Published May, 2009

RESEARCH

Creeping Bentgrass Putting Green Turf Responses to Two Irrigation Practices: Quality, Chlorophyll, Canopy Temperature, and Thatch–Mat

Jinmin Fu and Peter H. Dernoeden*

ABSTRACT

Frequent vs. infrequent irrigation are two common irrigation practices. This field study was conducted on 'Providence' creeping bentgrass (*Agrostis stolonifera* L.) grown on a sand-based rootzone and maintained as a putting green. The objectives of this study were to measure several creeping bentgrass performance and physiological factors as influenced by light and frequent (LF) vs. deep and infrequent (DI) irrigation. The LF plots were irrigated daily to moisten the upper 4 to 6 cm of soil, while DI plots were irrigated at leaf wilt to wet soil to a depth of ≥24 cm. The LF-irrigated creeping bentgrass exhibited very good color and quality throughout most of 2006 and 2007, whereas DI-irrigated bentgrass exhibited acceptable quality in 2007 but not in 2006. The DI-irrigated bentgrass had lower chlorophyll levels in leaf and sheath tissue in 2006, but developed better color and quality and had higher chlorophyll levels in late summer of 2007 vs. LF-irrigated bentgrass. Creeping bentgrass subjected to DI irrigation developed a less thick thatch–mat layer that contained less organic matter than that found in LF-irrigated plots. Twice the amount of water was applied to the LF- vs. the DI-irrigated plots.

J. Fu, Wuhan Botanical Garden, The Chinese Academy of Science, Wuhan City, Hubei 430074, P.R. China; P.H. Dernoeden, Dep. of Plant Science and Landscape Architecture, Univ. of Maryland, College Park, MD 20742. Received 3 June 2008. *Corresponding author (pd@umd.edu).

Abbreviations: DI, deep and infrequent irrigation; ET, evapotranspiration; LF, light and frequent irrigation.

The decline of creeping bentgrass (*Agrostis stolonifera* L.) putting greens in summer is a common problem and is largely a response to environmental and mechanical stresses (Dernoeden, 2002; Fry and Huang, 2004). Careful water management is critical to growing quality creeping bentgrass during summer stress periods. Golf course superintendents often use daily irrigation combined with hand-watering and syringing practices when managing creeping bentgrass in the summer. Frequent or excessive irrigation, however, not only increases costs associated with water consumption but can reduce environmental stress tolerance and predispose turf to injury from mechanical stresses, cyanobacteria, moss, and diseases (Beard, 1973; Dernoeden, 2002; Turgeon, 2008).

Two contrasting practices that can be used to maintain putting greens are light and frequent (LF) and deep and infrequent (DI) irrigation. Light and frequent irrigation involves maintaining soil at field capacity, whereas DI irrigation is imposed at the first sign of leaf wilt (Fry and Huang, 2004). Deep and infrequent irrigation at the time turf shows signs of wilt is generally recommended in summer for cool-season grasses (Beard, 1973; Fry and Huang, 2004). Some researchers have found that moderate drought does not greatly affect the summer performance of turfgrasses (Gibeault et al., 1985; Jordan et al., 2003; Fu et al., 2004; DaCosta and Huang, 2006b). For example, Fu et al. (2004) reported that tall fescue (*Festuca arundinacea*

Published in Crop Sci. 49:1071–1078 (2009).
doi: 10.2135/cropsci2008.06.0311

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

Schreb.), bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt Davy], and zoysiagrass (*Zoysia japonica* Steud.) displayed the same level of turf quality as well-watered turfgrass when irrigated at 60 or 80% of evapotranspiration (ET). Gibeault et al. (1985) reported that tall fescue, Kentucky bluegrass (*Poa pratensis* L.), and perennial ryegrass (*Lolium perenne* L.) produced best turf quality when irrigated at 100% ET, but quality was only slightly lower at 80% ET. Jordan et al. (2003) observed that creeping bentgrass putting green turf irrigated every 4 d compared with irrigation every 1 or 2 d, had significantly improved turf quality in one of two study years. DaCosta and Huang (2006b), however, observed a significant decrease in creeping bentgrass quality when irrigated at 60 vs. 100% ET.

Creeping bentgrass is aggressively stoloniferous and produces a well-defined thatch and/or mat layer (hereafter thatch–mat) at the soil surface. Thatch–mat accumulation can have a multitude of negative effects on turfgrasses (Murray and Juska, 1977; Murphy et al., 1993, McCarty, 2001; McCarty et al., 2007). There is a dearth of information on the influence of irrigation practices on thatch–mat accumulation as well as chlorophyll production and canopy temperature in creeping bentgrass. Therefore, the objectives of this field study were to evaluate DI vs. LF irrigation for their impact on creeping bentgrass color and quality, chlorophyll production, thatch–mat accumulation, and canopy temperature in the summer.

MATERIALS AND METHODS

The study was conducted on a research green built to United States Golf Association specifications at the University of Maryland Turfgrass Research Facility in College Park in 2006 and 2007. Soil was a modified sand mix (97% sand, 1% silt, and 2% clay) with a pH of 6.5 and 10 mg organic matter g^{-1} soil. In September 2005, the study site was treated with glyphosate [*N*-(phosphonomethyl)glycine], and the sod was removed and seeded with 'Providence' creeping bentgrass (50 kg seed ha^{-1}) as described by Fu and Dernoeden (2009). Fertilizer was applied as outlined in Fu and Dernoeden (2009). Briefly, a total of 250 kg N ha^{-1} was applied between 20 Sept. and 11 Nov. 2005. A total of 78.4 kg N ha^{-1} from urea was applied in multiple applications in small quantities during the 2006 experimental period. Another 71 kg N ha^{-1} was applied between 20 Sept. and 17 Nov. 2006. In 2007, the bentgrass was fertilized weekly (4.9 kg N ha^{-1}) with urea between 30 April and 27 August to provide a total of 88.2 kg N ha^{-1} during the experimental period. Pest control and core cultivation were performed as described by Fu and Dernoeden (2009).

