7.6 cm depth)†	Firmness‡	Infiltration§	BRD¶	NDVI#	OM††
	%	cm	cm h^{-1}	1-9	cm	%
		Main Effect of Novel Cultivation Practices				
Control	21.0 a†††	-1.16 b	44.6 a	0.71 a	256.8 a	2.2 a
AIC	20.8 a	-1.15 ab	47.9 a	0.71 a	257.4 a	2.1 a
SIC Fall	20.8 a	-1.14 a	46.3 a	0.71 a	258.9 a	2.2 a
SIC Spring	20.6 a	-1.16 b	48.1 a	0.71 a	255.2 a	2.1 a
		Main Effect of Conventional Cultivation Practices				
With HTC	19.7 b	-1.16 b	55.1 a	0.70 b	255.5 b	2.0 b
Without HTC	22.0 a	-1.13 a	38.3 b	0.72 a	258.7 a	2.2 a

†Volumetric water content was measured using handheld soil moisture meter (FieldScout TDR 300, Spectrum Technologies, Inc. Plainfield, IL) in nine randomly selected points across a grid and then averaged to get overall surface firmness of each individual plot.

‡Surface firmness was measured using a handheld firmness meter (Field Scout TruFirm; Spectrum Technologies, Inc. Aurora, IL) which records the penetration depth of a falling plunger as it hits a surface. Firmness was measured following single drop of the plunger in nine point across a grid and then averaged to get overall surface firmness of each individual plot. Firmness values are presented as negative values indicating depth below the horizon.

§Infiltration rate was measured using a double-ring infiltrometer (15 and 30 cm rings) and falling head technique. Infiltration rate was recorded as the decrease in water within the inner ring after ten minutes.

¶Ball roll distance was measured using a 35 cm long modified USGA Stimpmeter. Three balls were rolled in two directions and the average distance traveled by balls was measured.

#Normalized difference vegetation index (NDVI) was measured using a hand-held reflectance meter (Trimble Navigation Inc. Sunnyvale, CA). Measurements were made every week after cultivation event as a single pass across the middle of the plots.

††Organic matter content was determined by the loss on ignition method.

††† Means within each column followed by the same letter are not significantly different at the $p = 0.05$ significance level.

Table 6. Main effects of novel cultivation practices using air injection (AIC) or sand injection (SIC) and main effects of conventional cultivation practices using hollow-tine cultivation (HTC) on annual mean volumetric water content (VWC) at 7.6 cm depth, surface firmness, infiltration rate, ball roll distance (BRD), normalized difference vegetation index (NDVI), and organic matter content (OM) one week after cultivation event on a creeping bentgrass putting green in Stillwater, Oklahoma.

Treatment	VWC (7.6 cm depth)†	Firmness‡	Infiltration§	BRD¶	NDVI#
	%	cm	cm h^{-1}		cm
		Main Effect of Novel Cultivation Practices			
Control	20.4 a‡	-1.16 a	49.7 a	0.72 a	255.3 a
AIC	20.3 a	-1.15 a	53.1 a	0.72 a	257.9 a
SIC Fall	20. 6 a	-1.16 a	50.7 a	0.70 b	261.1 a
SIC Spring	20.6 a	-1.17 a	48.5 a	0.70 b	253.2 a
		Main Effect of Conventional Cultivation Practices			
With HTC	19.3 b	-1.19 b	61.1 a	0.69 b	252.5 b
Without HTC	21.7 a	-1.13 a	40.0 b	0.73 a	261.2 a

†Volumetric water content was measured using handheld soil moisture meter (FieldScout TDR 300, Spectrum Technologies, Inc. Plainfield, IL) in nine randomly selected points across a grid and then averaged to get overall surface firmness of each individual plot.
‡Surface firmness was measured using a handheld firmness meter (Field Scout TruFirm; Spectrum Technologies, Inc. Aurora, IL) which records the penetration depth of a falling plunger as it hits a surface. Firmness was measured following single drop of the plunger in nine point across a grid and then averaged to get overall surface firmness of each individual plot. Firmness values are presented as negative values indicating depth below the horizon.
§Infiltration rate was measured using a double-ring infiltrometer (15 and 30 cm rings) and falling head technique. Infiltration rate was recorded as the decrease in water within the inner ring after ten minutes.
¶Ball roll distance was measured using a 35 cm long modified USGA Stimpmeter. Three balls were rolled in two directions and the average distance traveled by balls was measured.
#Normalized difference vegetation index (NDVI) was measured using a hand-held reflectance meter (Trimble Navigation Inc. Sunnyvale, CA). Measurements were made every week after cultivation event as a single pass across the middle of the plots.
††Means within each column followed by the same letter are not significantly different at the $p = 0.05$ significance level.

Table 7. Analysis of variance for effect of air injection cultivation on daily mean soil oxygen concentration of a creeping bentgrass putting green in Stillwater, Oklahoma.

Effect	df	Soil oxygen
	Averaged within Each Year	
Treatment	2	***
Year	1	***
Treatment*Year	2	NS[†]
	One Day after a Cultivation Event	
Treatment	2	***
Year	1	***
Year*Treatment	2	NS

*, **, *** significant $p = 0.05$, 0.01, and 0.001, respectively.

[†] NS, not significant at $p = 0.05$.

Table 8. Effect of air injection cultivation (AIC) on daily mean soil oxygen concentration of a creeping bentgrass putting green in Stillwater, Oklahoma.

Treatment†	Oxygen concentration‡	
	Annual Mean	One Day after Event
	---------------%---------------	
Control	18.30 a§	18.13 a
AIC at 10.2 cm	18.31 a	18.29 a
AIC 22.8 cm	17.09 b	17.12 b

† AIC = air injection cultivation (Air2G2; GT Airinject Inc., Jacksonville, FL); air injection is applied on March, June and September.

