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RESEARCH

Creeping Bentgrass Putting Green Turf Responses to Two Summer Irrigation Practices: Rooting and Soil Temperature

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ABSTRACT

Light and frequent (LF) and deep and infrequent (DI) irrigation are two common practices for golf course managers. Few studies have compared the effects of these two opposing irrigation practices on summer root performance in creeping bentgrass (*Agrostis stolonifera* L.). The objectives of this field study were to quantify summer root development and longevity in response to LF vs. DI irrigation in 'Providence' creeping bentgrass grown on a sand-based rootzone. The LF plots were irrigated daily to moisten the upper 4 to 6 cm of soil, whereas DI plots were irrigated at leaf wilt to wet soil to a depth ≥24 cm. Root measurements were obtained using the minirhizotron imaging technique and included total root count, total root length (TRL), total root surface area (TRSA), and average root diameter. When averaged over the entire 0- to 24-cm rootzone depth, DI-irrigated creeping bentgrass produced a greater number of roots, longer root lengths, and a larger root surface area than LF-irrigated turf. Average root diameters were smaller in DI-irrigated creeping bentgrass in the summer of 2007. Compared with data collected in 2006, the 2-yr-old turf had 55 and 32% fewer roots in LF- and DI-irrigated bentgrass by September 2007, respectively. There were similar reductions in TRL and TRSA between years in both irrigation regimes. Deep and infrequent irrigation stimulated root growth throughout the 0- to 24-cm rootzone in May and June and promoted root longevity in summer.

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Abbreviations: ARD, average root diameter; DI, deep and infrequent irrigation; ET, evapotranspiration; LF, light and frequent irrigation; TRC, total root count; TRL, total root length; TRSA, total root surface area.

Creeping bentgrass (*Agrosis stolonifera* L.) is considered to be the most reliable cool-season turfgrass species grown on golf greens in the mid-Atlantic region of the United States. Root production and growth are critical components contributing to plant adaptation to environmental stresses. Irrigation management has a direct influence on root growth and longevity. Light and frequent (LF) vs. deep and infrequent irrigation (DI) are two common irrigation practices for golf course managers during summer months. Light and frequent irrigation involves applying water before wilt is evident and maintaining soil moisture at or near field capacity (Fry and Huang, 2004). Deep and infrequent irrigation is defined as irrigating at the first signs of leaf wilt to replenish the rootzone with water (Fry and Huang, 2004). Deep and infrequent irrigation generally is recommended for maintaining cool-season grasses in summer (Beard, 1973; Fry and Huang, 2004).

Researchers have reported enhanced rooting when forage and turfgrasses were DI irrigated. Bennett and Doss (1960) and Doss et al. (1960) observed that rooting of cool- and warm-season forage grasses was enhanced by allowing the surface 60 cm of soil to dry to 15 vs. 70% of available water content. Kentucky bluegrass (*Poa pratensis* L.) rooting was enhanced by watering every 20 d compared with watering every 3 d (Madison and Hagan,

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1962). More zoysiagrass (*Zoysia japonica* Steud.) roots were present deep in the soil profile when watered DI vs. LF (Qian and Fry, 1996). Fu et al. (2007) observed a greater root number, longer root length, and greater root surface area at the 7.4- to 18.4-cm soil depth in tall fescue (*Festuca arundinacea* Schreb.) turf irrigated twice weekly at 20% evapotranspiration (ET) compared with turf irrigated at 60 and 100% ET. Jordan et al. (2003) reported that irrigation on a 4-d interval resulted in an increase in root length density in creeping bentgrass grown on a sand-based rootzone compared with irrigating daily or every other day.

Soil temperature is a factor affecting root growth and longevity. In summer, excess water in soil and thatch can accumulate heat from the sun and retain heat for a longer period of time than dry soil. This is due to the higher specific heat of water, which is responsible for a slow change in the temperature of soil water. Davis and Dernoeden (1991) investigated soil temperature changes in response to irrigation. In that study, Kentucky bluegrass was grown on a silt loam and soil temperature was monitored before and after irrigation. Soil temperatures at 2.0 cm below the soil surface rose on average 1.6°C within 120 min of irrigation, and soil temperatures as high as 33.5°C were recorded on sunny days (Davis and Dernoeden, 1991). Research has shown that high soil temperature (≥25°C) results in root growth decline in creeping bentgrass (Huang et al., 1998; Xu et al., 2003). It remains unclear, however, if summer irrigation affects rooting by changing soil temperature in creeping bentgrass grown at putting green height (<5 mm) on a sand-based rootzone.

Most studies that involved quantifying roots have been conducted by destructive sampling using soil coring techniques. Soil coring techniques, however, cannot differentiate between living and dead roots. The minirhizotron imaging technique allows for nondestructive monitoring of root production and growth (Murphy et al., 1994; Liu and Huang, 2002). Its greatest advantage is that it provides information on seasonal changes of the same roots. A major disadvantage of the minirhizotron imaging technique is that examination and analysis of the root images is labor intensive (Murphy et al., 1994).