Each plot measured 1.8 by 2.4 m and was bordered by fiberglass polymer edging (Easy Gardener Products Inc., Waco, TX) set 10 cm deep in soil to minimize lateral movement of water. There also was a 60-cm creeping bentgrass perimeter border separating individual plots. Each plot was individually irrigated between 0700 and 0800 h using a handheld hose equipped with a showerhead nozzle and calibrated as described by Fu and Dernoeden (2009).

Two irrigation regimes were assessed as follows: i) LF irrigation, and ii) DI irrigation. In the LF irrigation regime, water was applied daily to replace moisture lost due to ET. This ensured that soil was maintained in a moistened state to a depth of about 4 to 6 cm each morning. In the DI irrigation regime, water was provided at the first visual sign of leaf wilt as determined by footprinting and/or the appearance of a bluish-gray leaf color. Irrigation frequency was variable for the DI treatment and depended on weather conditions. Therefore, DI irrigation frequency was sometimes as often as every 3 d or as infrequently as 7 d. A standard amount of 50 L (11.6 mm) of water was applied to each DI plot when irrigated. Using a soil probe and ruler, it was determined that this amount of water wet soil to a depth of 6 to 8 cm within 5 min, and water penetrated to a depth of ≥24 cm within 20 min after irrigation ceased. On sunny days, plots were hand-syringed about three times daily depending on weather conditions. To minimize the impact of rain, two tarps were used to cover all eight plots before the onset of rain between 22 May and 31 August in 2006 and 2007 as described Fu and Dernoeden (2009). Six rain events in 2006 (total 16.3 mm) and five events in 2007 (21.6 mm) occurred before plots could be covered. On those days, LF-irrigated plots were not irrigated. An additional 59.7 mm of rain inadvertently fell on uncovered plots on 20 and 21 Aug. 2007. Irrigation treatments were initiated on 22 May and ended in early September in both years.

To measure soil moisture, two soil cores (2.5 cm diam. and 15 cm deep) were taken from each plot and the foliage and thatch were removed. Soil cores were collected about 1 d before irrigating DI plots on the dates shown in Table 1. Each core was separated into segments of 0 to 5.0 cm, 5.1 to 10 cm, and 10.1 to 15 cm (hereafter 0 to 5 cm, 5 to 10 cm, and 10 to 15 cm), and each segment was placed in an envelope and weighed. Soil cores were dried at 80°C for 72 h and reweighed to obtain percent soil moisture. The average of the two soil cores from each plot was used in the statistical analysis.

Turf color and quality were assessed visually on a weekly basis using a scale of 0 to 10, where 0 = brown or dead turf; 7.0 = minimum acceptable color or quality; 8.0 = very good summer color or quality; and 10 = optimum greenness, uniformity, and cover. Clippings, which contained mostly leaf and some sheath tissue (hereafter leaf or leaves), were collected every 4 wk from late May until late August and analyzed for chlorophyll *a* and *b*. Clippings were placed immediately in liquid nitrogen and stored in a freezer at −80°C until analyzed. Chlorophyll was extracted by soaking about 0.05 g of leaf and sheath tissue in dimethyl sulfoxide for 48 h as described by Fu and Huang (2001). Absorbance of the extract was measured at 663.2 nm ($OD_{663.2}$) and 646.8 nm ($OD_{646.8}$) with a spectrophotometer (Beckman Coulter, Inc., Fullerton, CA). Chlorophyll *a* and *b* were quantified using the following equations as described by Fu and Huang (2001):

$$\text{Chlorophyll } a = (12.25 \times OD_{663.2} - 2.79 \times OD_{646.8})/\text{Fresh weight}$$

$$\text{Chlorophyll } b = (21.5 \times OD_{646.8} - 5.1 \times OD_{663.2})/\text{Fresh weight}$$

For thatch–mat depth and organic matter measurements, cores 2.5 cm diam. by 8 cm deep were taken from each plot on the dates noted below. Two cores were taken on 11 June, 21 July, and 18 Aug. 2006, and five soil cores were removed from each plot on 28 Sept. 2006 and 22 May, 18 July, and 5 Sept. 2007. The uncompressed thatch–mat depth of each core was measured with a ruler. Green leaf and sheath tissue and soil below the thatch–mat layer of each soil core were removed with scissors. Thatch–mat samples taken between 28 Sept. 2006 and 5 Sept. 2007 then were dried for 1 h at 125°C and then weighed. Thatch–mat samples then were combusted for 2 h at 550°C and reweighed to determine the amount of organic matter present. The average thatch–mat depth or amount of organic matter from either two or five cores per plot was used in the statistical analyses.

Canopy temperature was measured at 1- to 2-wk intervals from 31 May through 29 Aug. 2006 and 8 June, 7 and 15 July, and 13 and 30 Aug. 2007. Measurements were obtained before syringing on sunny days using a handheld infrared thermometer (Rayst2pu; Raytek, Santa Cruz, CA). Measurements were obtained between 1100 and 1500 h, and the infrared thermometer was held approximately 1.0 m above the canopy surface. Two measurements were taken in each plot and the average temperature per plot was used in the statistical analyses.

