Evaluation of Different Aerification Methods for Ultradwarf Hybrid Bermudagrass Putting Greens

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KEYWORDS. *Cynodon*, hollow needle tine, hollow tine, organic matter, sand injection, topdressing, turfgrass

ABSTRACT. **Aerification and topdressing are important cultural management practices that help prevent organic matter accumulation and soil compaction in golf greens. However, these practices result in surface disruption and decreased putting quality during recovery. A 2-year study was conducted on a 'TifEagle' hybrid bermudagrass (*Cynodon dactylon* × *C. transvaalensis*) putting green to determine the effect of different aerification methods and topdressing materials on soil properties and turfgrass recovery. Plots were aerified four times per year (May to Aug.) using 1/2-inch hollow tines, 1/4-inch hollow needle tines, hollow tines 2X + hollow needle tines 2X, or sand injection, and topdressed with either 90:10 (sand:peat) or green-dyed sand. Visual quality, normalized difference vegetation index, percent green cover, dark green color index (DGCI), surface firmness and volumetric water content were measured before initial aerification and at 7 and 21 days after aerification. Saturated hydraulic conductivity (K_{sat}) and organic matter (OM) content were measured monthly. Aerification with hollow tines and hollow tines 2X + hollow needle tines 2X resulted in lower firmness and OM and higher K_{sat} compared with hollow needle tines and sand injection. Sand injection showed the highest percent green cover and similar OM content compared with hollow tines and hollow tines 2X + hollow needle tines 2X. Green-dyed sand showed a higher percent green cover and DGCI compared with 90:10 sand:peat. Using hollow tines only or alternating them with hollow needle tines is the best option to decrease OM content while increasing K_{sat} in hybrid bermudagrass greens; however, their use could result in slower turfgrass recovery compared with other aerification methods.**

Aerification along with topdressing is an important cultural management practice that helps prevent the accumulation of OM in turf systems (Christians et al. 2016). Physically excising plugs of the topmost layer of turf, thatch, and surface soil and replacing them with either sand or a different topdressing amendment is an intensive routine that can be disruptive to golfers as well as those who maintain turf (Whitlark and Thompson 2019). Studies have shown that increased frequency of aerification and topdressing can reduce OM levels and improve surface firmness (Atkinson et al. 2012; Schmid et al. 2014). However, it was found that reducing the frequency of aerification events improved turf visual quality and recovery time (Atkinson et al. 2012; Landreth et al. 2008).

Although aerification can be unsightly, its functional purpose is of the utmost importance when it comes to long-term management strategies and, when neglected, can lead to OM accumulation, and decreased ability to drain water (Bevard 2011). Aerification during the right time of year can alleviate and prevent these issues and reduce soil compaction (Braun et al. 1998; Klingenberg et al. 2013; Schmid et al. 2014; White and Dickens 1984). Currently, hollow tine core aerators are the standard for this practice because they are specifically designed to remove plugs of soil closest to the surface of the turf, where OM predominantly tends to accumulate (McClellan et al. 2009). However, various styles of tines exist and offer a range of core sizes and shapes, including solid tines, which perforate the surface of the greens without removal of any material (Amgain et al. 2021). Alternatives to core aeration, such as sand or air injection, are methods that seek to improve soil physical properties while minimizing surface disruption. Sand injection uses high-pressure water-based injection that creates perforations that are filled with sand using the Venturi effect. Recent research found no effect of sand injection alone on soil physical properties compared with the uncultivated control on a creeping bentgrass (*Agrostis stolonifera*) putting green constructed on a sand-based root zone mix in Oklahoma, USA (Amgain et al. 2023).

Topdressing is an important follow-up treatment to aerification because it replaces any removed material with sand, which alters the surface soil as it embeds within the thatch layer, forming a more porous surface layer (Wang et al. 2021). White and Dickens (1984) reported that four topdressings per year reduced thatch accumulation in hybrid bermudagrass (*Cynodon dactylon* × *C. transvaalensis*) putting greens. Topdressing effects on

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
0.0283	ft^3	m^3	35.3147
3.0480	$ft^3/1000\ ft^2$	$m^3 \cdot ha^{-1}$	0.3281
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
48.8243	$lb/1000\ ft^2$	$kg \cdot ha^{-1}$	0.0205

water infiltration into putting greens have been inconsistent, with some studies reporting an improvement in water infiltration while others report no change or a reduction of water infiltration (Baker and Canaway 1990; Espevig et al. 2012; McCarty et al. 2005, 2007). Topdressing is also an important component of aerification recovery. Research results show that recovery mixtures based on sand amended with organic or inorganic materials could shorten recovery time (Carey and Gunn 2000; Patton et al. 2011). Snyder (2015) found green cover of 'TifEagle' hybrid bermudagrass was greater in sand mixtures containing pegylated-polymer- and clay-coated sand, biosolids with or without peat, than sand alone or sand and peat.

Data are needed to assess how different aerification methods interact with different topdressing materials to alter soil properties and aesthetics of ultradwarf hybrid bermudagrass putting greens. Understanding which aerification methods and topdressing materials bolster the performance of soil and the recovery and health of hybrid bermudagrass greens will better enable superintendents to use these tools efficiently to enhance playability and aesthetics while improving soil properties. The objectives of this study were to determine whether there is an advantage to topdressing with sand compared with green-dyed sand, and to determine if different aerification methods significantly alter turfgrass performance and soil properties.

