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Aerification Strategies Affecting Golf Green Subsurface Properties

Research Article

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Abstract

Golf greens often become compacted due to:

1. Construction of less-than-ideal soil containing high percentages of silt and clay.
2. Extensive traffic not only from daily play but continuous maintenance often with heavy machinery.
3. Traffic not being sufficiently curtailed during periods of excessive soil moisture.

A two-year field experiment was conducted on a 14-year-old U.S. Golf Association (USGA)-specified Crenshaw creeping bentgrass [Agrostis stolonifera L. var palustris (Huds.)] research putting green in Clemson, SC, to evaluate the effects of varying spring HTA size and timing on turfgrass rooting, soil organic matter (OM) and soil properties. Spring HTA treatments included 1.2-cm i.d. tines spaced at 5.1 cm x 5.1 cm in March and May (standard); 1.2-cm i.d. tines spaced at 3.8 cm x 3.4 cm in March only (2x); 0.9-cm i.d. tines spaced at 3.8 cm x 3.4 cm in March and May; and 0.6-cm i.d. tines spaced at 3.8 cm x 3.4 cm in March, April, May and June. All aerification was to a depth of 7.6 cm, with cores removed.

Plots aerified with 0.6-cm tines had the least 2-year reduction in dry root weight (DRW). Plots aerified with 1.2-cm tines in March only (2x) had the greatest reduction in DRW and had the deepest thatch mat depth (TMD) across both years. This “doubling up” treatment would not be advisable on greens where low root mass or thatch accumulation is a concern. Plots aerified with 1.2-cm tines had higher thatch OM content in Year 2. Plots aerified with 0.6-cm tines had higher soil OM content across both years. Repetitive equal depth aerification did not create a layer of increased compaction. Turf managers can vary their spring HTA size and timing to increase TQ during periods where this is important (e.g., for a tournament) with manageable effects on surface, OM, and soil properties.

Abbreviations

BD: Soil bulk density; DAT: Days after treatment; DRW: Dry root weight; HTA: Hollow tine aerification; ID: Inside diameter; OM: Organic matter; SBD: Summer bentgrass decline; SOM: Soil organic matter; STA: Solid tine aerification; TMD: Thatch mat depth; TOM: Thatch mat organic matter; TQ: Turf quality; USGA: United States Golf Association; WAIT: Weeks after initial treatment; WIR: Water infiltration rate.

Core Ideas

1. Aerification (or coring) is one of the most controversial agronomic practices turf managers face.
2. Questions on “doubling” up aerification instead of having two separate events to reduce the time of less than desired putting surfaces are often asked.
3. Overall, this study suggests bentgrass greens in the transition

zone include two spring hollow tines aerifications applications with 1.2-cm tines at 5.1 cm x 5.1 cm spacings or 0.9-cm tines at 3.8 cm x 3.4 cm spacing (March and May), monthly solid tine aerifications during the summer, and a fall hollow tine aerification with 1.2-cm tines at 5.1 cm x 5.1 cm spacings.

Golf greens are aerified for several reasons including improving thatch control, reduced soil compaction, increased and more uniform water infiltration, improved surface aeration, and improved rooting [1-5]. An aerification program impacting (removing) 15 to 20% of the surface area on a yearly basis has been suggested to maintain high quality turf [6]. However, HTA may increase turfgrass injury due to stress, increase weed establishment, decrease turfgrass quality through disruption of the turf surface, and possibly slow water percolation through creation of a compacted zone of soil (“hardpan”) below the depth of coring tines [3,4,7]. Because HTA removes turfgrass shoots and roots, it is usually scheduled when the turfgrass is actively growing, to minimize time for adequate regrowth to fill voids.

A typical aerification program for bentgrass greens in the transition zone includes two spring HTA applications with larger tines (e.g., 1.2-cm i.d. tines in March and May), monthly STA during the summer, and HTA in early fall [8]. Recently, the practice of “doubling up” spring HTA has gained interest as a means to reduce labor cost and disruptions to play [9]. This is typically accomplished by aerifying twice on the same or consecutive days and eliminating the second spring HTA. Other possible alternative spring HTA programs include using smaller diameter tines at closer spacing [9]. This method may be used to impact approximately the same surface area on the same schedule as standard larger tines, while offering the advantage of faster recovery. Even smaller tines may be used to impact as little as half the surface area of the standard treatment, to further reduce recovery time. This obviously requires an increase in the number of spring HTA applications required to impact the same surface area.

Data to study corresponding effects on surface, soil, and OM are needed to fully evaluate these alternative spring HTA treatments. Turfgrass and surface properties should be evaluated frequently to provide a continuous picture of the effect of the varying HTA treatments during the time they were being applied in spring when temperatures are typically favorable for bentgrass growth, and throughout summer when the higher temperature and humidity of the transition zone is stressful to bentgrass, thus SBD is more likely to occur.

Organic matter and soil properties generally change more slowly and effects of different aerification programs would likely be less noticeable. It is this lack of direct correlative visual effects that can lead to problems in the soil and organic matter profile which contribute to SBD. Often the desire to maintain optimal turfgrass and surface properties lead turfgrass managers to minimize impact from cultural practices like HTA. Comprehensive research is essential to provide complete information to turfgrass management professionals for use in planning maintenance programs including aerification which allows optimal use of the turfgrass surface without sacrificing overall turf health.

Materials and Methods

A two-year field experiment was conducted between March and November 2011 (Year 1) and 2012 (Year 2), on a certified Crenshaw creeping bentgrass [Agrostis stolonifera L. var palustris (Huds.)] research putting green established in 1997 at the Clemson University Turfgrass Research Complex, Clemson, SC (34°40’14” N, 82°50’15” E). The experiment was designed to test the null hypothesis that varying the size and timing of spring hollow tine aerification (HTA) would not affect turfgrass organic matter and soil properties. The research green was originally built to USGA specifications with a 30.5-cm root zone consisting of an 85:15 sand:peat mixture on a volume basis, overlying 10 cm of pea gravel with a diameter range of 6.4 to 9.5 mm, covering drain lines trenched into the subgrade at 4.6-m spacing [10]. Particle-size distribution and physical properties of the sand are presented in Table 1.

Table 1: Soil physical properties of rootzone sand initially used to construct a research green in Clemson, SC.

Soil separation (mm)			Bulk density	Hydraulic conductivity	Total porosity	Organic matter
Sand	Silt	Clay				
0.05-1	0.002-0.05	<0.002				
-------------% by weight-------------			gcm-3	cmhr-1	%	gkg-1
98.5	0.4	0.1	1.46	17	44.8	14
Sieve size/sand fraction						
Sand particle diameter						
Percent retained						
No. 10	No. 18	No. 35 coarse	No. 60 medium	No. 140	No. 270	
	very coarse			fine	very fine	
2mm	1mm	0.5mm	0.2 mm	0.15mm	0.05mm	
0	0	24.8	67.8	6	1.1	

Research plots were maintained to golf course standards by mowing five times weekly with solid rollers at a height of 3.2 to 4.0mm (0.125 to 0.156 in). Preventative disease and weed control programs were applied as needed over the duration of the study. Irrigation consisted of two weekly applications at a rate of 2.3cm hr-1 accumulating to approximately 5.8cm wk-1, plus supplemental hand-watering during periods of heat stress. Fertilizer applications provided 342kg N ha-1, 86kg P ha-1, and 171kg K ha-1 annually. Prior to this study, HTA was performed twice yearly with 1.2-cm i.d. hollow tines in March and September and 0.9-cm i.d. tines in May. All prior HTA treatments employed tines at 5.1cm x 5.1cm spacing to a depth of 7.6cm. Prior to this study, solid tine aerification (STA) was performed three times yearly, in June, July and August, with 0.6-cm diam. solid round tines spaced at 3.8cm x 3.4cm to a depth of 7.6m.

