Anthracnose Disease and Annual Bluegrass Putting Green Performance Affected by Mowing Practices and Lightweight Rolling

John C. Inguagiato, James A. Murphy,* and Bruce B. Clarke

ABSTRACT

Anthracnose (*Colletotrichum cereale* Manns sensu lato Crouch, Clarke & Hillman) has been a devastating disease on annual bluegrass (ABG) [*Poa annua* L. f. *reptans* (Hausskn.) T. Koyama] putting green turf over the past 15 yr. The objectives of this 2-yr field trial on ABG were to evaluate the impact of mowing height (2.8, 3.2, and 3.6 mm), mowing frequency (seven and 14 times wk^{-1}), lightweight rolling (none and every other day), and possible interactions of those factors on anthracnose severity and golf ball roll distance (BRD). Mowing height had the greatest effect on anthracnose. Mowing at 2.8 mm increased disease severity 3 to 21% compared with mowing at 3.6 mm, while 3.2 mm was intermediate to higher and lower heights. Mowing frequency had little effect on anthracnose, although mowing 14 times wk^{-1} occasionally reduced disease severity 1 to 14% compared with seven times wk^{-1}. Rolling every other day also occasionally reduced disease severity 5 to 6% under moderate disease pressure. Mowing at 2.8 mm generally provided the greatest BRD. However, similar or greater BRDs were achieved at 3.2 and 3.6 mm, using combinations of increased mowing frequency and/or rolling compared with mowing at 2.8 mm seven times wk^{-1} without rolling. Thus, anthracnose severity on ABG greens can be reduced by raising the mowing height as little as 0.4 mm, and BRD (≥2.9–3.2 m) can be maintained by increasing mowing frequency and/or rolling without increasing disease severity.

Dep. of Plant Biology and Pathology, 59 Dudley Rd., Rutgers Univ., New Brunswick, NJ 08901-8520. New Jersey Agricultural Experiment Station Publication no. D-12294-07-08. Received 25 July 2008. *Corresponding author (murphy@aesop.rutgers.edu).

Abbreviations: ABG, annual bluegrass; BRD, ball roll distance.

Anthracnose (caused by *Colletotrichum cereale* Manns sensu lato Crouch, Clarke & Hillman) is a destructive fungal disease of annual bluegrass (ABG) [*Poa annua* L. f. *reptans* (Hausskn.) T. Koyama] (Crouch et al., 2006) throughout Australia, Canada, the United States, and Western Europe (Smith et al., 1989; Smiley et al., 2005; Peart, 2007). Anthracnose epiphytotics on golf course putting greens have increased in frequency and severity during the past 15 yr (Landschoot and Hoyland, 1995; Dernoeden, 2002; Wong and Midland, 2004). Reasons for this increase are not fully understood; however, changes in turf management practices (e.g., lower mowing height, increased mowing frequency, lightweight rolling) to enhance playability may be partly responsible (Vermeulen, 2003; Zontek, 2004). Research documenting the effect of specific factors and potential interactions between management practices on the incidence and severity of anthracnose on ABG turf is limited (Inguagiato et al., 2008).

Mowing is a fundamental practice of turfgrass culture required to maintain function (Beard, 1973). It is well known that there is an inverse relationship between mowing height and ball roll distance (BRD)—a common measure of putting green playability (Nikolai, 2005). Annual bluegrass can tolerate routine mowing at heights <3.2 mm (Vargas and Turgeon, 2004), although plant stress is often enhanced at lower heights of cut (Fry and Huang, 2004). Putting greens are commonly maintained at or below 3.2 mm (Beard, 2002;

Published in Crop Sci. 49:1454–1462 (2009).
doi: 10.2135/cropsci2008.07.0435

677 S. Segoe Rd., Madison, WI 53711 USA

Zontek, 2006) and are frequently affected by anthracnose or other biotic and abiotic stresses (Dernoeden, 2002; Vermeulen, 2003). Backman et al. (2002) observed that ABG turf mowed at 3.2 and 3.6 mm had greater anthracnose severity compared with 4.0 mm. Similarly, Uddin and Soika (2003) determined that mowing a mixed ABG–creeping bentgrass (*Agrostis stolonifera* L.) green at 1.9 mm increased anthracnose severity compared with 3.2 or 4.1 mm. The severity of other diseases such as summer patch (caused by *Magnaporthe poae* Landschoot & Jackson) (Davis and Dernoeden, 1991), melting-out [caused by *Drechslera poae* (Baudys) Shoemaker] (Lukens, 1970), and rust (caused by *Puccinia* spp. and *Uromyces* spp.) (Smiley et al., 2005) are also increased as foliage is removed at lower mowing heights, thought to be due in part to depleted carbohydrate production and storage. Although reduced mowing heights can enhance anthracnose severity, the effect of mowing height combined with other management practices (e.g., mowing frequency or rolling) has yet to be determined.

More frequent mowing (five times wk^{-1} vs. one time wk^{-1}) has been shown to reduce rooting, carbohydrate reserves, and clipping yield of Kentucky bluegrass (*Poa pratensis* L.) maintained at 25.4 or 50.8 mm (Juska and Hanson, 1961). However, daily mowing is generally required for putting green turf to maintain playing consistency and density and to avoid scalping (Beard, 1973). It is not uncommon to mow putting green turf multiple times a day (e.g., mowing twice per day), which may increase damage (wounding) to leaf tissues and has been suggested to contribute to increased anthracnose severity (Dernoeden, 2002; Smiley et al., 2005).

