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Creeping Bentgrass Surface Properties Following Aerification

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Abstract

The desire to maintain optimal turfgrass and surface properties often leads turfgrass managers to minimize impact from cultural practices like Hollow Tine Aerification (HTA). Comprehensive research is essential to developing aerification programs which allow optimal use of turfgrass surfaces without sacrificing overall turf health. 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 quality and surface properties.

Spring HTA treatments included 1.2-cm i.d. tines spaced at 5.1cm x 5.1cm in March and May (standard); 1.2-cm i.d. tines spaced at 3.8cm x 3.4cm in March only (2x); 0.9-cm i.d. tines spaced at 3.8cm x 3.4cm 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 7.6cm, with cores removed.

Varying spring HTA tine size and timing did not affect Turfgrass Quality (TQ) within or across years. Reducing surface area impacted by a single HTA event contributed to increases in TQ, recovery (TREC) and regrowth (TREG) up to 4 wk and decreased the time required for turfgrass to recover to acceptable levels by 1 to 4 wk.

Even though surface properties fluctuated significantly, treatment effects were not observed within or across study years and lasted ≤2 wk. 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 properties.

Abbreviations: BRD: Ball Roll Distance; DAT: Days After Treatment; HTA: Hollow Tine Aerification; ID: Inside Diameter; OM: Organic Matter; SBD: Summer Bentgrass Decline; STA: Solid Tine Aerification; SC: Surface Compressibility, SF: Surface Firmness; TREC: Turfgrass Recovery; TREG: Turfgrass Regrowth; TQ, Visual Turfgrass Quality; WAIT: Weeks After Initial Treatment; WIR: Water Infiltration Rate.

Core Ideas

- Aerification (or coring) is one of the most controversial agronomic practices turf managers face.
- Questions on "doubling" up aerification instead of having two separate events to reduce the time of less than desired putting surfaces are often asked.
- 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 5.1cm spacings or 0.9-cm tines at 3.8 cm x 3.4cm spacing (March and May), monthly solid tine aerifications during the summer, and a fall hollow tine aerification with 1.2-cm tines at 5.1cm x 5.1cm spacings.

Creeping bentgrass is the most commonly used cool season turfgrass on golf greens [1]. It is well suited as a putting surface due to its tolerance of low mowing heights, excellent density, soft texture, and narrow leaf blade (0.62 to 0.91mm) [2]. Bentgrass and other cool-season (C3) grasses coexist with warm-season (C4) grasses in the transition zone, located in the eastern and central United States (1). The movement of bentgrass outside its natural adapted environments often leads to lower quality during summer months. This condition is referred to as Summer Bentgrass Decline (SBD) [3-5].

Factors contributing to SBD often include high temperatures, high relative humidity, excessive shade, poor air circulation, poor soil aeration, excessive or deficient soil water, salt stress, and soil-borne disease organisms [4,5]. Hollow Tine Aerification (HTA) is an agronomic practice commonly used to manage thatch-mat layers and improve Turf Quality (TQ) by promoting uniform water infiltration, reducing soil surface wetness, reducing compaction, and improving aeration and rooting. However, HTA may decrease TQ through disruption of the turf surface, increase plant injury due to stress, increase weed establishment, and possibly slow water percolation by creating a compacted zone of soil ("hardpan") below the depth of coring. Solid Tine Aerification (STA), also called venting or spiking, is the puncture of the turfgrass and soil profile, leaving holes but not removing soil or Organic Matter (OM) like HTA. Solid tines are typically round in cross-section shape but may be spoon- or cross-shaped. Tine diameters for round solid tine aerification typically range from 0.5 to 1.5cm (0.2 to 0.6 in). Depth of tine penetration varies among equipment, typically ranging from 5 to 18cm (2 to 7 in). Solid tine aerification is often used instead of HTA when turfgrass is under increased stress, as it is generally less injurious to the turfgrass, does not remove roots, and requires less time for the turf surface to recover. Solid tine aerification also requires less labor than HTA, especially when topdressing is not applied.