The experiment was arranged in a completely randomized block design with four replications. Treatment effects were determined by the analysis of variance using the general linear model procedure of the Statistical Analysis System (SAS Institute, Cary, NC). Significantly different means were separated using Fisher's protected least significant difference test ($P \leq 0.05$). The analysis of variance revealed significant differences among treatments and years. Therefore, data are presented for each year separately.

Table 1. Percent soil moisture in response to light and frequent vs. deep and infrequent irrigation in 'Providence' creeping bentgrass in 2006 and 2007.

Soil depth	Irrigation†	2006			2007		
		11 June	21 July	18 Aug.	19 June	15 July	31 Aug.
cm		Soil moisture (kg kg^{-1} × 100)					
0–5	LF	8.0a‡	12.6a	13.0a	14.5a	15.8a	15.7a
	DI	3.4b	8.0b	5.3b	6.0b	7.4b	6.9b
5–10	LF	7.8a	10.2a	9.6a	7.4a	8.6a	8.4a
	DI	4.5b	8.9b	7.9b	5.5b	6.9b	7.2b
10–15	LF	7.9a	10.8a	10.3a	7.4a	8.1a	8.2a
	DI	6.6a	10.2a	9.7a	7.0a	7.6a	7.6a

†Light and frequent (LF) irrigation was applied daily in the absence of rain to wet soil to a 4- to 6-cm depth. Deep and infrequent (DI) irrigation was applied at visual foliar wilt to wet soil to a depth of ≥24 cm.

‡Means in a column for each soil depth followed by the same letter are not significantly different based on Fisher's protected LSD test ($P \leq 0.05$).

RESULTS

Nearly twice the amount of water was applied to LF- vs. DI-irrigated plots in both years between 22 May and 31 August. The total amounts of water applied were 339 and 344 mm in LF-irrigated and 168 and 157 mm in DI-irrigated plots in 2006 and 2007, respectively. Hereafter, LF-irrigated and DI-irrigated will be referred to as LF and DI, respectively. Soil moisture was significantly higher in the 0- to 5-cm and 5- to 10-cm soil depths on all dates in both years in LF vs. DI plots (Table 1). Soil moisture within the 0- to 5-cm depth ranged from 8.0 to 15.8% in LF plots and 3.4 to 8.0% in DI plots. Soil moisture at the 5- to 10-cm depth ranged from 7.4 to 10.2% in LF and from 4.5 to 8.9% in DI plots. No differences in soil moisture (range 9.5–15.4%) were observed between irrigation treatments at the 10- to 15-cm soil depth.

Turf color and quality were evaluated between 22 May and 10 September in 2006 and 2007. Beginning on 5 June 2006, DI bentgrass exhibited a lower color and quality level than LF bentgrass (Fig. 1 and 2). Thereafter, DI bentgrass had unacceptable color and quality during most of the experimental period (12 June–14 August) in 2006. Turf color and quality in LF plots were judged to be very good (i.e., rating ≥8.0) on most rating dates. There was, however, a decline in turf quality in early August 2006 in LF plots, which was due to the appearance of numerous yellow spots. The etiology of the yellow spots is unknown, but the malady was described by Dernoeden and Fu (2008). Yellow spots did not develop in DI plots and diminished by late August in LF bentgrass. Regardless, quality remained acceptable (i.e., >7.0) at this time in LF plots, despite the yellow spots.

In 2007, turf color and quality ratings from DI bentgrass generally were lower from mid-May until late August vs. LF bentgrass (Fig. 1 and 2). On 20 and 21 August, 31.8 and 27.9 mm of rain fell on uncovered plots, respectively. Before the aforementioned rain events, however, turf color began to decline in LF vs. DI plots on 26 July. Color ratings were higher in DI vs. LF plots on 7 and 15 August, which was before the rain events. The quality of DI plots did not become equal to LF plots until 23 August. On 6 and 10 September, however, quality of DI plots surpassed the quality of LF plots.

In 2006, canopy temperature often ranged from 35 to 40°C, with temperatures as high as 43°C being recorded in DI plots on 14 July 2006 (Fig. 3). On four of eight measurement dates in 2006, the average canopy temperature was 2.3°C higher in DI plots (average = 40.2°C) vs. LF (average = 37.9°C) plots. In 2007, canopy temperatures generally were lower than were observed in 2006 but were >33°C on all dates. On three of five measurement dates in 2007, the average canopy temperature was 2.3°C higher in DI (average = 38.2°C) vs. LF (average = 35.9°C) plots.

Deeply and infrequently irrigated bentgrass leaves had a lower chlorophyll *a* content on three (15 June, 13 July, and 7 September) out of five 2006 measurement dates than LF bentgrass (Table 2). Chlorophyll *b* level also was lower on 7 Sept. 2006 for DI vs. LF bentgrass. Total chlorophyll (i.e., *a* + *b*) levels were similar between irrigation regimes