Aerification Methods

All aerification treatments were applied with a walking aerification unit (ProCore model no. 648, The Toro Company, Bloomington, MN). The aerification unit had a Kohler, 2-cylinder, 17kW (23 horsepower) engine with a max speed of 2.42kmh-1, and an aerating width

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of 1.22m (48 in). Lateral tine spacing was set by selecting tine heads with the desired distance between tine mount locations. Longitudinal spacing was set by selecting the desired detent to mechanically fix the aerification unit drive wheel rotation speed to the resultant rotation speed of the cam which drives the tines. Following all HTA treatments, ejected cores were allowed to dry, then removed. Remaining leaf and organic debris was removed with a backpack blower. All aerified plots were topdressed the same day following HTA treatments in March, May and September with a power belt spreader (model no. TD1500, Cushman Inc., Lincoln, NE) delivering a consistent layer of 0.3cm deep (30m3ha–1) washed, medium-coarse USGA-specified sand similar to the one described in Table 1. No topdressing was applied following STA. Topdressing sand was brushed in by hand to completely fill aerification holes and incorporate remaining sand into the turf canopy. Light irrigation (~2.5mm) was applied to all plots following topdressing and brushing.

Plots were rolled by traversing the entire plot area once in each of two perpendicular directions 1 and 2 d after treatment (DAT), with a 345-kg, gas-powered greens roller (model no. 09010, Salsco Inc., Cheshire, CT). Plots were walk-mowed following rolling 2 DAT with mowing height raised to 6 mm. Plots were then mowed every 2 d thereafter for 14 d, with mowing height lowered gradually to 4 mm. All sand and grass clippings were collected and removed from the site. Thereafter, plots returned to a routine mowing schedule.

Spring Aerification Treatments

Spring aerification treatments included:

1. HTA with 1.2-cm i.d. tines spaced at 5.1cm x 5.1cm to a depth of 7.6cm in March and May (1.2cm Mar, May)

2. HTA with 1.2-cm i.d. tines spaced at 3.8cm x 3.4cm to a depth of 7.6cm in March only (1.2cm Mar 2x)

3. HTA with 0.9-cm i.d. tines spaced at 3.8cm by 3.4cm to a depth of 7.6cm in March and May (0.9cm Mar, May)

4. HTA with 0.6-cm i.d. tines spaced at 3.8cm x 3.4cm to a depth of 7.6cm in March, April, May and June (0.6 cm Mar, Apr, May, June)

(Table 2) The treatment with 1.2-cm i.d. tines spaced at 3.8 cm x 3.4 cm in March only (1.2cm Mar 2x) is equivalent to aerifying twice with 1.2-cm i.d. tines spaced at 5.1cm x 5.1cm. This practice is often referred to as "doubling up" and is performed to reduce labor cost and to potentially minimize the cumulative annual recovery time from the negative effects of aerification. All plots were maintained similarly throughout the summer, fall, and winter by performing STA with 0.6-cm diam. solid round tines spaced at 3.4cm x 3.8cm to a depth of 7.6cm in July and August. In September, all plots received a final HTA with 1.2-cm i.d. tines spaced at 5.1cm x 5.1cm to a depth of 7.6cm. All treatments in this study resulted in an annual total area impacted between 17.9 and 19.0% (Table 2).

Table 2: Area impacted annually by various spring hollow tine aerification treatments on creeping bentgrass greens, March through November 2011 and 2012. All aerification events were to a soil depth of 7.6 cm.

Aerification (i.d.) treatment	Area hole[1]	Tine spacing	Holes	Area impacted event[1]	Total area impacted yr^{-1a}
	cm2	cm	m-2	----------------- --%------------- -----	
1.2cm Mar., May	1.12	5.1 x 5.1	388	4.3	17.9
1.2cm Mar. 2xb	1.12	3.8 x 3.4	776	8.6	17.9
0.9cm Mar., May	0.57	3.8 x 3.4	776	4.4	18.1
0.6cm Mar., Apr., May, June	0.32	3.8 x 3.4	776	2.5	19

[a] Includes 0.6-cm diam. solid tines at 3.8 cm x 3.4 cm spacing in July and August, and 1.2-cm inside diam. hollow tines at 5.1 cm x 5.1 cm spacing in September.

[b] 1.2-cm tines at 3.8 cm x 3.4 cm increased number of holes per m2 and area impacted per event 100% (2x) compared to 1.2-cm tines at 5.1 cm x 5.1 cm.

Aerification Treatment Timing

Aerification treatments were initiated on all plots during the first week of spring each study year (23 March Year1 and 21 March Year 2). Plots aerified with 1.2-cm i.d. hollow tines spaced at 5.1 cm x 5.1cm received a second aerification 8 weeks after initial treatments (WAIT). Plots aerified with 1.2-cm i.d. hollow tines spaced at 3.8cm x 3.4cm were not aerified again until all plots were aerified at the onset of summer STA at 16 WAIT. Plots aerified with 0.9-cm i.d. hollow tines spaced at 3.8cm x 3.4cm received a second aerification 8 WAIT. Plots aerified with 0.6-cm i.d. hollow tines spaced at 3.8cm by 3.4cm received subsequent aerifications at 4, 8, and 12 WAIT. Twelve WAIT was the last week of spring.

All plots received the same summer STA 16 and 20 WAIT with 0.6-cm diam. solid round tines spaced at 3.4cm x 3.8cm to a depth of 7.6cm. All plots received the same final HTA 24 WAIT with 1.2-cm i.d. tines spaced at 5.1cm x 5.1cm to a depth of 7.6cm.

Measurements

The four treatments were designed to evaluate the impact of various spring HTA regimes on turfgrass thatch mat depth (TMD), thatch mat organic matter content (TOM), soil organic matter content (SOM), dry root weight (DRW), and soil bulk density (BD). Data were collected from late March until early November each of the two study years. Organic matter and soil properties (TMD, TOM, SOM, DRW, and BD) were measured prior the first aerification treatment (0 WAIT) of each study year and then 8, 16, 24 and 32 WAIT (March, May, July, September and November). At the end of the study (32 WAIT, Year 2), additional samples were taken in all blocks from small buffer strips between plots. Strips were untreated with respect to spring HTA but received summer STA and fall HTA equal to all plots.

Thatch mat depth (TMD) was determined from physical measurements of two 1.9-cm diam. cores per plot. Cores were allowed to air-dry. All verdure was removed from the core surface with sharp pointed scissors. Loose sand and roots were removed below the bottom of the mat layer. TMD was recorded as average depth measured at a minimum of two locations on the circumference of the uncompressed cores. The depths of the two cores taken from each plot on each date were averaged before statistical analysis. The two thatch and mat OM (TOM) cores taken from each plot on each date were placed together in crucibles, oven-dried for 48hr at 60°C, weighed, ashed by placement in a muffle furnace for 2 hr at 550°C, and re-weighed to determine TOM as percentage of weight lost on ignition [11].

Soil organic matter (SOM) content was determined from two relatively undisturbed 5.7-cm diam., 6-cm deep soil cores per plot, taken between 2 and 8cm below the soil surface with a soil core sampler (model 0200, Soilmoisture Equipment Co., Santa Barbara, CA). The top 2cm of the 8-cm deep core was removed to eliminate verdure and mat OM. Rootzone soil was oven-dried for 48hr at 60°C, weighed, ashed by placement in a muffle furnace for 2hr at 550°C, and re-weighed to determine SOM as percentage of weight lost on ignition [11]. The two measurements taken in each plot on each date were averaged before statistical analysis.

