USGA Ultradwarf Bermudagrass Putting Green Properties as Affected by Cultural Practices

J. H. Rowland,* J. L. Cisar, G. H. Snyder, J. B. Sartain, and A. L. Wright

ABSTRACT

Accumulation of organic matter (OM) at the soil surface (mat OM) and below (soil OM) can negatively affect putting green performance characteristics. The objective of this study was to evaluate cultural practices for control of OM and their effects on performance characteristics of a mature, USGA-specified ultradwarf bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burt Davy] green in a subtropical climate. Two ultradwarf cultivars, 'TifEagle' and 'Champion', were subjected to hollow tine aerification (HTA) 1, 2, or 3 times yr^{-1}, verticutting (VC) 3 times yr^{-1}, solid tine aerification (STA) 5 times yr^{-1}, and no treatment (control) for two consecutive years. Cultivars and treatments were arranged in a split-plot, randomized complete block design. Although mat OM depth was similar among treatments, concentration was reduced after 2 yr by VC, HTA 2 times yr^{-1}, and HTA 3 times yr^{-1}. Solid TA (5 times yr^{-1}) and hollow TA (2 and 3 times yr^{-1}) reduced soil OM concentration compared with the control. Since VC also provided the highest turfgrass quality, firmest surface, least mower scalping, and least localized dry spots (LDS), it proved to be the best cultural practice tested, particularly since HTA 3 times yr^{-1} increased saturated hydraulic conductivity (K_{sat}), which reduced volumetric water content and increased LDS. TifEagle was the better performing cultivar, as it had higher quality and less mower scalping.

United States Golf Association (USGA) greens construction methods have been used for more than 40 yr due to their successful, scientifically tested guidelines (USGA Green Section Staff, 2004). Recommendations for particle-size distribution in the root zone media limits soil compaction and helps turfgrass withstand continuous traffic (Carrow, 2003; Wienecke, 2009). Recommended USGA particle-size diameters range from fine gravel (2.0–3.4 mm) to clay (<0.002 mm). Limiting fine gravel and very coarse sand (1.0–2.0 mm) to ≤10% limits saturated hydraulic conductivity (K_{sat}), allowing sufficient water to be held in the root zone (USGA Green Section Staff, 2004). Silt (0.002–0.05 mm) and clay (i.e., total fines) are also limited to ≤10% for control of compaction and excess moisture, as fines occupy micropores that sand-sized particles cannot (Gaussoin et al., 2006; USGA Green Section Staff, 2004). These guidelines provide an initial porosity of 35 to 55%, in which air-filled and capillary porosity make up 15 to 30% and 15 to 25%, respectively. Near-ideal conditions for plant growth and drainage are provided by these initial specifications (Brady and Weil, 1999). Over time, performance characteristics of USGA greens diminish as OM levels increase (Carrow, 2003).

TifEagle and Champion bermudagrasses have increased shoot density, lower vertical growth, and finer texture than the previous standard 'Tifdwarf' (Foy, 1997). These new cultivars, referred to as ultradwarves, can withstand regular mowing below 3 mm and produce green speeds in excess of 3 m (Busey and Boyer, 1997; Foy, 1997). Ultradwarf bermudagrasses have thus become the most prevalent warm-season cultivars used on greens, and rival creeping bentgrass [*Agrostis stolonifera* L. var *palustris* (Huds.) Farw.], the standard cool-season grass, for putting speed and quality at transition zone golf courses (Foy, 2005; Hartwiger and O'Brien, 2006; McCarty et al., 2007). Ultradwarves, however, are rapid thatch producers and can quickly generate excessive mat OM, negatively affecting greens performance characteristics if cultural practices of sufficient frequency and magnitude are not implemented (Carrow, 2003; Hartwiger, 2004; Foy, 2000; McCarty and Miller, 2002; White et al., 2004). Golf greens require a minimum mat OM depth of 0.6 cm to tolerate wear stress (Moore, 2007), while a depth greater than 1.3 cm is considered excessive (Christians, 1998; McCarty and Miller, 2002). Adequate levels of mat OM provide a necessary cushioning effect for foot traffic and incoming golf shots (McCarty and Miller, 2002; Vermeulen and Hartwiger, 2005), prevent volatilization of ammonia (Petrovic, 1990), prevent leaching of pesticides into groundwater (Horst et al., 1996; Snyder and Cisar, 1995), and reduce summer heat stress (Christians, 1998). Excessive mat OM, which can occur even under excellent management (Carrow, 2003), causes numerous problems including: inconsistent

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Abbreviations: CEC, cation exchange capacity; HTA, hollow tine aerification; K_{sat}, saturated hydraulic conductivity; LDS, localized dry spot; LOI, loss on ignition; OM, organic matter; STA, solid tine aerification; TA, tine aerification, USGA, United States Golf Association; VC, verticutting; VWC, volumetric water content.

ball roll, increased ball marks (Vermeulen and Hartwiger, 2005), pathogen and insect populations (Christians, 1998; Bevard, 2005), scalping (McCarty et al., 2007; Vermeulen and Hartwiger, 2005), reduced infiltration (Bevard, 2005), and pesticide efficacy (McCarty et al., 2007).

