

Thatch and Mat Management in an Established Creeping Bentgrass Golf Green

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ABSTRACT

Thatch is a layer of partially decomposed organic matter between green shoot tissue and the soil surface, and mat is thatch partially intermixed with topsoil. Excessive thatch–mat layering (>2.54 cm) is generally detrimental to turfgrass management, and numerous techniques including various mechanical and topdressing regimes, have been attempted to reduce its severity. This factorial experiment investigated the effectiveness of combining mechanical–biological and topdressing treatments for controlling thatch–mat levels in an established USGA-specified golf green planted with ‘A-1’ creeping bentgrass [*Agrostis stoloniferous* L. var. *palustris* (Huds.)]. Two levels of topdressing were used, and the mechanical–biological treatments included vertical mowing at two different depths and timings, core cultivation, grooming, a biological granular supplement (Thatch-X), and combinations of core cultivation with grooming and/or vertical mowing. Differences among the mechanical–biological treatments were detected following 2 consecutive yearly applications. Thatch–mat depth (mm) was 12 to 15% greater for Thatch-X and topdressing alone compared with other treatments. Organic matter content (g kg^{-1}) increased 32% for the untreated and decreased 19% for core cultivation combined with vertical mowing and grooming, whereas all other treatments maintained pre-study levels. Compared with the untreated, surface hardness was reduced ~9% for all treatments using core cultivation, while water infiltration rates increased 127 to 168%. Vertical mowing treatments improved water infiltration rates by 40 to 65%. Turfgrass quality was not greatly impacted by the mechanical–biological treatments as ratings ranged from 8.4 to 10.0. However, mower scalping and dry spots contributed to unacceptable or only marginally acceptable turfgrass quality (6.4–7.2) for the untreated by the end of the study. Compared with topdressing alone, ball roll distance was decreased 6% by vertical mowing 7 days after treatment (DAT) and 5 to 8% by core cultivation up to 14 DAT. Sand topdressing alone was insufficient for managing thatch–mat levels in an established creeping bentgrass golf green.

CREeping BENTGRASS is the most widely used cool season turfgrass on golf greens as it provides a dense, smooth, uniform surface and true ball roll (Salaiz et al., 1995). Newer varieties of creeping bentgrass such as A-1, are becoming more popular as they offer significant improvements in turfgrass quality, putting characteristics, color, and density (National Turfgrass Evaluation Program, 2003).

Thatch is a tightly intermingled layer of living and dead plant tissue that develops between the green vegetation and soil surface (Decker, 1974), while mat is a tan-to brown-colored tightly intermingled layer of thatch

intermixed with soil (Williams and McCarty, 2005). Thatch is formed primarily from periodically sloughed roots, horizontal stems (stolons and rhizomes), stubble, and mature leaf sheaths and blades (Engel, 1954; Roberts and Bredakis, 1960), while mat forms when thatch is slow to decompose following sand topdressing. Thatch accumulation occurs when turfgrass production of organic matter exceeds the decomposition rate (Beard, 1973). Any climatic, edaphic, or biotic factor that stimulates excessive plant growth or impairs decomposition of organic material contributes to thatch development (Hurto et al., 1980).

Excessive thatch is commonly associated with negative physical and biological effects on the soil profile such as reductions in hydraulic conductivity (Harris, 1978), decreased water infiltration (Murray and Juska, 1977), increased localized dry spots (Cornman, 1952), reduced tolerance to cold temperatures (White, 1962; Beard, 1973; Thompson, 1967), increased disease and insect problems (Musser, 1960; Mascaro, 1961; Thompson, 1967; Sprague, 1970), and reduced pesticide effectiveness (Cornman, 1952; Latham, 1955; Musser, 1960).

Mechanical practices such as vertical mowing, core cultivation, grooming, and topdressing are commonly used for managing thatch–mat development in golf greens. Although somewhat effective in physically removing thatch–mat, core cultivation and vertical mowing are more disruptive than grooming or topdressing to the turfgrass playing surface. Core cultivation may provide some additional benefits to the soil environment such as reduced surface compaction, improved water infiltration rates, and increased surface aeration and rooting (Carrow et al., 1987; Dunn et al., 1995; Ledebor and Skogley, 1967; Shildrick, 1985; White and Dickens, 1984). Improved biological conditions are also promoted by core cultivation and vertical mowing as these practices provide additional oxygen for soil organisms that naturally decompose thatch–mat (Williams and McCarty, 2005).

Since golf greens are maintained at extremely low heights, golf course superintendents face the difficult task of producing a high quality, stress-tolerant turfgrass with an acceptable putting distance or “speed” (Salaiz et al., 1995). Golf course superintendents and turfgrass researchers continually seek new regimens for combating excessive thatch production and are reconsidering some past thatch control methods to combine with new strategies such as chemical control agents, which minimize surface disruption.