Dry root weight (DRW) was determined from four 1.9-cm diam., 15-cm deep cores per plot. Cores were oven-dried for 48 hr at 60°C. The root zone was separated from the mat OM layer and a 1-mm diam. sieve was used to separate most soil from the roots. Roots were collected from the remaining soil with sharp tweezers. Roots from the four cores taken from each plot on each date were combined and weighed, then ashed by placement in a muffle furnace for 2hr at 550°C and re-weighed to determine ash weight. Dry RW was reported as oven-dry weight minus ash weight [11]. Determination of sufficient time for ashing in the muffle furnace was verified by weighing samples after 2hr at 550°C, placing samples in the furnace for a third hour and re-weighing. Differences in weights were not observed after a third hour of ashing. Bulk density (BD) was measured prior the first aerification treatment of each study year and then 8, 16, 24 and 32 WAIT (March, May, July, September and November). Rootzone BD was determined from the soil cores taken to measure SOM, using mass (g) after being oven-dried for 48hr at 60°C. Bulk density (gcm−3) was determined by dividing dry soil core mass by total soil core volume (153.91cm3). The two measurements taken in each plot on each date were averaged before statistical analysis.

Final Measurements of OM and Soil Properties

The last measurement date of the second study year was 1 Nov. On that date, all plots had recovered to a level where mean TQ for all treatments was rated as acceptable on a commercial golf course. Additional samples for all OM and soil properties measured were taken from 0.6 m strips separating the three blocks in the study area. These strips did not receive any spring aerification treatments. Sample locations were chosen to provide measurements in each block equal to those taken for each of the four treatments. It should be noted that these "untreated" strips did receive summer STA with 0.6-cm diam. solid round tines spaced at 3.4cm x 3.8cm to a depth of 7.6 cm at 16 and 20 WAIT and a final fall HTA with 1.2-cm i.d. tines spaced at 5.1cm x 5.1cm to a depth of 7.6cm at 24WAIT in both study years, simultaneous with all "treatment" plots in the study.

Samples were taken from all plots and from the "untreated" strips in the spring (29 March 2013) following the last November 2012 measurements to indicate if treatment effects were still detectable. Data from these samples were analyzed to compare responses of all OM and soil properties (TMD, TOM, SOM, DRW, and BD) to all treatments and to "no spring aerification" treatment. The changes in all OM and soil properties from the beginning of spring prior to the commencement of the study until the beginning of spring following the study 24mo later, were also analyzed, comparing all treatments with each other and "no spring aerification" treatment.

Experimental Design and Statistical Analysis

Each of the four treatments was applied to one of four 3.6 m x 3.6 m plots in each of three blocks, resulting in a one-way treatment design and a randomized complete block experimental design. Repeated measurements of turfgrass organic matter and soil properties (TMD, TOM, SOM, DRW, BD) were measured prior the first aerification treatment of each study year and then every 8 wk (8, 16, 24, and 32 WAIT). Where multiple measurements were taken within the same plot on the same rating date, values were averaged prior to being included in the statistical analysis. Statistical analysis of data for each of the 12 properties measured in the study was performed to relate the response of each property to the effect of each treatment and repeated measures (time); adjusting for the effects of blocks and random error. Model parameters were estimated and assessed using generalized least squares.

First, data across all rating dates and both study years were analyzed using the model:

$y\ ijkl = \mu + \quad i + \tau\ j + \varepsilon\ a(ij) + Wk\ l + (\tau\ j \times Wk\ k) + Yr\ l + \varepsilon\ b(ijkl)$

where:

y ijkl = response in block "i", treatment "j", year "k", and week "l"

μ = overall mean of the response

i = block effect (change in the mean value of response due to block "i")

τ j = treatment effect (change in the mean value of response due to treatment "j")

ε a(ij) = error for testing and τ

Wk k = week effect (change in the mean value of response due to week "k")

(τ j x Wk k) = interaction of τ and Wk

Yr l = year effect (change in the mean value of response due to year "l")

ε b(ijkl) = error for testing Wk and interaction of Wk and Yr

Second, data were averaged across all rating dates within each of the two study years, and analyzed using the model:

$y\ ijkl = \mu + \quad i + \tau\ j + \varepsilon\ a(ij) + Wk\ k + (\tau\ j \times Wk\ k) + \varepsilon\ b(ijk)$ (by Yr l)

Third, data were analyzed for each rating date (every 8 wk for OM and soil properties) using the model:

$y\ ijkl = \mu + \quad i + \tau\ j + \varepsilon\ a(ij)$ (by Wk k and Yr l)

End of Study Test for Hardpan

Data from infiltrometer tests for the existence of a hardpan layer just below the 7.6-cm tine depth used throughout the study were analyzed to compare the differences in mean WIR resulting from each increase in depth of holes (simulated tine depth); adjusting for the effects of blocks, treatment and random error, using the model:

$y\ ijk = \mu + \quad i + \tau\ j + \varepsilon\ a(ij) + TD\ k + (\tau\ j \times TD\ k) + \varepsilon\ b(ijk)$

Where:

y ijk = response in block "i", treatment "j", and tine depth "k"

μ = overall mean of the response

i = block effect (change in the mean value of response due to block "i")

τ j = treatment effect (change in the mean value of response due to treatment "j")

ε a(ij) = error for testing and τ

TD k = effect of increased tine depth to depth "k"

(Change in the mean value of response due to increase in tine depth to depth "k")

(τ j x TD k) = interaction of τ and TD k

ε b(ijk) = error for testing TD and interactions of and τ with TD

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End of Study Measurements of OM and Soil Properties

Data from measurements taken at the end of the study (1 Nov 2012) and prior to first normal spring aerification in the following year (29 Mar 2013) were analyzed, with the added "no spring aerification" treatment data, using the model:

$$y\ ij = \mu + \quad i + \tau\ j + \varepsilon\ ij$$

Analysis of Variance

An Analysis of Variance (ANOVA) was performed to test for significance of all model effects factors and interactions. An F-test was performed to test the null hypothesis that all mean values for properties measured were statistically equal across treatments and/or time. Where the F-test found the null hypothesis to be false (mean values for all treatments were not statistically equal), Fisher's protected LSD method was used to test statistical significance of specific differences between all pairs of treatments. Alpha (the probability of Type I error, i.e., concluding that mean responses to treatments are significantly different when they are actually not different) was set at 0.05 for turfgrass properties and surface properties. For organic matter and soil properties, alpha was set at 0.10 to better avoid Type II errors (concluding that mean responses to all treatments are equal when they are actually different) that might occur due to inherent variability in soil measurements [12,13]. The General Linear Model procedure (GLM) of SAS was used for all calculations, utilizing JMP software (SAS Institute, Cary, NC).

Results and Discussion

End of Study Test for Hardpan

Engel, et al. [14-16] suggested that repeated hollow or solid tine cultivation to similar depths disrupts soil structure and potentially introduces a compacted layer at the bottom of the cultivation zone. All HTA and STA during the entire study was performed to a depth of 7.6 cm. Additional infiltration testing was performed at the end of this study to measure the effect of repeated aerification to the same depth. In a uniform soil profile without compacted layers, equal increases in STA depth with the same tine diameter and spacing would result in proportionately equal increases in WIR at the same hydraulic head, due to the reduction in soil depth below aerification holes through which water would have to infiltrate.

A layer of increased compaction (hardpan) would have less pore space compared to the rest of the profile. This reduced pore space would decrease the rate of water movement through the hardpan layer. Increasing STA depth to penetrate through such layers would create avenues to allow water to bypass any compacted soil, resulting in a greater increase in WIR compared to the same increase in depth of STA in the uniform soil profile. Significant increase in WIR between tine depths of 7 and 15cm, compared to differences in other tine depth increases (0 to 7cm, 15 to 22cm) would indicate penetration of a compacted layer between 7 and 15cm deep (at or just below the 7.6-cm tine depth used throughout the study).