Soil OM provides multiple benefits to the soil environment including: increased pH buffering capacity, chelation of trace elements, C source for microorganisms, N, cation exchange capacity (CEC), and porosity (Brady and Weil, 1999; Noer, 1928; Kerek et al., 2003; Wolf and Snyder, 2003). When soil OM levels are too low, increased fertilization and irrigation are required to maintain acceptable turfgrass quality (McCarty and Miller, 2002; McCoy and McCoy, 2005). Limited CEC, which is highly related to low soil OM content in sandy soils (Brady and Weil, 1999), allows nutrients, pesticides, and water to move quickly through the root zone (Beard, 1973), which may create nonpoint-source pollution in ground and surface waters (Florida Department of Environmental Protection, 2007). Conversely, excessive soil OM can reduce K_{sat}, pesticide efficacy, and promote anaerobic conditions that cause turfgrass quality to decline (Carrow, 2004a, 2004b, 2004c; Hartwiger, 2004; McCarty et al., 2007). Golf course greens are commonly renovated when soil OM levels rise above 4% (wt.) and performance characteristics (e.g., $K_{sat} < 15$ cm h^{-1}) are reduced to a state that cannot be corrected by cultural practices.

Since conventional tillage cannot be used on turfgrass without destroying sod characteristics (Beard, 1973; McCarty and Brown, 2004), less destructive cultural practices including hollow tine aerification (HTA), solid tine aerification (STA), verticutting (VC), topdressing, and grooming are used to control mat OM and soil OM, and to improve performance characteristics (Beard, 1973; Christians, 1998; Cisar, 1999; Hanna, 2005; McCarty and Miller, 2002; Vavrek, 2006). These practices are implemented to physically remove mat OM and soil OM; to increase soil aeration, rooting, and water movement; and to improve soil physical properties and surface characteristics (Beard, 1973; Bevard, 2005; Cisar, 1999; McCarty and Miller, 2002; Unruh and Elliott, 1999). However, when HTA and VC are used in "accelerated" programs, they can cause unacceptable damage to the putting green surface (Hollingsworth et al., 2005; Landreth et al., 2007).

The objective of this study was to evaluate cultural practices for control of OM, both mat and soil, and their effects on soil physical properties and surface characteristics of a mature, USGA-specified ultradwarf bermudagrass putting green, maintained in a subtropical environment.

MATERIALS AND METHODS

Experimental Site

This experiment was performed on an 8-yr-old, 930 m^2 ultradwarf bermudagrass research green with Champion and TifEagle cultivars from 2007 to 2008. The green was constructed in 1999 with a USGA-specified, 90:10 (sand/sphagnum peat moss, v/v) greens soil mix (USGA Green Section Staff, 2004). The green had a 1.7-cm deep mat OM layer above a 5.9-cm deep soil OM layer before initiation of cultural practice treatments. The green was mowed daily to a 3.2-mm height, and fertilized with ammonium sulfate and Harrell's 12–4–12 greens grade fertilizer at 100 g N m^{-2}, 26 g P m^{-2}, and 91 g K m^{-2} yr^{-1} in 2007, and 85 g N m^{-2}, 22 g P m^{-2}, and 77 g K m^{-2} yr^{-1} in 2008. Irrigation was applied as needed to maintain healthy turfgrass. Pesticides were used on a curative basis and included chlorothalonil (tetrachloroisophthalonitrile) fungicide and bifenthrin [(2-methyl[1,1-biphenyl]-3-yl) methyl 3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate] insecticide for algae and sod webworm control, respectively.

Experimental Design and Statistical Analysis

A split-plot, randomized complete block design was used to increase treatment effect precision (Littell et al., 2006). Each 14.4-m^2 whole plot unit consisted of an ultradwarf bermudagrass cultivar that received all six cultural practice treatments. The experimental area was further separated into six randomized blocks (i.e., reps) to reduce spatial variability (Littell et al., 2006). SAS (version 9.0) PROC MIXED, along with the Tukey-Kramer multiple-comparison procedure, were used to determine significant ($P < 0.05$) main effects of cultivars and cultural practices (SAS Institute, 2004). When multiple measurements of a response variable on the same experimental unit were taken across time, the Kenward-Rogers method for repeated measures was used (Littell et al., 2006).

Turfgrass Cultivation Treatments

Hollow TA was performed with a walking core aerator (model ProCore 648, The Toro Company, Bloomington, MN) 1, 2, or 3 times yr^{-1} (Table 1). Ejected cores were removed, and a washed, coarse USGA-specified silica sand with 35% total porosity (22% macropores) was applied to fill holes (USGA

Table 1. Specifications and timings of cultural practice treatments used on a mature ultradwarf bermudagrass golf green, 2007–2008.