Solid tine aerification is used to increase water infiltration and improve gas exchange. However, Bunnell et al. [6] noted Carbon Dioxide (CO_2) reductions were not evident when measured 15 and 30 d after STA on a 'Crenshaw' creeping bentgrass green. Soil CO_2 was reduced 15 d following HTA to a depth of 9cm on 'Penn A-1' but was not reduced following STA to the same depth [6]. 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 another HTA in early fall. Recently, the practice of "doubling up" spring HTA has gained interest as a means to reduce labor cost and disruptions to play. 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. 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. The purpose of this two-year study was to evaluate the effects of varying spring HTA size and timing on several key turfgrass and surface properties.

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 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 HTA would not affect turfgrass and surface 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 9.5mm, covering drain lines trenched into the subgrade at 4.6-m spacing [7]. Particle-size distribution and physical properties of the sand were determined as previously reported [8-10] and included 44% total soil porosity, 1.46gcm-3 bulk density, 14gha-1 OM and 17cmhr-1 Ksat.

Bentgrass plots were maintained to golf course standards by mowing 5x weekly with solid rollers at a height of 3.2 to 4.0mm (0.125 to 0.156in). 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 2.3cmhr-1 accumulating to approximately 5.8cm wk-1, plus supplemental hand-watering during periods of heat stress. Fertilizer applications provided 342kgNha-1, 86kg Pha-1 and 171kgKha-1 annually. Prior to study initiation, HTA was performed 2x 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, STA was performed 3x yearly, in June, July and August, with 0.6-cm diam. solid round tines spaced at 3.8 cm x 3.4 cm to a depth of 7.6cm.

Aerification Methods

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, 17 kW (23 horsepower) engine with a max speed of 2.42 km h-1 and an aerating width of 1.22 m (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 0.3-cm deep (30m3ha-1) washed, medium-coarse USGA-specified sand [7]. Topdressing was not applied following STA. Topdressing sand was hand brushed in 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 Days 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 mowed every 2d thereafter for 14d, with mowing height lowered gradually to 4mm. All sand and grass clippings were collected and removed from the site. Thereafter, plots returned to a routine mowing schedule [8].

Spring Aerification Treatments

Spring aerification treatments included: (1) HTA with 1.2-cm i.d. tines spaced at 5.1 cm x 5.1 cm to a depth of 7.6 cm 22 March and 18 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 7.6 cm 22 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 7.6 cm 22 March and 18 May (0.9cm Mar., May); (4) HTA with 0.6-cm i.d. tines spaced at 3.8 cm x 3.4 cm to a depth of 7.6 cm 22 March, 18 April, 18 May and 16 June (0.6 cm Mar., Apr., May, June) (Table 1). The treatment with 1.2-cm i.d. tines spaced at 3.8 cm x 3.4cm in March only (1.2cm Mar. 2x) is equivalent to aerifying 2x with 1.2-cm i.d. tines spaced at 5.1 cm x 5.1 cm. 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 i.d. diam. solid round tines spaced at 3.4 cm x 3.8 cm 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 5.1 cm x 5.1cm to a depth of 7.6cm [9,10].

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Table 1: 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 7.6cm.

Aerification (i.d.) Treatment	Area Hole^{-1}	Tine Spacing	Holes	Area Impacted per Event	Total Area Impacted yr^{-1} †
	cm^2	cm	m^{-2}	%	
1.2cm Mar, May	1.12	5.1 x 5.1	388	4.3	17.9
1.2cm Mar 2x ‡	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

† 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 5.1cm x 5.1cm spacing in September.

‡ Note that 1.2-cm tines at 3.8 cm x 3.4 cm increases number of holes per m2 and area impacted per event 100% (2x) compared to 1.2-cm tines at 5.1cm x 5.1cm.

All treatments in this study impacted between 17.9 and 19.0% of turf surface area annually (Table 3). An aerification program impacting (removing) 15-20% of turf surface area on an annual basis has been suggested to maintain high quality turf [11].