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Abbreviations: CIV, Clegg Impact Value; C+G, core cultivation four times annually + grooming twice weekly; C+V, core cultivation four times annually + vertical mowed twice annually; C+G+V, core cultivation four times annually + grooming twice weekly + vertical mowed twice annually; DAT, days after treatment; USGA, United States Golf Association.

Table 1. Soil physical properties of the growth media and topdressing sand used on an established 'A-1' creeping bentgrass golf green.

Soil separation, %			Sieve fraction sand particle diameter, % retained						Bulk density	Hydraulic conductivity	Total porosity	Organic matter
Sand 1-0.05	Silt 0.05-0.002	Clay <0.002	Gravel 2	V. Coarse 1	Coarse 0.5	Medium 0.25	Fine 0.15	V. Fine 0.05				
99	0.4	0.1	0.0	0.0	25	68	6.0	1.1	1.46	17	45	14

This study investigated the effectiveness of combining various mechanical-biological treatments with topdressing for managing thatch-mat levels in an established A-1 creeping bentgrass golf green without adversely affecting turfgrass quality. The research hypothesis was that topdressing alone would not adequately manage thatch-mat levels and must be supplemented by one or more mechanical-biological treatments.

MATERIALS AND METHODS

Studies to investigate various thatch-mat reduction procedures on 3-yr-old A-1 creeping bentgrass golf greens were conducted from 2001 to 2002 at Clemson University in Clemson, SC. The research green consisted of an 85:15 sand/peat mixture on a volume basis, overlying 10 cm of pea gravel (diameter range of 6.4-9.5 mm) covering drain lines trenched into the subgrade (USGA Green Section Staff, 1993). Particle-size distribution and physical properties of the sand were determined as reported in Danielson and Sutherland (1986), Gee and Bauder (1986), and Klute and Dirksen (1986) and are provided in Table 1. Bentgrass plots were maintained to golf course standards by walk mowing daily with solid rollers at 3 to 4 mm height (depending on season) and using a preventative disease control program with chlorothalonil (tetra-chloroisophthalonitrile) fungicide applied every 14 d during the summer. Irrigation was applied twice weekly during heat stress and supplied approximately 3.8 cm wk⁻¹. Yearly fertilizer applications provided 390 kg N ha⁻¹, 42 kg P ha⁻¹, and 163 kg K ha⁻¹. Before this study, core cultivation was performed three times yearly in 1998 and 1999 using 1.6-cm diameter hollow tines in March and September and 0.64-cm diameter hollow tines in May both utilizing 2.5 by 2.5 cm spacing. Topdressing was also applied the same day as core cultivation using a power rotary spreader delivering a consistent layer of 0.6 cm of medium-coarse (0.5-1.0 mm diameter) sand that was brushed to incorporate into the plant canopy. The only thatch control methods applied to experimental plots during the 2-yr study were the assigned experimental treatments.

Treatments evaluated were an untreated control plus a 2 × 9 factorial of topdressing levels and mechanical-biological methods (Table 2). Topdressing was applied either twice monthly at 0.6 mm or once monthly at 1.2 mm from March through October using a calibrated drop spreader (The Scotts Company, Marysville, OH). Ten passes totaling either 0.6 or 1.2 mm, were made over the designated plots to achieve adequate uniformity. Particle-size distribution and physical properties of the topdressing sand were identical to the sand fraction in the growth media (Table 1). The mechanical-biological thatch control methods were none, core cultivation, vertical mowing (two levels), grooming, a biological thatch control agent (Thatch-X), and three combination treatments using two or three mechanical methods: core cultivation and grooming (C+G); core cultivation and vertical mowing (C+V); and core cultivation, grooming, and vertical mowing (C+G+V) (Table 2). The untreated plots received no topdressing or mechanical-biological thatch control method.

Vertical Mowing and Grooming

Two vertical mowing treatments, differing in depth and frequency, were applied using a commercial vertical mower (model GS 04, Graden Industries Pty. Ltd., Somerton Victoria, Australia), with 2-mm wide tempered steel, tungsten-tipped blades spaced 25 mm apart. One treatment consisted of vertical mowing to a depth of 6.4 mm on the 15th ± 2 d of March, May, September, and October each year (Table 2). The second treatment consisted of vertical mowing to a depth of 19.1 mm on the 15th ± 2 d of March and October each year. Organic material and plant debris removed during mowing was allowed to dry on the turfgrass surface and then removed using a backpack blower.