Lightweight rolling is conducted to smooth and improve uniformity of the turf canopy on putting greens as well as to increase BRD (Hartwiger et al., 2001; Nikolai, 2005). Hartwiger et al. (2001) evaluated rolling frequencies on creeping bentgrass turf growing on sand and gravely sandy loam root zones and found that rolling four or seven times wk^{-1} reduced turf quality of both root zones and increased soil bulk density of the gravely sandy loam compared with no rolling or rolling one time wk^{-1}, whereas bulk density of the sand root zone was unaffected. Nikolai et al. (2001) observed that rolling creeping bentgrass turf three times wk^{-1} did not affect turf quality or bulk density of sand mixtures (85:15 [sand:peat v/v]; 80:10:10 [sand:soil:peat v/v/v]) or a sandy clay loam compared with nonrolled turf. In the same study, the incidence of dollar spot (caused by *Sclerotinia homoeocarpa* F.T. Bennett) was reduced and Microdochium patch [caused by *Microdochium nivale* (Fr.) Samuels & I.C. Hallett] increased in turf rolled three times wk^{-1} (Nikolai et al., 2001). The effect of lightweight rolling on anthracnose severity is unknown but has been suggested to enhance disease severity (Dernoeden, 2002; Smiley et al., 2005).

Thus, the objectives of this field trial were to evaluate the impact of mowing height, mowing frequency, lightweight rolling, and the potential interactions of these factors on anthracnose severity, BRD, and turf quality of ABG maintained as a putting green.

MATERIALS AND METHODS

A 2-yr field trial was initiated in 2004 on 33-mo-old ABG turf grown on a Nixon sandy loam (fine-loamy, mixed, mesic Typic Hapludaults) with a pH of 5.4 in North Brunswick, NJ. A monostand of ABG turf was established in September 2002 using seed indigenous to the site and ABG introduced in 1998 from Plainfield Country Club, Plainfield, NJ (Samaranayake et al., 2008). A 3.2-mm mowing height was achieved by September 2003. The site was inoculated with *C. cereale* isolate HFIIA using 20,000 conidia mL^{-1} on 2 Aug. 2004 to ensure uniform symptom development throughout the trial. Inoculum was prepared, harvested, and applied to ABG turf in the field using the procedures described by Inguagiato et al. (2008). *Colletotrichum cereale* was reisolated from symptomatic tissue to confirm presence of the pathogen in 2004 5 d after inoculation.

When treatments were not imposed, turf was mowed seven times wk^{-1} with a triplex greens mower (Models 3000-04350 and 3150-04357, Toro Co., Bloomington, MN) at a bench setting of 3.2 mm. Nitrogen (water-soluble sources) was applied to the trial 19 times from March to November 2004, totaling 173 kg ha^{-1}, and 11 times from March to August 2005, totaling 78.2 kg ha^{-1}. Phosphorus and potassium were applied based on soil test results at 17.1 and 136 kg ha^{-1} in 2004 and 10.8 and 20.5 kg ha^{-1} in 2005 as elemental P and K, respectively. The trial was topdressed at 88.7 cm^3 m^{-2} every 14 d from May to September, with subangular silica sand conforming to the particle size distribution recommended for sand root zones (Green Section Staff, 2004). Sand was incorporated immediately after topdressing with a cocoa mat drag (Ace Equipment and Supply Co., Henderson, CO). Irrigation was applied only when wilt stress was evident and to wash-in fertilizer to maintain relatively dry soil conditions. Trinexapac-ethyl [4-(cyclopropyl-α-hydroxy-methylene)-3,5-dioxocyclohexanecarboxylic acid ethylester] was applied at 0.05 kg a.i. ha^{-1} every 14 d from 28 Apr. to 22 Sept. 2004 and from 26 May to 19 Oct. 2005 to mimic growth regulation practices employed on golf course putting greens. Anthracnose was suppressed in May and June 2004 with chlorothalonil (tetrachloroisophthalonitrile) at 8.1 to 10.1 kg a.i. ha^{-1} and in May 2005 at 12.9 to 13.3 kg a.i. ha^{-1} to permit collection of early-season BRD data on turf undamaged by this disease. The anthracnose epidemic was arrested between trial years with the application of chlorothalonil at 9.5 kg a.i. ha^{-1} on 27 Sept. 2004 to allow plots to recover. Diseases other than anthracnose and various insects were controlled throughout the season. Fungicides utilized for disease control were selected based on previous research showing that they were not effective against the anthracnose pathogen (Inguagiato et al., 2008).

Treatment Design

The trial used a 3 × 2 × 2 factorial arranged in a split-split plot design with four replications. The main plot (4.6 by 7.1 m) factor was mowing height, the subplot (4.6 by 3.0 m) factor was mowing frequency, and the sub-subplot (4.6 by 1.5 m) factor was lightweight rolling. Levels of each factor were randomly assigned within respective experimental units and repeated in the same location each year. Mowing height treatments were bench settings of 2.8, 3.2, or 3.6 mm on a walk-behind mower (Model 220B, Deere & Company, Moline, IL) equipped with a grooved front roller (Model AMT2979, Deere & Company, Moline, IL). The effective height of cut for this mower was less than the triplex mower used before treatments were imposed; therefore, mowing height for the 2.8- and 3.2-mm treatments was reduced gradually over a 2- to 3-wk period before 24 May each year. The 3.6-mm treatment was similar to the preexisting height of turf mowed with the triplex mower. Mowing frequency treatments consisted of mowing seven or 14 times wk^{-1} (i.e., once or twice daily). Mowing treatments were performed between 0800 and 0930 h each day through 16 Oct. 2004 and 17 Aug. 2005. Lightweight rolling levels were either none or one pass every other day with a triplex-attached vibratory roller (Model UR3T, Turfline, Inc., Moscow Hills, MO) immediately after mowing from 24 May to 16 Oct. 2004 and from 25 May to 17 Aug. 2005.