Most investigations on the effect of irrigation on turfgrass rooting were performed in the western United States. Little information is available on irrigation management effects on summer creeping bentgrass root production, growth, longevity, or mortality under field conditions, especially in the eastern United States. Furthermore, we are not aware of any root studies that have taken into consideration soil temperature as influenced by summer irrigation. The primary objective of this field study was to evaluate rooting of creeping bentgrass grown on a sand-based rootzone at putting green height in response to LF and DI irrigation practices. Soil temperatures were monitored in LF- and DI-irrigated plots to determine if either practice would greatly influence soil temperature and, consequently, summer root decline.

MATERIALS AND METHODS

This study was conducted on a research green built to United States Golf Association recommendations (Green Section Staff, 1993) 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 to expose bare ground. The area was seeded (50 kg seed ha^{-1}) with ‘Providence’ creeping bentgrass in September 2005. The green was fertilized (25 kg N ha^{-1} + 11 kg P ha^{-1} + 20 kg K ha^{-1}) eight times (20, 23, 28, and 30 September, 18 and 20 October, and 1 and 3 November) in 2005 with a 20–9–16 fertilizer. A 19–2–16 fertilizer was applied on 11 November to provide 50 kg N ha^{-1}, 2.5 kg P ha^{-1}, and 40 kg K ha^{-1}. A total of 250 kg N ha^{-1} was applied between 20 Sept. and 11 Nov. 2005. The bentgrass was fertilized biweekly with 4.9 kg N ha^{-1} from urea between 1 May and 7 June and then weekly through 24 August for a total of 78.4 kg N ha^{-1} during the experimental period in 2006. The bentgrass was fertilized (12 kg N ha^{-1}) six times between 20 Sept. and 17 Nov. 2006 with 20–9–16 fertilizer to provide a total of 71 kg N ha^{-1} during the autumn of 2006. In 2007, the bentgrass was fertilized weekly with 4.9 kg N ha^{-1} from urea between 30 April and 27 August to provide a total of 88.2 kg N ha^{-1} during the experimental period.

Iprodione [3-(3,5-dichlorophenyl)-*N*-(1-methylethyl)-2,4-dioxo-1-imidazolidinecarboxamide; 14.7 kg a.i. ha^{-1}] was applied biweekly in 2006 and 2007 to control dollar spot (*Sclerotinia homoeocarpa* F.T. Bennett) and brown patch (*Rhizoctonia solani* Kuhn). Deltamethrin ([(*S*)-cyano-(3-phenoxyphenyl)methyl] (1*R*,3*R*)-3- (2,2-dibromoethenyl)-2,2-dimethyl-cyclopropane-1-carboxylate; 2.2 kg a.i. ha^{-1}) was applied on 26 July and 24 Aug. 2006 and on 18 July 2007 to control sod webworm (*Crambus* spp.). Turf was mowed three times weekly to a height of 6 mm in spring 2006. Mowing height was reduced to 4 mm on 3 July 2006 and maintained at that height throughout the remainder of the study. The green was mowed about five times weekly and clippings were removed in both years. The study site was core cultivated on 29 Oct. 2006 using a Toro Greens Aerator (Toro Co., Minneapolis, MD) equipped with twelve 1.27-cm-diam. hollow tines. Holes were on a 5.0-cm spacing and there were about 400 holes m^{-2}. Holes were filled to the surface with the previously described sand mix used to build the green.

Two irrigation regimes were assessed in both years as follows: (i) DI irrigation, and (ii) LF irrigation. 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. Individual plots also were separated by a 60-cm perimeter border of creeping bentgrass. Each plot was individually irrigated between 0700 and 0800 h with a handheld hose equipped with a Dramm 400 PL Water Breaker showerhead nozzle (Dramm Corp., Manitowoc, WI).

The quantity of water applied was monitored with a digital flow meter attachment having a 5% inaccuracy (Model 01M31LM;

Great Plains Industries, Inc., Wichita, KS). The flow rate to dispense a given amount of water was controlled by a ball valve to ensure an even distribution of water within each plot. 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. Evapotranspiration was estimated using an atmometer (ET Gauge; Spectrum Technologies, Inc., Plainfield, IL) located within 10 m of the center of the study site. In the DI irrigation regime, water was provided at the first visual sign of leaf wilt, such as footprinting or the appearance of a bluish-gray canopy. The frequency of DI irrigation was variable and depended on weather conditions, which could be as often as every 3 d or as infrequently as 7 d. Since soil was dried to about the same level at wilt, 50 L of water were applied to each DI plot. 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 ≥24 cm within 20 min after irrigation ceased. On sunny days, plots were hand-syringed about 3 times daily depending on weather conditions to cool leaves during the experimental period. When syringed, the canopy was moistened, but little or no water wet the thatch–mat layer. To minimize the impact of rain, two tarps (each 3.3 by 11 m) were used to cover all eight plots before the onset of rain between 22 May and 31 August in 2006 and 2007. 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. Each tarp was slightly wider than half of the plot area and was constructed from 0.30-mm (12-mil) black/white reinforced polyethylene sheeting (Model 12 BW; Integra Plastics, Madison, SD). The white side of the tarps faced up and tarps usually were removed within 15 min after weather had cleared.