Grooming, vertical slicing 3 mm deep with blade spacing 6.4 mm apart, was performed twice weekly (Mondays and Fridays) with a commercial walk mower (model 220A, John Deere, Moline, IL) and grooming attachment (model BM18115, John Deere, Moline, IL) from 1 April to the end of September each year. The grooming depth of 3 mm was measured from the cutting edge of the bed-knife to the soil surface. Two passes

Table 2. Timing, depth, diameter, and spacing of thatch management treatments used on an established 'A-1' creeping bentgrass golf green, 2001-2002.

Treatment†	Timing	Depth	Diameter-width		Spacing
			mm		
Untreated	-	-	-	-	-
Topdressing (factor 1 with 2 levels)					
Twice monthly	March-October	0.6	-	-	-
Monthly	March-October	1.2	-	-	-
Mechanical-biological (factor 2 with 9 levels)					
None (topdressing only)					
Vertical mowed twice annually (V)	March and October	19	2		25
Vertical mowed four times annually	March, May, September, October	6.4	2		25
Core cultivation four times annually (C)	March, May, June, September	76	6.4 and 15.8‡		76
Grooming twice weekly (G)	April-September	3	-	-	-
Biological thatch control agent	May and July	-	-	-	-
C+G combination					
C+V combination					
C+V+G combination					

† Topdressing was used with all single and combination mechanical and biological treatments.

‡ Core diameter was 6.4 mm in May and June and 15.8 mm in March and September.

in opposite directions were made during each grooming event, and all plant debris and turfgrass clippings captured in the front basket of the walk mower were removed. Nongroomed plots were twice-mowed during each grooming event.

Core Cultivation (or Cultivation)

Cultivation was performed with a core cultivator (model GA 30, Ryan, Barrington, IL) using conventional hollow tines (JRM, Wilmington, NC) with a tine depth of 76 mm on 76-mm centers. In March and September of each year, 16-mm diameter tines were used, while in May and June, core cultivation was accomplished with 6.4-mm diameter tines. Smaller tines were used in May and June to minimize surface disruption before and during summer stress. Cultivation was performed on the 25th \pm 3 d of each application month. Ejected cores were allowed to air-dry on the surface for approximately 30 min and then reincorporated by hand brushing with a push broom. Remaining leaf and organic debris was removed with a backpack blower followed by the appropriately timed topdressing treatment (Table 2) plus 3.3 mm of irrigation.

Biological Thatch Control Product

Thatch-X, a commercial product manufactured by Ocean Organics (Ocean Organics/Emerald Isle Ltd., Ann Arbor, MI), was evaluated as a biological thatch control agent. According to the manufacturer, Thatch-X has a fertilizer analysis of 4–0.9–0.4 (N–P–K) from specific feed grade organics, cold-water sea plants, fishmeal, and alfalfa (*Medicago sativa* subsp. *sativa*) meal. It also contains “selected microorganisms and other bioactive ingredients” designed to accelerate thatch reduction. Specific organisms, levels, and viability were unavailable due to manufacturer product content secrecy. Thatch-X was applied at 146 kg product ha⁻¹ in May and July each year using a granular shaker can. Plots were swept with a greens broom before application to open the dense turfgrass canopy and permit granular particle penetration. Immediately after application, 3.3 mm of irrigation was applied.

Combination Treatments

Three combination treatments (C+G, C+V, and C+G+V) using multiple mechanical methods described earlier were investigated (Table 2). Treatment C+G included four annual core cultivations and twice weekly grooming; C+V consisted of four annual core cultivations and two annual vertical mowings; and C+G+V provided four annual core cultivations, grooming twice weekly, and vertical mowing twice annually. Vertical mowing was implemented 14 d after cultivation for C+V and C+G+V to minimize canopy damage.

Measurements

Treatment effects were assessed by measuring thatch–mat depth and percentage organic matter content, water infiltration rates, surface hardness or firmness, visual turfgrass quality, and ball roll distance.

Thatch–Mat Depth and Organic Matter Content

Thatch–mat depth and organic matter content were determined from two soil cores per plot (19-mm diam. and 51 mm deep) extracted on the 15th \pm 3 d of March, May, September, and December each year. Roots below the mat layer and foliage material above the thatch layer were removed. Thatch depth was measured on the uncompressed soil cores at two points (Smith, 1979). Thatch–mat organic matter content was

determined using the procedure described by Carrow et al. (1987). Soil cores were dried at 100°C for 48 h and weighed. Samples were weighed again after combusting in a muffle furnace at 700°C for 5 h to provide the ashed organic weight. Thatch–mat accumulation (g kg⁻¹) was determined as the difference between these two measurements. The two depth and organic matter determinations obtained during each sampling month for each plot were averaged before statistical analysis.