‡The gaseous oxygen content was measured using a soil oxygen sensor (SO-110, Apogee Instruments, Inc., Logan, Utah) fitted with a diffusing head. The sensor was installed vertically with the sensor opening pointed down in accordance with manufacturer recommendations.

§Means within each column followed by the same letter are not significantly different at the $p = 0.05$ significance level.

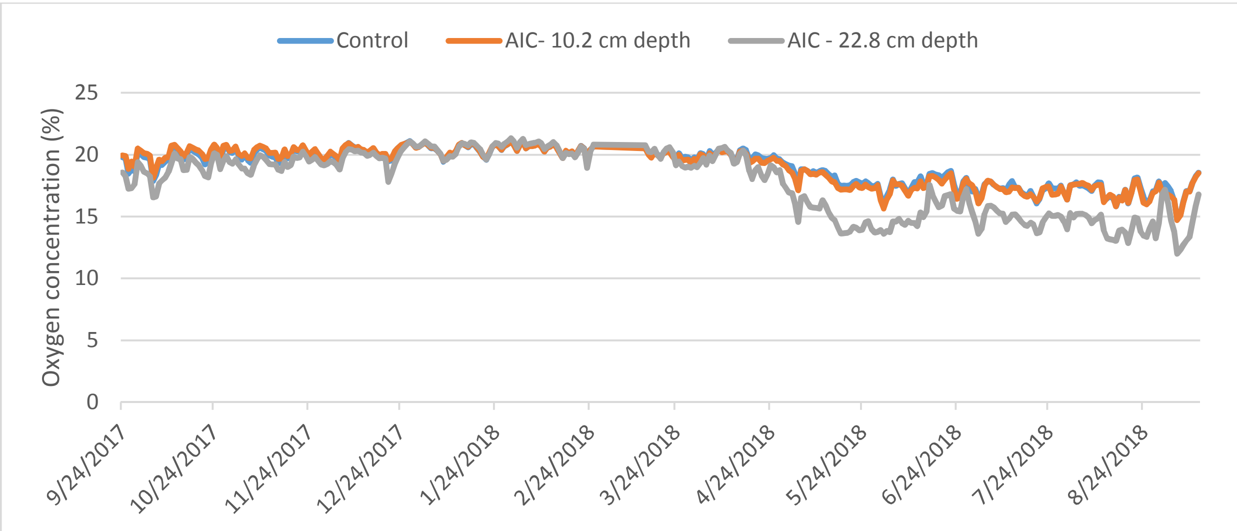

Figure 1. Effect of air injection cultivation (AIC) on daily mean soil oxygen concentration of a creeping bentgrass putting green in Stillwater, Oklahoma from September 2017 to September 2018. Air injection cultivation was applied on 25 Sept. 2017, 16 March 2018, and 9 June 2018

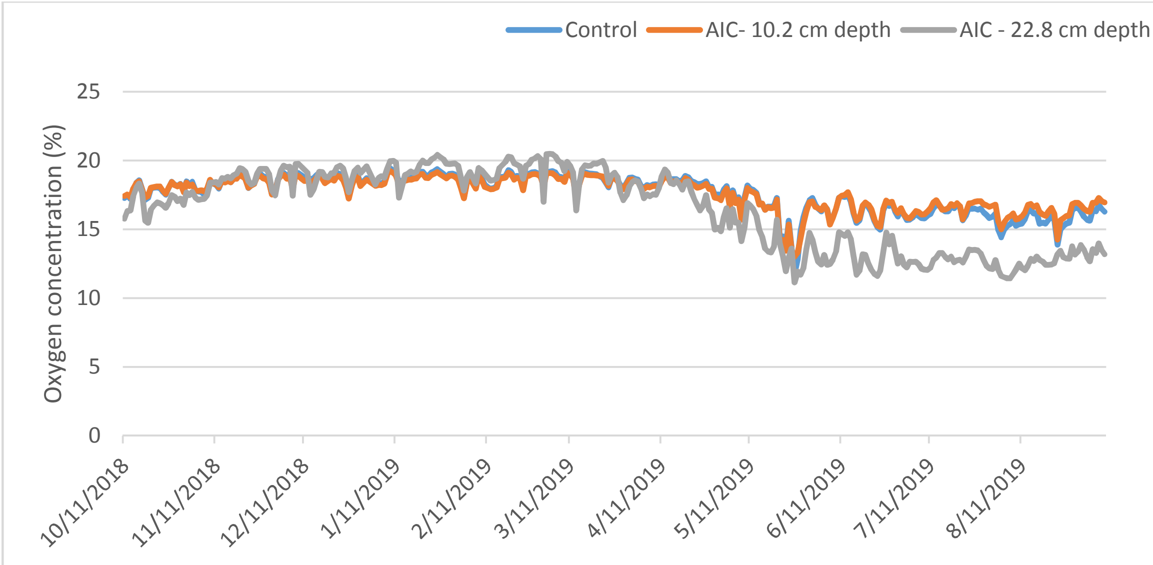

Figure 2. Effect of air injection cultivation (AIC) on daily mean soil oxygen concentration of a creeping bentgrass green in Stillwater, Oklahoma from October 2018 to September 2019. Air injection cultivation was applied on 11 Oct. 2018, 18 March 2019, and 30 May 2019