Treatment	Timing	Spacing	Depth	Width	Surface area impacted	Sand applied
			cm		%	m^3 ha^{-1}
Control†	–	–	–	–	–	–
Hollow tine aerification	1 time yr^{-1}: May	5.1	7.6	1.6	7.7	47.3
Hollow tine aerification	2 times yr^{-1}: May, July	5.1	7.6	1.6	15.4	94.6
Hollow tine aerification	3 times yr^{-1}: March, May, July	5.1	7.6	1.6	23.1	141.9
Verticutting	3 times yr^{-1}: March, May, July	1.3	2.5	0.2	46.8	48.8§
Solid tine aerification	5 times yr^{-1}: March–July	5.1	7.6‡	1.0	15.7	39.6¶

† All treatments received grooming 32 times yearly, and an additional 42.7 m^3 (4.3 mm) USGA-specified sand ha^{-1} yr^{-1}.

‡ Tine depth was 10.2 cm in 2007.

§ Topdressing was increased to 91.5 m^3 ha^{-1} in 2008.

¶ Topdressing was decreased to 30.5 m^3 ha^{-1} in 2008.

Green Section Staff, 2004). Deep (2.5 cm) VC was performed 3 times yr^{-1} with a commercial scarifier [model 117462, Sisis Equipment (Macclesfield) Ltd., Cheshire, UK]. Verticutting debris was removed and open grooves were filled with sand. Solid TA was performed 5 times yr^{-1} with the same aerator used for HTA and holes were filled with sand. All treatments, including the control, received 42.7 m^3 (4.3 mm) sand ha^{-1} yr^{-1} applied as a surface topdressing, and shallow vertical mowing (i.e., grooming). Topdressing was applied using a calibrated rotary spreader (The Scotts Company, Marysville, OH), with rates and timing dependent on turfgrass growth. Rates ranged from 1.5 to 3.0 m^3 (0.15–0.30 mm) sand ha^{-1} per application, and were applied at 2- to 4-wk intervals. Grooming was performed 32 times yr^{-1} by a commercial walk mower (model 522, Jacobsen, A Textron Company, Charlotte, NC) with grooming attachment. Grooming blades were 0.6 cm apart and set 1.6 mm below the bedknife to reach just above the soil line. Each grooming was performed in a different direction than the previous one to control directional growth (i.e., heliotropism), and facilitate incorporation of topdressing through the dense turfgrass cover (Foy, 1999; Vavrek, 2006).

Qualitative Measurements

Many factors influence the quality and playability of putting greens after cultivation. These include denseness and color of canopy, rate of recovery, surface compressibility, mower scalping, ball roll speed, and localized dry spot (LDS) incidence due to hydrophobic soil conditions. Denseness and color of canopy were rated weekly, for 35 wk, starting the week before application of initial yearly treatments (Table 1), as turfgrass quality on a 1 to 10 scale (1 = dead, 6 = minimally acceptable, and 10 = best possible quality). Treatment recovery was rated weekly, starting the week after initial yearly treatments were applied (Table 1), on a 1 to 10 scale (10 = completely recovered). Surface compressibility was determined with the Volkmeter, a weight-based thatch displacement instrument that allowed nondestructive, rapidly repeated measurements (Cisar and Snyder, 2003; Volk, 1972). Three readings per 2.4-m^2 plot were taken weekly, starting the week before application of initial yearly treatments, after mowing and dissipation of surface moisture. Visual estimates of mower scalping were rated on a 1 to 10 scale (10 = complete loss of turfgrass foliage). Ball roll speed was obtained by averaging the distance of two golf balls rolled in two opposite directions using a 19-cm modified USGA stimpmeter (Gaussoin et al., 1995) after all treatments were applied and green was allowed to recover. Theta readings for volumetric water content (VWC) were taken at a depth of 6 cm with a Soil Moisture Meter (model TH2O, Dynamax, Houston, TX) calibrated for a mineral soil. Measurements were taken at the end of each year after LDS symptoms developed following withholding of irrigation. Localized dry spot was rated concurrently with thetas, on a 1 to 10 scale (10 = most severe symptoms).