Surface Hardness

Surface hardness was assessed using a Clegg Impact Soil Tester (2.5-kg model, Lafayette Instrument Co., Lafayette, IN). The weighted hammer was dropped from a distance of 0.46 m to the turfgrass surface to provide a Clegg Impact Value (CIV). Two readings were taken per plot monthly from March to October each year, 2 d after irrigation or rainfall to help ensure uniform soil water content. The CIVs were multiplied by 10 to convert to g_{max} (peak deceleration) (Lush, 1985). The two values obtained each month for each plot were averaged before statistical analysis.

Infiltration Rate

Infiltration rates were evaluated using a double ring infiltrometer (model 13a, Turf-Tec International, Coral Springs, FL). The double ring infiltrometer measured 30 cm on the outside ring and 15 cm on the inside ring. One measurement was taken per plot monthly from March to October each year, 2 d following irrigation to field capacity. The infiltrometer was randomly placed within each plot and inserted 2 cm into the soil. Water was filled to the top of the infiltrometer (10.0 cm), and after drainage initiation, rings were refilled and time necessary for water to vacate the 10 cm center ring was recorded and converted to cm h⁻¹ (Gregory et al., 2005).

Turfgrass Quality

Visual turfgrass quality ratings were based on color, shoot density, and uniformity of stand using a scale of 1 to 10, where 1 equaled no live turfgrass and 10 equaled dark green, dense uniform grass (Johnson et al., 1987). Mower scalp was not specifically rated; however, reduction in uniformity due to scalping was reflected in turfgrass quality ratings. Turfgrass quality ratings were recorded weekly from March to October, and the weekly ratings obtained each month were averaged for each plot before statistical analysis.

Ball Roll Distance

Ball roll distance is commonly accepted as an important aspect of putting green playability (Salaiz et al., 1995). Ball roll distance was determined 7, 14, and 21 days after treatment (DAT) each year for three treatments (topdressing alone, core cultivation four times annually, and vertical mowing two times per year) using a modified U.S. Golf Association (USGA) stimpmeter (Gaussoin et al., 1995). The average distance for three golf balls rolled in one direction and then re-rolled in the opposite direction was determined at 1000 h for each plot receiving one of these treatments. Ball rolls were parallel to vertical mowing direction.

Statistical Analysis

A split-block (strip plot) experimental design (Kuehl, 2000) with three replications was used for the two-factor study. Each

replication consisted of two topdressing strip plots and nine mechanical-biological method strip plots arranged perpendicular to each other plus an untreated plot. Size of the intersecting perpendicular strip plots was 2 by 1 m. Analyses of variance were performed to evaluate main and interaction effects of the two factors and to determine whether treatment effects were consistent across dates and years. Means separation was performed using Fisher's Protected LSD with $\alpha = 0.05$ except for organic matter results that were examined using $\alpha = 0.10$.

RESULTS

The only interaction of treatments with years occurred for turfgrass quality ratings. Since no topdressing by mechanical-biological method interactions or main effects of topdressing were detected in the study, only the main effects for mechanical-biological treatments will be discussed.

Thatch-Mat Depth and Organic Matter Content

None of the mechanical-biological methods reduced thatch-mat depth compared with the untreated (Table 3). However, thatch-mat depth increased 12% with the biological thatch control agent and 15% with topdressing alone compared with the untreated.

Organic matter content of the thatch-mat layer averaged 20 g kg^{-1} before treatment applications (Table 4). During the 2-yr study, percentage organic matter content by weight increased 32% in the untreated plots and declined 19% in plots receiving the C+G+V combination treatment. All other thatch management treatments effectively maintained organic matter content of the thatch-mat layer at prestudy levels.

Surface Hardness

Surface hardness for topdressing alone, vertical mowing, grooming, and the biological treatment was sim-

Table 3. Thatch-mat depth, surface hardness, and water infiltration rates for thatch management treatments used on an established 'A-1' creeping bentgrass golf green, 2001-2002.

Treatment	Thatch-mat depth [†]	Surface hardness [‡]	Water infiltration [‡]
	mm	g max	cm h^{-1}
Untreated	32.4	81	61
Topdressing only	37.1	76	73
Vertical mowed twice annually at 19.1 mm depth (V)	34.7	81	102
Vertical mowed four times annually at 6.4 mm depth	34.7	80	86
Grooming twice weekly (G)	34.6	79	72
Core cultivation four times annually (C)	33.3	74	157
Biological thatch control agent	36.4	79	72
C+G	34.1	73	140
C+V	33.2	73	164
C+G+V	32.8	74	149
LSD (0.05)	2.7	6.0	20

[†] Measurements obtained in December of 2002 and averaged across topdressing levels.