Soil temperature was measured by installing a temperature sensor in each plot (Model 107; Campbell Scientific, Logan, UT) about 2.0 cm below the thatch–mat layer. This location was chosen because temperatures close to stems where roots emanate were desired. Temperature sensors were connected to a CR-10 datalogger (Campbell Scientific) and programmed to measure soil temperature at 15-min intervals. Loggers were checked weekly and data were downloaded onto a laptop computer. Soil temperature data were averaged over four replicates in DI- and LF-irrigated plots for statistical analysis. Air temperature was obtained from a USDA weather station located 3 km from the experimental site.

Soil moisture was measured at 0- to 6.5-cm and 0- to 15-cm rootzone depths. Measurements were taken in the 0- to 6.5-cm rootzone depth because LF-irrigated plots were maintained in a moistened state at the 4- to 6-cm depth. Measurements in the 0- to 15-cm rootzone depth would give a better indication of soil moisture level in DI-irrigated plots. Soil moisture in the 0- to 6.5-cm rootzone was measured using an HH2 moisture meter (Delta-T Devices Ltd., Cambridge, UK). Soil moisture in the 0- to 15-cm rootzone was determined using Trase time-domain reflectometry (Soil Moisture Equipment Corp., Santa Barbara, CA). Soil moisture usually was measured 1 d before DI plots were irrigated. The two measurements from each plot were averaged for each instrument to determine the soil moisture level at the two rootzone depths.

Roots were monitored by using the minirhizotron imaging technique as described by Liu and Huang (2002) and Murphy et al. (1994). Before treatments were imposed, two cores (5 cm diam. by 60 cm long), 60 cm apart, were removed from each plot at a 30° angle from the soil surface. Two clear butyrate plastic tubes of a size equivalent to the voids were plugged with a black rubber stopper at both ends and manually forced into the holes. The lower end was sealed with clear silicon sealant. Each tube was positioned with the upper end oriented north. The black rubber stopper was recessed slightly below the soil surface so that the tubes did not interfere with mowing. Tubes were installed in April 2006 in the Providence creeping bentgrass and remained in ground over winter between April 2006 and September 2007. Video images of roots visible against the surface of the tubes were recorded sequentially from the soil surface to the bottom of tubes using a high-magnification minirhizotron camera (Bartz Technology Corp., Santa Barbara, CA). Images (1.35 by 1.8 cm) were taken incrementally at 0- to 47-cm diagonal soil length (actual depth 0–23.5 cm) for a total of 35 images tube^{-1}. Root number and length data represent the total number or length of all observed roots in an image. Root images were captured as bitmap (.BMP format) files onto a desktop computer. All visible roots were traced and analyzed using an image analysis program (RooTracker 2.03; Duke Univ., Durham, NC). This program determines root number, length, and diameter within each image. Root surface area was calculated based on the length and diameter of roots. Irrigation treatments were initiated on 22 May and ended in early September in both years. Root data were collected on three dates in 2006 (14 June, 12 July, and 6 September) and 2007 (23 May, 20 July, and 4 September).

The experiment was arranged in a completely randomized block design with four replications for each irrigation regime. Because of an extremely large data set, root measurements were averaged over intervals of 6-cm soil depths as well as the entire 0- to 24-cm rootzone. The actual measurements ranged from 6.0 to 6.05 cm, but hereafter will be referred to as 0 to 6 cm, 6 to 12 cm, etc. These depths represent the vertical rootzone (i.e., diagonal depth × 0.5-cm vertical soil depth zone). The partitioned 6-cm soil depths are hereafter referred to as rootzones. Treatment effects were determined by analysis of variance according to the general linear model procedure of the Statistical Analysis System (SAS Institute, Cary, NC). Significantly different means were separated by Fisher's protected least significant difference test ($P \leq 0.05$). The analysis of variance revealed that significant differences among all root parameter measurements occurred in each year. Therefore, data from each year and parameter measured are shown separately. There were no irrigation × year interactions.

RESULTS

Soil Moisture and Air and Soil Temperature

Average soil moisture over the entire experimental period (i.e., 2006 and 2007) was much lower in DI-irrigated plots. The DI-irrigated plots had an average soil moisture of 10.5% and LF-irrigated plots had an average of 19.4% in the 0- to 6.5-cm rootzone in 2006 and 2007. Similarly, the

DI-irrigated plots (11.2% average in 2006 and 2007) had lower soil moisture levels than LF-irrigated plots (17.5% average in 2006 and 2007) in the 0- to 15-cm rootzone. Hereafter, LF-irrigated and DI-irrigated will be referred to as LF and DI, respectively.

Maximum and minimum air temperatures were monitored in July and August in 2006 and 2007. Mean maximum and minimum air temperatures were 31.6 and 20.0°C in July and 31.6 and 18.2°C in August 2006, respectively. Mean maximum and minimum air temperatures were 31.0 and 17.5°C in July and 31.5 and 20.2°C in August 2007, respectively. When data were averaged over each 24-h period in July and August, soil temperature at the 2.0-cm soil depth was only 0.2°C higher in LF vs. DI plots in both years. Since there were no large differences in average soil temperature data among plots in each year, the maximum and minimum daily soil temperatures were averaged over LF and DI plots (Fig. 1). Across both years the average maximum air (31.4°C), maximum soil LF (31.4°C), and soil DI (31.5°C) temperatures were nearly identical. The largest significant difference in soil temperature between irrigation regimes in July and August of both years occurred between 1800 and 2200 h. Average soil temperatures in July and August ranged from 0.3 to 1.4°C and 0.1 to 0.9°C higher between 1800 and 2200 h in LF compared with DI plots in 2006 and 2007, respectively.