Materials and methods

Site description and maintenance. A 2-year experiment (2021–22) was conducted on a mature 'TifEagle' hybrid bermudagrass putting green established in 2016 at the University of Florida Institute of Food and Agricultural Sciences Fort Lauderdale Research and Education Center in Davie, FL, USA. The putting green root zone consisted of a 90:10 (sand:peat) root zone that conformed to the US Golf Association (USGA) recommendations (USGA 2018). The green was mowed five times per week at a 1/8-inch height of cut with clippings removed after each mowing. The area was fertilized weekly at 1/4 lb/1000 ft^2 nitrogen (N) with ammonium sulfate (21N–0P–0K). Irrigation was applied daily at 90% reference evapotranspiration to prevent drought stress. The putting green was also treated for prevention of disease and insects to minimize turf damage and rolled every 2 weeks to simulate traffic. Weeds were controlled using a preemergence herbicide containing bensulide and oxadiazon (Goosegrass/Crabgrass Control; The Andersons Inc., Maumee, OH, USA) applied twice per year at 1.31 lb/1000 ft^2.

Treatments. The green was aerified monthly from the end of May to August. The experiment was set up to compare tine-aerated treatments and sand injection (Table 1). Tine-aerated treatments were performed with an aerator [eight sets of four tines (ProCore 648; The Toro Company, Bloomington, MN, USA)] with either hollow tines four times per year (industry standard for south Florida, USA; considered as control), twice with hollow needle tines (Ninja XL™ Tines; Trigon Turf Sciences LLC, Miami, FL, USA), and twice with hollow tines, or with hollow needle tines four times per year. Sand injection was performed using a sand injector (model 4800; DryJect Inc., Hatboro, PA, USA) four times per year. After aerification, cores were removed using a turbine blower (Torrent 2; Turfco, Blaine, MN, USA). Topdressing followed aerification using either 90:10 (sand:peat) standard USGA specifications, or green-dyed sand [88% silica sand, 12% acrylic copolymer clay (Divot Recovery mix; Harrell's, Lakeland, FL, USA)] applied with a drop spreader (Topdresser 2500, The Toro Company). Kiln-dried sand (Golf Agronomics, Moore Haven, FL, USA) was used as injected material in the sand injection treatment (Table 2). Each plot aerified with an aerator (ProCore 648) received 2.5 ft^3 (11 ft^3/1000 ft^2) of topdressing material to fill the holes created by the hollow tines. Given that the volume of the holes created by the sand injection was 86% of that created by the hollow tines, sand injection plots were topdressed with ~15% of the volume of the tine-aerated plots. Each experimental unit was 24 ft × 8 ft and treatments were repeated at the same location over time.

Data collection. Visual quality, normalized difference vegetation index (NDVI), percent green cover, DGCI, surface firmness, and volumetric water content (VWC) were measured before initial aerification and at 7 and 21 d after aerification (DAA). Visual quality was measured on a scale of 1 to 9 where 1 = dead/brown turf and 9 = optimal healthy/green. NDVI was assessed using a handheld sensor (RapidSCAN CS-45; Holland Scientific, Lincoln, NE, USA). Percent green cover and DGCI were assessed through digital image analysis (Karcher and Richardson 2003; Richardson et al. 2001) from two images taken per plot. Surface firmness was measured using a turf firmness meter (Field Scout TruFirm; Spectrum Technologies, Aurora, IL, USA) and were analyzed as an average of three

Table 1. Aerification treatments applied to a 'TifEagle' hybrid bermudagrass putting green in Ft. Lauderdale, FL, USA, in 2021 and 2022.

Treatment[i]	Tine size	Spacing	Depth	Surface area[iii]
	(inches)[ii]			%
Hollow tines	0.50	2 × 3	4	13.2
Hollow tines 2x + hollow needle tines 2x[iv]			4	11.5
Hollow needle tines	0.25	1.4 × 1.4	4	10.0
Sand injection	0.43	3 × 1.5	3.5	12.9

[i] Treatments were applied monthly (four times per year) from the end of May to August in 2021 and 2022.
[ii] 1 inch = 2.54 cm.
[iii] Total impacted surface area per year after four aerification events.
[iv] Each treatment was applied twice and interspersed between each other.

Table 2. Particle size distribution of sand applied during the study to a 'TifEagle' hybrid bermudagrass putting green in Ft. Lauderdale, FL, USA, in 2021 and 2022.