[‡] Measurements obtained monthly from March to October each year and are averaged across sampling dates, topdressing levels, and years.

Table 4. Organic matter concentration by weight for thatch management treatments used on an established 'A-1' creeping bentgrass golf green, 2001-2002.

Treatment	Organic matter [†]			Reduction or increase
	Initial	Final	Change	
	g kg^{-1}			%
Untreated	19	25	+6*	+32
Topdressing only	21	20	-1	-5
Vertical mowed twice annually at 19.1 mm depth (V)	20	18	-2	-10
Vertical mowed four times annually at 6.4 mm depth	20	18	-2	-10
Grooming twice weekly (G)	19	21	+2	+11
Core cultivation four times annually (C)	20	18	-2	-10
Biological thatch control agent	23	20	-3	-13
C+G	21	19	-2	-10
C+V	19	16	-3	-16
C+G+V	21	17	-4*	-19
LSD (0.10)			3.4	

* Change significantly different from zero ($P < 0.10$).

[†] Measurements are averaged across topdressing levels. Initial denotes measurements obtained before treatment application; Final denotes measurements obtained in December, 2002; and Change = Final - Initial.

ilar to the untreated (Table 3). Core cultivation alone reduced surface hardness 9% compared with the untreated, whereas combining grooming and/or vertical mowing with core cultivation did not provide additional reductions. Core cultivation treatments appeared to reduce surface hardness more than treatments that only reduced surface organic matter levels. Reduced surface hardness is often desired on surfaces such as golf greens or sports fields for cushioning ball bounce or minimizing sports injuries.

Water Infiltration

Compared with the untreated, the only mechanical-biological treatments that did not improve water infiltration rates were topdressing alone, grooming, and the biological treatment (Table 3). Treatments that incorporated core cultivation increased infiltration rates by an average of 150% compared with the untreated, while vertical mowing alone increased infiltration rates by an average of 54%. Combining grooming and/or vertical mowing with core cultivation did not enhance infiltration rates of core cultivation alone.

Turfgrass Quality

Turfgrass quality results are presented separately for each year and examined by sampling date due to significant treatment \times sampling date interactions (Tables 5 and 6). Turfgrass quality was acceptable (>7.0) for all mechanical-biological treatments throughout the study, and the only unacceptable rating (6.4) occurred for the untreated plots in September of 2002. From June to October in 2001, treatments utilizing core cultivation generally reduced turfgrass quality compared with topdressing alone (Table 5); however, the lowest rating (8.9) was still acceptable.

During 2002, mower scalping was very evident from August to October for the untreated plots, and turfgrass quality deteriorated from a rating of 10 in July to 6.4 by

Table 5. Turfgrass quality for thatch management treatments used on an established 'A-1' creeping bentgrass golf green, 2001.

Treatment	March	April	May	June	July	August	September	October
	1–10†							
Untreated	10.0	10.0	9.8	10.0	10.0	9.5	9.3	9.7
Topdressing only	9.1	9.1	9.7	10.0	10.0	10.0	10.0	10.0
Vertical mowed twice annually at 19.1 mm depth (V)	9.4	9.4	9.7	10.0	10.0	10.0	10.0	10.0
Vertical mowed four times annually at 6.4 mm depth	9.4	9.5	9.7	9.9	10.0	10.0	9.8	9.9
Grooming twice weekly (G)	9.3	9.4	9.7	10.0	9.9	9.9	9.6	9.7
Core cultivation four times annually (C)	9.0	9.4	9.7	9.1	9.2	9.3	9.5	9.3
Biological thatch control agent	9.7	9.7	9.8	10.0	10.0	10.0	10.0	9.9
C+G	9.3	9.3	9.8	9.1	9.1	9.3	9.0	8.9
C+V	9.1	9.1	9.7	9.2	9.2	9.2	9.8	9.3
C+G+V	9.2	9.0	9.6	9.0	8.9	9.2	9.3	9.0
LSD (0.05)	NS	NS	NS	0.21	0.19	0.51	0.61	0.33

† Turfgrass quality ratings on 1–10 scale with 1 = no live turfgrass and 10 = dark green, dense uniform turfgrass. Ratings are averaged across topdressing levels.

September (Table 6). Excellent turfgrass quality (>9) was consistently achieved with topdressing alone, vertical mowing, and the biological treatment. As observed in 2001, treatments utilizing core cultivation generally reduced turfgrass quality from June to October but did not seriously impact turfgrass quality. The lowest rating (8.4) occurred with the C+G combination treatment in October.