Data Collection and Analysis

Anthracnose severity was assessed from August to September 2004 and June through August 2005 as the percent turf area infested with *C. cereale* using a line-intercept grid count method (Inguagiato et al. 2008). Ball roll distance was determined between 1030 and 1500 h one to three times wk^{-1} in June and July each year before the turf area infested with anthracnose exceeded 5%. Three golf balls were released from a Stimpmeter (Green Section Staff, 1996) in two opposing directions within each plot, and the average of these six ball rolls determined BRD. Soil bulk density was measured monthly from July to September 2004 and from June to August 2005 at three in situ locations $plot^{-1}$ using a surface moisture-density gauge (Model 3411-B, Troxler Electronic Laboratories, Research Triangle Park, NC) in the backscatter mode. Turf quality was visually rated on a scale of 1 to 9 (where 9 represented the best quality and 5 the minimum acceptable level) from June through August each year. Turf quality ratings took into account plant density, uniformity, color, disease severity, and algal growth on the turf/soil surface. Algal growth was visually estimated on a scale from 1 to 9 (where 9 represented no algae; 8 = 2–5%; 7 = 5–10%; 6 = 10–20%; 5 = 20–35%; 4 = 35–50%; 3 = 50–65%; 2 = 65–80%; 1 = 80–100% of the turf/soil surface covered with algae) on 25 July 2005.

All data were subjected to analysis of variance to identify significant ($P \leq 0.05$) treatment effects using the General Linear Model procedure for a split-split plot design in Statistical Analysis System software v. 8.2 (SAS Institute Inc., Cary, NC). Means of main effects and significant interactions were separated by Fisher's protected least significant difference test at the 0.05 probability level or lower using the appropriate formulae described by Gomez and Gomez (1984). Frequency distributions of BRDs measured for each treatment combination throughout the study were generated to evaluate treatment effects. Each treatment was compared with turf mowed at 2.8 mm seven times wk^{-1} with no rolling, a low-cost (i.e., time, labor, and equipment) regimen that consistently produced BRD in the current trial similar to those sought by the industry (2.9–3.2 m [Niven, 2008]). These comparisons were made by pooled *t* tests ($\alpha = 0.05$) or the Satterthwaite approximation (Steel et al., 1997), methods that compare means of samples with equal or unequal variances, respectively.

RESULTS AND DISCUSSION

Anthracnose Severity

Chlorotic leaves, black rotted crown tissue, acervuli, and fusiform conidia consistent with anthracnose basal rot were apparent by 29 July 2004 and, after the field was inoculated on 2 August, the disease gradually increased in severity to a moderate level (45–62%) in mid-September (Table 1). Disease developed earlier in 2005 (15 June) as a natural infestation and progressed slowly before dramatically increasing to severe levels (79–92%) by 16 Aug. 2005 during favorable conditions for disease development in mid-July and August.

Main factors represented the majority of treatment effects observed throughout this 2-yr trial. However, limited significant interactions did occur; presentation of these data are provided to indicate subtle treatment effects observed on individual dates.

Mowing Height

Mowing height had the most pronounced effect on anthracnose throughout the study, frequently (63% of observations) increasing disease severity at lower heights. Mowing at 2.8 mm increased disease severity 3 to 17% and 13 to 21% compared with 3.6 mm in 2004 and 2005, respectively (Table 1). Turf mowed at 3.2 mm had 8 to 10% less disease than mowing at 2.8 mm, but 11% more disease than mowing at 3.6 mm on 19 July 2005 and 5 to 9% more disease on the last observation date of each season (Table 1). Previous reports also indicated that lower mowing heights increase anthracnose severity (Backman et al., 2002; Uddin and Soika, 2003); however, these studies evaluated much greater incremental differences in mowing height (Uddin and Soika, 2003) or a greater mowing height range (Backman et al., 2002). Data from our trial indicate that relatively small increases in mowing height (0.4 mm) at low heights (2.8 and 3.2 mm) can reduce anthracnose severity. Anthracnose is believed to be more severe on weakened or stressed turf (Smiley et al., 2005). Routine mowing, particularly at reduced heights, can stress plants by removing photosynthetic tissue and severing protective cuticular layers (Beard, 1973). Defoliation of the upper nodes of maize (*Zea mays* L.) plants has been reported to reduce total sugars within pith tissues and increase anthracnose severity [caused by *C. graminicola* (Ces.) G.W. Wils.], due at least in part to reduced photosynthetic capacity (Mortimore and Ward, 1964). Similarly, Kentucky bluegrass maintained at lower mowing heights (i.e., greater defoliation) reduces carbohydrates and enhances summer patch (Davis and Dernoeden, 1991) and melting-out diseases (Lukens, 1970). Lower mowing heights can also reduce rooting (Juska and Hanson, 1961; Beard and Daniel, 1966; Liu and Huang, 2002) and tolerance of turfgrasses to environmental stress (Beard and Daniel, 1966).

Although not measured in our trial, it is possible that carbohydrates and rooting were enhanced at increased mowing heights, thus reducing plant stress and improving tolerance to anthracnose.

Mowing Frequency

The mowing frequency main effect or its interaction with mowing height affected anthracnose severity on three of four dates in 2004 and no dates in 2005 (Table 1). Mowing turf 14 times wk^{-1} decreased disease severity 1 and 14%, compared with mowing seven times wk^{-1}, on 2 Aug. and 15 Sept. 2004 on plots mowed at 3.2 mm (Table 2). Mowing 14 times wk^{-1} at 3.2 or 3.6 mm reduced disease compared with 2.8 mm on these same dates. When turf was mowed seven times wk^{-1}, mowing height had no effect on 2 August, but on 15 September, less disease was observed in plots mowed at 3.6 mm compared with plots mowed at 2.8 or 3.2 mm (Table 2). Mowing 14 times wk^{-1} reduced disease 9% compared with mowing seven times wk^{-1} across all heights on 23 Aug. 2004 (Table 1).