Sand type	Very coarse (1–2 mm)[i]	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)
	(% by wt)				
90:10 topdressing sand	4	51	26	15	4
Green-dyed topdressing sand	3	51	28	15	3
Kiln-dried sand	6	55	23	14	2
USGA recommendations[ii]	≤10	------------≥60-----------------		≤20	≤5

[i] Particle size was classified based on the particle size distribution of US Golf Association root zone mix (USGA 2018). Particle sizes were separated by passing soil samples through US standard sieve mesh (No. 18, 35, 60, 100, and 270); 1 mm = 0.0394 inch.
[ii] USGA (2018) recommendations for putting green construction.

readings per plot. VWC was measured at a 3-inch depth using a time domain reflectance sensor (Field Scout TDR 350, Spectrum Technologies) and were analyzed as an average of nine readings per plot. To determine K_{sat} three samples (2 inches diameter × 3.25 inches deep) were removed monthly from each plot, saturated via capillarity in a soaking tray and transferred to an integrated constant and falling hydraulic head permeameter (ASTM D2434; METER Group Inc., Munich, Germany), which used the falling head method. Organic matter content was determined by the loss on ignition method (Nelson and Sommers 1996). Three soil cores (2 inches diameter × 1 inch deep) were removed monthly using a standard soil probe in 2021 and 2022. Even though OM in golf greens accumulates mostly in the top 1 inch of soil (Carley et al. 2011), in an effort to clarify OM accumulation

Table 3. Analysis of variance for the effect of aerification, topdressing, month, and days after aerification on visual quality (VQ), normalized difference vegetation index (NDVI), percent green cover (GC), dark green color index (DGCI), surface firmness (SF), and volumetric water content (VWC) of a 'TifEagle' hybrid bermudagrass putting green in Ft. Lauderdale, FL, USA, in 2021 and 2022.

Source	VQ	NDVI	GC	DGCI	SF	VWC
	2021					
Aerification (A)	NS	NS	**	NS	NS	NS
Topdressing (T)	NS	NS	NS	NS	NS	NS
A × T	NS	NS	NS	NS	NS	NS
Month (M)	NS	NS	NS	NS	NS	NS
A × M	**	NS	***	NS	*	NS
T × M	NS	***	NS	NS	NS	NS
A × T × M	NS	NS	NS	NS	NS	NS
Days after aerification (DAA)	***	***	NS	***	NS	NS
A × DAA	NS	NS	NS	NS	NS	NS
T × DAA	NS	NS	NS	NS	NS	NS
M × DAA	NS	NS	NS	NS	NS	NS
A × T × DAA	NS	NS	NS	NS	NS	NS
A × M × DAA	NS	NS	NS	NS	NS	NS
T × M × DAA	NS	NS	NS	NS	NS	NS
A × T × M × DAA	NS	NS	NS	NS	NS	NS
	2022					
A	NS	NS	NS	NS	NS	NS
T	NS	NS	NS	NS	NS	NS
A × T	NS	NS	NS	NS	NS	*
M	NS	NS	NS	NS	NS	NS
A × M	NS	NS	NS	NS	**	NS
T × M	*	NS	NS	**	NS	NS
A × T × M	NS	NS	NS	NS	NS	NS
DAA	***	***	NS	NS	NS	NS
A × DAA	NS	NS	NS	NS	NS	NS
T × DAA	NS	NS	***	NS	NS	NS
M × DAA	NS	NS	NS	NS	NS	NS
A × T × DAA	NS	NS	NS	NS	NS	NS
A × M × DAA	NS	NS	NS	NS	NS	NS
T × M × DAA	NS	NS	NS	*	NS	NS
A × T × M × DAA	NS	NS	NS	NS	NS	NS

*, **, *** significant at $P \leq 0.05$, 0.01, or 0.001, respectively; NS = nonsignificant at $P > 0.05$.