Ball Roll

Ball roll distance was determined 7, 14, and 21 DAT for only three treatments: topdressing alone, core cultivation four times annually, and vertical mowing four times annually. Ball roll distance was reduced by vertical mowing and core cultivation (6 and 8%, respectively) at 7 DAT compared with topdressing alone (Table 7). At 14 DAT, ball roll distances for vertical mowing were similar to topdressing alone, while distances for core cultivation were approximately 6% lower. By 21 DAT, there were no detectable differences in ball roll distance among the treatments.

DISCUSSION

Topdressing

Topdressing has been recognized as an effective practice for controlling thatch by improving the microenvironment for thatch decomposition (Ledebor and Skogley, 1967). However, some researchers have concluded that dilution, rather than decomposition, of the

thatch occurs with topdressing and that dilution is at least as important as accelerated biodegradation in controlling the problems associated with excessive layers (Couillard et al., 1997; Rieke, 1994). Regardless of the mechanism, topdressing effects on thatch–mat levels have been inconsistent in previous research studies. Engel and Alderfer (1967), Smith (1979), and Rieke (1994) reported no enhancement in thatch decomposition with topdressing alone. In our study, topdressing alone increased thatch–mat depth 15% compared with the untreated plots (Table 3).

Several studies have reported that topdressing helps reduce thatch layers in established turfgrass. Eggens (1980) observed that topdressing alone was an effective thatch control treatment on 'Penncross' creeping bentgrass. Carrow et al. (1987) found that topdressing 'Tifway' bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* (Burt-Davis)] reduced thatch by 44 and 62% for one and two annual applications, respectively. White and Dickens (1984) noted topdressing four times yearly reduced thatch accumulation more than a single topdressing, and Callahan et al. (1998) concluded that topdressing a sand-based bentgrass putting green six times yearly decreased thatch more than topdressing three times yearly.

Although topdressing alone failed to control thatch–mat accumulation or improve water infiltration in this study, turfgrass quality and water infiltration of plots receiving topdressing alone was excellent (Tables 3, 5, and 6). Topdressing alone maintained organic matter content of the thatch–mat layer at the prestudy level

Table 6. Turfgrass quality for thatch management treatments used on an established 'A-1' creeping bentgrass golf green, 2002.

Treatment	March	April	May	June	July	August	September	October
	1–10†							
Untreated	9.8	10.0	9.7	10.0	10.0	7.2	6.4	7.1
Topdressing only	9.2	9.0	9.7	10.0	10.0	9.6	9.5	9.5
Vertical mowed twice annually at 19.1 mm depth (V)	9.6	9.4	9.7	10.0	10.0	9.5	9.5	9.5
Vertical mowed four times annually at 6.4 mm depth	9.5	9.5	9.7	9.7	9.9	9.8	9.4	9.7
Grooming twice weekly (G)	9.4	9.3	9.7	10.0	9.9	8.7	8.7	8.7
Core cultivation four times annually (C)	9.7	9.3	9.7	9.0	9.0	8.7	8.8	8.7
Biological thatch control agent	9.2	9.7	9.9	10.0	10.0	9.4	9.5	9.5
C+G	9.0	9.3	9.8	9.0	8.8	8.7	8.8	8.4
C+V	9.0	9.0	9.6	9.1	8.7	9.0	9.0	8.5
C+G+V	9.3	9.0	9.5	9.0	8.5	8.7	9.0	8.5
LSD (0.05)	NS	NS	NS	0.09	0.25	0.98	1.22	0.91

† Turfgrass quality ratings on 1–10 scale with 1 = no live turfgrass and 10 = dark green, dense uniform turfgrass. Ratings are averaged across topdressing levels.

Table 7. Ball roll distance 7, 14, and 21 d after treatment (DAT) for selected thatch management treatments used on an established 'A-1' creeping bentgrass golf green, 2001–2002.†

Treatment	7 DAT	14 DAT	21 DAT
Topdressing only	151	154	155
Vertical mowed two times annually at 19.1 mm depth	142	156	154
Core cultivation four times annually	139	146	147
LSD (0.05)	7	8	NS

† Measurements are averaged across sampling dates, topdressing levels, and years.