Total Root Count

2006

Total root count (TRC) was defined as the sum of all roots counted within a specified rootzone depth. In 2006, DI bentgrass had a greater TRC in the 0- to 6-cm rootzone on all three measurement dates compared with LF bentgrass (Table 1). The DI irrigation resulted in a greater TRC in the 6- to 12-cm rootzone on 14 June vs. LF irrigation. No differences in TRC, however, were found between irrigation regimes in the 6- to 12-cm rootzone on 12 July or 6 September. Bentgrass subjected to DI irrigation had greater TRC in the 12- to 18-cm rootzone on 14 June and 6 Sept. 2006 than LF bentgrass. Bentgrass in DI plots had greater TRC in the 18- to 24-cm rootzone on two (14 June and 6 September) out of three dates compared with LF bentgrass. When TRC data were summed over the 0- to 24-cm rootzone, greater TRC was observed on all three measurement dates in DI vs. LF bentgrass. On the last measurement in September 2006, 57, 25, 12, and 6% of roots in LF plots were found in the 0- to 6-cm, 6- to 12-cm, 12- to 18-cm, and 18- to 24-cm rootzones, respectively (Fig. 2). For DI bentgrass, 57, 17, 15, and 11% of all roots were found in the 0- to 6-cm, 6- to 12-cm, 12- to 18-cm, and 18- to 24-cm rootzones, respectively. Percentage of TRC within LF and DI treatments in the 0- to 6-cm rootzone was similar but was greater for LF bentgrass in the 6- to 12-cm rootzone. Conversely, the percentage of TRC in the 12- to 18-cm and 18- to 24-cm rootzones was greater in DI than in LF bentgrass.

2007

There were fewer numbers of roots observed in 2007 than in 2006. In 2007, bentgrass subjected to DI irrigation had a greater TRC in the 0- to 6-cm, 12- to 18-cm, and 18- to 24-cm rootzones on all three measurement dates compared with LF bentgrass (Table 1). The DI irrigation resulted in a greater TRC in the 6- to 12-cm rootzone on 20 July but not on 23 May or 4 September. When TRC data were summed over the 0- to 24-cm rootzone, a greater TRC was observed on all three measurement dates in DI vs. LF bentgrass. On 4 September, 60% (LF) and 70% (DI) of the TRC were observed in the 0- to 6-cm rootzone (Fig. 2). In LF plots on the final measurement date in 2007, 23, 13, and 4% of all roots were observed in the 6- to 12-cm, 12- to 18-cm, and 18- to 24-cm rootzones, respectively. In DI plots on the final date, 12, 12, and 7% of all roots were observed in the 6- to 12-cm, 12- to 18-cm, and 18- to 24-cm rootzones, respectively. Percentage of TRC was greater in 0- to 6-cm and 18- to 24-cm rootzones in DI vs. LF bentgrass. In the 6- to 12-cm rootzone, the percentage of TRC was greater in LF bentgrass, but the percentage of TRC was similar between treatments in the 12- to 18-cm rootzone.

Total Root Length

2006

In 2006, total root length (i.e., sum of the length of all roots measured throughout a specified soil zone; TRL) was greater in the 0- to 6-cm rootzone on all three measurement dates in DI vs. LF bentgrass (Table 2). Bentgrass subjected to DI irrigation had longer TRL in the 6- to 12-cm rootzone on 14 June, but no differences were observed on 12 July or 6 September. Greater TRL was observed in DI vs. LF bentgrass in the 12- to 18-cm and 18- to 24-cm rootzones on 14 June and 6 September, but there were no differences on 12 July. When data were summed over the entire 0- to 24-cm rootzone, DI bentgrass had a greater TRL on all three 2006 measurement dates compared with LF bentgrass.

2007

Like TRC, root length declined between 2006 and 2007. Total root length was greater in DI compared with LF bentgrass in the 0- to 6-cm rootzone on all three measurement dates in 2007 (Table 2). The DI irrigation resulted in an increase in TRL in the 6- to 12-cm rootzone on 20 July compared with LF bentgrass. No significant effect of irrigation on TRL was observed in the 6- to 12-cm rootzone on 23 May or 4 September. Total root length was greater in DI than in LF bentgrass in the 12- to 18-cm and 18- to 24-cm rootzones on all three measurement dates. When TRL data were summed over the 0- to 24-cm rootzone, a greater TRL was observed in DI vs. LF bentgrass on all dates.