CHAPTER V

EFFECTS OF TEMPORAL SHADE ON PHOTOSYNTHETIC RATE OF CREEPING BENTGRASS

Abstract

Shade can be detrimental to turfgrass growth, development, and quality. The most common and obvious effect of shading is the reduction in light intensity which limits energy available for photosynthesis. Shade is rarely constant and instead fluctuates throughout the day. The effect of shade timing on turfgrass performance has been examined under field studies for several species but still remains unclear. The objective of this study was to determine the effect of temporal shade on photosynthesis of creeping bentgrass (*Agrostis stolonifera* L.). Plugs of '007' creeping bentgrass were established in 2.5 cm diameter growth tubes containing sand and allowed to establish in the greenhouse for 4 weeks. Subsequently, growth tubes were placed adjacent to a vertical shade structure in order to apply "morning shade", "afternoon shade", or "non-shaded". Net photosynthesis was measured at multiple light intensities between 0 and 2000 $\mu molm^{-2}s^{-1}$. Plants subjected to shade demonstrated lower light compensation points (LCP), light saturation points (A_{max}), and dark respiration (R_D) compared to plants grown in the non-shaded environment. There was no difference between morning shade and afternoon

shade for A_{max}, LCP, or R_D. Shoot dry weight was lower in the morning shade compared to afternoon shade and non-shade control. Photosynthetic rate of creeping bentgrass under morning shade was not different from afternoon shade.

Introduction

Shade can be detrimental for the growth and development of turfgrass. In the United States, it is estimated that 25% of the turfgrass area are under shade condition (Beard, 1973). The most common and obvious effect of shading is the reduction in light intensity. Shading causes, the partial or complete interception of direct solar radiation. Morphological and physiological changes have been observed in turf growth in the presence of shade (McBee, 1969; Standford et al., 2005). Plants adapt to changing light conditions by adjusting leaf morphology, structure, and biochemistry (Patterson, 1980). Shaded plants are usually taller and have lower dry weights and thinner stems (Dudeck and Peacock, 1992). Shade also affects the internode length, stem, and rhizome branching. Root production as well as root: shoot ratio are reduced by a low light environment (Wherley et al., 2015). Shade stress also affects the physiology of turfgrasses such as pigment concentration and carbohydrates reserve (Bunnell et al., 2005c). Shade provided by trees, shrubs, and buildings often reduces air circulation and increases relative humidity resulting in a microclimate conducive to disease development (Bell and Danneberger, 1999).

Creeping bentgrass has good shade tolerance in comparison to many other turfgrasses (Turgeon, 1991). However, low mowing heights typical of putting greens reduces the residual leaf area available for photosynthesis and thus making plants more sensitive to shade stress. On golf courses, due to the orientation of trees and other structures, shade is rarely constant and instead fluctuates throughout the day. Some areas may be shaded for a partial day whereas others may be continuously under shade. Morning shade is often considered detrimental to turfgrass health (Freeman, 2012). When shade occurs in the morning, the leaf surface can remain wet with dew for many hours thus exacerbating disease pressure (Bell and Danneberger, 1999). Bell and Danneberger (1999) reported that creeping bentgrass receiving sunlight only for 40% of the day maintains color, density, and tissue mass even when it receives 31% less light than full sun. The result suggests that shade intensity and duration limits the turfgrass growth and development rather than timing of shade (Bell and Danneberger, 1999). The minimum quantity of light required to maintain healthy turfgrass can be defined in terms of a daily light integral (DLI), which is the accumulated photosynthetic photon flux density (PPFD) for a 24 h period and is measured in units of mol m^{-2} d^{-1} (Zhang et al., 2017).

Morning shade is often considered detrimental to turfgrass health (Freeman, 2012). However, Bell and Danneberger (1999) did not found any difference in turf color, density, and total nonstructural carbohydrates (TNC) of creeping bentgrass exposed to morning shade, afternoon shade, and full sun. In contrast, a recent study conducted on '007' creeping bentgrass greens in Arkansas demonstrated that afternoon shade was more detrimental to turfgrass quality than morning shade (Russell et al., 2019). Afternoon shade was more detrimental to 'TifEagle' bermudagrass [*Cynodon dactylon* (L.) Pers x *C. transvaalensis* Burtt-Davy] growth and performance than morning shade in South Carolina (Bunnell et al., 2005c). Dense afternoon shade (90%) reduced the turfgrass quality and lateral root growth by 31% and 17%, respectively, compared to the control whereas the morning shade reduced turfgrass quality and lateral root growth by 13% and

11%, respectively, compared with the control (Bunnell et al., 2005c). Seashore paspalum [*Paspalum vaginatum* Swartz] receiving 90% morning and afternoon shade for five hours exhibited no detrimental growth effects in the absence of traffic (Jiang et al., 2003). However, afternoon shade was more detrimental than morning shade when plants were subjected to concurrent traffic stress (Jiang et al., 2003).

Turfgrasses gain carbon through photosynthesis and utilizes it for growth, reproduction, and metabolic functions. If the assimilated carbon is more than required, then it is stored as carbohydrates for later use. The major nonstructural carbohydrates found in turfgrass are water soluble carbohydrates (i.e., glucose, fructose, sucrose) and storage carbohydrates (i.e. starch and fructans) (Smith, 1972). These TNC are considered as the energy reserve and used under stress conditions when its production could not meet the plant requirement. Total nonstructural carbohydrates are used as a physiological measure of stress tolerance in grass (Beard 1973; Watschke, et al., 1973). Previous studies have reported a reduction in TNC with reduced irradiance (Bunnell et al., 2005c; Jiang et al., 2005; Schnyder and Nelson, 1988). The total production of TNC in bermudagrass decreases with reduced irradiance (Bunnell et al., 2005a, 2005b, and 2005c). The TNC decreased by 43% when the irradiance was reduced from 300 to 60 $\mu mol\ m^{-2}\ s^{-1}$ (Schnyder and Nelson, 1988). The content of water soluble carbohydrate was decreased by 52% in Sea Isle 1 seashore paspalum and 66% in 'Tifsport' bermudagrass grown under low light conditions (60-100 $\mu mol\ m^{-2}\ s^{-1}$) (Jiang et al., 2005). Morning and afternoon shade application is reported to influence the TNC concentration of TifEagle bermudagrass (Bunnell et al., 2005c). Dense afternoon shade (90%) reduced TifEagle bermudagrass TNC by 27% compared to no afternoon shade. Morning shade had no effect on TNC (Bunnell et al., 2005c). In a contrast, Bell and Danneberger (1999) did not find any difference in TNC of creeping bentgrass exposed to morning shade, afternoon shade, and full sun.