The effects of increased depths of STA on WIR changes (increases) were not significantly different (data not shown), indicating consistent compaction vertically through the soil profile (no hardpan). The effects of spring HTA treatments were also not significant for any incremental increase in STA depth (data not shown). Figure 1 indicates the increase in WIR in response to equal increases in depth of solid tine aerification. The horizontal axis representing tine depth is to scale and incremental increases in tine depth were equal, so resultant increases in WIR in a uniform soil profile would result in equal vertical increases between data points. The resulting lines connecting data points have basically equal slopes, indicating the absence of a hardpan layer.

A layer of increased compaction below the 7.6-cm depth of aerification would have resulted in a change in slope at the 7-cm data point due to a significantly greater incremental increase in WIR when the holes from simulated STA penetrated and allowed water to bypass the compacted layer. Figure 2 indicates the lack of variance in WIR responses between spring HTA treatments measured immediately following simulated STA to depths of 0, 7 and 15cm. The variance between spring HTA treatments following simulated STA to a depth of 22cm is obviously larger than for the shallower depths, although still not significantly different ($p > 0.05$). All HTA and STA during the entire study was to a depth of 7.6cm. Repetitive equal depth cultivation during this two-year study did not create a (hardpan) layer of increased compaction.

Organic Matter and Soil Properties

Soil OM, like thatch OM, has both positive and negative effects on rootzone soil agronomic properties. Organic matter generally has much more water- and nutrient-holding capacity than mineral soil particles and is often added as an amendment to increase these properties in rootzone sand mixes. However, OM begins to accumulate and contribute to the loss of macropore space in the root zone, soon after turfgrass establishment occurs on sand-based root zones [17,18]. When averaged across all measurement dates and both study years, the effects of spring HTA treatments on TMD and SOM were statistically significant ($p < 0.10$), while the effect of spring HTA treatments on TOM, DRW, and BD were not ($p > 0.10$) (Tables 3 and 4).

Table 3: ANOVA for various spring hollow tine aerification treatment effects on organic matter (OM) and soil properties of creeping bentgrass greens, averaged across all measurement dates and study years, Clemson, SC, March through November 2011 and 2012.

Source of variation	df	Thatch mat depth	Thatch mat OM content	Soil OM content	Dry root weight	Bulk density
Treatment (τ)	3	†	ns	†	ns	ns
Block (β)	2	†	ns	†	†	ns
Year (Yr)	1	ns	ns	***	***	*
Week (Wk)	4	*	***	***	***	***
x τ	6	ns	†	ns	ns	*
Wk x τ	12	ns	ns	ns	ns	ns

*Significant at the 0.05 probability level.

***Significant at the 0.001 probability level.

†Significant at the 0.10 probability level.

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Table 4: Organic matter (OM) and soil properties response to various spring hollow tine aerification treatments on creeping bentgrass greens, averaged across all measurement dates and study years, Clemson, SC, March through November 2011 and 2012.

Aerification treatment	Thatch mat depth	Thatch mat OM content	Soil OM content	Dry root weight	Bulk density
	mm	%LOI†	%LOI†	g‡	gcm-3
1.2cm Mar, May	15.8 a§	10.77 a	1.45 a	0.082 a	1.30 a
1.2cm Mar 2x	16.5 b	10.40 a	1.44 a	0.080 a	1.29 a
0.9cm Mar, May	15.7 a	10.01 a	1.41 a	0.086 a	1.29 a
0.6cm Mar, Apr, May, June	15.4 a	9.81 a	1.50 b	0.078 a	1.29 a
Fisher's protected LSD (0.10)	0.64	ns	0.048	ns	ns

† Difference in oven-dry weight and ashed weight as percentage of dry weight lost on ignition (LOI).

‡ Oven-dry weight of roots from four 1.9-cm diam. (11.4 cm2 total surface area), 15-cm deep cores per plot.

§ Values followed by different letters within the same column are significantly different at the 0.10 significance level.

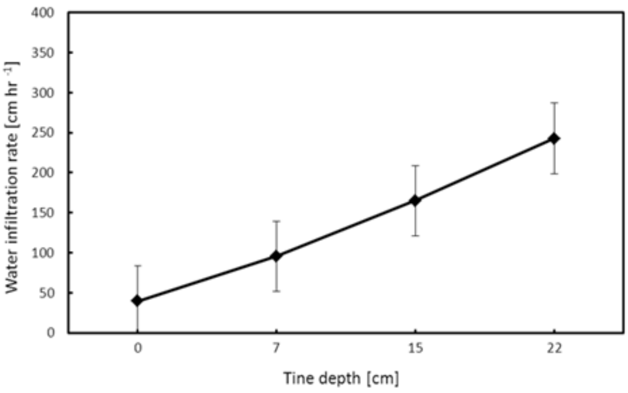

Figure 1: Effect of increased depths of solid tine aerification on water infiltration rate, at the end of a 2-year study on creeping bentgrass greens, Clemson, SC, 1 Nov 2012.

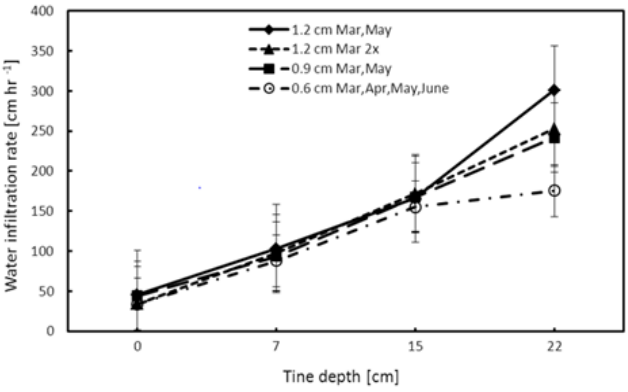

Figure 2: Effect of various spring hollow tine aerification treatments and increased depths of solid tine aerification on water infiltration rates, at the end of a 2-year study on creeping bentgrass greens, Clemson, SC, 1 Nov 2012.

When means were averaged across all rating dates for each year separately, the effect of spring HTA treatments on mean TMD was statistically significant for Year 1 and Year 2 ($p < 0.10$). The effect of spring HTA treatments on TOM was not statistically significant in Year 1 but was significant in Year 2 ($p < 0.10$). Spring HTA treatments had significant effect on SOM in Year 1 ($p < 0.05$), but not in Year 2. The effect of spring HTA treatments on DRW and BD were not statistically significant for either year ($p > 0.10$) (Table 5).The effect of study week (measurement date) was significant ($p < 0.05$) for TMD, TOM, SOM, DRW, and BD for both study years (Table 6). Therefore, means were analyzed for each measurement date in each study year. Table 7 and Table 8 list the significance of spring HTA treatment effects on TMD, TOM, SOM, DRW, and BD, based on ANOVA for treatment means by measurement date. These effects are discussed separately for each organic matter and soil property measured in the following sections. Treatment means are reported for all measurement dates (0, 8, 16, 24, and 32 WAIT) and both study years.

Previous research implies that as OM in a sand-based putting green reaches 4-5% by weight, the percentage of soil macropores (aeration pores) begins to decrease [19]. The decrease in macropores is accompanied by an increase in micropores (capillary or water-holding pores). Increased moisture content in the upper rootzone can make the surface less firm. Increased microporosity lowers the permeability of soil, decreasing water infiltration and minimizing gas exchange, leading to escalated levels of water runoff or puddling, and reduced ability to exchange CO2 with ambient air, causing a rise in CO2 concentration to potentially toxic levels [20]. Excessive OM accumulation may lead to secondary problems in putting green soils such as increase in black layer and soft surfaces. Secondary problems are further manifested in bentgrass by poor root growth, wet wilt, and increased potential for disease and frequent high-temperature injury. These secondary problems are often called summer decline [21].