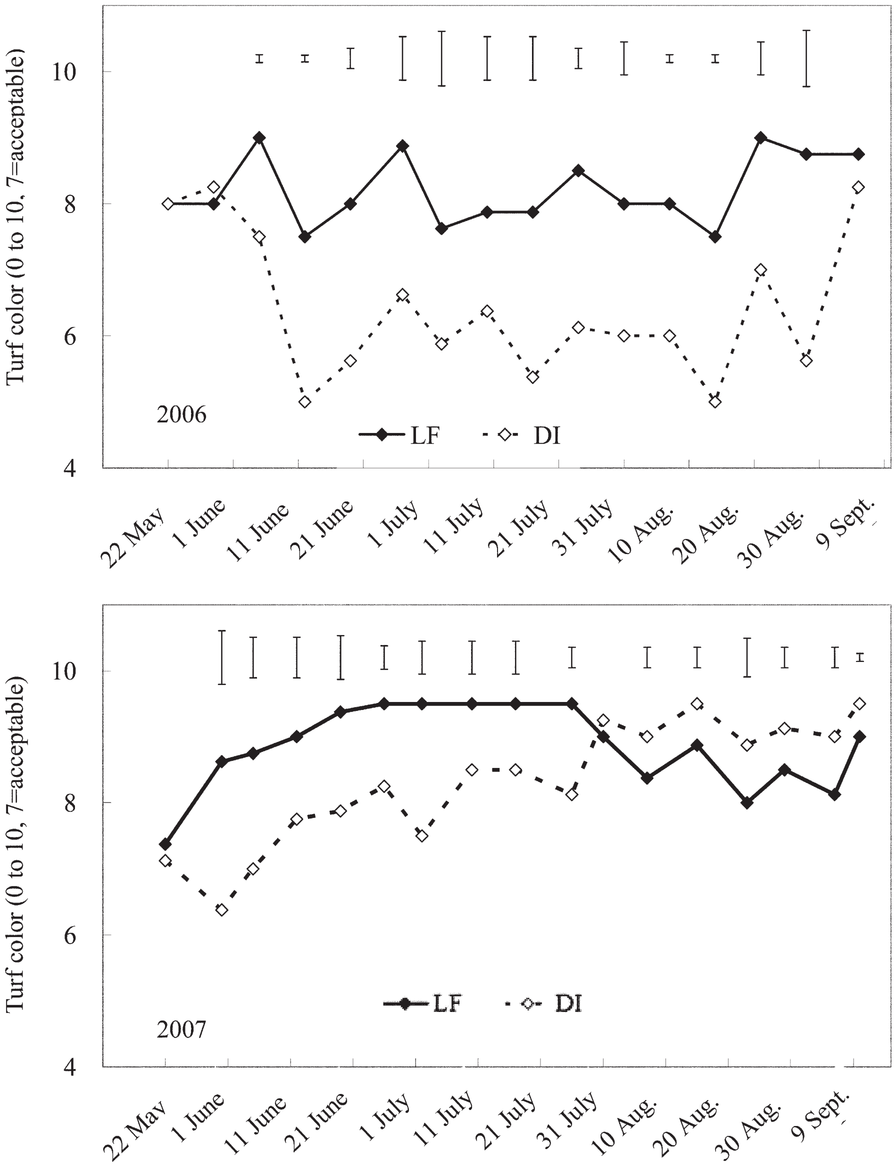

Figure 1. Turf color of 'Providence' creeping bentgrass in response to light and frequent (LF) irrigation (daily in the absence of rain to a wet soil to a 4- to 6-cm depth) and deep and infrequent (DI) irrigation (at leaf wilt to wet soil to soil depth of ≥24 cm) in 2006 and 2007. Bars indicate significantly different means based on Fisher's protected LSD test ($P \leq 0.05$).

on 19 May and 8 Aug. but were higher in LF bentgrass on 15 June, 13 July, and 7 Sept. 2006.

On 1 and 28 June 2007, there were no differences in leaf chlorophyll *a*, *b*, or *a* + *b* levels between the irrigation regimes. By 17 July 2007 and thereafter, leaf tissue from DI plots generally exhibited greater chlorophyll *a*, *b*, and *a* + *b* levels than from LF bentgrass (Table 2). The only exception was on 6 September, when leaf chlorophyll *b* levels were similar between irrigation regimes. Hence, leaf chlorophyll levels increased before the observed improvement of turf color in DI plots on 26 July (Fig. 1) and well in advance of the 59.7 mm of rainfall on 20 and 21 August.

Thatch thickness data were collected on three dates in both years. The thatch–mat layer was thicker in LF vs. DI bentgrass on all dates, except 31 May 2006, when similar thatch–mat depths were observed (Table 3). The largest increase in thatch–mat thickness occurred between 19 Aug. 2006 and 20 May 2007, which was during the period when plots were not subjected to wilt and when a considerable amount of N was applied. Total organic matter (loss on ignition) in the thatch–mat layer was found to be lower in DI plots than in LF plots on all dates (Table 4).

DISCUSSION

It should be noted that this study site had an infiltration rate of nearly 50 cm h^{-1} and water perolated to a depth of ≥24 cm in 20 min. Soil moisture was measured at the 0- to 5-cm, 5- to 10-cm, and 10- to 15-cm rootzone depths. Compared with LF plots, DI plots had significantly lower soil moisture levels in the 0- to 5-cm (average of 6.2 vs. 13.2%) and 5- to 10-cm soil depths (average of 6.8 vs. 8.7%). Similar moisture levels were observed at the 10- to 15-cm (average of 8.2 vs. 8.8%) depth between irrigation treatments. These data show the importance of obtaining soil moisture measurements at various levels in the rootzone when assessing the influence of LF and DI irrigation practices. About twice the amount of water was applied to LF (average = 342 mm) vs. DI (average = 162 mm) plots in both years. Hence, substantial reductions in water usage can be achieved by irrigating to a soil depth of ≥24 cm when visual symptoms of wilt are evident, compared with watering every day to replace ET.