Table 1. Anthracnose disease severity response to mowing height, mowing frequency, and lightweight rolling on annual bluegrass turf in North Brunswick, NJ, during 2004 and 2005.

Main effects	2004				2005			
	2 Aug.	11 Aug.	23 Aug.	15 Sept.	17 June	1 July	19 July	16 Aug.
	%							
Mowing height (MH)								
2.8 mm	4.2	36.8	51.7	61.8	2.2	4.8	47.1	92.2
3.2 mm	2.6	32.2	48.0	53.6	0.9	2.0	36.7	83.9
3.6 mm	1.1	28.8	40.5	44.5	1.5	1.9	25.9	79.2
$LSD_{0.05}$	2.2	NS	8.8	7.3	NS	NS	5.4	3.2
Mowing frequency (MF)								
7 mowings wk^{-1}	2.7	34.5	51.0	55.9	1.7	2.6	38.8	84.1
14 mowings wk^{-1}	2.5	30.8	42.4	50.7	1.4	3.2	34.4	86.1
Lightweight rolling (LR)								
None	3.0	34.2	49.0	56.2	1.6	3.1	39.5	84.8
Every other day	2.3	31.0	44.4	50.4	1.4	2.7	33.6	85.4
	ANOVA							
Source of variation								
MH	*	NS	*	**	NS	NS	***	***
MF	NS	NS	**	*	NS	NS	NS	NS
LR	*	NS	*	***	NS	NS	**	NS
MH × MF	*	NS	NS	*	NS	NS	NS	NS
MH × LR	NS	NS	NS	NS	NS	NS	NS	NS
MF × LR	NS	NS	NS	NS	NS	NS	NS	NS
MH × MF × LR	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	34.1	16.9	13.9	9.9	51.2	27.7	20.1	3.8

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
***Significant at the 0.001 probability level.

Limiting mowing frequency has been recommended to reduce anthracnose severity because it was thought to minimize wounding stress (Dernoeden, 2002; Smiley et al., 2005). Conversely, data from the current trial indicate that increased mowing frequency had no negative effect on anthracnose, occasionally reducing disease, particularly in turf mowed at 3.2 mm. Frequent mowing of turf is necessary at low mowing heights to increase shoot density (Madison, 1962) and avoid scalping damage (Beard, 1973). Thus, frequent mowing may enhance the plants' tolerance to a low mowing height (e.g., 3.2 mm) and reduce the tendency for scalping injury, thereby minimizing stress and occasionally reducing anthracnose severity. It should be noted that, in practice, increased mowing frequency would increase traffic along the perimeter of putting greens due to turning of equipment; however, any effect of increased equipment traffic on anthracnose severity is currently unknown.

Lightweight Rolling

Rolling every other day slightly reduced anthracnose severity (5–6%) under moderate disease pressure during 2004 and 2005 (Table 1). Rolling also produced a very small reduction (1%) in anthracnose when disease severity was low on 2 Aug. 2004 but had no effect under similar conditions in 2005. Moreover, rolling had no effect during severe disease pressure (79–92%) on the last rating date in 2005 (Table 1). Admittedly, the reduction in anthracnose severity in our trial caused by rolling was subtle and would probably be difficult to perceive on the golf course. More importantly, however, these data indicate that rolling does not enhance disease severity as previously suggested (Dernoeden, 2002; Smiley et al., 2005). Rolling has been shown to reduce dollar spot disease on creeping bentgrass greens (Nikolai et al., 2001). Dispersion of dew

Table 2. Anthracnose disease severity response to mowing height and mowing frequency on annual bluegrass turf in North Brunswick, NJ, during 2004.

Mowing height	2 Aug.		15 Sept.	
	Mowing frequency, times wk^{-1}			
	7	14	7	14
mm	%			
2.8	3.6a†A‡	4.7aA	60.0aA	63.6aA
3.2	3.3aA	2.0bB	60.6aA	46.5bB
3.6	1.3aA	0.8bA	47.1bA	41.9bA

†Means within columns followed by the same lowercase letter are not significantly different according to Fisher's protected LSD ($P = 0.05$).
‡Means within rows and date followed by the same uppercase letter are not significantly different according to Fisher's protected LSD ($P = 0.05$).

and gutation water (Nikolai et al., 2001), enhancement of phytoalexin production, and increased surface water holding capacity have been proposed as possible reasons for reduced dollar spot incidence, although the actual mechanism(s) remains unknown (Nikolai, 2005). Furthermore, routine rolling can produce a more prostrate turf canopy and limit the gradual elevation of plant crowns at the thatch–soil surface during the growing season (Beard, 2002); these effects could reduce the amount of leaf blade and leaf sheath tissue removed or damaged at low mowing heights. This could also enhance photosynthetic capacity because the youngest leaf blades, which would be most often removed by mowing, are the most photosynthetically active (Youngner, 1969). Additionally, maintaining the position of crowns lower in the mat layer may reduce plant exposure to high temperature stress because temperatures are often greatest just below the surface of dense, short-mowed turf (Beard, 1973). It should be noted that the mowing frequency effect in the current trial may be related to the effect caused by rolling because the large drive roller of our walk-behind mower effectively rolled the turf as it was being mowed.

Ball Roll Distance

Mowing Height

As expected, lower mowing height increased BRD on 67% of measurement dates in 2004 and 100% of the dates in 2005 (Tables 3 and 4). The 2.8-mm mowing height increased BRD 0.13 to 0.25 m and 0.15 to 0.24 m compared with 3.2 mm in 2004 and 2005, respectively, and increased BRD 0.15 to 0.40 m and 0.18 to 0.43 m compared with 3.6 mm in 2004 and 2005, respectively (Tables 3 and 4).