Huylenbroeck et al. (2001) observed that net photosynthesis of shade tolerant grasses reached saturation at a lower photosynthetic photon flux density (PPFD) compared to less tolerant species. A field study was conducted to evaluate the effect of reduced irradiance (65% of ambient sunlight) on photosynthetic capacity, pigment content, and growth of commercial cultivars of perennial rye grass (*Lolium perene* L.), red fescue (*Festuca rubra* L.), smooth-stalked meadowgrass (*Poa pratensis* L.) and crested (*Koeleria macrantha* (Ledeb.) Schultes). Difference between species in net photosynthesis measured at 700 μmol m^{-2} s^{-1} were observed. A reduction in maximum photosynthetic rate, increased in maximum photosynthetic rate, and no difference in light response curve were observed between turf plots grown under shade and non-shade control. A decrease in light saturation, net photosynthesis rate, dark respiration, and light compensation point was also observed in grass grown under shade (Wilkinson et al., 1975). In contrast, Kephart et al., (1992) reported C_3 and C_4 grass grown in 37 and 70% of ambient sunlight regimes for 55 days had similar net CO_2 exchange rate compared to those grown in full sunlight.

Field observations suggest that morning shaded areas decline more readily than those areas shaded in the afternoon (Bell and Danneberger, 1999; Freeman, 2012). Despite this, the results of most field studies investigating temporal shade have either been inconclusive or concluded afternoon shade as more detrimental. A filed study conduct at University of Arkansas on creeping bentgrass reported afternoon shade resulted in lower turfgrass coverage than morning shade (Russell et al., 2019). The objective of this study was to evaluate the effect of morning or afternoon shade on creeping bentgrass photosynthesis and to evaluate the difference in photosynthesis measured in morning vs afternoon.

Materials and Methods

Two greenhouse studies were conducted at the Oklahoma State University Horticulture Research Greenhouse located in Stillwater, Oklahoma. Experiment 1 was conducted from 10 June to 10 Aug. 2019. Experiment 2 was conducted from 10 Aug. to 20 Oct. 2019.

Plugs of '007' creeping bentgrass were collected to 2.5 cm depth from an established green and grown in a pot of 3.8 cm diameter and 10 cm in height (LI COR, Inc., Lincoln, NE). The pot contained sand as a growth medium. Grasses were fertilized at 4.8 kg ha^{-1} N using Peters Professional 20-20-20 N-P_2O_5-K_2O (The Scotts Company, Marysville, OH) every week. Grasses were clipped at a height of 1 cm every three days and clippings were collected. Irrigation was provided to avoid drought stress or wilt. Grasses received natural light plus supplemental lighting from a 400-watt high pressure sodium lamp (Rudd lighting Inc., Racine, WI). One month after planting, pots were assigned one of three shade treatments: 'morning shade', 'afternoon shade', or 'no shade'. The experiment was designed as a completely randomized design with four replications of each treatment. Pots were rearranged every week within their respective shade treatment. The shade was created using 90% light reduction black polyester shade cloth (International Greenhouse Company, model # SC-BL90, Danville, IL) (Bell and Danneberger, 1999; Russell et al., 2019) hung on a vertical structure constructed using polyvinyl chloride pipe. The shade structure was 150 cm long and 150 cm high and oriented facing the east and west. Pots were placed within close proximity of the structure such that shade was applied uniformly to plants in accordance with their respective treatment assignment (e.g., morning shade was applied from dawn to ~1200 h to plants on the west side of the structure).

Net photosynthesis was measured using a portable photosynthesis system (LI-6400XT, LI COR, Inc., Lincoln, NE) equipped with an Arabidopsis chamber following methods similar to Kreuser (2004). The chamber provides constant relative humidity of 60% and at 30 °C and 400 ppm sample CO_2 concentration. Measurements were made at discrete light intensities using an AutoProgram that progressively lowered PPFD from 2000 to 0 µmol $m^{-2}s^{-1}$ (2000, 1500, 1000,750, 500, 250, and 0 µmol $m^{-2}s^{-1}$). Measurements were taken in morning (0900- 1200 h) and afternoon (01300- 1600 h) and measurements were completed in 2 days. In Experiment 1, measurements were made at 6, 7, and 8 weeks after treatment (WAT), and in Experiment 2 measurements were made at 5, 6, 9 and 10 WAT.

A non-rectangular hyperbola model (Eq. 1) was used to fit the photosynthetic-light response curve (Lambers et al., 1998).

$$A = \frac{\varphi Q + Amax \sqrt{(\varphi Q + Amax)^2 - 4\varphi Q\theta Amax}}{2\theta} - R_D \qquad \text{Eq. 1}$$

Where φ is the apparent quantum efficiency, Q is the PPFD, A_{max} is the asymptotic estimate of maximum net CO_2 assimilation, θ is the curvature factor, and R_D is the rate of dark respiration.