Thatch Mat Depth

Thatch is a brown- to black-colored, tightly intermingled layer of living and dead plant tissue that develops between the green vegetation and soil surface [8]. Thatch is made up of vascular strands of horizontal stems (stolons and rhizomes), leaf sheaths, intact fibrous roots, nodes and crown tissue [22]. Mat is a tan- to brown-colored tightly intermingled layer of partially decomposed thatch intermixed with soil [5,8]. Mat forms when thatch is slow to decompose and aggregates with sand, usually from topdressing. Thatch accumulation occurs when turfgrass production of OM exceeds the decomposition rate [23]. The shallow, fibrous root systems of several turfgrass species are almost completely regenerated each year, and thus potentially contribute to thatch buildup [24]. Any climatic, edaphic, or biotic factor that stimulates excessive plant growth or impairs decomposition of organic material contributes to thatch development [22]. Thatch contains a high amount of lignin, which inhibits decomposition by blocking microbial degradation of the cellulosic cell structures that comprise the lower thatch layer [8]. Leaf blade clippings are low in lignin content and do not contribute to long-term thatch accumulation [25].

Table 5: ANOVA for various spring hollow tine aerification treatment effects on organic matter (OM) and soil properties of creeping bentgrass greens, averaged across all measurement dates, by year, Clemson, SC, March through November 2011 and 2012.

Year	Source of variation	df	Thatch mat depth	Thatch mat OM content	Soil OM content	Dry root weight	Bulk density
2011	Treatment (τ)	3	†	ns	*	ns	ns
	Block (β)	2	*	ns	**	*	ns
	Week (Wk)	4	***	***	***	***	**
	β x π	6	ns	*	ns	ns	ns
	Wk x τ	12	ns	ns	ns	ns	ns
2012	Treatment (τ)	3	†	†	ns	ns	ns
	Block (β)	2	ns	ns	ns	ns	ns
	Week (Wk)	4	***	***	**	***	***
	β x π	6	ns	ns	ns	ns	**
	Wk x τ	12	ns	†	ns	ns	ns

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Significant at the 0.10 probability level.

Table 6: Organic matter (OM) and soil properties response to various spring hollow tine aerification treatments on creeping bentgrass greens, averaged across all measurement dates, by year, Clemson, SC, March through November 2011 and 2012.

Year	Aerification treatment	Thatch mat depth	Thatch mat OM content	Soil OM content	Dry root weight	Bulk density
		mm	%LOI†	%LOI†	g‡	gcm-3
2011	1.2cm Mar, May	15.8 ab§	10.93 a	1.42 a	0.077 a	1.30 a
	1.2cm Mar 2x	16.1 a	10.32 a	1.40 ab	0.073 a	1.29 a
	0.9cm Mar, May	15.3 b	10.22 a	1.38 b	0.081 a	1.29 a
	0.6cm Mar, Apr, May, June	15.5 b	9.92 a	1.47 c	0.075 a	1.29 a
	Fisher's protected LSD (0.10)	0.47	ns	0.04	ns	ns
2012	1.2cm Mar, May	15.7 a	10.60 a	1.47 a	0.087 a	1.29 a
	1.2cm Mar 2x	16.9 b	10.48 a	1.47 a	0.088 a	1.29 a
	0.9cm Mar, May	16.1 ab	9.81 b	1.44 a	0.091 a	1.29 a
	0.6cm Mar, Apr, May, June	15.2 a	9.70 b	1.53 a	0.081 a	1.28 a
	Fisher's protected LSD (0.10)	1.04	0.67	ns	ns	ns

† Difference in oven-dry weight and ashed weight as percentage of dry weight lost on ignition (LOI).

‡ Oven-dry weight of roots from four 1.9-cm diam. (11.4 cm2 total surface area), 15-cm deep cores per plot.

§ Values followed by different letters within the same column in the same year are significantly different at the 0.10 significance level.

Table 7: ANOVA for various spring hollow tine aerification treatment effects on organic matter (OM) and soil properties of creeping bentgrass greens, by measurement date, Clemson, SC, 23 Mar 2011 through 1 Nov 2011.

WAIT‡	Date	Thatch mat depth	Thatch mat OM content	Soil OM content	Dry root weight	Bulk density
0	23-Mar	ns	ns	ns	ns	**
8	19-May	ns	†	ns	ns	ns
16	13-Jul	*	ns	ns	ns	ns
24	06-Sep	ns	ns	†	ns	ns
32	01-Nov	ns	ns	ns	ns	ns

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

† Significant at the 0.10 probability level.

‡ WAIT, weeks after initial treatments.

Table 8: ANOVA for various spring hollow tine aerification treatment effects on organic matter (OM) and soil properties on creeping bentgrass greens, by measurement date, Clemson, SC, 21 Mar 2012 through 1 Nov 2012.

WAIT‡	Date	Thatch mat depth	Thatch mat OM content	Soil OM content	Dry root weight	Bulk density
0	21-Mar	ns†	ns	ns	ns	ns
8	17-May	ns	ns	ns	ns	ns
16	11-Jul	ns	**	ns	ns	ns
24	07-Sep	ns	ns	ns	ns	ns
32	01-Nov	ns	*	ns	ns	ns

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

† Not significant at the 0.10 probability level.

‡ WAIT, weeks after initial treatments.

Thatch mat contributes to desirable turf properties by increasing resilience and wear tolerance, and by acting as a buffer for moderation of soil temperatures [26]. Thatch mat at moderate depths provides a desirable cushioning effect for traffic and incoming golf shots [27]. Organic matter has also been shown to hold pesticides until they are broken down by microorganisms, limiting environmental contamination from ground water pollution [28]. Thatch mat accumulation exceeding a depth of 2.5 cm has been suggested as excessive [12]. Excessive thatch is commonly associated with negative physical and biological effects within the soil profile. Negative effects include reduced hydraulic conductivity, decreased water infiltration, reduced tolerance to cold temperatures, reduced pesticide effectiveness, increased localized dry spots, and increased disease and insect problems [8,23,29,30].

When averaged across all measurement dates and both study years, mean TMD on plots aerified with 1.2 cm Mar 2x was 4% higher than 1.2cm Mar, May; 5% higher than plots aerified with 0.9cm Mar, May; and 7% higher than plots aerified with 0.6cm Mar, Apr, May, June (Table 4). Mean TMD in Year 1 was 5% higher on plots aerified with 1.2cm Mar 2x than plots aerified with 0.9cm Mar, May and 4% higher than plots aerified with 0.6cm Mar, Apr, May, June. Mean TMD in Year 2 was 8% higher on plots aerified with 1.2cm Mar 2x than 1.2cm Mar, May and 11% higher than plots aerified with 0.6 cm Mar, Apr, May, June (Table 6).

Following completion of all varying spring HTA in Year 1, prior to the first summer STA of all plots 16 WAIT, mean TMD in plots aerified with 1.2cm Mar 2x was ~14% greater than for all other treatments. Mean TMD was similar between treatments prior to 16 WAIT and for the remainder of measurement dates in Year 1, when all plots received the same STA and final HTA (Table 9). Mean TMD was not significantly different between treatments for any measurement dates in Year 2 (data not shown).

Thatch Mat Organic Matter Content

The effect of spring HTA treatments on TOM was not statistically significant ($p > 0.10$) in Year 1 but was in Year 2 ($p < 0.10$) (Table 5). Mean TOM in Year 2 was 8% higher on plots aerified with 1.2cm Mar, May than plots aerified with 0.9 cm Mar, May and 9% higher than plots aerified with 0.6cm Mar, Apr, May, June. Mean TOM in Year 2 was also 7% higher on plots aerified with 1.2 cm Mar 2x than plots aerified with 0.9cm Mar, May and 8% higher than plots aerified with 0.6c m Mar, Apr, May, June. Mean TOM in plots aerified with 1.2cm Mar, May was not significantly different than in plots aerified with 1.2cm Mar 2x (Table 6). Prior to HTA 8 WAIT in Year 1, mean TOM was 10% greater in plots aerified with 1.2-cm tines at 5.1cm x 5.1cm spacing in March (1.2cm Mar, May) than 1.2-cm tines at 3.4cm x 3.8cm (1.2cm Mar 2x), and 14% greater than in plots aerified with 0.6-cm tines at 3.4cm x 3.8 cm in March and April (0.6cm Mar, Apr, May, June). All treatments received subsequent HTA 8 WAIT except for plots aerified with 1.2cm Mar 2x. Mean TOM was not significantly different between treatments for the remainder of Year 1 (Table 10).