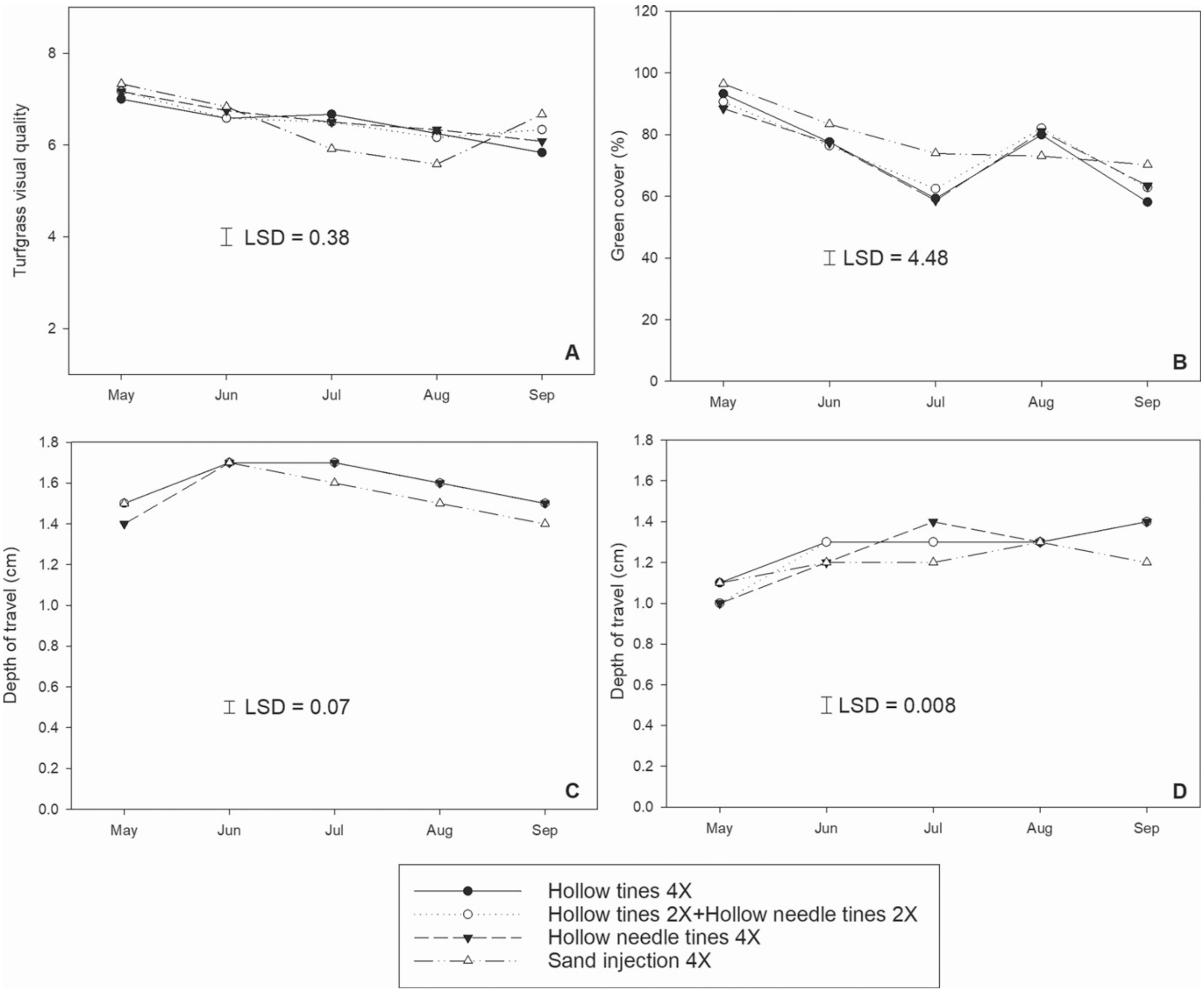

Fig. 1. Turfgrass visual quality on a scale of 1 to 9 where 1 = dead/brown turf and 9 = optimal healthy/green in 2021 (A), percent green cover assessed through digital image analysis on a scale of 0% to 100% in 2021 (B), surface firmness measured using a turf firmness meter expressed as depth of travel in 2021 (C), and 2022 (D) of a 'TifEagle' hybrid bermudagrass putting green in Ft. Lauderdale, FL, USA, as affected by the interaction of aerification method and months. Aerification treatments included hollow tines four times per year (industry standard for south Florida, considered as control), twice with hollow needle tines and twice with hollow tines, hollow needle tines four times per year and sand injection four times per year. Data are pooled over two topdressing materials, two rating days after aerification and three replicates and represent an average of nine data points; 1 cm = 0.3937 inch.

through the soil profile in 2022, additional soil cores were collected at a depth of 2 inches (Craft et al. 2016).

Statistical analysis. The study was arranged as a randomized complete block design with three replicates, with topdressing material serving as the main plot and aerification methods as split plot. Model residuals were analyzed for normality and homogeneity of variance with the Studentized residual test. Where necessary, data were transformed logarithmically, which satisfied assumptions of analysis of variance (ANOVA). Compound symmetry covariance structure Proc Glimmix (SAS ver. 9.4: SAS Institute Inc., Cary, NC, USA) was used to analyze variables using DAA and months as repeated measures. Initial ANOVA revealed a year effect for turfgrass performance variables, firmness, and VWC; thus, years were analyzed and presented separately. No significant effect of year was observed for OM and K_{sat}; therefore, data were pooled across year. Where appropriate means were separated using least significant difference test at the 0.05 significance level.

Results

Turfgrass performance. Turfgrass quality was affected by the interaction of aerification treatment and month during year 1 (Table 3). Quality declined after each event, with the highest decline on sand injection during July and August (19% and 24% reduction, respectively) with ratings less than minimum quality (5.9 and 5.6, respectively). However, by the end of 2021, no differences among treatments were observed (Fig. 1A). During 2022, the interaction of topdressing material