Mowing Frequency

Mowing 14 times wk^{-1} increased BRD compared with seven times wk^{-1} on every observation date of the trial (Tables 3 and 4); differences in BRD ranged from 0.17 to 0.42 m and from 0.32 to 0.41 m in 2004 and 2005, respectively. This increase in BRD caused by mowing twice daily (14 times wk^{-1}) was similar to or greater than those resulting from lowering the mowing height from 3.6 to 2.8 mm. However, more frequent mowing did not increase, and in some cases decreased disease severity, whereas lowering the mowing height increased severity as much as 21%.

Lightweight Rolling

Rolling every other day did not affect BRD as consistently or to the same extent as lowering the mowing

Table 3. Ball roll distance response to mowing height, mowing frequency, and lightweight rolling on annual bluegrass turf in North Brunswick, NJ, during 2004.

Main effects	June								July						
	4	11	14	16	21	24	28	29	1	2	7	13	15	19	20
	m														
Mowing height (MH)															
2.8 mm	2.87	3.26	3.32	3.26	3.60	3.23	3.35	3.44	3.38	3.41	3.50	3.05	3.08	3.14	3.16
3.2 mm	2.99	3.20	3.14	3.14	3.35	3.14	3.38	3.35	3.23	3.26	3.13	2.92	2.99	2.99	3.11
3.6 mm	2.80	3.05	3.08	3.08	3.20	3.02	3.20	3.29	3.02	3.14	3.00	2.88	2.98	2.89	2.92
$LSD_{0.05}$	NS	NS	0.13	0.14	0.17	0.10	NS	0.11	0.07	0.12	NS	0.11	NS	0.12	0.07
Mowing frequency (MF)															
7 times wk^{-1}	2.77	3.05	2.99	3.02	3.23	2.96	3.23	3.23	3.11	3.11	3.00	2.82	2.93	2.90	2.93
14 times wk^{-1}	2.99	3.29	3.38	3.29	3.54	3.29	3.41	3.51	3.32	3.44	3.42	3.07	3.10	3.11	3.20
Lightweight rolling (LR)															
None	2.87	3.11	3.14	3.14	3.29	3.11	3.26	3.32	3.11	3.26	3.16	2.84	2.92	2.91	3.04
Every other day	2.93	3.23	3.23	3.20	3.47	3.17	3.35	3.41	3.32	3.26	3.25	3.06	3.12	3.11	3.08
	ANOVA														
Source of variation															
MH	NS	NS	**	*	**	**	NS	*	***	**	NS	*	NS	**	***
MF	***	**	***	***	***	***	*	**	***	***	*	***	*	**	***
LR	NS	***	**	NS	***	**	*	*	***	NS	NS	***	***	***	NS
MH × MF	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
MH × LR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
MF × LR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	***	***	NS
MH × MF × LR	NS	NS	**	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	3.8	3.1	2.8	3.6	4.2	2.4	4.0	4.3	4.4	2.9	18.5	5.0	4.4	1.8	3.9

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

***Significant at the 0.001 probability level.

height or increasing the mowing frequency (Tables 3 and 4). However, rolling did increase BRD 0.09 to 0.22 m in 2004 and 0.06 to 0.12 m in 2005 without increasing and in some cases decreasing disease severity. Increased BRD associated with rolling in our trial was less than has previously been reported (Hartwiger et al., 2001; Nikolai et al., 2001), although different types of rollers were used in each study. Nikolai (2004) evaluated lightweight rollers that imparted varying degrees of surface pressure and observed that the type of roller attached to a triplex (similar to the one used in our trial) enhanced BRD less than roller types with greater rolling pressures. Moreover, these previous studies evaluated rolling effects on creeping bentgrass, which has a more prostrate growth habit; thus, the effect of rolling on ABG in our trial may also have differed due to its more erect growth habit.

The limited interactions observed in the current trial influencing BRD indicated that there were conditions, albeit infrequent, when one management practice tended to offset the effect of another practice. The interaction between mowing frequency and rolling on 15 and 19 July 2004 and 28 June 2005 (Tables 3 and 4) indicated that rolling increased BRD of turf mowed seven times wk^{-1} but had no effect on turf mowed 14 times wk^{-1}, although rolling increased BRD at both mowing frequencies on 19 July (Table 5). Mowing 14 times wk^{-1} increased BRD regardless of rolling except on turf rolled every other day on 15 and 19 July. Other factors interacted to influence BRD on a few observation dates; however, treatment differences were inconsistent among dates and considered as random effects (data not shown).

Preferred BRD for daily play ranges from 2.9 to 3.2 m for putting greens in the northeastern United States (Niven, 2008). Mowing heights of <3.2 mm are commonly used in the golf industry to achieve desired BRD; turf mowed at 2.8 mm seven times wk^{-1} without rolling (least labor-intensive treatment) produced a BRD between 2.9 and 3.2 m 64% of the time (or ≥2.9 m 82% of the time) (Table 6). Similarly, plots mowed 14 times wk^{-1} or turf rolled every other day, regardless of mowing height, produced BRDs at or above the 2.9- to 3.2-m range 73 to 100% of the time (Table 6). Pooled *t* tests indicated that turf mowed at 2.8 and 3.2 mm 14 times wk^{-1} with or without rolling, and turf mowed at 3.6 mm 14 times wk^{-1} and rolled every other day had a 0.2- to 0.4-m greater mean BRD than mowing at 2.8 mm seven times wk^{-1} without rolling (Table 6). Mowing at 3.2 mm seven times wk^{-1} with or without rolling, and mowing at 3.6 mm 14 times wk^{-1} without rolling or seven times wk^{-1} with rolling produced a mean BRD similar ($P > 0.05$) to turf mowed at 2.8 mm seven times wk^{-1} without rolling. Only turf mowed at 3.6 mm seven times wk^{-1} without rolling resulted in a mean BRD less (0.2 m) than that achieved on turf mowed at 2.8 mm seven times wk^{-1} without rolling. Although the mean BRD of turf mowed at 3.2 mm seven times wk^{-1} without rolling was not different from that of turf mowed at 2.8 mm seven times wk^{-1} without rolling, the relatively large frequency of observations (36%) where BRD was in the 2.6- to 2.9-m range would probably be undesirable. These data indicate that a BRD between 2.9 and 3.2 m or greater can be achieved at higher mowing heights (i.e., 3.2 and 3.6 mm) by increasing daily mowing frequency and/or rolling every other day, practices that did not enhance and in some cases reduced anthracnose severity.