Measurements

The four treatments were designed to evaluate the impact of various spring HTA regimes on TQ, Turfgrass Recovery (TREC), Turfgrass Regrowth (TREG), Surface Compressibility (SC), Surface Firmness (SF), Ball Roll Distance (BRD) and Water Infiltration Rate (WIR). Data were collected from late March until early November each of the two study years.

Turfgrass Properties

Turfgrass properties (TQ, TREC, and TREG) were rated prior to the first aerification treatment of each study year and then weekly for 32 Weeks After Initial Treatment (WAIT). Turfgrass quality was rated visually based on color, shoot density, and uniformity on a scale from 1 to 9, where 1= dead or missing turfgrass and 9= dark green, dense, uniform turfgrass. Reduction in uniformity due to unrecovered aerification holes or darker color in regrowth was reflected in TQ ratings. Reduction in uniformity due to scalping was also reflected in TQ ratings. A rating <7 indicated TQ deemed unacceptable on a commercial golf course. Turfgrass Recovery (TREC) following aerification was rated visually based on turfgrass regrowth and uniformity on a scale from 1 to 9, where 1= no recovery and 9= all holes fully covered by turfgrass of uniform color with no visual signs of aerification effects remaining. A rating <7 indicated turfgrass recovery deemed unacceptable on a commercial golf course.

Turfgrass Regrowth (TREG) following aerification was measured by placing a 30-cm square grid at two areas randomly located in each plot on each rating date. The number of sites where new turfgrass had not fully covered the impacted area of an aerification hole was recorded. Measurements were reported as percentage of impacted sites fully recovered. The two measurements for each plot on each date were averaged before statistical analysis.

Surface Properties

Surface properties (SC, SF, BRD, and WIR) were measured prior to the first aerification treatment of each study year and then weekly for 32 WAIT. All dates for HTA and STA coincided with dates for weekly measurements. On those dates, SC, SF and BRD were measured prior to aerification and WIR was measured prior to, and again following aerification. Surface Compressibility (SC) was measured with the Volkmeter in two areas at opposite ends of each plot and recorded as the average of five readings taken within 15 cm of each other in each area. The device measures the vertical displacement of the turf surface due to a compressive force of 570gcm-2 applied by a 72 g cylinder across its flat 7.92cm2 surface, to simulate walking traffic based on the weight of an average man [12,13]. Measurements were made ~36 hr after irrigation or rainfall to help ensure uniform soil water content. Two measurements taken in each plot on each date were averaged before statistical analysis.

Surface firmness (SF) was determined from two readings taken at opposite ends of each plot with a Clegg Impact Soil Tester (Lafayette Instrument Co., Lafayette, IN). The 2.25-kg weighted hammer was dropped from a distance of 0.45m to the turfgrass surface. The energy transferred from the falling hammer to the turf surface was measured to provide a Clegg Impact Value (CIV) [14,15]. Measurements were made ~36 hr after irrigation or rainfall to help ensure uniform soil water content. Readings were recorded in CIV and converted to gmax (peak deceleration) according to the following equation [16]:

$$gmax = 10(CIV)$$

The two measurements taken in each plot on each date were averaged before statistical analysis.

Ball Roll Distance (BRD) was obtained by averaging the distance of golf balls (Titleist Pro V1, Acushnet Company, Brockton, MA) rolled in two opposite directions from a 29-cm modified USGA stimpmeter [17]. Measurements were made ~36 hr after irrigation or rainfall to help ensure uniform soil water content.

Water Infiltration Rate (WIR) was measured with double-ring infiltrometers (model 13a, Turf-Tec International, Coral Springs, FL). Infiltrometers had a 30-cm diam. outside ring and 15-cm diam. inside ring. Both rings had a total depth of 10 cm. Both rings were driven into the soil to a depth of 2 cm. The inner ring was filled with water to a depth of 8 cm above the soil surface and the time for water to fully infiltrate the soil surface was recorded and used to calculate the infiltration rate (cmhr-1). Water was maintained in the outside ring at approximately the same level as that of the inner ring to reduce lateral water movement below the soil surface and increase the accuracy of measurements of vertical infiltration in the inner ring [18]. Measurements were made approximately ~36 hr after irrigation or rainfall to help ensure uniform soil water content.