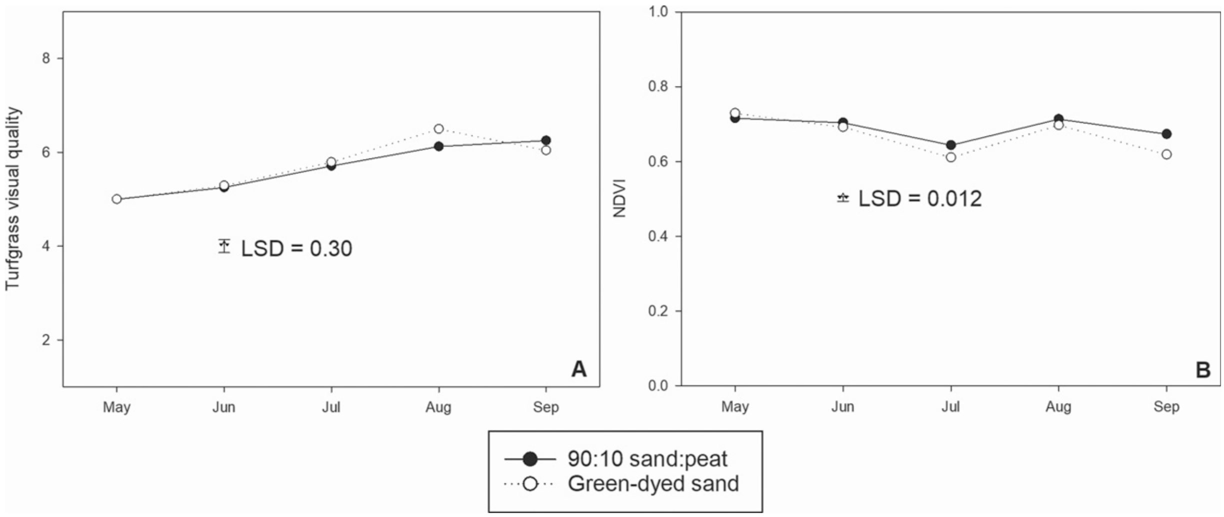

Fig. 2. Turfgrass visual quality on a scale of 1 to 9 where 1 = dead/brown turf and 9 = optimal healthy/green in 2022 (A), and normalized difference vegetation index (NDVI) on a scale from 0.0 to 0.99 in 2021 (B) of a 'TifEagle' hybrid bermudagrass putting green in Ft. Lauderdale, FL, USA, affected by the interaction of topdressing materials and month. Plots were topdressed with either 90:10 sand (sand:peat) or green-dyed sand (88% silica sand, 12% acrylic copolymer clay) immediately after an aerification event. Data are pooled over four aerification methods, 2 ratings days after aerification and three replicates and represent an average of 24 data points.

and month affected turfgrass quality (Table 3). Both top-dressing materials increased turfgrass quality over time with a slight difference between treatments in August (6.2 for 90:10 sand and 6.5 for green-dyed sand) (Fig. 2A). For each year, quality ratings were affected by days after aerification (Table 3). During 2021, average quality 7 DAA was 6.1 and increased to 6.6 at 21 DAA (data not shown). A similar trend was observed during 2022 [5.6 at 7 DAA and 6.2 at 21 DAA (data not shown)].

For year 1, the interaction between topdressing and month affected NDVI (Table 3). In 2021, plots topdressed with 90:10 sand exhibited a higher NDVI during July and September than plots topdressed with green-dyed sand (0.6435 and 0.6109 in July and 0.6734 and 0.6186 in September; Fig. 2B). Similar to turfgrass quality, DAA affected NDVI each year (Table 3). NDVI was observed to be higher 21 DAA (0.70 and 0.66 in 2021 and 2022, respectively) compared with 7 DAA (0.63 and 0.61 in 2021 and 2022, respectively; data not shown).

In 2021, percent green cover was affected by the interaction of aerification and month (Table 3). There was an observable decline of green cover after the May and June aerification events. Plots aerated with sand injection showed a greater green cover (74%) compared with tine-aerated treatments (average 61%) in July (Fig. 1B). In September, green cover of sand injection was higher than hollow tines (70% and 58%, respectively). In 2022, the interaction of topdressing and DAA affected green cover (Table 3). Plots exhibited similar green cover 21 DAA regardless of topdressing material (Table 4). However, 7 DAA, plots topdressed with green-dyed sand showed a higher green cover (62%) than those topdressed with 90:10 sand (56%).

In 2021, DGCI was only affected by DAA (Table 3). At 21 DAA, DGCI was higher (0.5563) than at 7 DAA (0.4903) (data not shown). During year 2, the interaction of topdressing, month and DAA affected DGCI (Table 3). Differences among topdressing treatments were evident at 7 DAA in June and August (Fig. 3). During both months, plots topdressed with green-dyed sand showed a higher DGCI than those topdressed with 90:10 sand (0.62 and 0.57 in June and 0.66 and 0.56 in August). By the end of the experiment, both topdressing treatments resulted in similar DGCI.

Soil properties. For each year, firmness was affected by the interaction of aerification and month (Table 3). All aerification treatments decreased firmness after May aerification. On average, the depth of travel (centimeters) increased by 13% for all treatments in 2021 (Fig. 1C) and 22% in 2022 (Fig. 1D). However, during year 1, the effect of aerification treatments on firmness decreased after the June aerification event. By the end of both years, sand injected plots exhibited the firmest playing surface (1.4 and 1.2 cm, respectively), and no difference was observed among tine-aerated treatments (Fig. 1C and D).

Table 4. Percent green cover at 7 and 21 d after aerification (DAA) of a 'TifEagle' hybrid bermudagrass putting green following topdressing in Ft. Lauderdale, FL, USA, in 2022.

Topdressing[i]	DAA	Green cover (%)[ii]
90:10 sand	0	87.5 a[iii]
	7	56.1 d
	21	71.5 b
Green-dyed sand	0	88.7 a
	7	61.8 c
	21	70.1 b

[i] Plots were topdressed with either 90:10 sand (sand:peat) or green dyed sand (silica sand, 12% acrylic copolymer clay) immediately after an aerification event.

[ii] Green cover was determined by digital image analysis of two images per plot using a scale from 0% to 100%, where 100% = full coverage. Data are pooled over four aerification methods, 5 mo., and three replicates and represent an average of 60 data points.