Physical Measurements

Bulk density, and pore space of the root zone were determined in the lab by ASTM method F 1815–06 on relatively undisturbed 5.1-cm diam. by 9.4-cm deep soil cores with verdure and mat OM removed (ASTM, 2006). Saturated hydraulic conductivity was determined on a constant hydraulic head permeameter, with samples collected over 0.5 h (ASTM, 2006). In 2007, K_{sat} was evaluated with mat OM and verdure intact, as well as removed. Since physical removal of mat OM and verdure with a knife affected measurements ($P < 0.001$; data not shown), soil cores with mat OM and verdure still intact were used to report effects. Particle-size distribution and physical properties of the topdressing mix used in all treatments were determined from laboratory-packed samples by ASTM methods F 1632–03 (ASTM, 2003) and F 1815–06, respectively (data not shown). Mat OM depth and soil OM concentration were determined by direct physical measurement and percentage loss on ignition (LOI), respectively. Six 15-cm deep soil cores were removed from the green with an open-sided, 1.9-cm diam. soil probe. After direct physical measurement of mat OM, it and the unadulterated original soil beneath the soil OM layer were separated and removed with a metal spatula. Percentage LOI of soil OM was determined by ashing samples in a 550°C muffle furnace (Snyder and Cisar, 2000). Bulk density, K_{sat}, pore space, mat OM depth, and soil OM % LOI were determined a week before yearly treatments, and after all treatments had been applied and the green allowed to recover. Mat OM % LOI was determined at the end of the study in 2008 from 5.1-cm diam. and 5.1-cm deep pelts. Mat OM was separated from soil with a long, serrated knife, oven-dried (60°C), weighed, ashed in a 550°C muffle furnace, and re-weighed to determine % LOI (Snyder and Cisar, 2000). Oven-dry root weights were determined from 10.2-cm diam. and 15-cm deep cup cutter cores. The root zone was separated from the mat OM layer with a long, serrated knife, and a 2-mm diam. sieve was used to rinse soil from roots. Roots were then oven-dried (60°C) before weighing (Snyder and Cisar, 2000).

RESULTS AND DISCUSSION

Because main effects of cultural practices and cultivars were significant, and interactive effects were not, only the main effects of the two factors are discussed.

Quality and Recovery

In 2007, VC provided highest quality on five rating dates (Table 2). In 2008, HTA 3 times yr^{-1} and VC both had higher quality than the control before the second application of each

Table 2. Effect of cultural practice treatments on turfgrass quality of a mature ultradwarf bermudagrass golf green in 2007: postrecovery data shown.

	Turfgrass quality (1–10)‡				
Treatment†	**5 July**	**12 July**	**5 Oct.**	**12 Oct.**	**16 Nov.**
Control	7.2 b§	7.2 b	7.5 b	7.5 b	7.2 b
HTA (1 time yr^{-1})	7.3 b	7.2 b	7.5 b	7.5 b	6.9 c
HTA (2 times yr^{-1})	7.4 b	7.2 b	7.5 b	7.5 b	7.2 b
HTA (3 times yr^{-1})	7.4 b	7.4 b	7.5 b	7.5 b	7.0 bc
VC (3 times yr^{-1})	7.8 a	7.9 a	7.7 a	7.9 a	7.5 a
STA (5 times yr^{-1})	6.4 c	6.4 c	7.5 b	7.5 b	7.2 bc
LSD	0.3	0.3	0.1	0.1	0.24

† HTA = hollow tine aerification; STA = solid tine aerification; VC = verticutting.

‡ Turfgrass quality ratings: 1 = dead, 6 = minimum acceptable, and 10 = best color and density.

§ Mean estimates, averaged over cultivars, with same letter within column are not statistically different at the 0.05 significance level based on the Tukey-Kramer method.

Table 3. Effect of cultural practice treatments on turfgrass quality of a mature ultradwarf bermudagrass golf green in 2008: postrecovery data shown.

	Turfgrass quality (1–10 scale)‡			
Treatment†	**4 July**	**11 July**	**18 July**	**25 July**
Control	6.1 b§	5.5 b	6.0 bc	6.2 c
HTA (1 time yr^{-1})	6.1 b	5.7 b	6.0 c	6.2 c
HTA (2 times yr^{-1})	6.5 ab	5.8 b	6.1 bc	6.5 bc
HTA (3 times yr^{-1})	6.7 a	6.5 a	6.5 ab	6.8 ab
VC (3 times yr^{-1})	6.9 a	6.7 a	6.7 a	7.0 a
STA (5 times yr^{-1})	6.5 ab	6.1 ab	6.5 abc	6.2 c
LSD	0.6	0.6	0.5	0.5

† HTA = hollow tine aerification; STA = solid tine aerification; VC = verticutting.

‡ Turfgrass quality ratings: 1–10 (1 = dead, 6 = minimum acceptable, and 10 = best color and density).

§ Mean estimates, averaged over cultivars, with same letter within column are not statistically different at the 0.05 significance level based on the Tukey-Kramer method.

treatment (Table 3). Champion had lower overall quality (0.2 units in both years) than TifEagle (data not shown). Verticutting and HTA treatments required similar amounts of recovery time in both years. The higher quality of VC in 2007 was due in large part to its darker green color. Older greens can contain significant N, which has been sequestered in soil OM from prior fertilizer applications (Kerek et al., 2003). This soil OM N contains a mobile fraction of hydrolyzable amino acids, and a more stabile fraction that is chemically protected from enzymatic and microbial degradation by bonds formed with polyvalent cations (Kerek et al., 2003). Soil disruption caused by VC may have increased hydrolysis of amino acids, destabilized intra-molecular bridging of organic molecules (Kerek et al., 2003), or increased oxidation of soil humus allowing increased mineralization of N (Wolf and Snyder, 2003). Reduced turfgrass quality in 2008 was due to the aggressive nature of cultural practices used in this study (data not shown).

Table 4. Surface compressibility (Volkmeter) and turfgrass scalping on a mature ultradwarf bermudagrass golf green from 2007–2008.