Total Root Surface Area

2006

Irrigation regime had an effect on total root surface area (i.e., sum of surface area measurements of all roots at a specified soil depth; TRSA) in both years. In 2006, DI bentgrass had greater TRSA in the 0- to 6-cm rootzone on 14 June and a similar TRSA on 12 July and 6 September compared with LF bentgrass (Table 3). Total root surface area was greater in the DI bentgrass in the 6- to 12-cm rootzone on 14 June, but there were no differences on 12 July or 6 September compared with LF bentgrass. The DI-irrigated bentgrass had a greater TRSA in the 12- to 18-cm and 18- to 24-cm rootzones on all three measurement dates compared with LF bentgrass. When TRSA data were summed throughout the entire 0- to 24-cm rootzone, TRSA was greater in DI on all three measurements vs. LF bentgrass.

2007

Total root surface area measurements were much less in 2007 than in 2006. In 2007, DI bentgrass had a greater TRSA in the 0- to 6-cm rootzone on all three measurement dates compared with LF bentgrass (Table 3). Differences between regimes in the 6- to 12-cm rootzone were observed only on 20 July, when DI bentgrass had a larger TRSA. Bentgrass subjected to DI irrigation had a greater TRSA in the 12- to 18-cm and 18- to 24-cm rootzones on all three measurement dates vs. LF bentgrass. When TRSA data were summed over the entire 0- to 24-cm rootzone, DI bentgrass had a greater TRSA on all three measurement dates vs. LF bentgrass.

Average Root Diameter

2006

Average root diameter (i.e., average of all root diameters at a specified soil zone; ARD) was smaller in DI bentgrass in the 0- to 6-cm rootzone on two (14 June and 12 July) out of three 2006 measurement dates compared with LF bentgrass (Table 4). Average root diameter also was smaller in DI bentgrass in the 6- to 12-cm

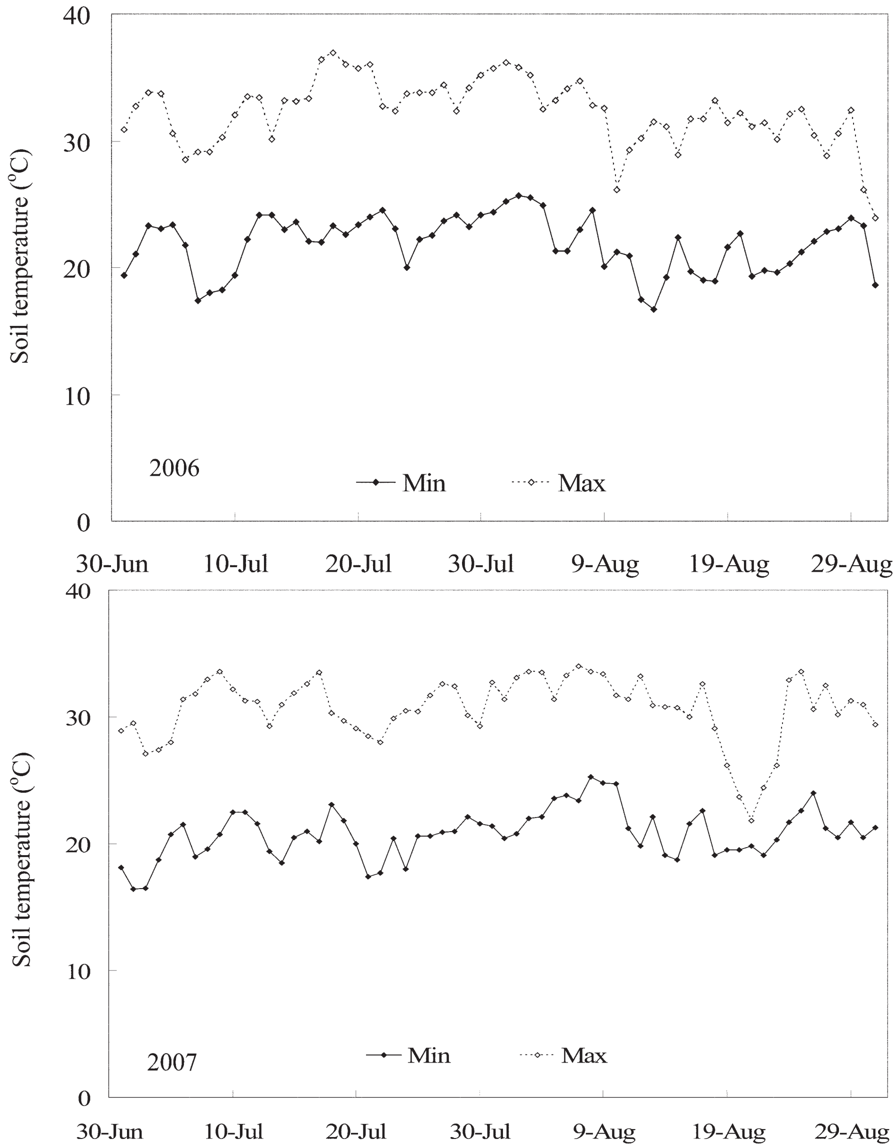

Figure 1. Minimum and maximum soil temperatures at the 2.0-cm depth in ‘Providence’ creeping bentgrass in July and August of 2006 and 2007.

Table 1. Total root count in response to light and frequent vs. deep and infrequent irrigation in ‘Providence’ creeping bentgrass in 2006 and 2007.