[iii] Values followed by the same letter in a column are not statistically different from one another according to least significant difference test ($P \leq 0.05$).

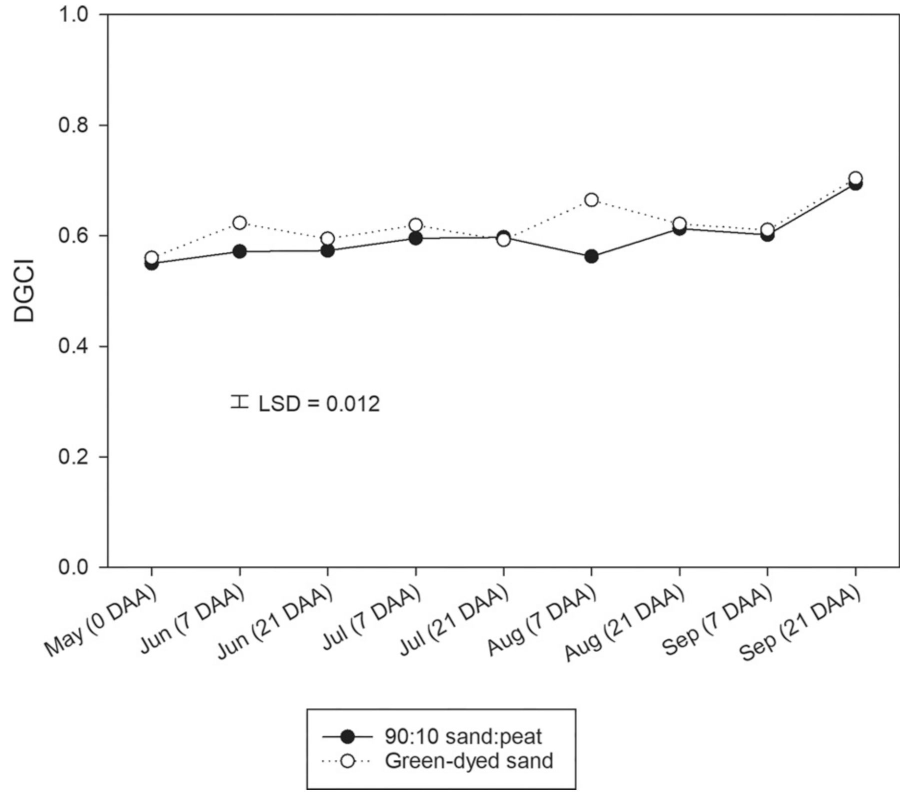

Fig. 3. Dark green color index (DGCI) assessed through digital image analysis using a scale of 0 to 1 of a 'TifEagle' hybrid bermudagrass putting green in Ft. Lauderdale, FL, USA, in 2022 as affected by the interaction of topdressing material, month, and days after aerification (DAA). Plots were topdressed with either 90:10 sand (sand:peat) or green-dyed sand (88% silica sand, 12% acrylic copolymer clay) immediately after an aerification event. Data are the average of two images per plot and are pooled over four aerification methods and three replicates and represent an average of 12 data points.

No effect of aerification method and topdressing material was evident in VWC in year 1. In 2022, the interaction between aerification and topdressing influenced VWC (Table 3). Plots topdressed with 90:10 sand had no observable differences regardless of aerification method. However, within the plots topdressed with green-dyed sand, hollow needle tines alone had higher VWC (25.5%) than hollow tines (21.6%) (Table 5).

K_{sat} was affected by the interaction between aerification and month (Table 6). K_{sat} increased in all plots following aerification (Fig. 4A). Plots aerated with hollow tines alone or combined with hollow needle tines increased K_{sat} after all aerification events. Overall, sand injection had a lower K_{sat} compared with tine-aerated treatments. By the end of the experiment, hollow tines alone or in combination with hollow needle tines resulted in higher K_{sat} compared with other treatments.

The interaction between aerification by month affected OM content at 1-inch depth (Table 6). After the May aerification, all treatments exhibited a decline in OM accumulation.

Table 5. Volumetric water content (VWC) of a 'TifEagle' hybrid bermudagrass putting green topdressed with 90:10 sand or green dyed sand following various aerification methods in Ft. Lauderdale, FL, USA in 2022.

Topdressing[i]	Aerification methods[ii]	VWC (%)[iii]
90:10 sand	Hollow tines	24.9 ab[iv]
	Hollow tines 2X + hollow needle tines 2X	23.4 ab
	Hollow needle tines	23.9 ab
	Sand injection	24.7 ab
Green-dyed sand	Hollow tines	21.6 b
	Hollow tines 2X + hollow needle tines 2X	23.7 ab
	Hollow needle tines	25.5 a
	Sand injection	24.2 ab

[i] Plots were topdressed with either 90:10 sand (sand:peat) or green dyed sand (silica sand, 12% acrylic copolymer clay) immediately after an aerification event.

[ii] Aerification methods included hollow tines four times per year (industry standard for south Florida, considered as control), twice with hollow needle tines and twice with hollow tines, hollow needle tines four times per year and sand injection four times per year.