The light compensation point (LCP) was calculated as described by Lobo et al., 2013 (Eq.2).

$$LCP = \frac{RD(\varphi RD - Amax)}{\varphi (RD - Amax)} \qquad \text{Eq. 2}$$

Photosynthetic photon flux was measured using a quantum light sensor (Spectrum Technologies, Inc., Plainfield, IL), and data were recorded every 30 min using Watchdog 1000 (Spectrum Technologies, Inc., Plainfield). The PPFD data were converted to a daily light integral (DLI) and averaged over treatment period for each experiment. Relative humidity and air temperature were also recorded at a similar resolution using the same instruments.

Shoot dry weight (SDW) and root dry weight (RDW) were determined at the end of the study. Roots were washed over a sieve to remove sand. Shoots and roots were then oven dried at 80 °C for 48 hours, allowed to cool to room temperature, and then weighed.

Statistical Design and Analysis

Light response curves were fitted to the nonrectangular hyperbola model (Eq.1) using a non-linear least square procedure using ‘onls’ package in R (Spies, 2015). Analysis of variance was performed to determine the effects of shade on A_{max}, light compensation point (LCP), and dark respiration (R_D) derived from light response curve, and the treatment difference was analyzed with the GLIMMIX procedure in Statistical Analysis System (Version 9.3; SAS Inc., Cary, NC). All tests were performed at a significance of 0.05.

Results and Discussion

Vegetative Growth

In both Experiment 1 and Experiment 2, SDW was lower in plants subjected to morning shade compared to afternoon shade or non-shaded control (Table 2). In Experiment 1, root dry weight was lower in plants subjected to shade than non-shaded control regardless of timing. In Experiment 2, morning shade resulted in lower RDW than non-shaded control (Table 1). Root dry weight was not different between shaded treatments. Similar to this study, Kosugi et al. (2010) reported lower shoot and root weight in the shaded plots compared to plots on open sun. In contrast to our result, Bell and Danneberger et al. (1999) reported no variation in root mass and density among 100% morning, 100% afternoon, 80% morning, 80% afternoon, and full sun. Lower clippings and root mass under afternoon shade suggest little growth or development. Plant growth is directly related to carbon assimilation rate and process that limit photosynthesis reduces the growth rate (Monteith, 1978; Taiz and Leigher, 2005). The result of present study is in agreement with earlier report showing morning shade had lower SDW compared to a non-shaded control under greenhouse conditions (Loewer et al., 2020). Their study also showed morning shade had lower TNC compared to the non-shaded control and afternoon shade.

Leaf Photosynthesis Light Response

Experiment 1.

The treatment effect was significant for A_{max}, and R_D. No treatment effect was observed for LCP. The shaded plant had lower A_{max} and R_D compared to non-shade control (Table 3). Time of measurement had no effect on A_{max}, LCP or R_D. The non-shaded control had higher or equal A_{max}, LCP and R_D compared to morning and afternoon shade. In contrast, no difference was observed among morning and afternoon treatment. The shaded plants had higher assimilation rates under low PPFD and lower rates under higher PPFD (Figure 1). A low light compensation point and lower carbon assimilation rate is the common attributes of plant grown under shade. Lower light compensation point is the advantageous attributes of shade tolerance as it may help to maintain positive carbon balance under low light conditions. At 6 WAT, no differences in A_{max}, LCP, and R_D were observed among treatments (Table 4). At 8 WAT, non-shaded control resulted in higher A_{max}, LCP, and R_D compared to afternoon shade but not different than morning shade. In contrast, at 8 WAT, morning shade and non-shaded control had similar A_{max} and LCP.

Experiment 2.

The treatment effect was significant for A_{max}, LCP and R_D. Time of measurement had no effect on A_{max} or R_D, but the morning measurement had lower LCP than in the afternoon (Table 3). Similar to Experiment 1, shaded plants had higher assimilation rates under low PPFD and lower rates under higher PPFD (Figure 2). In the morning measurement, afternoon shade had lower A_{max} than non-shaded control at 5, 6, and 10 WAT; lower LCP at 10 WAT and lower R_D at 5 and 10 WAT (Table 5). In the morning measurement, R_D of morning shade and afternoon shade was not different. During the morning, afternoon shade had a lower LCP than morning shade at 10 WAT and lower A_{max} at 5 WAT. Similarly, in the morning measurement, morning shade had lower A_{max} than non-shaded control at 5 and 10 WAT. The LCP of morning shade was not different from the non-shaded control at 5 and 10 WAT.

In afternoon measurement, afternoon shade had lower A_{max} than the non-shaded control sun at 9 and 10 WAT; lower LCP at 9 WAT; and lower R_D at 9 and 10 WAT. Similarly, in the afternoon measurement, morning shade had higher A_{max} than the non-shaded control at 5 WAT. The LCP of morning shade was lower than the non-shaded control at 9 WAT while the R_D was lower at 9 and 10 WAT. Afternoon shade had lower A_{max} than morning shade at 5, 9, and 10 WAT and a lower LCP at 10 WAT.

Morning measurements had higher carbon assimilation rates than afternoon measurements (Figure 1 and 2). It is known that photosynthesis increased after sunrise, reached maximum around mid-morning and then decreased in afternoon. The causes of this pattern are high afternoon temperature, photorespiration in C_3 plant, and feedback regulation by accumulated carbohydrates (Koyama and Takemoto, 2014).

It is speculated that differences in A_{max} were mainly due to acclimation to the light environment, which included reduction in the amount of photosynthetic tissues per unit area of leaf area in shade plants (Dias-Filho, 2002). Although the results were not consistent, the non-shaded control had higher A_{max} and R_D compared to shaded plants. Afternoon shade plant had lower A_{max} compared to morning shade. No difference in R_D was observed between morning and afternoon shade.