Prior to the first summer STA of all plots 16 WAIT in Year 2, mean TOM in plots aerified with 1.2cm Mar, May was 14% greater than 1.2cm Mar 2x; 33% greater than in plots aerified with 0.9cm Mar, May; and 25% greater than in plots aerified with 0.6 cm Mar, Apr, May, June. Mean TOM in plots aerified with 1.2cm Mar 2x was also 16% greater than in plots aerified with 0.9cm Mar, May; but not significantly greater than in plots aerified with 0.6cm Mar, Apr, May, June (Table 11). Mean TOM was not different between treatments 24 WAIT in Year 2. At 32 WAIT, mean TOM in plots aerified with 1.2cm Mar 2x was 23% greater than in plots aerified with 0.9cm Mar, May and 35% greater than in plots aerified with 0.6cm Mar, Apr, May, and June. Mean TOM in plots aerified with 1.2cm Mar, May was also 19% greater than in plots aerified with 0.6cm Mar, Apr, May, June (Table 11).

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Table 9: Thatch mat depth response to various spring hollow tine aerification treatments, by measurement date, creeping bentgrass greens, Clemson, SC, 23 Mar 2011 through 1 Nov 2011.

Aerification treatment	Thatch mat depth				
	23-Mar	19-May	13-Jul	06-Sep	01-Nov
	0 WAIT†	8 WAIT	16 WAIT	24 WAIT	32 WAIT
	------------------------------mm--				
1.2cm Mar, May	15.2 a‡	17.6 a	15.7 a	15.2 a	15.6 a
1.2cm Mar 2x	14.3 a	17.7 a	17.8 b	15.0 a	15.9 a
0.9cm Mar, May	14.2 a	16.3 a	15.8 a	14.8 a	15.8 a
0.6cm Mar, Apr, May, June	14.4 a	17.2 a	15.6 a	14.4 a	16.2 a
Fisher's protected LSD (0.10)	ns	ns	1.23	ns	ns

† WAIT, weeks after initial aerification treatments.

‡ Values followed by different letters within the same rating date are significantly different at the 0.10 significance level.

Table 10: Thatch mat organic matter response to various spring hollow tine aerification treatments, by measurement date, creeping bentgrass greens, Clemson, SC, 23 Mar 2011 through 1 Nov 2011.

Aerification treatment	Thatch mat organic matter content				
	23-Mar	19-May	13-Jul	06-Sep	01-Nov
	0 WAIT†	8 WAIT	16 WAIT	24 WAIT	32 WAIT
	----------------------------%LOI‡----------------------------				
1.2cm Mar, May	12.27 a§	11.71 a	10.01 a	10.48 a	10.16 a
1.2cm Mar 2x	11.94 a	10.62 bc	8.83 a	10.44 a	9.78 a
0.9cm Mar, May	11.18 a	11.38 ab	9.21 a	9.92 a	9.42 a
0.6 m Mar, Apr, May, June	11.33 a	10.23 c	8.15 a	10.49 a	9.38 a
Fisher's protected LSD (0.10)	ns	0.893	ns	ns	ns

† WAIT, weeks after initial aerification treatments.

‡ Difference in oven-dry weight and ashed weight as percentage of dry weight lost on ignition (LOI).

§ Values followed by different letters within the same rating date are significantly different at the 0.10 significance level.

Table 11: Thatch mat organic matter response to various spring hollow tine aerification treatments, by measurement date, creeping bentgrass greens, Clemson, SC, 21 Mar 2012 through 1 Nov 2012.

Aerification treatment	Thatch mat organic matter content				
	21-Mar	17-May	11-Jul	07-Sep	01-Nov
	0 WAIT†	8 WAIT	16 WAIT	24 WAIT	32 WAIT
	----------------------------%LOI‡----------------------------				
1.2cm Mar, May	11.07 a§	11.96 a	10.89 a	8.55 a	10.54 ab
1.2cm Mar 2x	10.08 a	11.50 a	9.53 b	9.34 a	11.98 a
0.9cm Mar, May	11.37 a	11.19 a	8.20 c	8.56 a	9.71 bc
0.6cm Mar, Apr, May, June	10.81 a	11.39 a	8.89 bc	8.54 a	8.88 c
Fisher's protected LSD (0.10)	ns	ns	0.452	ns	1.652

† WAIT, weeks after initial aerification treatments.

‡ Difference in oven-dry weight and ashed weight as percentage of dry weight lost on ignition (LOI).

§ Values followed by different letters within the same rating date are significantly different at the 0.10 significance level.

Table 12: Soil organic matter response to various spring hollow tine aerification treatments, by measurement date, creeping bentgrass greens, Clemson, SC, 23 Mar 2011 through 1 Nov 2011.

Aerification treatment	Soil organic matter content				
	23-Mar	19-May	13-Jul	06-Sep	01-Nov
	0 WAIT†	8 WAIT	16 WAIT	24 WAIT	32 WAIT
	-----------------------------%LOI‡----------------------------				
1.2cm Mar, May	1.41 a§	1.59 a	1.40 a	1.31 a	1.42 a
1.2cm Mar 2x	1.47 a	1.52 a	1.37 a	1.25 a	1.37 a
0.9cm Mar, May	1.32 a	1.55 a	1.35 a	1.33 ab	1.38 a
0.6cm Mar, Apr, May, June	1.43 a	1.59 a	1.48 a	1.40 b	1.44 a
Fisher's protected LSD (0.10)	ns	ns	ns	0.09	ns

† WAIT, weeks after initial aerification treatments.

‡ Difference in oven-dry weight and ashed weight as percentage of dry weight lost on ignition (LOI).

§ Values followed by different letters within the same rating date are significantly different at the 0.10 significance level.

Soil Organic Matter Content

When averaged across all measurement dates and both study years, mean SOM in plots aerified with 0.6 cm Mar, Apr, May, June was 3% higher than plots aerified with 1.2cm Mar, May; 4% higher than plots aerified with 1.2cm Mar 2x; and 6% higher than plots aerified with 0.9cm Mar, May (Table 4). Spring HTA treatments affected SOM in Year 1 ($p < 0.05$), but not in Year 2 ($p > 0.10$). Mean SOM in Year 1 in plots aerified with 0.6cm Mar, Apr, May, June was 4% higher than plots aerified with 1.2cm Mar, May; 5% higher than plots aerified with 1.2cm Mar 2x; and 7% higher than plots aerified with 0.9cm Mar, May. Mean SOM in Year 1 was also 3% higher on plots aerified with 1.2cm Mar, May than plots aerified with 0.9cm Mar, May (Table 6).

Mean SOM differed between treatments at only one measurement date over the entire study. Prior to the final HTA in Sep 2011, 24 WAIT, mean SOM in plots aerified with 0.6 cm Mar, Apr, May, June was 7% greater than plots aerified with 1.2cm Mar, May and 12% greater than plots aerified with 1.2cm Mar 2x (Table 10). Differences were not seen in Year 2 (data not shown).