Table 4. Ball roll distance response to mowing height, mowing frequency, and lightweight rolling on annual bluegrass turf in North Brunswick, NJ, during 2005.

Main effects	June						July
	1	7	13	21	22	28	1
	m						
Mowing height (MH)							
2.8 mm	3.25	3.19	3.39	3.39	3.44	3.06	3.49
3.2 mm	3.18	3.10	3.24	3.15	3.24	2.99	3.32
3.6 mm	3.07	2.98	3.08	2.96	3.16	2.83	3.17
$LSD_{0.05}$	0.10	0.13	0.09	0.04	0.06	0.15	0.15
Mowing frequency (MF)							
7 times wk^{-1}	2.98	2.92	3.05	2.96	3.12	2.78	3.15
14 times wk^{-1}	3.35	3.26	3.42	3.37	3.44	3.14	3.50
Lightweight rolling (LR)							
None	3.16	3.05	3.21	3.11	3.22	2.93	3.28
Every other day	3.17	3.13	3.26	3.22	3.34	2.99	3.37
	ANOVA						
Source of variation							
MH	*	*	***	***	***	*	**
MF	***	***	***	***	***	***	***
LR	NS	NS	NS	*	**	*	*
MH × MF	NS	NS	NS	NS	NS	NS	NS
MH × LR	NS	NS	NS	NS	NS	NS	NS
MF × LR	NS	NS	NS	NS	NS	*	NS
MH × MF × LR	NS	NS	NS	NS	NS	NS	**
CV (%)	4.1	3.8	3.6	4.7	4.0	3.7	3.4

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
***Significant at the 0.001 probability level.

Table 5. Ball roll distance response to mowing frequency and lightweight rolling on annual bluegrass turf in North Brunswick, NJ, during 2004 and 2005.

Mowing frequency	2004				2005	
	15 July		19 July		28 June	
	Lightweight rolling					
	None	Every other day	None	Every other day	None	Every other day
times wk^{-1}	m					
7	2.75b†B‡	3.12aA	2.76bB	3.04aA	2.71bB	2.84bA
14	3.10aA	3.11aA	3.05aB	3.17aA	3.14aA	3.14aA

† Means within columns followed by the same lowercase letter are not significantly different according to Fisher's protected LSD ($P \le 0.05$).

‡ Means within rows and rating date followed by the same uppercase letter are not significantly different according to Fisher's protected LSD ($P \le 0.05$).

Table 6. Frequency distribution (n = 22) of ball roll distances and comparison of mean ball roll distance for all combinations of mowing height, mowing frequency, and lightweight rolling levels on annual bluegrass turf in North Brunswick, NJ, during 2004 and 2005.

Mowing height	Mowing frequency	Lightweight rolling	Ball roll distance range (m) 2.3–2.6	2.6–2.9	2.9–3.2	3.2–3.5	3.5–3.8	3.8+	Mean†	SD	Equality of variances‡	*t* test§
mm	times wk^{-1}	d	%						— m —		*P* > *F*	*P* > *t*
2.8	7	None	0	18	64	18	0	0	3.06	0.17		
2.8	7	Every other	0	5	59	36	0	0	3.15	0.17	0.9052	0.0802
2.8	14	None	0	0	14	50	27	9	3.46	0.30	0.0180	<0.0001
2.8	14	Every other	0	0	5	55	41	0	3.47	0.19	0.7457	<0.0001
3.2	7	None	0	36	59	5	0	0	2.96	0.16	0.8101	0.0633
3.2	7	Every other	0	0	23	73	5	0	3.10	0.14	0.3185	0.3672
3.2	14	None	0	0	23	73	5	0	3.26	0.14	0.3654	0.0002
3.2	14	Every other	0	0	23	59	18	0	3.34	0.16	0.7279	<0.0001
3.6	7	None	5	64	32	0	0	0	2.82	0.15	0.4800	<0.0001
3.6	7	Every other	0	27	73	0	0	0	2.98	0.14	0.2879	0.1002
3.6	14	None	0	5	59	36	0	0	3.14	0.15	0.4246	0.1097
3.6	14	Every other	0	0	50	45	5	0	3.21	0.15	0.4644	0.0030

†Mean ball roll distance of 22 observations made during 2004 and 2005 for each treatment combination.

‡Equality test between sample variances of ball roll distance distributions for each treatment combination and mowing at 2.8 mm every 7 d without rolling assessed using the ratio of the folded-form *F* statistic. Sample variances are equal when *P* > 0.05.

§Ball roll distance (BRD) distributions for each treatment combination were compared with mowing at 2.8 mm every 7 d without rolling to determine if BRD differences were observed during 2004 and 2005. A pooled *t* test α = 0.05 was used to detect differences when sample variances were equal (*P* > 0.05); when unequal (*P* ≤ 0.05), comparisons were made using the Satterthwaite approximation.