The study was conducted inside the greenhouse using upright and single sided shade structure which causes little disturbance to air movement. In real field condition, the shade combines with other environmental factors like reduce air movement, dew formation, and root competition. In our study, there was no root competition and no or little disturbance to air movement. Addition of other factors like restricted air movement and root competition may add adequate information for the selection and use of trees in the landscape maintaining a healthy environment for turfgrass. The present study also used a neutral density shade fabric which may not be representative of vegetative shade which typically has a lower red to far red ratio (R:FR). The R:FR ratio of sunlight is reported to be 1.15 (Homes and Smith, 1977) whereas the R:RF ratio under deciduous and conifer shade is reported to be 0.91 and 0.80, respectively (Bell et al., 2000). Wherley et al. (2005) reported the R:RF ratio of full sun, neutral shade and deciduous shade as 1.16, 1.02 and 0.428 respectively.

Conclusion

Under the condition encountered in this study, morning shade had lower shoot dry weight (SDW) compared to afternoon shade and non-shaded control. Consistent differences were not observed for light saturation (A_{max}), light response curve (LCP), and dark respiration (R_D). Further study is needed to evaluate the carbohydrate concentration in plant tissue to better understand the relationship between photosynthesis, growth, and carbohydrate accumulation under changes in temporal shade.

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Table 1. Mean air temperature and average daily light integrals measured during shade study.

Treatment[†]	Month			
	July	August	September	October
	Mean Air Temperature (^{o}C)			
	33.5	31.9	31.5	25
	Daily light integral[†]			
	---mol m^{-2} d^{-1}---			
Non-shade control	36.14[‡]	27.63	25.02	23.64
Afternoon Shade	17.9	16.76	15.7	13.29
Morning Shade	20.65	17.76	17.59	14.29

[†] Non-shade control received sun from sunrise to sun set; afternoon shade received full sun from sunrise to solar noon and then gets 90% shade; morning shade received 90% shade from sunrise to solar noon and then gets full sun until sun set.

[‡]Photosynthetically active radiation was recorded every 30 min using quantum light sensor and data were aggregated across month.

Table 2. Shade treatment effect on shoot and root weight of creeping bentgrass.

Treatment[†]	Shoot biomass	Root biomass
	Experiment 1	
	--------------------------g	--------------------------
Non-shade control	0.339 a[‡]	0.101 a
Afternoon shade	0.331 a	0.067 b
Morning shade	0.301 b	0.055 b
	Experiment 2	
Non-shade control	0.405 a	0.102 a
Afternoon shade	0.392 a	0.076 ab
Morning shade	0.363 b	0.061 b

[†] Non-shade control received sun from sunrise to sun set; afternoon shade received full sun from sunrise to solar noon and then gets 90% shade; morning shade received 90% shade from sunrise to solar noon and then gets full sun until sun set.

[‡]Means within each column followed by the same letter are not significantly different at the 0.05 significance level.

Table 3. Shade treatment effect on light saturation (A_{max}), light compensation point (LCP), and dark respiration (R_D) of a creeping bentgrass.

Treatment[†]	Amax	LCP	R_D
	Experiment 1		
	$\mu molCO_2m^{-2}s^{-1}$	$\mu molm^{-2}s^{-1}$	$\mu mol\ CO_2m^{-2}s^{-1}$
Non-shade control	30.1 a[‡]	176.9 a	5.7 a
Afternoon shade	21.6 b	132.5 a	4.2 a
Morning shade	22.8 b	147.5 a	4.5 a
	Experiment 2		
Non-shade control	25.7 a	186.7 a	6.5 a
Afternoon shade	21.1 b	163.5 b	5.0 b
Morning shade	20.9 b	154.9 b	4.8 b

[†] Non-shade control received sun from sunrise to sun set; afternoon shade received full sun from sunrise to solar noon and then get 90% shade; morning shade received 90% shade from sunrise to solar noon and then get full sun until sun set.
[‡]Means within each column followed by the same letter are not significantly different at the $p = 0.05$ significance level.

Table 4. Model parameter estimates for light saturation (A_{max}), light compensation point (LCP), and dark respiration (R_D) as affected by shade treatment and time of application of shade treatment in experiment 1.

	6 weeks after shade		7 weeks after shade		8 weeks after shade	
Treatment[†]	Morning[‡]	Afternoon	Morning	Afternoon	Morning	Afternoon
------------------------A_{max} (μmol $CO_2 m^{-2}s^{-1}$) ------------------------						
Non-shade control	28.7 a[§]	32.0 a	24.5 a	33.8 a	33.9 a	27.6 a
Afternoon shade	28.5 a	22.5 a	22.5 ab	17.3 b	19.8 b	19.1 b
Morning shade	30.7 a	30.0 a	17.0 b	11.7 b	22.0 ab	25.3 ab
------------------------LCP (μmol$m^{-2}s^{-1}$) ------------------------						
Non-shade control	180.4 a	185.9 a	143.1 a	229.6 a	205.9 a	116.4 b
Afternoon shade	142.7 a	74.9 a	154.0 a	156.7 a	67.1 b	199.4 a
Morning shade	190.8 a	103.4 a	164.3 a	152.9 a	138.6 a	135.2 ab
--------------------R_D (μmol $CO_2 m^{-2}s^{-1}$) ----------------------------						
Non-shade control	5.6 a	5.6 a	4.9 a	7.1 a	6.8 a	4.0 b
Afternoon shade	5.0 a	2.8 b	4.5 a	4.0 b	3.1 b	6.1 a
Morning shade	6.8 a	2.8 b	4.2 a	2.6 b	4.4 b	6.0 a

[†] Non-shade control received sun from sunrise to sun set; afternoon shade received full sun from sunrise to solar noon and then get 90% shade; morning shade received 90% shade from sunrise to solar noon and then get full sun until sun set.
[‡]Morning measurement was taken from 0900 h to 1200 h and afternoon measurement was taken from 1300 to 1600 h.
[§]Means within each column followed by the same letter are not significantly different at the $p = 0.05$ significance level.