Excessive irrigation can promote numerous negative effects in turfgrasses, including reduced soil aeration; accelerated root loss in summer; increases in cyanobacteria, moss, and disease; and increased susceptibility to environmental and mechanical stresses (Beard, 1973; Hodges, 1992; Huang et al., 1998; Dernoeden, 2002; Fry and Huang, 2004). The overwhelming preponderance of data from this study, however, showed that continuously applying water to ensure a moist 4- to 6-cm rootzone each morning resulted in very good summer color and quality. Indeed, on most rating dates, creeping bentgrass subjected to LF irrigation achieved quality ratings above 8.0 (i.e., very good summer quality), whereas DI plots had an average quality rating of 6.8 (range 5.7–9.3) in 2006. Creeping bentgrass quality ratings in DI plots averaged

7.7 (range 6.3–9.0) in 2007, which was above the minimum acceptable level (i.e., 7.0). The lower quality ratings in 2006 observed in DI bentgrass were attributed to the relative immaturity of the creeping bentgrass, which may have been more adversely affected by wilt stress during the first summer of establishment.

Creeping bentgrass color and quality in DI plots improved after mid-June 2007 and exceeded LF bentgrass by September. This improvement may have been due in part to the 59.7 mm of rainfall that occurred on 20 and 21 August, when plots were not covered. Improvements in color and increased chlorophyll levels in DI plots, however, were detected in mid- to late July and exceeded LF plots before rainfall on 7 and 15 August. Quality of DI plots, however, did not exceed LF plots until 23 Aug. 2007. Hence, the aforementioned rainfall appeared to have had a more beneficial quality response in DI rather than LF plots in late summer of the second year. Regardless, by September 2007 DI plots continued to exhibit improved quality compared with LF plots. Other possible reasons for the improvement in DI bentgrass quality in 2007 are discussed below.

Since we are not aware of any investigations in which creeping bentgrass was irrigated at wilt stress, it is difficult to compare our results with other studies. Previous studies, however, have shown that turfgrass quality responds positively to deficit irrigation (Fry and Butler, 1989; Richie et al., 2002; Jordan et al., 2003; DaCosta and Huang, 2006b). For example, Jordan et al. (2003) reported creeping bentgrass putting green quality was improved by irrigating every 4 d compared with irrigating every 1 or 2 d. In a study conducted by DaCosta and Huang (2006b), creeping bentgrass was maintained to a height of 9.5 mm and grown on a sandy loam, and plots were irrigated every 3 d to either 40, 60, 80, or 100% ET. They reported that creeping bentgrass irrigated at 80% ET maintained acceptable summer quality. Irrigating creeping bentgrass at 60% ET significantly reduced quality, and irrigating at 40% ET resulted in poor summer quality (DaCosta and Huang, 2006b). In our study, soil likely would have been much drier than the sandy-loam irrigated at 40% ET by DaCosta and Huang (2006b). By continuously subjecting creeping bentgrass to wilt stress, leaves of some plants turned brown. Browning of tissue in response to wilt stress often reduced color and quality ratings, but drought-damaged plants invariably recovered. Additionally, the generally higher canopy temperatures in DI plots could have contributed to an increase in heat stress. The improvement in color and quality in DI bentgrass throughout 2007, and in particular late summer, indicated that the turf may have adapted to wilt stress over time. For example, turfgrasses subjected to deficit irrigation can develop a larger root system and store more carbohydrates than well-watered plants (Jordan et al., 2003; Fry and Huang, 2004; DaCosta and Huang, 2006a; Fu