[iii] Volumetric water content was measured at a 3-inch (7.6-cm) depth using a time domain reflectance sensor and were analyzed as an average of nine readings per plot. Data are pooled over 2 rating days after aerification, 5 mo., and three replications and represent an average of 30 data points.

[iv] Values followed by the same letter in a column are not statistically different from one another according to the least significant difference (LSD) test ($P \leq 0.05$).

Table 6. Analysis of variance for the effect of aerification, topdressing, month, and year on saturated hydraulic conductivity (K_{sat}) and organic matter content at 1-inch (2.5-cm) depth (OM_1) of a 'TifEagle' hybrid bermudagrass putting green in Ft. Lauderdale, FL, USA.

Source of variation	K_{sat}	OM_1
Aerification (A)	NS	NS
Topdressing (T)	NS	NS
A × T	NS	NS
Month (M)	***	***
A × M	**	**
T × M	NS	NS
A × T × M	NS	NS
Year (Y)	NS	NS
A × Y	NS	NS
T × Y	NS	NS
M × Y	NS	NS
A × T × Y	NS	NS
A × M × Y	NS	NS
T × M × Y	NS	NS
A × T × M × Y	NS	NS

*, **, *** significant at $P \leq 0.05$, 0.01, or 0.001, respectively; NS = nonsignificant at $P > 0.05$.

After the June aerification event, plots aerated with hollow tines had lower OM than plots aerated with hollow needle tines alone (6.7% and 9%, respectively; Fig. 4B). At the end of the experiment, plots aerated with hollow needle tines showed higher OM content (8.5%) compared with hollow tines alone (6.3%). When compared at 1 and 2 inches in 2022, OM was affected by the effects of depth, aerification treatment, and month (Table 7), with OM at 1 inch (7.8%) being higher than OM observed at 2 inches (6.7%; data not shown). When averaged over depth, OM was higher on hollow needle tine-aerated plots (7.8%) compared with sand injection (7.1%) and hollow tines (6.8%); hollow needle tines combined with hollow tines was comparable to all the other treatments (7.3%; data not shown). Highest organic matter was detected in May, pre-aerification (8.7%). After May aerification, OM content in June dropped to 6.6%. No statistical differences were detected afterward with OM content ranging from 6.7% in July to 7.3% in September (data not shown).

Discussion

Traditional aerification practices temporarily reduce the aesthetics and performance of putting greens because of their highly disruptive nature (Amgain et al. 2021; Rowland et al. 2009). Research indicates that quality of 'TifEagle' hybrid bermudagrass can be reduced up to 4 weeks after an aerification event (Atkinson et al. 2012). Our results agree with these findings, as quality declined after each aerification event. Research findings show that hollow tines present a slower recovery time compared with other aerification methods, due to the larger affected surface area (Amgain et al. 2021) and the greater amount of topdressing sand on the surface (Lindsey et al. 2022). Additionally, results indicate that tine size also affects the speed of recovery. When using smaller tines (0.6 and 1.3 cm), recovery of 'MS Supreme' hybrid bermudagrass was similar to that of sand injection (Craft et al. 2016). Conversely, no differences were found on turfgrass performance when using smaller tines in this study. Alternative aerification methods, such as sand injection, could achieve minimal surface disruption and reduce recovery time (Craft et al. 2016). In this study, all aerification methods reduced green cover; however, reduction was lower when using sand injection (Fig. 1B). Furthermore, the dyed sand resulted in higher quality ratings during the hottest month of the trial (August), which may indicate a use case for managers dealing with hotter climates (Table 2, Fig. 3). More research is needed to investigate whether these results are due only to the color of the sand material or if there are underlying physiological processes involved with applying green-dyed sand.