Rootzone depth	Irrigation†	2006			2007		
		14 June	12 July	6 Sept.	23 May	20 July	4 Sept.
cm		Root number					
0–6	LF	115.8b‡	122.0b	127.3b	81.1b	56.5b	60.4b
	DI	174.0a	174.2a	166.1a	149.3a	157.8a	138.6a
6–12	LF	37.8b	65.1a	56.3a	39.4a	36.3b	23.3a
	DI	63.2a	67.4a	50.0a	45.1a	62.0a	22.9a
12–18	LF	44.8b	82.4a	26.9b	23.3b	30.4b	13.1b
	DI	83.1a	96.6a	44.6a	37.5a	46.5a	23.5a
18–24	LF	14.8b	39.3a	14.3b	6.8b	6.9b	3.8b
	DI	36.5a	45.0a	30.9a	17.0a	24.5a	13.9a
Total (0–24)	LF	213.2b	308.8b	224.8b	150.6b	130.1b	100.6b
	DI	356.8a	383.2a	291.6a	248.9a	290.8a	198.9a

†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 rootzone depth followed by the same letter are not significantly different based on Fisher’s protected LSD test ($P \leq 0.05$).

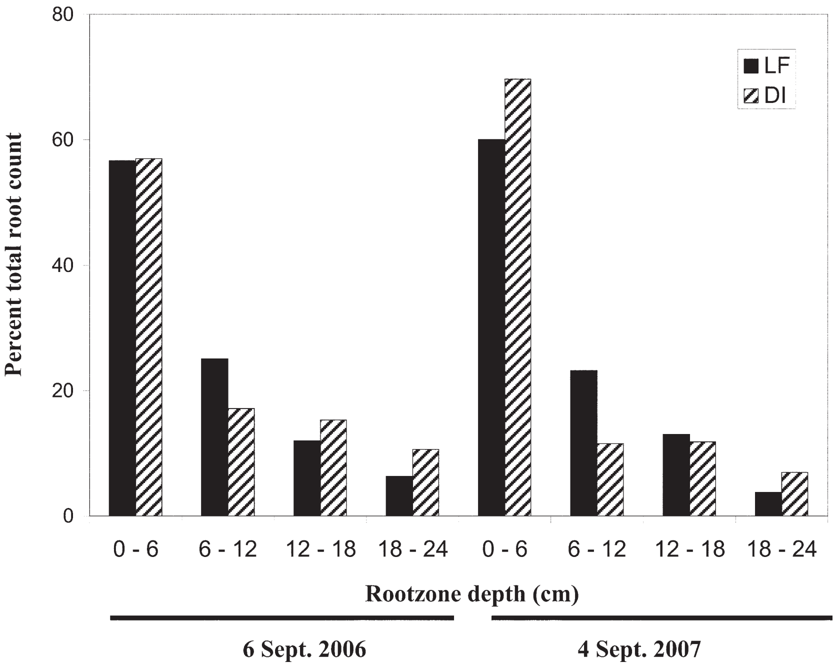

Figure 2. The percentage of the total root count at four rootzone depths in response to light and frequent (LF) and deep and infrequent (DI) irrigation in ‘Providence’ creeping bentgrass on 6 Sept. 2006 and 4 Sept. 2007.

rootzone on 14 June compared with LF bentgrass. Irrigation regimes had no effects on ARD in the 12- to 18-cm soil depth zone on all three measurement dates in 2006. Bentgrass subjected to DI irrigation had a smaller ARD in the 18- to 24-cm rootzone on 14 June and 12 July compared with LF bentgrass. When ARD data were averaged throughout the 0- to 24-cm rootzone, DI had a smaller ARD on only 14 June in 2006 compared with LF bentgrass.

2007

Average root diameter data were similar between years. In 2007, ARD were smaller at 0- to 6-cm rootzone in DI bentgrass on all three measurement dates compared with LF bentgrass. A similar ARD was observed between irrigation regimes in the 6- to 12-cm, 12- to 18-cm, and 18- to 24-cm rootzones on all three measurement dates. When ARD data were averaged over the entire 0- to 24-cm rootzone, DI bentgrass had a smaller ARD than was observed in LF bentgrass on 20 July and 4 Sept. 2007.

Table 2. Total root length in response to light and frequent vs. deep and infrequent irrigation in ‘Providence’ creeping bentgrass in 2006 and 2007.

Rootzone depth	Irrigation†	2006			2007		
		14 June	12 July	6 Sept.	23 May	20 July	4 Sept.
cm		Root length (cm)					
0–6	LF	85.4b‡	87.4b	87.3b	42.6b	28.5b	28.4b
	DI	122.0a	111.4a	100.5a	73.6a	113.3a	56.8a
6–12	LF	28.1b	44.6a	42.9a	25.7a	20.3b	14.4a
	DI	43.4a	47.7a	36.7a	27.5a	32.1a	13.6a
12–18	LF	27.0b	49.8a	19.9b	15.4b	17.1b	6.7b
	DI	53.0a	65.1a	32.3a	24.1a	27.4a	13.8a
18–24	LF	9.8b	23.5a	10.3b	3.7b	3.3b	0.9b
	DI	23.8a	32.9a	24.7a	11.5a	15.7a	8.5a
Total (0–24)	LF	150.3b	205.3b	160.4b	87.7b	62.4b	50.4b
	DI	242.2a	257.1a	194.2a	136.6a	188.5a	92.5a

†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 rootzone depth followed by the same letter are not significantly different based on Fisher’s protected LSD test ($P \leq 0.05$).