Statistical Analysis

The experiment was a one-way treatment design and a randomized complete block experiment design as each of the four treatments was applied to one of four 3.6 m x 3.6 m plots in each of three blocks.

Repeated measurements of turfgrass properties (TQ, TREC, TREG) and surface properties (SC, SF, BRD, WIR) were taken prior the first spring aerification treatment (March) of each year and then weekly for 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 properties measured 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 tested using 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")

$\varepsilon_{a(ij)}$ = error for testing and τ

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

$(\tau_j \times Wk_k)$ = interaction of τ and Wk

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

$\varepsilon_{b(ijkl)}$ = 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 (weekly for turfgrass properties and surface properties) using the model:

$y_{ijkl} = \mu + \quad_i + \tau_j + \varepsilon_{a(ij)}$ (by Wk_k and Yr_l)

Analysis of Variance (ANOVA) was performed to test for significance of all model effects factors and interactions. When the ANOVA found a model effect to be significant (mean values were not statistically equal), Fisher's Protected LSD method was used to determine the exact nature of the effect by testing statistical significance of pairs of means. Alpha (the probability of Type I error) was set at .05 all tests of significance. The General Linear Model procedure (GLM) of SAS was used for all calculations, utilizing JMP software (SAS Institute, Cary, NC).

Results and Discussion

Turfgrass Properties

Turfgrass quality: Previous studies regarding HTA effects on TQ have been inconsistent. Some indicate HTA improved TQ [12,19-23], while others observed a decrease in TQ due to HTA [24-26]. In this study, significant differences in mean weekly TQ ratings did occur for the majority of the first 16 WAIT (spring and early summer) of each study year, when HTA treatments were being applied with varying timing, tine sizes and spacing (Table 2).

Implementation of cultural practices like HTA results in temporary reduction of TQ, which varied with the extent of disruption to the turfgrass surface. This was evident in the significant separation of mean TQ ratings for weeks immediately following each aerification date when treatments varied in surface area impacted.

All treatments included HTA at the initiation of the study in March of each year. Ratings for TQ for the following 4 wk indicated that increasing the surface area impacted by a HTA event decreased short-term TQ, mainly due to the increased amount of green surface area removed. This was evident in the ratings for plots aerified with 1.2-cm tines at 2x area impacted in March only (1.2 cm Mar. 2x), where the greatest surface area was impacted and mean TQ ratings were 15 to 38% lower than all other treatments 2 to 4 WAIT in Year 1 and 18 to 27% lower 2 WAIT in Year 2 (Table 2). Furthermore, plots aerified with 1.2-cm Mar. 2x had 8 to 27% lower TQ than plots aerified with 0.6-cm and 0.9-cm tines 2 to 4 WAIT in Year 2. Plots aerified with 0.6-cm tines had least surface area impacted by the initial spring HTA and their mean TQ was 20 to 60% higher than all other treatments 3 to 4 WAIT in Year 1 and 10 to 38% higher 2 to 4 WAIT in Year 2 (Table 2).

Only plots aerified with 0.6-cm tines received subsequent HTA treatments 4 WAIT and mean TQ was reduced to 15 to 38% lower than all other treatments 5 WAIT in Year 1 and 14 to 31% lower at 5 to 7 WAIT in Year 2 (Table 2). Differences in TQ did not occur 6 to 7 WAIT in Year 1 (Table 2). All treatments except 1.2 cm Mar. 2x received subsequent HTA 8 WAIT. Mean TQ of plots aerified with 1.2 cm Mar. 2x was rated 26 to 60% higher than all other treatments 9 to 10 WAIT in Year 2 (Table 2). Afterwards, TQ for all treatments was similar until 12 WAIT. Only plots aerified with 0.6-cm tines received subsequent HTA treatments 12 WAIT and TQ was reduced to 18 to 26% lower than all other treatments 13-14 WAIT in Year 1 and 19 to 46% lower 13-15 WAIT in Year 2 (Table 2).