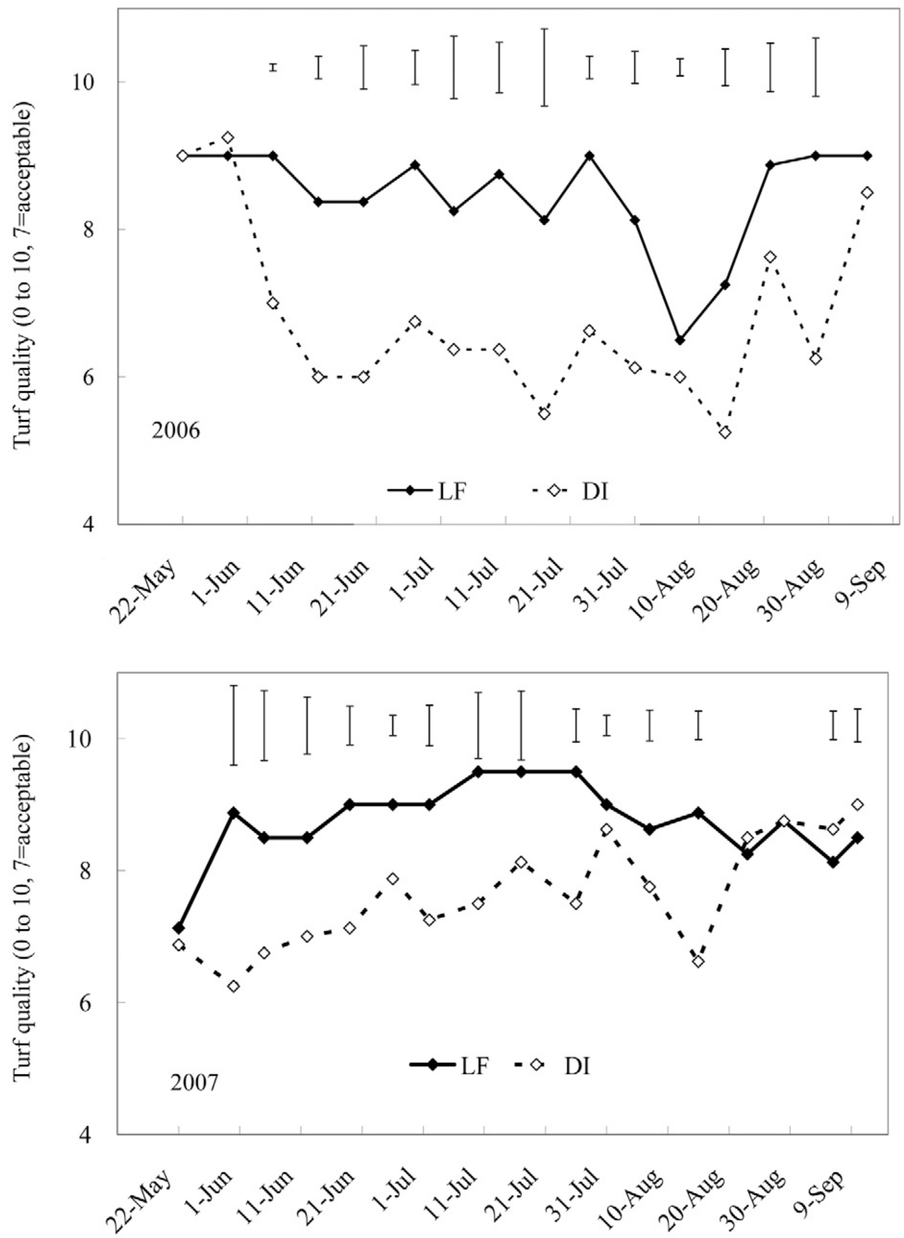

Figure 2. Turf quality of ‘Providence’ creeping bentgrass in response and light and frequent (LF) irrigation (daily in the absence of rain to wet soil to a 4- to 6-cm depth) and deep and infrequent (DI) irrigation (at leaf wilt to wet soil to ≥24 cm) in 2006 and 2007. Bars indicate significantly different means based on Fisher’s protected LSD test ($P \leq 0.05$).

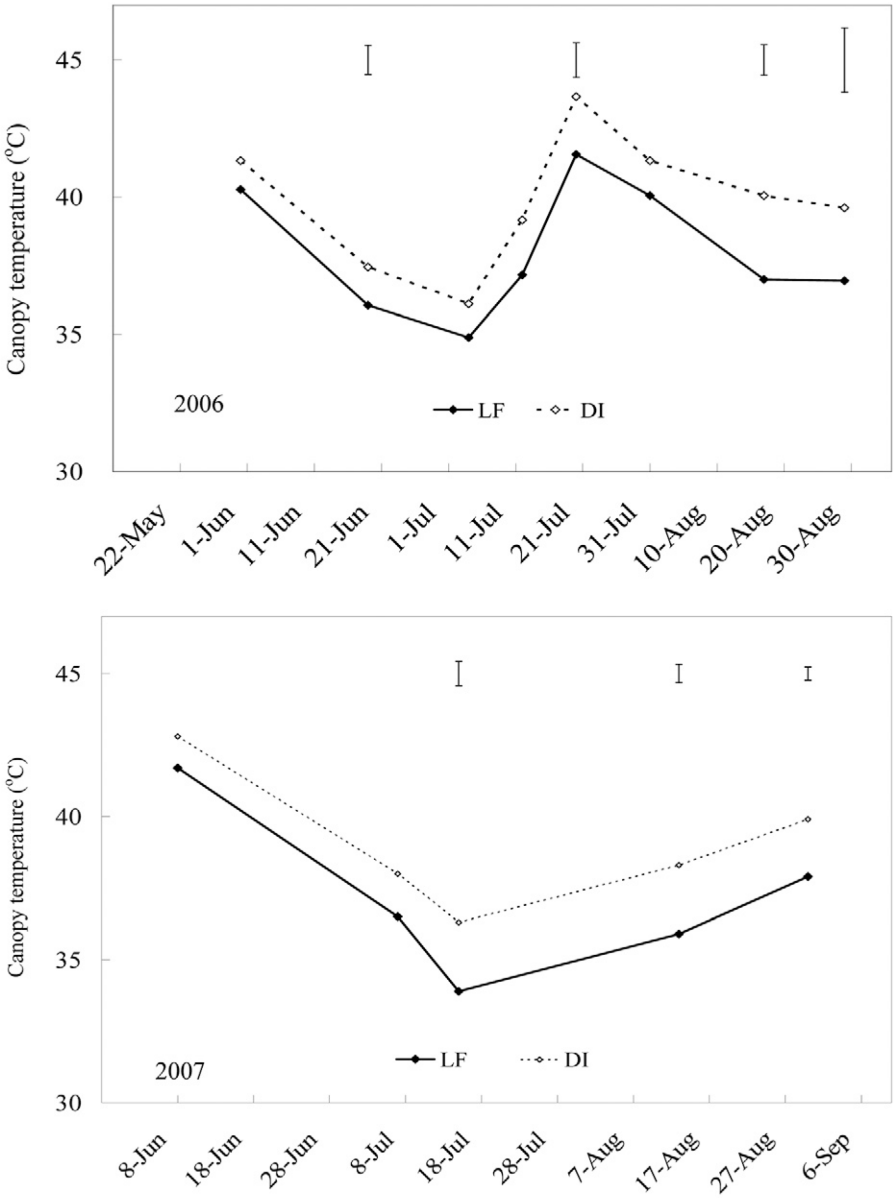

Figure 3. Canopy temperature of 'Providence' creeping bentgrass in response to light and frequent (LF) irrigation (daily in the absence of rain to a soil depth of 4- to 6-cm) and deep and infrequent (DI) irrigation (at leaf wilt to wet soil to a soil depth of ≥24 cm) in 2006 and 2007. Bars indicate significantly different means based on Fisher's protected LSD test ($P \leq 0.05$).

and Dernoeden, 2008; Fu and Dernoeden, 2009). Hence, the generally higher color and quality levels in DI plots in 2007 may be the result of a more expansive root system and improved carbohydrate status that develops when moisture stress is imposed on mature turf.