DISCUSSION

Soil moisture levels were invariably higher in LF (average = 19.4% in 0- to 6.5-cm and 17.5% in the 0- to 15-cm rootzones) plots vs. DI (average = 10.5% in 0- to 6.5-cm and 11.2% in the 0- to 15-cm rootzones) plots. Data showed that LF plots exhibited only a slightly higher but not statistically different soil temperature in July and August at a 2.0-cm depth compared with DI plots. In both 2006 and 2007, average maximum temperatures at the 2.0-cm soil depth ranged between 30.6 and 33.1°C for July and August. In situations where putting green rootzones become waterlogged during periods of high temperature stress and high humidity, soil temperatures in the upper 5 cm of soil can be 2 to 3°C higher than ambient air temperature in the Mid-Atlantic region (Dernoeden, 2006). In this study site, water infiltration (49.8 cm h^{-1}) and percolation (≥24 cm in 20 min) were rapid and water puddling never occurred. Also, the site was in full sun, open, and usually there was some air movement. The aforementioned air and water drainage factors may have helped preclude heat accumulation and retention in this sand-based rootzone. Therefore, the small increases in soil temperature observed in LF plots probably had little or no impact on root survival or function. Creeping bentgrass root growth ceases at temperatures >25°C and plants are subjected to indirect heat stress at temperatures >30°C (Huang et al., 1998; Fry and Huang, 2004). In this study, the average maximum soil temperature at the 2.0-cm depth was approximately 31°C, which was supraoptimal and would be expected to contribute to summer root decline.

Unlike other irrigation studies involving root measurements, this investigation quantified only living roots throughout a 0- to 24-cm rootzone during the first 2 yr following establishment. With few exceptions, data collected in 2006 and 2007 showed that creeping bentgrass subjected to DI irrigation produced more roots and longer root lengths at most rootzone depths on most measuring dates than LF bentgrass. Exceptions included a few dates when there were no TRC and TRL differences between the 6- to 24-cm rootzone depths and LF and DI treatments in 2006. These findings corroborate other studies showing that soil drying results in improved rooting in turfgrasses (Qian and Fry, 1996; Huang and Fry, 1998; Jordan et al., 2003; Fu et al., 2007). In the only other published investigation similar to the present study, Jordan et al. (2003) reported that root length density (i.e., TRL divided by sample volume) to a 15-cm soil depth increased in response to irrigation every 4 d compared with irrigation every 1 or 2 d in the second year of a 2-yr study. In the first year of the study, differences in rooting were not observed due to frequent rain events. Jordan et al. (2003) suggested that less frequent irrigation could have resulted in greater root uptake of water and increased drainage of excess irrigation water, which could have improved soil aeration and stimulated root growth.

Table 3. Total root surface area in response to light and frequent vs. deep and infrequent irrigation in 'Providence' creeping bentgrass in 2006 and 2007.

Rootzone depth	Irrigation†	2006			2007		
		14 June	12 July	6 Sept.	23 May	20 July	4 Sept.
cm		Root surface area (mm^2)					
0–6	LF	540.4b‡	412.3a	375.4a	189.3b	111.4b	115.2b
	DI	668.5a	417.8a	395.3a	291.3a	369.0a	191.7a
6–12	LF	177.4b	204.1a	198.1a	117.9a	83.2b	63.3a
	DI	256.3a	222.7a	160.2a	122.3a	116.2a	56.1a
12–18	LF	166.6b	222.8b	90.3b	71.8b	72.1b	25.5b
	DI	291.8a	285.2a	147.2a	97.2a	104.3a	52.9a
18–24	LF	71.6b	110.6b	47.8b	14.9b	12.0b	13.3b
	DI	137.3a	142.9a	107.8a	43.2a	56.2a	30.8a
Total (0–24)	LF	956.0b	949.8b	711.6b	393.9b	278.7b	217.3b
	DI	1353.9a	1068.6a	810.5a	554.0a	645.7a	331.5a

†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 rootzone depth followed by the same letter are not significantly different based on Fisher's protected LSD test ($P \leq 0.05$).