	Volkmeter‡		Scalping (1–10)§	
Treatment†	**2007**	**2008**	**2007**	**2008**
	cm			
Control	1.68 a¶	1.44 a	2.2 a	4.5 a
HTA (1 time yr^{-1})	1.63 a	1.44 a	2.3 a	4.2 a
HTA (2 times yr^{-1})	1.56 b	1.42 a	2.1 a	3.7 a
HTA (3 times yr^{-1})	1.50 c	1.35 b	2.0 a	3.6 a
VC (3 times yr^{-1})	1.42 d	1.27 c	1.2 b	2.0 b
STA (5 times yr^{-1})	1.52 bc	1.37 b	2.2 a	3.8 a
LSD	0.05	0.04	0.59	1.39
Cultivar				
Champion	1.56 a	1.37 a	2.4 a	3.5 a
TifEagle	1.54 a	1.39 a	1.6 b	3.8 a
LSD	0.03	0.04	0.25	0.66

† HTA = hollow tine aerification; STA = solid tine aerification; VC = verticutting.

‡ Grand means from measurements taken weekly from initiation of yearly treatments until recovery from all treatments was complete.

§ Measurements were taken when mowing caused scalping damage. Scalping: 1–10 (1 = none, and 10 = complete loss of turfgrass cover).

¶ Mean estimates with same letter within column are not statistically different at the 0.05 significance level based on the Kenward-Roger method.

Surface Compressibility, Mower Scalping, and Ball Roll

The control was more compressible than HTA 3 times yr^{-1}, STA, and VC in both years (Table 4). Verticutting had the firmest surface, indicated by lower Volkmeter readings, in both years. Each additional yearly HTA increased surface firmness, as HTA 1 time yr^{-1} was more compressible than HTA 2 times yr^{-1}, and HTA 3 times yr^{-1} was the firmest. Verticutting resulted in the least mower scalping for both years (Table 4). An 11% overall increase in surface firmness occurred between 2007 and 2008. TifEagle had less mower scalping than Champion in 2007 (Table 4). There were no significant differences in ball roll after greens were allowed to recover. An optimum greens surface is soft enough to accept a well-struck golf shot, yet has sufficient firmness to minimize mower scalping, ball marks, and provide fast ball roll speed (McCarty and Miller, 2002). Scalping, which is the excessive removal of leaf tissue from mowing (Christians, 1998), occurred frequently on the experimental green due to the deep thatch–mat layer. Scalping was most severe when mowed from south to north, and during the summer when top growth was accelerated. Heliotropism and geotropism can cause turfgrass to grow toward the sun and downhill on slopes, and is commonly referred to as "grain" (Foy, 2005). In the northern hemisphere, above the Tropic of Cancer, the sun is positioned to the south at differing degrees throughout the year. This seemed to cause growth toward the south, as rubbing grass from south to north revealed this phenomena. Since the research green was laser-graded flat, geotropism was not considered a significant influence on directional growth. Incorporation of sand into the mat OM layer after VC increased surface firmness and reduced mower scalping due to its high yearly surface impact. Since no cultural practices were conducted on the research green for >2 yr before the initiation of this study, grooming and topdressing, which were uniformly applied to all treatments, seemed to increase surface firmness. The lack of differences in ball roll were attributed to the extent of recovery from treatment, grooming, topdressing, and similarity between cultivars (data not shown).

Saturated Hydraulic Conductivity

Both HTA 2 times yr^{-1} and HTA 3 times yr^{-1} produced faster K_{sat} than VC, while HTA 3 times yr^{-1} was faster than the control (Table 5). In 2007, HTA 2 times yr^{-1} and HTA 3 times yr^{-1} increased K_{sat} 85% and 59% above prestudy levels, respectively, although final samplings in 2008 were 11 and 36% below prestudy levels. Removal of verdure and mat OM before placement on the permeameter decreased K_{sat} 11% (data not shown). Since HTA 2 times yr^{-1} and HTA 3 times yr^{-1} penetrated the entire 7.6-cm organic profile (e.g., mat and soil OM), they were more effective at increasing K_{sat} than VC and the control, which impacted 2.5 and 0 cm, respectively. Reduction in final 2008 K_{sat} levels can be attributed to decreased macropore space and increased root weights (Tables 6 and 7). Reduction of K_{sat}, when mat OM was cut off, likely occurred due to sealing of macro and biopores. Only HTA 2 times yr^{-1} and HTA 3 times yr^{-1} had K_{sat} above the USGA's recommended minimum of 15 cm h^{-1} in 2008 (USGA Green Section Staff, 2004). Shaving of soil cores for K_{sat} determination is not recommended (ASTM, 2006).

Table 5. Saturated hydraulic conductivity (K_{sat}) for cultural practice treatments and cultivars on a mature ultradwarf bermudagrass golf green from 2007–2008.