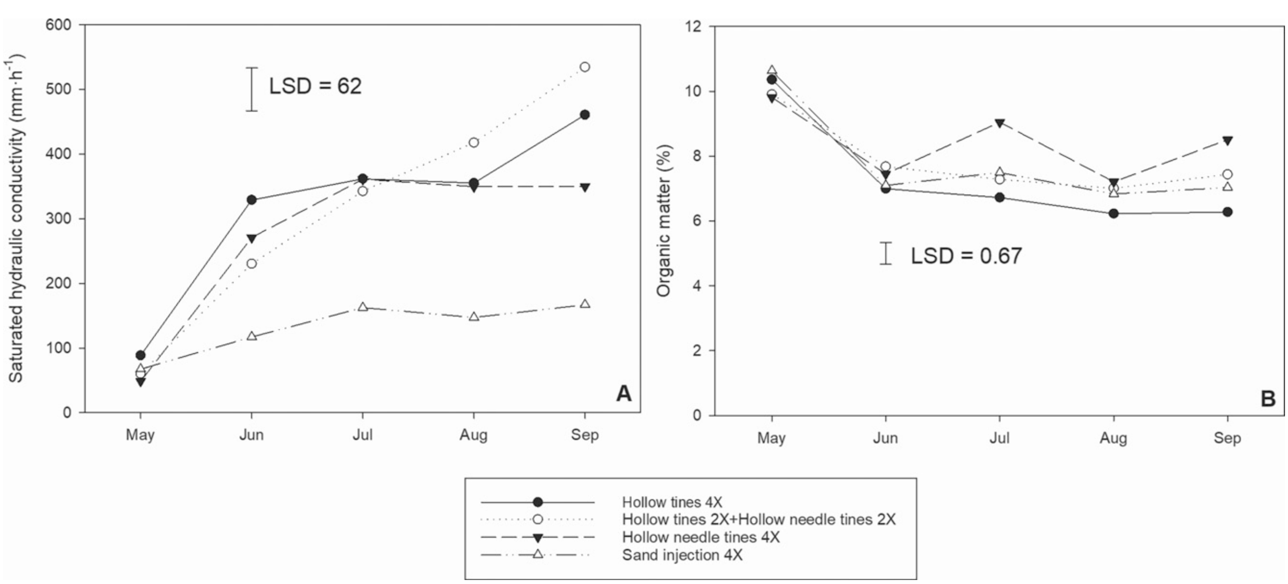

Fig. 4. Saturated hydraulic conductivity (K_{sat}) measured using an integrated constant and falling hydraulic head permeameter (A), and organic matter (OM_1) content at 1-inch (2.5-cm) depth determined by the loss of ignition method of a 'TifEagle' hybrid bermudagrass putting green in Ft. Lauderdale, FL, USA, as affected by the interaction of aerification method and month. Aerification treatments included hollow tines four times per year (industry standard for south Florida, considered as control), twice with hollow needle tines and twice with hollow tines, hollow needle tines four times per year and sand injection four times per year. Data are pooled over two topdressing materials and three replicates and represent an average of six data points; 1 mm = 0.0394 inch.

Table 7. Analysis of variance for the effect of aerification, topdressing, depth, and mo., on organic matter content at either 1 or 2 inches (2.5 and 5.1 cm) depth (OM_2) of a 'TifEagle' hybrid bermudagrass putting green in Ft. Lauderdale, FL, USA, in 2022.

Source of variation	OM_2
Aerification (A)	**
Topdressing (T)	NS
A × T	NS
Depth (D)	***
A × D	NS
T × D	NS
A × T × D	NS
Month (M)	***
A × M	NS
A × M	NS
D × M	NS
A × T × M	NS
A × D × M	NS
T × D × M	NS
A × T × D × M	NS

*, **, *** significant at $P \leq 0.05$, 0.01, or 0.001, respectively; NS = nonsignificant at $P > 0.05$.

During year 1, all aerification treatments decreased firmness after May aerification; however, that effect was not observed for the rest of 2021 (Fig. 1C). A different result was observed during year 2, where tine-aerated treatments increased depth of travel an average >30% compared with the beginning of the study (Fig. 1D). Reduction of firmness when using hollow tines on creeping bentgrass and hybrid bermudagrass sand-based putting greens has been well documented (Amgain et al. 2021, 2023; Atkinson et al. 2012; Craft et al. 2016; McCarty et al. 2007; Rowland et al. 2009). Previous studies have shown that sand injection aerification did not reduce firmness compared with an untreated control (Amgain et al. 2021, 2023; Craft et al. 2016). In this study, putting surfaces were ~12% firmer when using sand injection compared with tine-aerated treatments (Fig. 1C and D). These results suggest that this technology might be useful when trying to maintain soil firmness.

Traditional hollow tine aerification methods are known to increase K_{sat} (Amgain et al. 2021, 2023; Craft et al. 2016; McCarty et al. 2007; Schmid et al. 2014). However, this increase is dependent on the number of aerification events. Rowland et al. (2009) concluded that one or two aerification events did not increase K_{sat} on a sand-based hybrid bermudagrass putting green. Similar results were reported by Lindsey et al. (2022) on a sand-based creeping bentgrass putting green after two aerification events. In our study, all tine-aerated plots showed an increase in K_{sat} (Fig. 4A). However, toward the end of the season, hollow tines alone or combined with hollow needle tines resulted in a higher K_{sat} than hollow needle tines alone. This may be due to the higher OM content in hollow needle tine-aerated plots (Fig. 4B). Higher VWC was detected in hollow needle tine aeration compared with hollow tined only when topdressed with green-dyed sand (Table 5). This may be due to the acrylic copolymer clay content in green-dyed sand. Acrylic-based polymers are used as wetting agents to increase soil moisture (Xiang et al. 2021). Moreover, addition of peat to the soil profile using the 90:10 (sand:peat) may have increased water holding capacity of the soil profile even when cores were removed by hollow tine aerification. Our results suggest that hollow tines are a more effective method to reduce OM compared with hollow needle tines alone (Fig. 4B). Unlike previous research (Amgain et al. 2023), sand injection resulted in similar OM content compared with hollow tines. The lack of difference between hollow tines and sand injection in our study may be due to the additional sand applied to the sand injection treatment.

Conclusions

Overall, aerification with hollow tines alone or combined with hollow needle tines decreased surface firmness and OM content while increasing K_{sat}; however, it also resulted in a reduction in green cover. Under the conditions of this study, sand injection resulted in the firmest playing surface and the highest percent green cover but had the least impact on K_{sat}. Although disruptive, the use of hollow tines for aerification remains the most effective tool to ameliorate soil characteristics in hybrid bermudagrass putting greens. Moreover, green-dyed sand could shorten recovery period of hybrid bermudagrass after disruption caused by hollow tine aerification.

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