Chlorophyll content in living plants is an important factor in determining photosynthetic capacity as well as providing for visual green color. Moderate soil drying can increase leaf chlorophyll content. Jiang and Huang (2001) reported that leaf chlorophyll *a*, *b*, and *a* + *b* content increased within 12 d after conditions of drought stress were imposed in tall fescue and within 6 d for Kentucky bluegrass grown in a greenhouse. Using a meter, DaCosta and Huang (2006b) observed higher chlorophyll index readings in bentgrass subjected to 60 and 80% ET than in plots irrigated to 40 or 100% ET. Our results showed that DI irrigation reduced chlorophyll content in 2006 but resulted in an increase in chlorophyll by mid-July in 2007 compared with LF bentgrass. Higher chlorophyll levels in DI bentgrass were associated with improved visual color ratings after mid-July in 2007. The generally improved quality and increases in chlorophyll content in late summer of 2007 suggests that the creeping bentgrass was adapting to wilt stress and/or it was a function of maturity.

When measured in late summer in both years, thatch–mat thickness was about 32% less in DI vs. LF plots. Similarly, total organic matter was about 23% less in late summer of both years in DI vs. LF plots. Thatch decomposition by microorganisms would be expected to be impaired under dry conditions (Beard, 1973). Under conditions of restricted soil moisture and frequent wilt stress, however, there likely would be less stem and shoot growth, which could have resulted in less thatch–mat being produced. Regardless of the mechanism, thatch–mat accumulation was reduced when creeping bentgrass was routinely subjected to wilt stress in summer before being irrigated.

In practice, most golf course managers would not usually subject their putting greens to levels of wilt stress that would reduce quality to below acceptable levels. Obviously, a balance is necessary between maintaining soils as dry as possible while avoiding LF irrigation. The restrictive irrigation employed in DI plots in this study probably should be avoided in the first summer following creeping bentgrass establishment in sand-based rootzones. By restricting irrigation, however, it appears that more mature plants adapt overtime to the stress by increasing chlorophyll levels and by eventually exhibiting improvements in color and quality. Substantial savings in water usage also are achieved by DI irrigation. Furthermore, restricting irrigation will limit thatch–mat accumulation, which is very important for numerous reasons as outlined by McCarty (2001).

Acknowledgments

We were grateful for the financial support provided by the United States Golf Association. We thank the Mid-Atlantic Association

Table 2. Leaf and sheath chlorophyll *a*, *b*, and *a* + *b* content in 'Providence' creeping bentgrass in response to light and frequent vs. deep and infrequent irrigation in 2006 and 2007.

Irrigation†	2006				
	19 May	15 June	13 July	8 Aug.	7 Sept.
	Chlorophyll *a* (μg g^{-1} fresh wt.)				
LF	74.5 a‡	78.1 a	92.2 a	92.2 a	100.1 a
DI	74.7 a	73.9 b	90.1 b	93.4 a	92.7 b
	Chlorophyll *b* (μg g^{-1} fresh wt.)				
LF	17.5 a	17.9 a	22.7 a	21.9 a	24.5 a
DI	17.7 a	17.4 a	22.6 a	22.4 a	22.6 b
	Total chlorophyll *a* + *b* (μg g^{-1} fresh wt.)				
LF	91.9 a	95.9 a	114.8 a	114.1 a	124.7 a
DI	92.3 a	91.3 b	112.7 b	115.8 a	115.3 b
	2007				
	1 June	28 June	17 July	15 Aug.	6 Sept.
	Chlorophyll *a* (μg g^{-1} fresh wt.)				
LF	51.9 a	63.7 a	55.6 b	50.8 b	56.8 b
DI	50.4 a	62.3 a	59.1 a	52.9 a	59.2 a
	Chlorophyll *b* (μg g^{-1} fresh wt.)				
LF	12.1 a	15.3 a	12.7 b	11.7 b	12.8 a
DI	11.9 a	15.0 a	13.7 a	12.6 a	13.2 a
	Total chlorophyll *a* + *b* (μg g^{-1} fresh wt.)				
LF	64.0 a	79.0 a	68.4 b	62.5 b	69.6 b
DI	62.3 a	77.3 a	72.8 a	65.5 a	72.3 a

†Light and frequent (LF) irrigation was applied daily in the absence of rain to wet soil to a 4- to 6-cm depth. Deep and infrequent (DI) irrigation was applied at visual foliar wilt to wet soil to a depth of ≥24 cm.

‡Means in a column within each chlorophyll parameter followed by the same letter are not significantly different based on Fisher's protected LSD test ($P \leq 0.05$).

Table 3. Thatch–mat depth in 'Providence' creeping bentgrass in response to light and frequent vs. deep and infrequent irrigation in 2006 and 2007.