(20 g kg⁻¹), whereas the untreated plots increased to 25 g kg⁻¹ (Table 4). The maintenance of organic matter content with topdressing alone, in light of increased organic matter production indicated by untreated plots, has been suggested as the dilution theory offered by Couillard et al. (1997) and Rieke (1994). Carrow (1998) hypothesized that when organic matter content of sand-based putting greens reaches 3 to 4% by weight, the percentage of soil macropores begins to decrease, leading to secondary problems. The maximum organic matter by weight in our investigation was only 25 g kg⁻¹ for the untreated plots without topdressing. Differences in reported organic matter may involve the relatively young green (3-yr) in our study and our use of creeping bentgrass, while Carrow et al. (1987) did not report the age of their turfgrass, which was field-grown Tifway bermudagrass. Also, differences in thatch degradation measurements, such as thatch thickness, percentage OM, actual OM, or volumetric OM, might explain some of the discrepancies in this and other thatch control studies (Couillard et al., 1997). Severe scalping reduced desirable turfgrass conditions in our untreated plots by August of the second year.

Vertical Mowing

Neither two nor four vertical mowings annually reduced accumulation or organic matter content of the thatch–mat layer in this study compared with topdressing alone (Tables 3 and 4). The 2.5-cm blade spacing in our study probably provided inadequate surface area contact to effectively remove sufficient organic matter. Carrow et al. (1987) evaluated vertical mowing of Tifway bermudagrass with solid blades spaced 2.5 cm apart and set at a depth right above the soil surface. One vertical mowing annually did not influence percentage OM content, but two vertical mowings annually produced an 8% reduction. McWhirter and Ward (1976) reported a 4 to 12% decrease in thatch by vertical mowing every 2 to 4 wk on a 'Tifgreen' bermudagrass golf green. White and Dickens (1984) noted biweekly vertical mowing on three bermudagrass putting green cultivars did not control organic matter or thatch more effectively than twice yearly vertical mowings. However, the twice-yearly vertical mowings were less deleterious to the turfgrass surface than the biweekly treatment.

Vertical mowing was not detrimental to turfgrass quality as excellent ratings were achieved throughout the study (Tables 5 and 6); however, blade spacing was

somewhat detrimental to the putting surface as it reduced ball roll distance by 6% 7 DAT compared with the untreated. Additional studies evaluating vertical mower blade spacing and frequency are needed to better understand the effects of vertical mowing on thatch accumulation.

Grooming

When grooming turfgrass, vertically mounted blades typically penetrate the turfgrass surface very shallow (<3.8 mm) to reduce grain and remove top growth accumulated by the plant. Weekly grooming, along with timely topdressing and cultivation may reduce the need for vertical mowing (Williams and McCarty, 2005). Salaiz et al. (1995) noted light vertical mowing (vertical blades only penetrating the turfgrass surface canopy) enhanced putting green speed by controlling turfgrass grain and increasing surface smoothness. In our study, thatch–mat depth and turfgrass quality for the grooming treatment were similar to topdressing alone and vertical mowing (Tables 3, 5, and 6), and grooming maintained organic matter content of the thatch–mat layer at prestudy levels (Table 4).

Core Cultivation

Four annual core cultivations had no detectable effect on reducing thatch–mat accumulation compared with the untreated (Table 3), but maintained organic matter content of the thatch–mat layer at prestudy levels (Table 4). However, compared with topdressing alone, four annual core cultivations reduced thatch–mat depth 10%. McWhirter and Ward (1976) reported cultivation conducted three to six times a year on a Tifgreen bermudagrass golf green reduced thatch by 10% when cores were returned. White and Dickens (1984) found no differences in total organic matter or thatch levels when cultivation was performed twice yearly (May and September) or monthly (May–September) using 6.4 cm tines, 7 cm deep, on 5 cm centers. They also reported that cultivation frequency did not affect turfgrass quality, but turfgrass scalping was reduced when cultivation was performed monthly. Smith (1979) found twice yearly and monthly cultivation utilizing 1.25 cm hollow tines set at a 5-cm depth slightly decreased thatch thickness, but increasing cultivation frequency to biweekly did not provide additional benefits.

Soil hardness is a measurement of soil compaction or surface strength in situ (Lush, 1985). The higher the peak deceleration value using the Clegg impact hammer, the more energy being returned to the object contacting the surface, or the harder the surface (Rogers et al., 1998). Previous research by Bunnell et al. (2001) demonstrated some beneficial effects of core cultivation such as modifying soil compaction, increasing water infiltration, and promoting the release of soil carbon dioxide. Canaway et al. (1986) also noted conventional hollow tine cultivation of sand-based soccer fields improved infiltration rates. Based on work by Murphy et al. (1993), core cultivation should make the profile more porous and produce lower g_{max} values.