Following STA of all plots 16 WAIT, differences in weekly TQ ratings did not occur for the remainder (17-32 WAIT, summer and early fall) of either study year. During this part of each study year, all plots received summer aerification on the same dates (16, 20, and 24 WAIT) with the same tine size and spacing. No aerification was performed on any plots after HTA 24 WAIT until spring (March) of the following year. The negative effect of increasing the surface area impacted on TQ was often compounded due to injury from scalping. Treatments where larger diameter tines were used at closer spacing tended to "heave" as the surface was pulled upward by retracting tines, resulting in a less flat surface and a subsequent increase in mower scalping. Rolling 1 and 2 DAT corrected much of the surface unevenness but did not prevent scalping. Scalping was considered in TQ ratings. Turf heaving, scalping, desiccation, and mechanical injury are not uncommon in aerification studies and typically contributes to initial lower TQ until recovery occurs [27-29].

Minimizing surface disruption is an important consideration when developing a balanced, effective core aeration program. The trend of HTA initially causing a decrease in TQ but eventually improving was noted by Atkinson et al. [30] where an initial decline below 7 occurred for ~4 wk but improved above this thereafter. Increasing the surface area affected by HTA from 15 to 25% also initially decreased TQ ~4.5% but improved thereafter. Brown et al. [29] noted ~3% increase in TQ following aerification but further added short-term studies may not fully capture long-term effects of core aeration on turfgrass quality as many additional agronomic and environmental parameters also influence this. Increasing aerification events and surface area impacted has been associated with less scalping [23,28].

Turfgrass regrowth: When averaged across all weekly rating dates and both study years, mean TREG (measured as number of aerification holes fully covered with new growth) for plots aerified with 1.2cm Mar. 2x was 17% greater than plots aerified with 1.2cm Mar., May and 19% greater than plots aerified with 0.6 cm Mar, Apr, May, June. Mean

TREG for plots aerified with 0.9cm Mar, May was also 10% higher than plots aerified with 0.6cm Mar., Apr., May, Jun (Table 3). Mean TREG in Year 1 on plots aerified with 1.2cm Mar. 2x was 18% higher than 1.2cm Mar., May. Mean TREG in Year 2 on plots aerified with 1.2cm Mar. 2x was 17% higher than 1.2cm Mar., May and 29% higher than plots aerified with 0.6 cm Mar., Apr., May, June. Mean TREG for plots aerified with 0.9 cm Mar., May was 20% higher in Year 2 than plots aerified with 0.6cm Mar., Apr., May, June (Table 3).

Plots aerified with 0.6-cm tines had the least surface area impacted by the initial spring HTA and their mean TREG was 55 to 85% higher than all other treatments 2 to 4 WAIT Only plots aerified with 0.6-cm tines received subsequent HTA treatments 4 WAIT and the mean TREG was reduced 39 to 88% lower than all other treatments 5 WAIT in Year 1 and 23 to 82% lower 5 to 8 WAIT in Year 2 (Table 3). Differences did not occur in mean weekly TREG ratings (17 to 32 WAIT) in Year 1 (19 July to 1 Nov 2011). Differences were noted only on one rating date (23 WAIT, 28 Aug 2012) 17 to 32 WAIT in Year 2 (Table 3). During this part of each study year, all plots received summer aerification on the same dates (16, 20, and 24 WAIT) with the same tine size and spacing. No aerification was performed during the fall months.

The number of annual aerification events and the total surface area impacted by these versus TQ and TREC creates a perpetual conflict between research findings and what end-users can practically employ. Using small i.d. cores (6.4 mm) with two passes in spring had fastest recovery (24 DAT) compared to 31 to 36 DAT for various treatments consisting of single and sequential HTA with 12.8 i.d. cores [27]. In their work, impacting almost 27% surface area was considered too aggressive in terms of significantly delaying turf recovery time. Overall, spring HTA events had quicker turf recovery compared to fall events. Methods to optimize turf recovery include: timing aeration when weather (temperature) is optimum for turfgrass growth; sufficient sand topdressing to completely fill aerification holes; minimizing dragging of sand to avoid severe mechanical damage to the turf; and slightly increasing N fertility to stimulate turf growth [31].