In cool-season and warm-season forage grasses grown on native soils, a majority of roots were reported to be in the upper 30 cm of soil, with 50% of warm-season grass roots found in the upper 7.7 cm of soil (Bennett and Doss, 1960; Doss et al., 1960). Using the minirhizotron imaging technique, Liu and Huang (2002) observed that most creeping bentgrass roots were in the upper 10 cm of soil in a sand-based rootzone. In the current study, the distribution of living roots throughout the 0- to 24-cm rootzone was quantified. When the percentage of roots was averaged over both irrigation regimes in September of both years, 58% (range 56–59%) and 63% (range 57–70%) of the TRC were found in the 0- to 6-cm rootzone in 2006 and 2007, respectively. When considering the percentage of TRC within LF and DI plots in the 0- to 6-cm rootzone, a similar TRC percentage was found between regimes in 2006, but a greater percentage was found in DI vs. LF plots in 2007. There were no significant TRC differences in the 6- to 12-cm rootzone between irrigation regions, but a greater percentage of the TRC was observed in LF vs. DI plots in both years. Total root counts in the 12- to 18-cm and 18- to 24-cm rootzones generally were greater in DI plots on most rating dates than in LF plots. In September of each year, an average of 12 and 14% of TRC was found in the 12- to 18-cm rootzone in LF and DI bentgrass, respectively. In the 18- to 24-cm rootzone, an average of 5 and 9% TRC was observed in LF vs. DI bentgrass, respectively. When averaged over the entire 0- to 24-cm rootzone, TRC, TRL, and TRSA invariably were higher in DI vs. LF bentgrass. Water uptake from soil is a crucial function of the root system and determines the water status of shoots. Plants developing greater TRC, TRL, and TRSA in response to DI irrigation would likely to be able to survive longer periods of drought stress than those subjected to LF irrigation.

We are unaware of other studies in which TRSA and ARD were quantified in creeping bentgrass grown on a sand-based rootzone. In general, DI bentgrass had a similar or greater TRL and TRSA in 2006 and 2007 compared with LF bentgrass. A smaller ARD in DI vs. LF bentgrass, however, was observed on 14 June 2006, and on 20 July and 4 Sept. 2007. Creeping bentgrass roots subjected to DI irrigation (average ARD = 0.132 mm in

Table 4. Average root diameter in response to light and frequent vs. deep and infrequent irrigation in 'Providence' creeping bentgrass in 2006 and 2007.

Rootzone depth	Irrigation†	2006			2007		
		14 June	12 July	6 Sept.	23 May	20 July	4 Sept.
cm		Root diameter (mm)					
0–6	LF	0.204a‡	0.153a	0.137a	0.140a	0.122a	0.131a
	DI	0.176b	0.134b	0.129a	0.126b	0.104b	0.112b
6–12	LF	0.201a	0.148a	0.147a	0.141a	0.128a	0.138a
	DI	0.182b	0.149a	0.137a	0.141a	0.120a	0.130a
12–18	LF	0.201a	0.148a	0.144a	0.138a	0.132a	0.122a
	DI	0.191a	0.147a	0.148a	0.132a	0.122a	0.123a
18–24	LF	0.232a	0.157a	0.147a	0.125a	0.116a	0.113a
	DI	0.189b	0.144b	0.140a	0.125a	0.115a	0.124a
Total (0–24)	LF	0.205a	0.151a	0.143a	0.138a	0.126a	0.132a
	DI	0.184b	0.143a	0.138a	0.132a	0.115b	0.121b

†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 rootzone depth followed by the same letter are not significantly different based on Fisher's protected LSD test ($P \leq 0.05$).

2006 and 0.123 mm in 2007) exhibited a 16% reduction in root diameter compared with LF irrigation (average ARD = 0.157 mm in 2006 and 0.146 mm in 2007). Similar effects of drought on root diameter in other crops have been reported (Trillana et al., 2001; Iijima and Kato, 2007). Iijima and Kato (2007) observed in a greenhouse study that the root diameter of maize (*Zea mays* L.) was reduced by severe drying stress, but the overall diameter of cotton (*Gossypium hirsutum* L.) roots was not changed. Trillana et al. (2001) conducted a greenhouse experiment to identify drought resistance in rice (*Oryza sativa* L.). They reported that cultivar IRAT13 produced a smaller root diameter grown under drought stress than under well-watered conditions. The reduction of root diameter in response to dry soil conditions in maize was due to a reduction in the number of cortical cell layers and a reduction in the diameter of both the central cylinder and xylem vessels (Iijima and Kato, 2007).

By retaining the tubes in ground over winter, rooting could be monitored and quantified between years. As expected, TRC declined between July and September of each year, regardless of irrigation practice. There were, however, more and longer roots in 2006 than were observed in 2007. For example, between September 2006 and 2007, there was a 55 and 32% reduction in TRC in LF and DI bentgrass, respectively. Similarly, TRL was 69 and 52% less in LF and DI bentgrass between September of each year, respectively. A large reduction in TRSA in LF (30%) and DI (41%) bentgrass also was observed. Greater root growth in 2006 could be attributed to the higher amounts of N (250 kg N ha^{-1}) applied in the autumn of 2005 during establishment vs. the autumn of 2006 (71 kg N ha^{-1}). Furthermore, there was little or no thatch in the autumn months of establishment and seedlings may be more capable of rapidly producing roots than more mature plants. Regardless, there were far fewer roots present in the second year and the reduction in TRC and TRL was greater in LF bentgrass. While TRSA was greater in DI bentgrass, the reduction in TRSA between 2006 and 2007 was greater in DI (41%) than in LF (30%) bentgrass. A greater reduction in TRSA occurred in DI bentgrass because ARD was smaller in July and September 2007. This investigation has shown that creeping bentgrass grown in a sand-based rootzone and irrigated at visual signs of wilt stress produced a larger root system than LF bentgrass. A majority of roots, however, reside in the upper 0 to 6 cm of soil, regardless of how plots were irrigated.

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