Table 5. Model parameter estimates for light saturation (A_{max}), light compensation point (LCP), and dark respiration (R_D) as affected by shade treatment and time of application of shade treatment in experiment 2.

	5 weeks after shade		6 weeks after shade		9 weeks after shade		10 weeks after shade	
Treatment[†]	Morning[‡]	After	Morning	After	Morning	After	Morning	After
--------------------A_{max} (μmol $CO_2 m^{-2}s^{-1}$) ----------------------------								
Non-shade control	34.3 a[§]	20.3 b	29.4 a	25.1b	15.8 a	18.4 a	29.9 a	32.2 a
Afternoon shade	24.1b	16.5 b	22.1 b	35.6 a	16.8 a	11.7 b	23.3 b	18.4 b
Morning shade	16.1 b	29.9 a	28.8 a	20.4 b	13.4 a	18.0 a	17.5 b	22.9 a
------------------------LCP (μmol$m^{-2}s^{-1}$) ------------------------								
Non-shade control	226.6 a	109.8 a	133.3 a	215.8 a	183.6 a	318.1 a	185.9 a	120.7 a
Afternoon shade	173.6 a	169.9 a	156.8 a	293.8 a	139.2 a	135.5 b	113.4 b	125.7 a
Morning shade	149.5 a	128.2 a	120.0 a	231.5 a	129.9 a	178.3 b	171.4 a	130.2 a
--------------------R_D(μmol $CO_2 m^{-2}s^{-1}$) ----------------------------								
Non-shade control	10.5 a	3.7 a	5.8 a	7.0 a	4.5 a	7.5 a	7.2 a	5.9 a
Afternoon shade	5.8 b	4.6 a	5.6 a	7.7 a	4.5 a	3.2 b	4.4 b	4.2 b
Morning shade	4.3 b	5.0 a	5.0 a	5.7 a	3.8 a	5.0 b	5.5 b	4.3 b

[†] Non-shade control received full sun from sunrise to sun set; afternoon shade received full sun from sunrise to solar noon and then get 90% shade; morning shade received 90% shade from sunrise to solar noon and then get full sun until sun set.
[‡]Morning measurement was taken from 0900 h to 1200 h and afternoon measurement was taken from 1300 to 1600 h.
[§]Means within each column followed by the same letter are not significantly different at the $p = 0.05$ significance level.