Surface Properties

Surface compressibility: Even though SC varied significantly by week, differences were not observed between treatment means for any week in Year 1. Mean SC measured weekly in Year 2 had minor differences on two rating dates: 16 Apr. and 25 Sep 2012 (4 and 27 WAIT) (data not shown). Differences on these dates were well within the range of the multiple readings taken in each plot and averaged to calculate each recorded measurement. Rowland et al. [12] noticed firmer surfaces with more annual aerification events. This presumably resulted from less surface thatch/OM accumulation with additional HTA.

Surface firmness: Surface firmness varied between treatments for the first 2 wk following initial spring HTA treatments in Year 1. Plots aerified with 1.2 cm Mar, May were 24% firmer 1 WAIT than plots aerified with 1.2cm Mar. 2x where the area impacted was doubled and were also 23% firmer than plots aerified with 0.9cm Mar., May where the area impacted was the same. Plots aerified with 1.2cm Mar, May were 8 to 22% firmer than all other treatments 2 WAIT (Table 4). Mean SF values were similar between treatments 3 to 8 WAIT in Year 1. Only plots aerified with 1.2cm Mar. 2x did not receive subsequent HTA 8 WAIT. Differences between treatments were not observed 9 WAIT, but plots aerified with 1.2cm Mar. 2x were 9 and 12% firmer at 10 WAIT than plots aerified with 0.6cm Mar, Apr, May, June and 1.2cm Mar, May; respectively (Table 4). Mean SF did not differ between treatments 11 and 12 WAIT in Year 1.

Only plots aerified with 0.6 cm Mar., Apr., May, June received subsequent HTA 12 WAIT. Differences between treatments were not observed 13 WAIT, but plots aerified with 0.6 cm Mar, Apr, May, June had 23 to 26% lower SF than all other treatments 14 WAIT (Table 4). Mean SF did not differ between treatments 15 and 16 WAIT in Year 1. All plots received similar STA 16 WAIT. Plots aerified with 0.6cm Mar, Apr, May, June had 7 to 9% lower SF than all other treatments at 17 WAIT (Table 4). Mean SF values did not differ significantly between treatments 18 to 32 WAIT in Year 1. Mean SF values did not differ between treatments 1 to 4 WAIT in Year 2. However, following subsequent HTA, SF response was similar to Year 1.

Only plots aerified with 0.6 cm Mar, Apr, May, June received subsequent HTA 4 WAIT in Year 2. These plots had 17 and 18% lower SF at 5 WAIT than plots aerified with 1.cm Mar, May and 0.9cm Mar, May; respectively. These plots also had 13 and 15% lower SF compared to the same plots 6 WAIT (Table 4). Mean SF did not differ between treatments 7 and 8 WAIT in Year 2. Only plots aerified with 1.2 cm Mar. 2x did not receive subsequent HTA 8 WAIT in Year 2. These plots were 11 and 16% firmer 9 WAIT than plots aerified with 0.6cm Mar., May and 0.9cm Mar, May; respectively. These plots were 9 to 16% firmer than all other treatments 10WAIT (Table 4). Mean SF did not differ between treatments 11 and 12 WAIT in Year 2.

Table 4: Creeping bentgrass surface firmness following various spring hollow tine aerification treatments, for weekly measurement dates where treatment means were significantly different.