	K_{sat}†			
	2007		2008	
Treatment	Initial	Final	Initial	Final
	cm h^{-1}			
Control	19.5 a‡	18.9 b	3.0 b	5.1 ab
HTA§ (1 time yr^{-1})	21.5 a	28.7 ab	6.5 ab	9.7 ab
HTA (2 times yr^{-1})	18.9 a	34.5 ab	4.5 b	16.9 a
HTA (3 times yr^{-1})	25.3 a	40.2 a	10.5 a	16.2 ab
VC§ (3 times yr^{-1})	16.4 a	20.9 ab	2.7 b	3.1 b
STA§ (5 times yr^{-1})	21.8 a	40.2 a	4.9 b	5.9 ab
LSD	19.5	20.9	5.2	13.5
Cultivar				
Champion	25.1 a	26.7 a	5.9 a	10.6 a
TifEagle	16.1 b	34.5 a	4.9 a	8.3 a
LSD	7.1	12.2	2.5	2.9

† Initial measurements were taken before application of treatments. Final measurements were taken after all yearly treatments were applied and the green allowed to recover.

‡ Mean estimates with same letter within column are not statistically different at the 0.05 significance level based on the Tukey-Kramer method.

§ HTA = hollow tine aerification; STA = solid tine aerification; VC = verticutting.

Table 6. Macropore space for cultural practice treatments and cultivars on a mature ultradwarf bermudagrass golf green from 2007–2008.

	Macropore space†			
	2007		2008	
Treatment	Initial	Final	Initial	Final
	%			
Control	14.1 a‡	16.9 ab	9.3 ab	4.1 ab
HTA§ (1 time yr^{-1})	12.9 a	17.3 ab	10.0 ab	3.5 ab
HTA (2 times yr^{-1})	12.8 a	19.2 a	10.8 a	5.2 a
HTA (3 times yr^{-1})	13.3 a	19.3 a	11.2 a	4.7 a
VC§ (3 times yr^{-1})	12.4 a	15.8 b	8.1 b	2.5 b
STA§ (5 times yr^{-1})	14.1 a	18.7 ab	10.0 ab	3.4 ab
LSD	2.7	3.1	2.4	2.1
Cultivar				
Champion	13.8 a	18.2 a	10.5 a	3.7 a
TifEagle	12.7 a	17.5 a	9.3 a	4.1 a
LSD	3.4	1.1	1.3	1.1

† Initial levels were determined before initiation of yearly treatments. Final levels were determined after all yearly treatments were applied and the green allowed to recover.

‡ Mean estimates with same letter within column are not statistically different at 0.05 significance level based on the Tukey-Kramer method.

§ HTA = hollow tine aerification; STA = solid tine aerification; VC = verticutting.

Localized Dry Spot and Volumetric Water Content

In 2007, VC resulted in higher VWC than HTA 3 times yr^{-1}, and the least LDS among all treatments (Table 8). In 2008, VC had higher VWC and less LDS than HTA 2 times yr^{-1} and HTA 3 times yr^{-1}. Verticutting root weights were 21 and 19% higher than HTA 3 times yr^{-1} in 2007 and 2008, respectively (Table 7). Increased LDS and reduced VWC in HTA plots resulted from the physical removal of soil cores and subsequent replacement with inorganic sand. This procedure induced preferential flow through aerification holes, which accelerated dehydration of the surface, causing hydrophobic conditions and increasing LDS symptoms (Nektarios et al., 2007). Hollow TA is known to increase hydraulic conductivity, as McCarty et al. (2007) found a 150% increase from core cultivation compared with an untreated control. In newly constructed sand greens K_{sat} can already be excessive due to limited turfgrass development, while greens that have significant organic matter, silt, or clay may exhibit compaction of aerification hole walls, limiting lateral flow into the root zone. In both of these cases, HTA can cause an unwanted effect, as turfgrass cannot obtain adequate water for optimum growth.

Porosity

Total porosity ranged from 51 to 54% during the study (Table 9). In 2007, HTA 3 times yr^{-1} had higher total pore space than the control. Overall macropore space rose above a prestudy average of 13% in 2007, but fell below initial levels in 2008 (Table 6). Macropore space was higher for HTA 2 times yr^{-1}and HTA 3 times yr^{-1} in both years compared with VC. Micropore space fell slightly below a prestudy average of 38% in 2007, but increased above initial levels in 2008 (data

Table 7. Root weights for cultural practice treatments and cultivars on a mature ultradwarf bermudagrass golf green from 2007–2008.

	Root weight†	
Treatment	2007	2008
	g	
Control	7.5 ab‡	15.0 a
HTA (1 time yr^{-1})	7.1 ab	15.3 a
HTA (2 times yr^{-1})	6.8 ab	15.8 a
HTA (3 times yr^{-1})	7.2 ab	14.4 a
VC (3 times yr^{-1})	8.7 a	17.1 a
STA (5 times yr^{-1})	6.3 b	13.0 a
LSD	2.1	4.6
Cultivar		
Champion	8.0 a	15.0 a
TifEagle	6.6 a	15.2 a
LSD	2.0	2.7

† Measurements were taken after all yearly treatments were applied and the green allowed to recover. Root weights were determined from 15-cm deep soil cores.