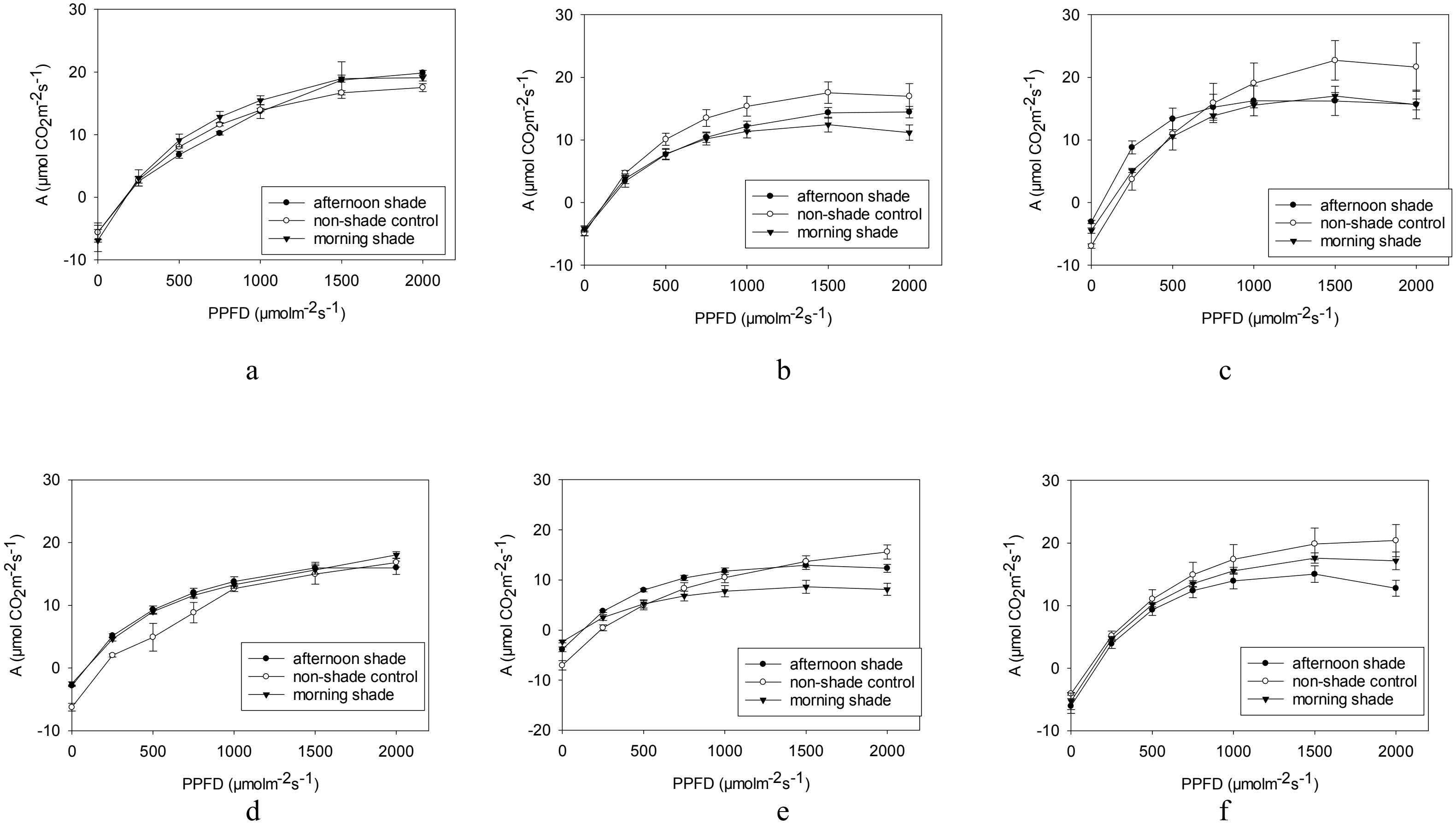

Figure 1. Effect of temporal shade on net CO_2 assimilation rates (A) in experiment 1; a, b, and c morning measurement at 6,7, and 8 weeks after treatment; d, e, and f afternoon measurement at 6,7, and 8 weeks after treatment. Vertical bars indicate ± standard error of means (n=4)

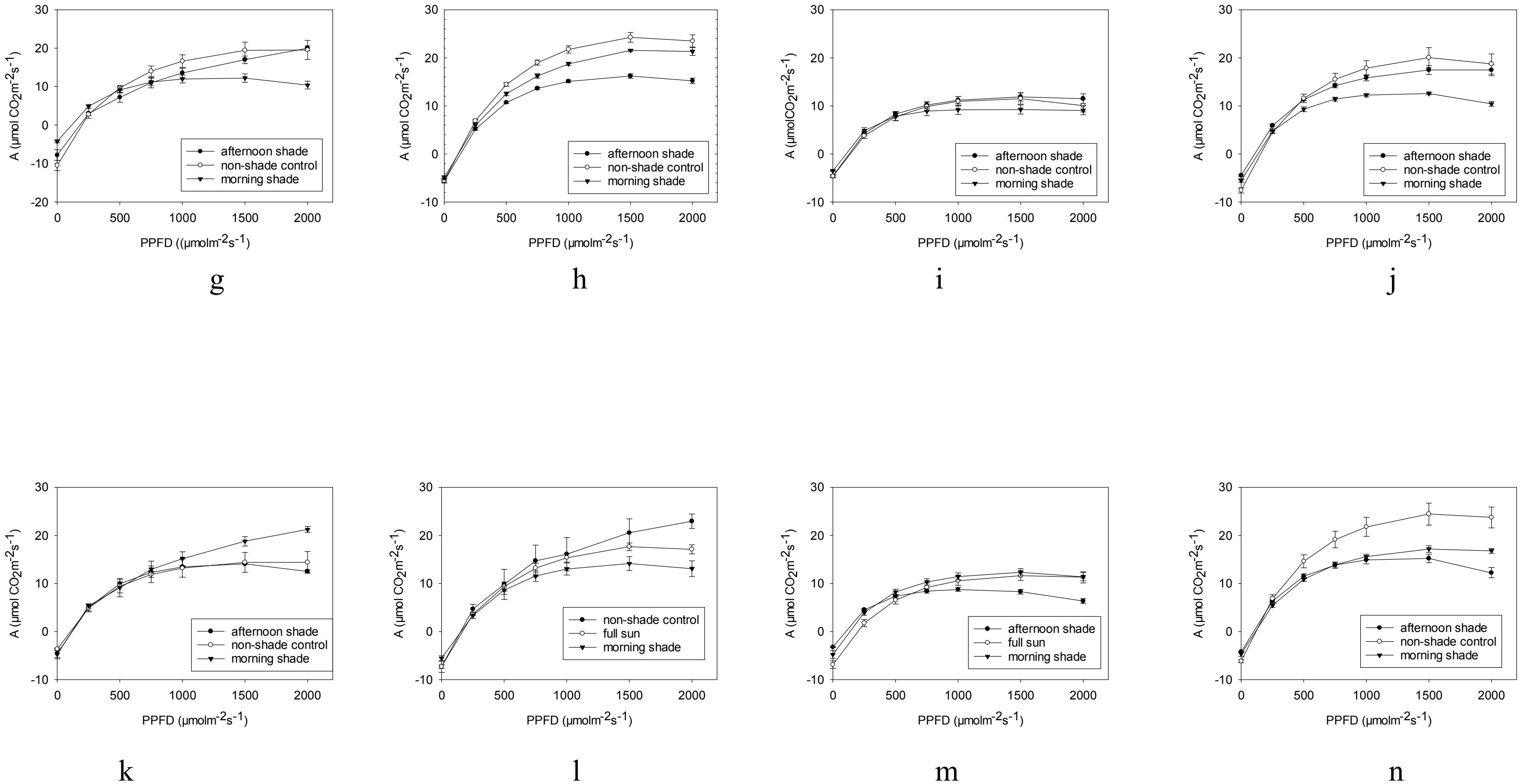

Figure 2. Effect of temporal shade on net CO_2 assimilation rates (A) in Experiment 2; g, h, i, and j morning measurement at 5, 6, 9 and 10 weeks after treatment; k, l, m, and n afternoon measurement at 5, 6, 9, and 10 weeks after treatment. Vertical bars indicate ± standard error of means (n=4)

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