Turf Quality

Turf quality was acceptable (≥5) for all treatment factors in the study during June and July each year; however, quality became unacceptable for all factors in August as disease severity increased (Table 7). Before the initiation of disease in July 2004, turf quality was highest at the 2.8- and 3.2-mm mowing heights due to increased turf density (a component of quality in our observations) (Table 7). However, in August 2004 and July 2005, quality was reduced at the 2.8-mm mowing height compared with 3.2 and 3.6 mm because disease severity was greater at this height of cut. Mowing frequency did not affect turf quality in our trial, and rolling slightly improved quality in August 2004 and July 2005 compared with nonrolled turf (Table 7) because rolling reduced disease and improved turf density and uniformity.

Algae was evident in plots on 25 July 2005 when turf quality (i.e., density) was reduced because of disease. Algal cover was generally greater at 2.8- than at 3.2- or 3.6-mm mowing heights (data not shown).

Soil Bulk Density

Soil bulk density ranged from 1.25 to 1.42 Mg m^{-3} during the study (data not shown) and was affected more often by mowing frequency than mowing height or rolling. Mowing 14 times wk^{-1} subtly increased soil bulk density (2%) compared with mowing 7 times wk^{-1} on four of six dates during the trial (data not shown). However, this increase in soil bulk density did not appear to be associated with turf performance; turf quality (Table 7) and disease severity (Table 1) were unaffected by mowing frequency when differences in soil bulk density were observed. It is probable that increased soil bulk density would probably be ameliorated by routine hollow-tine cultivation (Murphy et al., 1992). This is supported by the overall reduction in soil bulk density (0.12 Mg m^{-3}) from 13 Sept. 2004 to 6 June 2005 caused by one hollow-tine cultivation treatment on 25 Oct. 2004. Additionally, freeze–thaw cycles in cool temperate climates could also reduce surface bulk density (Hartwiger et al., 2001; McNitt and Landschoot, 2003).

CONCLUSIONS

As expected, increasing mowing height can reduce anthracnose severity and a relatively small increase (0.4-mm bench setting) in mowing height can reduce disease severity by as much as 11%. However, contrary to expectations, increasing mowing frequency (i.e., mowing twice per day) did not increase and occasionally reduced anthracnose severity, and rolling provided a subtle reduction in disease severity under moderate disease pressure. These effects of mowing twice per day and rolling are notable to turf managers challenged with providing acceptable playability (BRD) without increasing anthracnose severity. Mowing twice per day was as effective at increasing BRD as lowering the mowing height from 3.6 to 2.8 mm, and rolling also increased BRD. Thus, anthracnose severity on ABG putting greens can be reduced by raising the mowing height as little as 0.4 mm, yet playability (BRD of 2.9–3.2 m or greater) can be maintained by adjustments in other management practices such as increasing mowing frequency and/or rolling without increasing (in some cases reducing) anthracnose severity. These data do not suggest that commercially acceptable control of anthracnose disease should be expected by increasing mowing height, mowing frequency, or rolling in the absence of an effective fungicide program. However, a comprehensive management program integrating these practices with moderate N fertility may reduce the quantity and/or application interval of fungicides required to provide commercially acceptable disease control. Increased mowing frequency and rolling may increase surface soil bulk density of putting green turf; however, this did not affect turf performance (turf quality or anthracnose severity) and should be manageable with routine sand topdressing and hollow-tine cultivation, and in cool temperate climates, by freezing and thawing during winter months.

Table 7. Turf quality response to mowing height, mowing frequency, and lightweight rolling on annual bluegrass turf in North Brunswick, NJ, during 2004 and 2005.

Main effects	Turf quality					
	2004			2005		
	14 June	16 July	26 Aug.	16 June	14 July	27 Aug.
	1–9; 9 = best					
Mowing height (MH)						
2.8 mm	7.4	7.4	3.6	7.4	5.3	1.1
3.2 mm	7.1	8.1	4.3	7.3	6.3	2.1
3.6 mm	6.8	6.1	4.7	7.4	6.6	2.7
$LSD_{0.05}$	NS	0.67	0.52	NS	0.81	NS
Mowing frequency (MF)						
7 times wk^{-1}	7.0	7.1	3.9	7.0	6.0	2.0
14 times wk^{-1}	7.2	7.3	4.4	7.4	6.0	2.0
Lightweight rolling (LR)						
None	7.1	7.0	3.9	7.3	5.8	2.0
Every other day	7.1	7.3	4.5	7.1	6.3	2.0
	ANOVA					
Source of variation						
MH	NS	***	**	NS	*	NS
MF	NS	NS	NS	NS	NS	NS
LR	NS	NS	**	NS	*	NS
MH × MF	NS	NS	NS	NS	NS	NS
MH × LR	NS	NS	NS	NS	NS	NS
MF × LR	NS	NS	NS	NS	NS	NS
MH × MF × LR	NS	NS	NS	NS	NS	NS
CV (%)	11.9	8.8	16.5	7.8	15.1	30.7

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
***Significant at the 0.001 probability level.

Acknowledgments

The authors thank Dr. James Baird for his help in identifying experimental factors and objectives, and T.J. Lawson, Daniel Smith, and Sarah Kwiatkowski for their assistance in conducting and maintaining this field trial. This work was supported by the New Jersey Agricultural Experiment Station, State and Hatch Act Funds, Rutgers Center for Turfgrass Science, and other grants and gifts. Additional support was received from the Golf Course Superintendents Association of America, Golf Course Superintendents Association of New Jersey, United States Golf Association, and Tri-State Turf Research Foundation.