Weeks After Initial Aerification Event †							
Aerification treatment (i.d.)	**1**	**2**	**10**	**14**	**17**	**18**	
gmax ‡							
Year 1							
1.2cm Mar, May	89 a§	88 a	90 a	101 a	88 a	83 a	
1.2cm Mar. 2x	71 b	72 b	101 b	99 a	87 a	81 a	
0.9cm Mar, May	72 b	81 c	95 ab	96 a	89 a	83 a	
0.6cm Mar, Apr, May, June	83 ab	80 c	93 a	74 b	81 b	78 a	
	5	**6**	**9**	**10**	**13**	**14**	**15**
Year 2							

1.2cm Mar, May	62 a	66 a	60 ab	61 a	60 a	60 a	59 ab
1.2cm Mar. 2x	56 ab	60 bc	64 a	66 b	66 a	59 a	61 a
0.9cm Mar, May	61 a	64 ab	55 b	57 a	61 a	58 a	64 a
0.6cm Mar, Apr, May, June	51 b	56 c	58 b	58 a	43 b	50 b	52 b

† Initial aerification events occurred on 22 March of each year with subsequent aerification events on 18 Apr., 18 May or 16 June (+ 1 d).

‡ Surface firmness value quantifies deceleration of 2.25-kg weight dropped from height of 45 cm.

§ Values followed by different letters within the same rating date within year are significantly different at the 0.05 significance level.

Only plots aerified with 0.6 cm Mar., Apr., May, June received subsequent HTA 12 WAIT in Year 2. These plots had 29 to 35%, 13 to 16%, and 12 to 19% lower SF than all other treatments 13, 14, and 15 WAIT, respectively (Table 4). Mean SF values did not differ between treatments 16 to 32 WAIT in Year 2 (Table 4). Generally, the more surface area impacted, the less surface firmness or hardness results. Atkinson et al. [30] noted a ~4% lower in treatments impacting 25% surface area compared to HTA treatments impacting 15% surface area. As number of aerification events per year increased from one to three, surface firmness decreased up to 19%. McCarty et al. [28] and Bunnell et al. [6] observed a similar reduction in surface firmness as HTA was incorporated into a management plan. Murphy et al. [21] noted reduced surface firmness with both core and solid tine aeration; however, HTA maintained a less firm surface for an extended period of time compared to solid tine aeration treatments.

Ball Roll Distance

In Year 1, ball roll distance varied between treatments for the 2wk following initial spring HTA treatments. Plots aerified with 0.6cm tines had least surface area impacted and had 15 to 22% longer BRD than all other treatments 1 WAIT. These plots still had 16% longer BRD than plots aerified with 1.2cm Mar. 2x (greatest surface area impacted) at 2WAIT (Table 5). Mean BRD did not differ significantly between treatments 3 to 31 WAIT in Year 1, even though it did vary significantly between weeks. Plots aerified with 1.2cm Mar. 2x and plots aerified with 0.6cm Mar., Apr., May, June had 7 and 9% longer BRD, respectively, than plots aerified with 1.2cm Mar, May at 32WAIT in Year 1 (Table 5).

In Year 2, mean BRD was different for only one weekly measurement date (4 WAIT). On plots aerified with 0.6-cm tines, BRD was 4 and 7% longer than plots aerified with 1.2 cm Mar. 2x and 1.2 cm Mar, May, respectively (Table 5). Little previous research has been reported on aerification and resulting effects on ball roll. McCarty et al. [28] noted ~7% reduction in ball roll distances for 14 DAT after four annual HTA with combination of 6.4 and 15.8 mm i.d. tines, but by 21 DAT, no detectable differences in ball roll distance occurred.

Table 5: Ball roll distance response to various spring hollow tine aerification treatments on creeping bentgrass greens, for weekly measurement dates where treatment means were significantly different, mid-Mar. 2011 through mid-April 2011.

Weeks After Initial Aerification †				
	Year 1		Year 2	
Aerification treatment (i.d.)	**1**	**2**	**32**	**4**
m †				
1.2cm Mar, May	1.14 b‡	1.25 ab	1.54 b	1.36 b§
1.2cm Mar. 2x	1.07 b	1.14 b	1.65 a	1.39 b
0.9cm Mar, May	1.13 b	1.23 ab	1.62 ab	1.40 ab
0.6cm Mar, Apr, May, June	1.31 a	1.34 a	1.68 a	1.45 a

† Ball roll distance is average of golf balls rolled in two opposite directions from a 29-cm modified USGA stimpmeter.