A 9% reduction in surface hardness, compared with the untreated, was realized for all treatments incorporating core cultivation (Table 3), whereas surface hardness for all other treatments were similar to the untreated. Increases in water infiltration rates for core cultivation treatments ranged from 130 to 169% compared with the untreated. These benefits were achieved without reducing turfgrass quality below acceptable levels (Tables 5 and 6); however, ball roll distances were reduced by core cultivation (Table 7). Vertical mowing twice or four times annually increased water infiltration rates an average of 54% compared with the untreated. In a newly established creeping bentgrass golf green, surface hardness was reduced an average of 19% by treatments that included core cultivation, while water infiltration rates increased 58% after the first year and 188% the second year (McCarty et al., 2005).

Biological Thatch Control Product

Limited research has been reported on using “biological products” for thatch–mat reduction. Thatch decomposition without physically disrupting the turfgrass soil surface would be of tremendous value (Ledeboer and Skogley, 1967). Most biological products contain an array of sucrose, glucose, or other sugar sources, low nutrient content, various acids, and inoculated microorganisms. According to the manufacturer, Thatch-X consists of specific feed-grade organics, cold-water sea plants, fishmeal, and alfalfa meal. Following manufacturer recommended rates, timings, and frequency during the 2-yr study, Thatch-X did not control thatch–mat accumulation as thatch–mat thickness was 12% greater than the untreated (Table 3). Turfgrass quality with Thatch-X was comparable to topdressing alone, vertical mowing, and grooming (Tables 5 and 6), and organic matter content of the thatch–mat layer was maintained at prestudy levels (Table 4).

Inconsistency of biological thatch control products has been noted. Ledeboer and Skogley (1967) evaluated three biological treatments that included lime, 23–7–7 fertilizer, sucrose, and glucose and concluded that they provided no decrease of thatch. Murdoch and Barr (1976) found no evidence of thatch reduction for a commercial microorganism inoculum in common bermudagrass (*Cynodon dactylon* (L.) Pers. var. *dactylon*) over a 5-mo test period. Berndt et al. (1990), however, noted thatch thickness reduction on ‘Kentucky’ bluegrass (*Poa pratensis* L.) after 1 yr of applying three commercial bio-organic materials, but was unclear whether to attribute it to the added microorganisms or increased N fertility.

Combination Treatments

Thatch–mat levels for combination treatments incorporating core cultivation were similar to the untreated but lower than topdressing alone (Table 3). However, the addition of grooming and/or vertical mowing did not enhance the benefits of reduced surface hardness or in-

creased water infiltration rates provided by core cultivation alone. The combination treatment C+G+V was the only treatment that reduced organic matter content of the thatch–mat layer during the 2-yr study (Table 4). These results support the research hypothesis that topdressing alone would not adequately manage thatch–mat levels and must be supplemented by one or more mechanical–biological treatments. This research also supports field observations where single cultural practices alone rarely control thatch–mat accumulation. Although late season turfgrass quality was slightly reduced by core cultivation treatments each year, none of the ratings were below 8.4 (Tables 5 and 6).

Eggens (1980) observed that combining vertical mowing and core cultivation with topdressing was no more effective than topdressing alone for reducing thatch depth on Penncross creeping bentgrass. Carrow et al. (1987) reported vertical mowing and core cultivation were less effective than topdressing for reducing thatch (percentage OM) accumulation in Tifway bermudagrass. Callahan et al. (1998), however, noted reduced thatch depth for creeping bentgrass with vertical mowing plus core cultivation four times yearly.

In a related study where identical treatments were imposed on a newly seeded creeping bentgrass golf green, the most aggressive combination treatments, core cultivation four times annually, grooming twice weekly, vertical mowing twice annually, and topdressing were required to minimize thatch–mat accumulation (McCarty et al., 2005). In their study, the combination treatments had 53% increases in organic matter over 2-yr whereas the untreated had an increase of 123%. Combinations of core cultivation plus vertical mowing with or without grooming decreased organic matter 38 to 45% compared with the untreated. Topdressing increased depth of thatch–mat layering, probably through a dilution effect. A biological thatch control product did not prevent thatch–mat accumulation in this newly seeded turfgrass situation either.

CONCLUSIONS

Under the conditions encountered in this study, sand topdressing alone maintained acceptable turfgrass quality but did not adequately control thatch–mat development or improve water infiltration rates. The addition of Thatch-X, a biological thatch control product, did not improve results. Compared with the untreated, the inclusion of grooming or vertical mowing with topdressing controlled thatch–mat development, while vertical mowing marginally increased water infiltration rates. Core cultivation was necessary to achieve substantial improvement in water infiltration rates, but the addition of grooming and/or vertical mowing did not enhance this benefit provided by core cultivation alone. The combination treatment C+G+V was the only treatment that reduced organic matter content of the thatch–mat layer during the 2-yr study (Table 4). The benefits provided by the mechanical treatments were achieved without causing detrimental effects to turfgrass quality.

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