‡ Mean estimates with same letter within column are not statistically different at the 0.05 significance level based on the Tukey-Kramer method.

Table 8. Volumetric water content (θ) and localized dry spot (LDS) for cultural practice treatments and cultivars on a mature ultradwarf bermudagrass golf green from 2007–2008.†

	θ§		LDS (1–10 scale)¶	
Treatment‡	2007	2008	2007	2008
	%			
Control	35.8 a#	24.3 a	3.9 b	3.4 bc
HTA (1 time yr^{-1})	32.1 ab	21.1 ab	5.6 ab	3.4 bc
HTA (2 times yr^{-1})	32.9 ab	18.1 b	5.2 ab	4.1 b
HTA (3 times yr^{-1})	28.9 b	17.7 b	6.3 a	5.9 a
VC (3 times yr^{-1})	35.7 a	23.5 a	1.5 c	2.1 c
STA (5 times yr^{-1})	31.6 ab	21.0 ab	4.8 ab	3.5 bc
LSD	4.5	4.1	2.3	1.6
Cultivar				
Champion	32.1 a	20.7 a	5.0 a	3.9 a
TifEagle	33.5 a	21.2 a	4.0 a	3.5 a
LSD	2.2	2.4	1.2	1.3

† Measurements were taken at the end of each year after LDS symptoms developed following withholding of irrigation.

‡ HTA = hollow tine aerification; STA = solid tine aerification; VC = verticutting.

§ Measurements were taken at a 6-cm depth.

¶ LDS ratings: 1 = least, 10 = most symptoms.

Mean estimates with same letter within column are not statistically different at the 0.05 significance level based on the Tukey-Kramer method.

Table 9. Total pore space for cultural practice treatments and cultivars on a mature ultradwarf bermudagrass golf green from 2007–2008.

	Total pore space†			
	2007		2008	
Treatment	Initial	Final	Initial	Final
	%			
Control	51.7 a‡	53.1 b	52.8 a	51.6 a
HTA (1 time yr^{-1})	50.7 a	54.1 ab	54.4 a	50.6 a
HTA (2 times yr^{-1})	51.8 a	54.9 ab	54.2 a	51.7 a
HTA (3 times yr^{-1})	52.2 a	56.1 a	54.9 a	50.4 a
Verticutting (3 times yr^{-1})	52.0 a	54.0 ab	54.5 a	49.4 a
STA (5 times yr^{-1})	52.0 a	54.6 ab	54.6 a	50.1 a
LSD	1.6	2.8	2.7	3.2
Cultivar				
Champion	53.3 a	55.6 a	54.9 a	50.7 a
TifEagle	50.2 b	53.3 a	53.5 a	50.5 a
LSD	1.4	2.5	1.6	1.7

† Initial levels were determined before initiation of yearly treatments. Final levels were determined after all yearly treatments were applied and the green allowed to recover.

‡ Mean estimates with same letter within column are not statistically different, at 0.05 significance level based on the Tukey-Kramer method.

Table 10. Mat organic matter depth, and concentration for cultural practice treatments and cultivars on a mature ultradwarf bermudagrass golf green from 2007–2008.

	Mat depth‡				
	2007		2008		2008
Treatment†	Initial	Final	Initial	Final	Final
	cm				% LOI§
Control	1.67 a¶	1.65 a	1.02 a	0.80 a	10.07 a
HTA (1 time yr^{-1})	1.73 a	1.60 a	1.02 a	0.85 a	9.68 a
HTA (2 times yr^{-1})	1.67 a	1.65 a	1.04 a	0.85 a	8.14 b
HTA (3 times yr^{-1})	1.77 a	1.71 a	0.94 a	0.88 a	6.74 c
VC (3 times yr^{-1})	1.75 a	1.56 a	0.98 a	0.75 a	7.46 bc
STA (5 times yr^{-1})	1.69 a	1.67 a	0.88 a	0.79 a	9.33 a
LSD	0.27	0.19	0.17	0.22	0.92
Cultivar					
Champion	1.67 a	1.63 a	1.00 a	0.82 a	9.21 a
TifEagle	1.76 a	1.65 a	0.96 a	0.82 a	7.93 b
LSD	0.18	0.08	0.07	0.06	0.34

† HTA = hollow tine aerification; STA = solid tine aerification; VC = verticutting.

‡ Initial levels were determined before initiation of yearly treatments. Final measurements were taken after all treatments were applied and the green allowed to recover.

§ LOI = loss on ignition.

¶ Mean estimates with same letter within column are not statistically different at 0.05 significance level based on the Tukey-Kramer method.

not shown). Increased pore space for HTA was attributed to the removal of soil cores and replacement with inorganic sand. Changes in macro and micropore space volumes between 2007 and 2008 were attributed to a 107% increase in root weights.