Dry Root Weight

One of the major indicators of SBD is a decrease in root weight, sometimes measured as root length and width, root length density, or root volume. With a developed root system, plants are able to utilize greater quantities of available water and nutrients through an increase in total root surface area. Non-photosynthetic root cells consume O2 and generate CO2. Limited O2 diffusion results in increased CO2 due to their inverse relationship in soils. High soil CO2 concentrations negatively affect roots of many crop plants. Loss of turgor pressure and wilting can occur under low soil O2 conditions. Research has shown the importance of maintaining a quality soil atmosphere with adequate soil O2. For example, an increase to 5% soil CO2 levels caused a decline in bentgrass growth and quality from an imbalance between respiration and photosynthesis (31). These findings have stimulated usage of spring and summer cultivation as part of normal maintenance of highly trafficked turf [16,32].

The effect of spring HTA treatments on DRW was not statistically significant ($p > 0.10$) when averaged across all measurement dates and both study years (Table 4), nor when means were averaged across all measurement dates for each year separately (Table 8). Mean DRW was not significantly different between treatments for any measurement date in either study year (data not shown). The lack of variance in DRW between treatments throughout the study, and the reduction in DRW during the increase stress of summer, is apparent in the similarity of treatment trendlines in Figures 3 and 4.

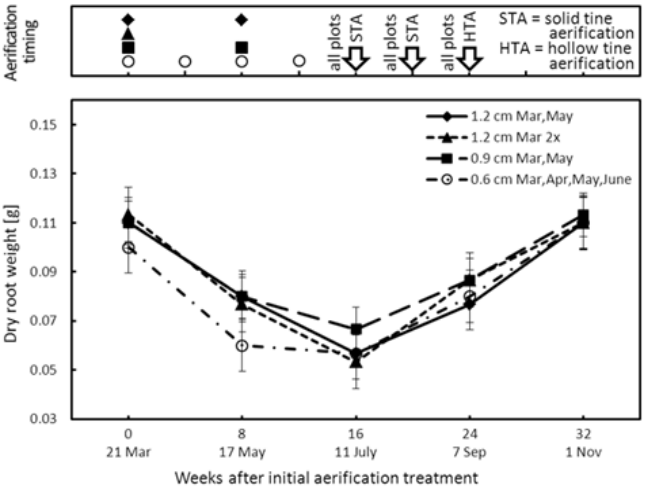

Figure 3: Effect of various spring hollow tine aerification treatments on dry root weight of creeping bentgrass greens, Clemson, SC, 23 Mar 2011 through 1 Nov 2011. Dry root weight as oven-dry weight of roots from four 1.9-cm diam. (11.4 cm2 total surface area), 15-cm deep cores per plot. Standard error bars do not include block variation. The box above the graph shows aerification timing with a marker corresponding to one of the four treatments in the legend above dates when that treatment was applied.

Previous research has shown root weights in creeping bentgrass vary significantly with temperature. Even heat tolerant creeping bentgrass cultivars are susceptible to root growth decline when air temperatures rise above 30° C (33). Root biomass (root weight) from 'Penncross' creeping bentgrass grown in the transition zone (central North Carolina, USA) was lowest in September, greatest in May, and intermediate in winter and early spring [34].

Soil Bulk Density (Porosity)

Bulk density (BD) is affected by a soil's structure, i.e., looseness or degree of compaction, as well as by its swelling and shrinking characteristics. BD is a good measure of soil compaction, especially in sandy soils where swelling and shrinkage are negligible [35]. Porosity is inversely proportional to BD. Increased compaction results in an increase in BD and a corresponding decrease in total porosity. The USGA specifications for rootzone soils recommend total porosity between 0.35 and 0.55cm3cm-3, which equates to BD between 1.19 and 1.72gcm-3 [10].

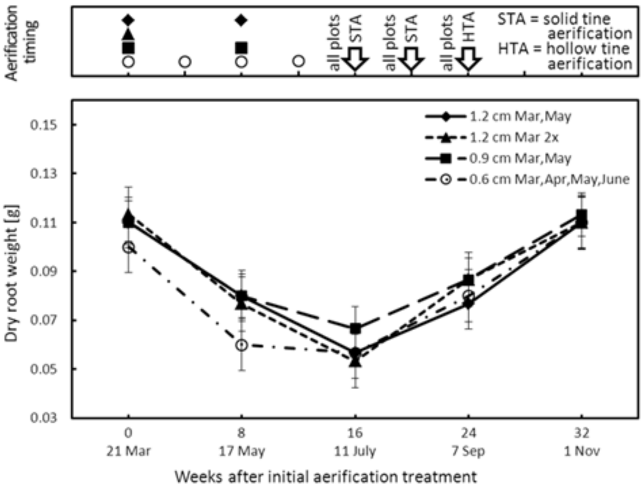

Figure 4: Effect of various spring hollow tine aerification treatments on dry root weight of creeping bentgrass greens, Clemson, SC, 21 Mar 2012 through 1 Nov 2012. Dry root weight as oven-dry weight of roots from four 1.9-cm diam. (11.4 cm2 total surface area), 15-cm deep cores per plot. Standard error bars do not include block variation. The box above the graph shows aerification timing with a marker corresponding to one of the four treatments in the legend above dates when that treatment was applied. Time is indicated on the horizontal axis in weeks after initial aerification treatments with concurrent calendar date below.

Porosity may be divided into macroporosity (also called aeration porosity, typically the ratio of soil pore volume filled with air at field capacity to total soil volume) and microporosity (also called capillary or water-holding porosity, typically the ratio of soil pore volume retaining water at field capacity to total soil volume). In areas receiving heavy traffic, i.e., golf course putting greens and sports turf fields, compaction occurs when macroporosity is decreased by a compressive force thereby increasing microporosity. Compacted soils may result in reduced root growth due to loss of growth channels and inability to counter high soil strength with adequate growing pressure [36]. Fry and Huang [37] noted that as BD decreases, soil macroporosity increases, allowing optimum root growth. In incidences of severe compaction, micropores become so small water becomes unavailable for plant uptake [20].

The removal of soil by conventional HTA has been shown to reduce soil strength and relieve compaction (lower BD). A decrease in BD also promotes more efficient gas exchange with ambient air to rid the rootzone of toxic gasses such as CO2 that may build up in a compacted soil, thus improving soil oxygenation [7,13] .The effect of spring HTA treatments on BD was not statistically significant ($p > 0.10$) when averaged across all measurement dates and both study years (Table 4), nor when means were averaged across all measurement dates for each year separately (Table 6).

Mean BD differed between treatments prior to study commencement, but did not differ thereafter (data not shown). These slight differences are likely due to innacuracies in gathering samples. Sampling errors were likely reduced with increasing experience with the large core sampler as the study progressed. Previous research indicates that soil aeration status can vary with differing cultivation practices [38]. Significant increase in O2 diffusion rates occur with long-term spoon cultivation [39]. In contrast, Petrovic [15] found vertical operating HTA had minimal effect on O2 diffusion rates. Previous research on the same 'Crenshaw' research plots used in this study showed CO2 reductions due to conventional HTA were not significant [16].

End of Study Measurements

At the last measurement date of Year 2, 1 November 2012, additional samples for all OM and soil properties were taken from 0.6-m strips separating the three blocks in the study area. These strips did not receive any spring aerification treatments, but did receive summer STA with 0.6-cm diam. solid round tines spaced at 3.4cm x 3.8cm to a depth of 7.6cm at 16 and 20 WAIT and a final HTA with 1.2-cm i.d. tines spaced at 5.1 cm x 5.1cm to a depth of 7.6cm at 24WAIT in both study years, simultaneous with all "treatment" plots in the study. Data from measurements on these dates, with the added "no spring aerification" treatment data, were analyzed to compare organic matter and soil properties when turfgrass had recovered from the effects of spring and summer aerification.

Mean TMD was 34-39% greater on plots with no spring aerification compared to all treatments (Table 4). Mean TOM in plots aerified with 1.2cm Mar, May and plots aerified with 1.2cm May 2x was higher than plots with no spring aerification (25 and 43%, respectively). Plots aerified with 0.9cm Mar, May or 0.6cm Mar, Apr, May, June did not differ significantly from those with no spring aerification. Mean SOM was 11-19% greater on plots which had no spring aerification compared to all treatments. Differences did not occur in DRW or BD between any treatments or plots with no spring aerification (Table 13).