References

Backman, P., G. Stahnke, and E. Miltner. 2002. Anthracnose update: Cultural practices affect spread of disease in northwest. TurfGrass Trends October:1–4.
Beard, J.B. 1973. Turfgrass: Science and culture. Prentice Hall, Englewood Cliffs, NJ.
Beard, J.B. 2002. Turf management for golf courses. 2nd ed. Ann Arbor Press, Chelsea, MI.
Beard, J.B., and W.H. Daniel. 1966. Relationship of creeping bentgrass (*Agrostis palustris* Huds.) root growth to environmental factors in the field. Agron. J. 58:337–339.
Crouch, J.A., B.B. Clarke, and B.I. Hillman. 2006. Unraveling evolutionary relationships among the divergent lineages of *Colletotrichum* causing anthracnose disease in turfgrass and corn. Phytopathology 96:46–60.
Davis, D.B., and P.H. Dernoeden. 1991. Summer patch and Kentucky bluegrass quality as influenced by cultural practices. Agron. J. 83:670–677.
Dernoeden, P.H. 2002. Creeping bentgrass management: Summer stresses, weeds, and selected maladies. John Wiley & Sons, Hoboken, NJ.
Fry, J., and B. Huang. 2004. Applied turfgrass science and physiology. John Wiley & Sons, Hoboken, NJ.
Gomez, K.A., and A.A. Gomez. 1984. Statistical procedures for agricultural research. 2nd ed. John Wiley & Sons, New York.
Green Section Staff. 1996. Stimpmeter instruction booklet. U.S. Golf Assoc., Far Hills, NJ.
Green Section Staff. 2004. USGA recommendations for a method of putting green construction. U.S. Golf Assoc. Green Section Construction Educ. Progr., Waco, TX.
Hartwiger, C.E., C.H. Peacock, J.M. DiPaola, and D.K. Cassel. 2001. Impact of light-weight rolling on putting green performance. Crop Sci. 41:1179–1184.
Inguagiato, J.C., J.A. Murphy, and B.B. Clarke. 2008. Anthracnose severity on annual bluegrass influenced by nitrogen fertilization, growth regulators, and verticutting. Crop Sci. 48:1595–1607.
Juska, F.V., and A.A. Hanson. 1961. Effects of interval and height of mowing on growth of Merion and common Kentucky bluegrass (*Poa pratensis* L). Agron. J. 53:385–388.
Landschoot, P., and B. Hoyland. 1995. Shedding some light on anthracnose basal rot. Golf Course Manage. 63:52–55.
Liu, X., and B. Huang. 2002. Mowing effects on root production, growth, and mortality of creeping bentgrass. Crop Sci. 42:1241–1250.
Lukens, R.J. 1970. Melting-out of Kentucky bluegrass, a low sugar disease. Phytopathology 60:1276–1278.

Madison, J.H. 1962. Mowing of turfgrass: III. The effect of rest on Seaside bentgrass turf mowed daily. Agron. J. 54:252–253.

McNitt, A.S., and P.J. Landschoot. 2003. Effects of soil reinforcing materials on the surface hardness, soil bulk density, and water content of a sand root zone. Crop Sci. 43:957–966.

Mortimore, C.G., and G.M. Ward. 1964. Root and stalk rot of corn in southwestern Ontario: III. Sugar levels as a measure of plant vigor and resistance. Can. J. Plant Sci. 44:451–457.

Murphy, J.A., P.E. Rieke, and A.E. Erickson. 1992. Core cultivation of a putting green with hollow and solid tines. Agron. J. 85:1–9.

Nikolai, T.A. 2004. Rollin', rollin', rollin'. Golf Course Manage. 72:121–124.

Nikolai, T.A. 2005. The superintendent's guide to controlling putting green speed. John Wiley & Sons, Hoboken, NJ.

Nikolai, T.A., P.E. Rieke, J.N. Rogers, and J.M. Vargas, Jr. 2001. Turfgrass and soil responses to lightweight rolling on putting green root zone mixes. Int. Turfgrass Soc. Res. J. 9:604–609.

Niven, S.E. 2008. The need for green speed. Tee to Green 38:2–5.

Peart, A. 2007. Anthracnose: A summer killer. Aust. Turfgrass Manage. J. 9:32–33.

Samaranayake, H., T.J. Lawson, and J.A. Murphy. 2008. Traffic stress effects on bentgrass putting green and fairway turf. Crop Sci. 48:1193–1202.

Smiley, R.W., P.H. Dernoeden, and B.B. Clarke. 2005. Compendium of turfgrass diseases. 3rd ed. Am. Phytopathological Soc., St. Paul, MN.

Smith, J.D., N. Jackson, and A.R. Woolhouse. 1989. Fungal diseases of amenity turf grasses. 3rd ed. E. & F.N. Spon, London.

Steel, R.G.D., J.H. Torrie, and D.A. Dickey. 1997. Principles and procedures of statistics: A biometrical approach. 3rd ed. McGraw-Hill, New York.

Uddin, W., and M.D. Soika. 2003. Effects of turfgrass cultural management practices on severity of anthracnose basal rot in mixed-annual bluegrass and creeping bentgrass greens. Phytopathology 93:S86.

Vargas, J.M., Jr., and A.J. Turgeon. 2004. *Poa annua*: Physiology, culture, and control of annual bluegrass. John Wiley & Sons, Hoboken, NJ.

Vermeulen, P.H. 2003. Maybe it's time for a change. U.S. Golf Assoc. Green Section Record 41:28.

Wong, F.P., and S. Midland. 2004. Fungicide-resistant anthracnose: Bad news for greens management. Golf Course Manage. 72:75–80.

Youngner, V.B. 1969. Physiology of growth and development. p. 187–216. *In* A.A. Hanson and F.V. Juska (ed.) Turfgrass science. ASA, Madison, WI.

Zontek, S. 2004. Have we gone too far? The grass is talking to you. Are you listening? U.S. Golf Assoc. Green Section Record 42:28.

Zontek, S.J. 2006. Understanding and managing mechanical damage. U.S. Golf Assoc. Green Section Record 44:1–5.