Mat Organic Matter Depth and Concentration

A steady decline in mat OM depth was observed during the 2-yr experiment, although there were no significant differences among cultural practice treatments or cultivars (Table 10). Previous attempts to reduce mat OM depth have produced mixed results. Callahan et al. (1998) found VC alone, and in combination with HTA, was most effective at reducing mat OM depth on a mature, 6-yr-old, 'Penncross' creeping bentgrass green. Topdressing with 6.4 mm sand yr^{-1} decreased mat OM depth more than 3.2 mm sand yr^{-1} when used in conjunction with cultural practice treatments (Callahan et al., 1998). McCarty et al. (2007) reported a 15% increase in mat OM depth when 9.6 mm sand yr^{-1} was used on a 3-yr-old 'A-1' creeping bentgrass green, and grooming, HTA, biological thatch control agent, topdressing, and VC (alone and in combinations) treatments were ineffective at reducing mat OM depth. Because mat OM depth was similar among treatments in both years of this study, the reduction was attributed to grooming and topdressing.

Verticutting, HTA 2 times yr^{-1}, and HTA 3 times yr^{-1} caused a reduction in mat OM % LOI compared with the control (Table 10). McCarty et al. (2007) obtained a 19% mat OM reduction with a combination treatment of grooming, HTA, and VC. Hanna (2005) found VC to a depth of 2.5 cm effectively removed mat OM from TifEagle, while 0.6 cm deep was insufficient. A study in Arkansas showed VC at a 2.5-cm depth was more effective in removing mat OM in the surface inch than HTA, although recovery took twice as long (Landreth et al., 2007). McCarty et al. (2007) found HTA combined with grooming and VC reduced mat OM more than the control. In this study, VC, HTA 2 times yr^{-1}, and HTA 3 times yr^{-1} treatments reduced mat OM due to their substantial surface impact and incorporation of topdressing (Table 1).

Table 11. Soil organic matter for cultural practice treatments and cultivars for a mature ultradwarf bermudagrass golf green from 2007–2008.

	Soil organic matter‡			
	2007		2008	
Treatment†	Initial	Final	Initial	Final
	% LOI§			
Control	4.6 a¶	4.2 a	3.8 a	4.3 a
HTA (1 time yr^{-1})	4.8 a	3.6 a	3.6 a	4.0 ab
HTA (2 times yr^{-1})	4.8 a	3.8 a	3.4 a	3.8 b
HTA (3 times yr^{-1})	4.6 a	3.4 a	3.4 a	3.6 b
VC (3 times yr^{-1})	4.5 a	4.0 a	3.7 a	4.1 ab
STA (5 times yr^{-1})	5.2 a	4.1 a	3.7 a	3.8 b
LSD	1.2	0.9	0.6	0.5
Cultivar				
Champion	4.6 a	3.8 a	3.7 a	4.0 a
TifEagle	4.9 a	3.9 a	3.5 a	3.9 a
LSD	0.4	0.4	0.3	0.4

† HTA = hollow tine aerification; STA = solid tine aerification; VC = verticutting.

‡ Initial concentrations were determined before initiation of yearly treatments. Final concentrations were determined after all yearly treatments were applied and the green allowed to recover.

§ LOI = loss on ignition.

¶ Mean estimates with same letter within column are not statistically different at 0.05 significance level based on the Tukey-Kramer method.

Soil Organic Matter Concentration

The HTA 2 times yr^{-1}, HTA 3 times yr^{-1}, and STA reduced soil OM concentration compared with the control after the final sampling for 2008 (Table 11). The HTA 3 times yr^{-1}, with 1.3-cm or greater tines, is considered adequate for managing root zone physical characteristics in Florida (Foy, 2000), although four or more HTA may be needed to improve highly trafficked greens (Unruh and Elliott, 1999). The USGA recommends impacting 15 to 20% of the putting green surface yearly with cultural practices and topdressing with 122.0 to 152.5 m^3 (12.2–15.2 mm) sand ha^{-1} yr^{-1} to manage thatch–mat and soil OM (Hartwiger and O'Brien, 2003). Carrow (2003) found

HTA 2 times yr^{-1} and 148.5 m^3 USGA sand ha^{-1} yr^{-1} diluted soil OM in a creeping bentgrass green. The HTA 2 times yr^{-1}, HTA 3 times yr^{-1}, and STA treatments in this study met or exceeded the USGA's recommendations for yearly surface impact and reduced soil OM after 2 yr of treatments. Verticutting, which had the greatest surface impact, did not reach deep enough into the 7.6-cm organic profile to affect soil OM concentration.

SUMMARY

Although VC did not reduce soil OM, it was the best overall cultural practice as it provided the firmest, darkest green surface; reduced thatch–mat, mower scalping, and LDS symptoms; and increased root weights. On greens with shallow (<3-cm) organic (i.e., mat OM and soil OM) profiles, VC also reduced soil OM. For greens with deeper organic profiles, HTA and STA are more effective at reducing soil OM and increasing K_{sat}. Because TifEagle had higher quality than Champion and reduced mower scalping and LDS, it proved to be more manageable in a subtropical climate.

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