‡ Values followed by different letters within the same rating date are significantly different at the 0.05 significance level.

Water Infiltration Rate

All plots received HTA at the initial measurement date each year (0 WAIT). Even though surface area impacted varied by 2x or 4x between treatments, mean WIRs were similar between treatments when measured immediately after initial spring HTA and topdressing during either year (Table 6). In Year 1, HTA with 1.2-cm tines at 3.4cm x 3.8 cm (1.2cm Mar. 2x) resulted in 40 to 53% and 20 to 45% higher mean WIR than other treatments 1 and 2 WAIT, respectively (Table 6). Mean WIR did not differ among the other three treatments on those dates. Mean WIR did not differ among any of the four treatments 3 to 10 WAIT, even though only plots aerified with 0.6-cm tines received HTA 4 WAIT and all treatments except 1.2cm Mar. 2x received HTA 8 WAIT.

Plots aerified with 0.6-cm tines received the only HTA 12 WAIT, and subsequently had 43 to 231% higher WIRs than all other treatments 12 to 16WAIT (Table 6). All plots received the initial summer STA 16 WAIT, after which WIR measured 16 to32 WAIT did not differ between treatments.

In Year 2, HTA with 1.2-cm tines at 3.4cm x 3.8cm (1.2cm Mar. 2x) resulted in 63 and 77% higher mean WIR than 0.6 tines at the same spacing 2 and 3WAIT, respectively (Table 6). Only plots aerified with

0.6-cm tines received HTA 4WAIT. Mean WIR did not differ among the four treatments immediately following this application, but at 5WAIT, plots aerified with 0.6-cm tines 4 WAIT had 29 to 56% higher mean WIRs than all other treatments (Table 6). Mean WIR did not differ between treatments 6 to 12WAIT, even though all treatments except 1.2 cm Mar. 2x received HTA 8 WAIT (Table 6). Plots aerified with 0.6-cm tines received the only HTA 12 WAIT, and subsequently had 92 to 216% higher mean WIRs than all other treatments immediately following this application (Table 6). However, mean WIR did not differ between treatments 13 to 16 WAIT. All plots received the initial summer STA 16 WAIT. Treatment means were significantly different on four measurement dates during the remainder of Year 2, but these differences were inconsistent (Table 6).

An important characteristic of healthy creeping bentgrass greens is adequate water infiltration rates. Carrow [4] noted following HTA with 12.7 to 15.9mm diameter tines increased water infiltration for 5 to 8wk, suggesting root growth encouraged by the HTA eventually refilled created macropores. McCarty et al. [28] noted treatments incorporating HTA increased infiltration rates by an average of 150% compared with the untreated over an 8mo period. HTA was performed four times annually in March, May, June, and September with a combination of 6.4 and 15.8 i.d. tines on 76 mm spacing. Atkinson et al. [30], Rowland et al. [12] and Bunnell et al. [6] noted 46 to 85% higher infiltration rates following various HTA treatments.

Conclusions

The null hypothesis that no differences would occur between treatments was proven false overall. When averaged across both study years, TREC and TREG differed between treatments. When averaged across each year separately; TREG differed in Year 1; TREC and TREG differed in Year 2. Differences also occurred on at least one rating or measurement date for each turfgrass and surface property considered. 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 3.8 cm x 3.4cm (March and May), monthly STA during the summer, and a fall HTA application with 1.2-cm tines at 5.1cm x 5.1cm.

Turf managers can vary their spring HTA schedule to increase TQ during periods where this is important (e.g., for a tournament). Varying tine size and spacing like treatments in this study will likely only affect surface properties ≤2 wk, but long-term positive effects on OM and soil properties should be considered. Additional evaluations of long-term core aeration programs are necessary to separate the short-term effects of core aeration on turfgrass density from the long-term impact of core aeration on overall plant health. Although the data presented here does not reflect a drastic nor immediate response in plant health or soil surface properties after a short-term core aeration program, it is overall supportive of an aerification program that utilizes frequent core aeration.

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