Irrigation†	2006		
	31 May	22 July	19 Aug.
	mm		
LF	1.5 a‡	3.3 a	4.4 a
DI	1.5 a	1.7 b	3.0 b
	2007		
	22 May	18 July	5 Sept.
	mm		
LF	7.9 a	9.5 a	10.0 a
DI	6.2 b	6.4 b	6.8 b

†Light and frequent (LF) irrigation was applied daily in the absence of rain to wet soil to a 4- to 6-cm depth. Deep and infrequent (DI) irrigation was applied at visual foliar wilt to wet soil to a depth of ≥24 cm.

‡Means in a column within a year followed by the same letter are not significantly different based on Fisher's protected LSD test ($P \leq 0.05$).

Table 4. Total organic matter (loss on ignition per unit of soil) in the thatch–mat layer of 'Providence' creeping bentgrass in response to light and frequent vs. deep and infrequent irrigation in 2006 and 2007.

Irrigation†	2006	2007		
	28 Sept.	22 May	18 July	5 Sept.
	Total organic matter (mg g^{-1} soil)			
LF	233 a‡	285 a	242 a	247 a
DI	249 a	223 b	222 b	200 b

†Light and frequent (LF) irrigation was applied daily in the absence of rain to wet soil to a 4- to 6-cm depth. Deep and infrequent (DI) irrigation was applied at visual foliar wilt to wet soil to a depth of ≥24 cm.

‡Means in a column followed by the same letter are not significantly different based on Fisher's protected LSD test ($P \leq 0.05$).

of Golf Course Superintendents and Eastern Shore Association of Golf Course Superintendents for their interest in and financial contributions to this study. This publication is a contribution of the Maryland Agricultural Experiment Station.

References

Beard, J.B. 1973. Turfgrass: Science and culture. Prentice Hall, Englewood Cliffs, NJ.

DaCosta, M., and B. Huang. 2006a. Changes in carbon partitioning and accumulation patterns during drought and recovery for colonial bentgrass, creeping bentgrass and velvet bentgrass. J. Am. Soc. Hortic. Sci. 131:484–490.

DaCosta, M., and B. Huang. 2006b. Minimum water requirements for creeping, colonial, and velvet bentgrasses under fairway conditions. Crop Sci. 46:81–89.

Dernoeden, P.H. 2002. Creeping bentgrass management: Summer stresses, weeds, and selected maladies. John Wiley & Sons, Hoboken, NJ.

Dernoeden, P.H., and J. Fu. 2008. Fungicides can mitigate injury and improve creeping bentgrass quality. Golf Course Manage. 76:116–120.

Fry, J., and J.D. Butler. 1989. Evapotranspiration rate of turf weeds and ground covers. HortScience 24:73–75.

Fry, J., and B. Huang. 2004. Applied turfgrass science and physiology. John Wiley & Sons, Hoboken, NJ.

Fu, J., and P.H. Dernoeden. 2008. Carbohydrate metabolism in creeping bentgrass as influenced by two summer irrigation practices. J. Am. Soc. Hortic. Sci. 133:678–683.

Fu, J., and P.H. Dernoeden. 2009. Creeping bentgrass putting green turf responses to two summer irrigation practices: Rooting and soil temperature. Crop Sci. 49:1063–1070.

Fu, J., J. Fry, and B. Huang. 2004. Minimum water requirements of four turfgrasses in the transition zone. HortScience 39:1740–1744.

Fu, J., and B. Huang. 2001. Involvement of antioxidants and lipid peroxidation in the adaptation of two cool-season grasses to localized drought. Environ. Exp. Bot. 45:105–114.

Gibeault, V.A., J.L. Meyer, V.B. Youngner, and S.T. Cockerham. 1985. Irrigation of turfgrass below replacement of evapotranspiration as a means of water conservation: Performance of commonly used turfgrasses. p. 347–356. *In* F. Lennaire (ed.) Proc. 5th Intl. Turfgrass Res. Conf., Avignon, France. 1–5 July 1985. INRA Publ., Versailles, France.

Hodges, F.C. 1992. Interaction of cyanobacteria and sulfate-reducing bacteria on subsurface black-layer formation in high-sand content golf greens. Soil Biol. Biochem. 24:15–20.

Huang, B., X. Liu, and J. Fry. 1998. Effect of high temperature and poor soil aeration on root growth and viability of creeping bentgrass. Crop Sci. 38:1618–1622.

Jiang, Y., and B. Huang. 2001. Drought and heat stress injury to two cool-season turfgrasses in relation to antioxidant metabolism and lipid peroxidation. Crop Sci. 41:436–442.

Jordan, J., R. White, D. Vietor, T. Hale, J. Thomas, and M. Engelke. 2003. Effect of irrigation frequency on turf quality, shoot density, and root length density of five bentgrass cultivars. Crop Sci. 43:282–287.

McCarty, L.B. 2001. Best golf course management practices. Prentice Hall, Upper Saddle River, NJ.

McCarty, L.B., M.F. Gregg, and J.E. Toler. 2007. Thatch and mat management in an established creeping bentgrass golf green. Agron. J. 99:1530–1537.

Murphy, J.A., P.E. Rieke, and A.E. Erickson. 1993. Core cultivation of a putting green with hollow and solid tines. Agron. J. 85:1–9.

Murray, J.J., and F.V. Juska. 1977. Effect of management practices on thatch accumulation, turf quality, and leaf spot damage in common Kentucky bluegrass. Agron. J. 69:365–369.

Richie, W.E., R.L. Green, and G.J. Klein. 2002. Tall fescue performance influenced by irrigation scheduling, cultivar, and mowing height. Crop Sci. 42:2011–2017.

Turgeon, A.J. 2008. Turfgrass management. 8th ed. Pearson Prentice Hall, Upper Saddle River, NJ.