In March 2013, samples were again taken from all plots and from the "untreated" strips. Plots had not been aerified for 28 wk. Differences were not seen at this time for any OM or soil property between any treatments or plots with no spring aerification (data not shown). When comparing OM and soil properties prior to study initiation with those 2yr later; changes in TMD, TOM, SOM, and BD did not differ from each other; or from plots which did not receive any spring aerification during the study (Table 14).

Table 13: Organic matter (OM) and soil properties response to various spring hollow tine aerification treatments, measured at end of study, creeping bentgrass greens, Clemson, SC, 1 Nov 2012.

Aerification treatment	Thatch mat depth	Thatch mat OM content	Soil OM content	Dry root weight	Bulk density
	mm	%LOI†	%LOI†	g‡	gcm-3
No spring aerification	20.5 a§	8.40 a	1.60 a	0.063 a	1.29 a
1.2cm Mar, May	14.8 b	10.54 bc	1.34 b	0.097 a	1.29 a
1.2cm Mar 2x	15.0 b	11.98 b	1.39 b	0.123 a	1.31 a
0.9cm Mar, May	14.8 b	9.71 ac	1.37 b	0.107 a	1.31 a

0.6cm Mar, Apr, May, June	15.3 b	8.88 a	1.44 b	0.110 a	1.29 a
Fisher's protected LSD (0.10)	1.73	1.606	0.103	ns	ns

† Difference in oven-dry weight and ashed weight as percentage of dry weight lost on ignition (LOI).

‡ Oven-dry weight of roots from 10.2-cm diam. (81.1 cm2 total surface area), 15-cm deep cores per plot.

§ Values followed by different letters within the same column are significantly different at the 0.10 significance level.

Table 14: Change in organic matter (OM) and soil properties response to various spring hollow tine aerification treatments, reported as differences between measurements taken prior to first spring aerification of first study year and measurements taken prior to first spring aerification of the year following study completion, creeping bentgrass greens, Clemson, SC, 23 Mar 2011 to 29 March 2013.

Aerification treatment	Change in property measured				
	Thatch mat depth	Thatch mat OM content	Soil OM content	Dry root weight	Bulk density
	mm	%LOI†	%LOI†	mg‡	gcm-3
No spring aerification	6.6 a§	-2.22 a	0.33 a	-43 ab	-0.01 a
1.2cm Mar, May	5.0 a	-3.31 a	0.04 a	-63 bc	0.00 a
1.2cm Mar 2x	6.5 a	-2.54 a	0.08 a	-73 c	0.01 a
0.9cm Mar, May	5.1 a	-1.64 a	0.21 a	-57 bc	-0.02 a
0.6cm Mar, Apr, May, June	4.9 a	-2.92 a	0.09 a	-27 a	-0.01 a
Fisher's protected LSD (0.10)	ns	ns	ns	27.6	ns

† Difference in oven-dry weight and ashed weight as percentage of dry weight lost on ignition (LOI).

‡ Oven-dry weight of roots from 10.2-cm diam. (81.1 cm2 total surface area), 15-cm deep cores per plot.

§ Values followed by different letters within the same column are significantly different at the 0.10 significance level.

However, during this 2-year period (23 Mar 2011 to 29 Mar 2013), mean DRW decreased in all treatments. Mean DRW decreased 170% more in plots aerified with 1.2 cm Mar 2x than in plots aerified with 0.6cm Mar, Apr, May, June and 70% more than in plots with no spring aerification. Mean DRW also decreased 133% more in plots aerified with 1.2cm Mar 2x, May and 111% more in plots aerified with 0.9cm Mar, May than in plots aerified with 0.6cm Mar, Apr, May, June (Table 14).

Conclusions

Varying spring HTA tine size and timing did not affect TQ averaged within or between study years. Reducing the number of spring HTA application events contributed to all increases observed in TREC and TREG. Reducing surface area impacted by a single HTA event contributed to increases in TQ, TREC, and TREG for up to 4wk. Increasing the surface area impacted by a single HTA event increased the time required for TREC to reach acceptable levels (rating ≥ 7) 1 - 4wk. Even though all surface properties fluctuated significantly during the study, differences between treatments were not observed within or across study years. The various spring HTA treatments did not affect SC during this study. The effect of varying spring HTA treatments on SF and BRD lasted ≤ 2wk. Treatments provided some effect on WIR for 1 - 2wk following the initial HTA of both years, but only on when >5 % of the plots' surface area was impacted. Repetitive equal depth cultivation during this two-year study did not create a (hardpan) layer of increased compaction.

All OM and soil properties were also very dynamic during and after spring HTA treatments, yet few differences occurred between treatments. Mean TMD in plots aerified with 1.2cm Mar 2x was greater than all other treatments across both study years and was greater than or equal to all other treatments within both study years. In Year 1, and when averaged across both study years, mean SOM in plots aerified with 0.6-cm tines was higher than for all other treatments. In Year 2, plots receiving spring HTA with 1.2-cm tines, regardless of spacing or timing, had 7 – 9 % higher TOM content than plots aerified with 0.9-cm or 0.6-cm tines. Mean DRW and BD were not significantly different between treatments for any measurement date during the study.

At the end of the study on 1 Nov 2012, mean TMD was 34 - 39% greater and mean SOM was 11 - 19% greater on plots with no spring aerification compared to all treatments. Plots aerified with 1.2-cm tines had 25 – 43 % higher TOM at the end of the study than plots with no spring aerification. When OM and soil properties were tested the following spring on 29Mar 2013, no differences were observed between treatments or untreated strips.

When comparing OM and soil properties measured before the study and after 2 yr; changes in TMD, TOM, SOM, and BD did not differ significantly between treatments, or from changes in these properties in strips with no spring aerification. During this 2-year period (23 Mar 2011 to 29 Mar 2013), mean DRW decreased for all treatments. Plots aerified with 0.6 cm Mar, Apr, May, June had 53 - 63 % less reduction in DRW than all other spring HTA treatments and was the only treatment which did not differ from strips with no spring aerification.

The null hypothesis that no differences would occur between treatments was proven false overall. When averaged across both study years; TREC, TREG, TMD, and SOM all differed between treatments. When averaged across each year separately; TREG, TMD, and SOM differed in Year 1; and TREC, TREG, and TOM differed in Year 2. Differences also occurred on at least one rating or measurement date for each property.

Recommendations

Overall, this study would support a recommended aerification program for bentgrass greens in the transition zone to include two spring HTA applications with 1.2-cm tines at 5.1cm x 5.1cm or 0.9-cm tines at 3.8cm x 3.4cm (March and May), monthly STA during the summer, and a fall HTA application with 1.2cm tines at 5.1cm x 5.1cm. Turf managers can vary their spring HTA schedule to increase TQ during periods where this is important (i.e., for a tournament). Varying tine size and spacing like treatments in this study will likely only affect surface properties ≤ 2wk, but long-term effects on OM and soil properties should be considered.

Reducing spring HTA to a single application, like the "doubling up" treatment in this study, would not be advisable on greens where thatch mat accumulation is a concern. More frequent aerification with smaller tines increased SOM in this study. Smaller diameter tines impact less surface area and the 0.6-cm i.d. tines left noticeably less rootzone sand on the surface to be removed with cores. This suggests that decreasing the area impacted by a single aerification event may decrease root loss, but this may not be advisable on greens where SOM accumulation is a concern (SOM content ≥ 4 %). Evidence of a hardpan layer was not seen in this study, but inclusion of at least one deeper STA application should be considered annually to help reduce the chance of creating a zone of increased compaction. If repetitive equal depth cultivation is practiced, regular testing should be done to check for such a layer.

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