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PURPOSE

The purpose of *USGA Turfgrass and Environmental Research Online* is to effectively communicate the results of research projects funded under USGA's Turfgrass and Environmental Research Program to all who can benefit from such knowledge. Since 1983, the USGA has funded more than 350 projects at a cost of $29 million. The private, non-profit research program provides funding opportunities to university faculty interested in working on environmental and turf management problems affecting golf courses. The outstanding playing conditions of today's golf courses are a direct result of ***using science to benefit golf***.

Editor

Jeff Nus, Ph.D.
1032 Rogers Place
Lawrence, KS 66049
jnus@usga.org
(785) 832-2300
(785) 832-9265 (fax)

Research Director

Michael P. Kenna, Ph.D.
P.O. Box 2227
Stillwater, OK 74076
mkenna@usga.org
(405) 743-3900
(405) 743-3910 (fax)

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

Jinmin Fu and Peter H. Dernoeden

SUMMARY

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 light frequent versus deep infrequent irrigation in 'Providence' creeping bentgrass grown on a sand-based rootzone. The light frequent irrigated plots were irrigated daily to moisten the upper 4 to 6 cm (1.6 to 2.4 in.) of soil; whereas, deep infrequent irrigated plots were irrigated at leaf wilt to wet soil to a depth approximately 24 cm (9.5 in.). Root measurements were obtained using the minirhizotron imaging technique and included total root count, total root length, total root surface area, and average root diameter. Key findings include:

- Deep infrequent-irrigated creeping bentgrass produced a greater number of roots, longer root lengths, and a larger root surface area than light frequent-irrigated turf throughout most of the 0 to 24 cm rootzone depth.
- When compared to data collected in the first year of establishment (2006), the two-year-old turf had 55% and 32% fewer roots in light frequent- and deep infrequent-irrigated bentgrass by September 2007, respectively. There were similar reductions in total root length and total root surface area between years in both irrigation regimes.
- Average daily maximum soil temperatures measured at a soil depth of 2.0 cm (0.8 in. or just below crowns where roots emanate) in light frequent- and deep infrequent-irrigated plots were similar to maximum air temperature. Hence, method of irrigation did not contribute to heat stress near the surface area of the sand-based rootzone.
- Deep and infrequent irrigation stimulated root growth throughout the 0 to 24 cm rootzone in May and June and promoted root longevity in summer, but a majority (average 60%) of roots were found in the upper 6.0 cm (2.6 in.), regardless of irrigation method.
- This research verifies the axiom that it is best to irrigate creeping bentgrass deeply and infrequently at wilt.

JINMIN FU; Ph.D., Horticulture Professor, Wuhan Botanical Garden, The Chinese Academy of Science, Wuhan City, Hubei, China; and PETER H. DERNOEDEN, Ph.D., Professor, Department of Plant Science and Landscape Architecture, University of Maryland, College Park, MD.

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 U.S. 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) versus 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 (6). Deep and infrequent irrigation is defined as irrigating at the first signs of leaf wilt to replenish the rootzone with water (6). Deep and infrequent irrigation generally is recommended for maintaining cool-season grasses in summer (1, 6).

Roots were monitored using the minirhizotron imaging technique where two clear butyrate plastic tubes were installed and allowed root images to be taken under each plot. 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.

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To minimize the impact of rain, tarps were used to cover all eight plots prior to the onset of rain between May 22 and August 31 in 2006 and 2007.

Researchers have reported enhanced rooting when forage and turfgrasses were irrigated deep and infrequently. Bennett and Doss (2) and Doss et al. (5) observed that rooting of cool- and warm-season forage grasses was enhanced by allowing the surface 60 cm of soil to dry to 15% versus 70% of available water content. Kentucky bluegrass rooting was enhanced by watering every 20 days compared to watering every 3 days (15). More zoysiagrass roots were present deep in the soil profile when watered deep and infrequently versus light and frequently (17). 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 turf irrigated twice weekly at 20% evapotranspiration (ET) compared to turf irrigated at 60 and 100% ET. Jordan et al. (13) reported that irrigation on a 4-day interval resulted in an increase in root length density in creeping bentgrass grown on a sand-based rootzone compared to 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 (3) investigated soil temperature changes in response to irrigation. 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^{o} C within 120 minutes of irrigation and soil temperatures as high as 33.5^{o} C (92^{o} F) were recorded on sunny days (3). Research has shown that high soil temperature (>25^{o} C; 77^{o} F) results in root growth decline in creeping bentgrass (11, 19). 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 (14, 16). 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 are labor intensive (16).

Most investigations on the effect of irrigation on turfgrass rooting were performed in the western U.S. Little information is available on irrigation management effects on summer creeping bentgrass root production, growth, longevity,

Over 14,000 photographed images were taken during the course of this study to quantify living roots as treatments were being applied.

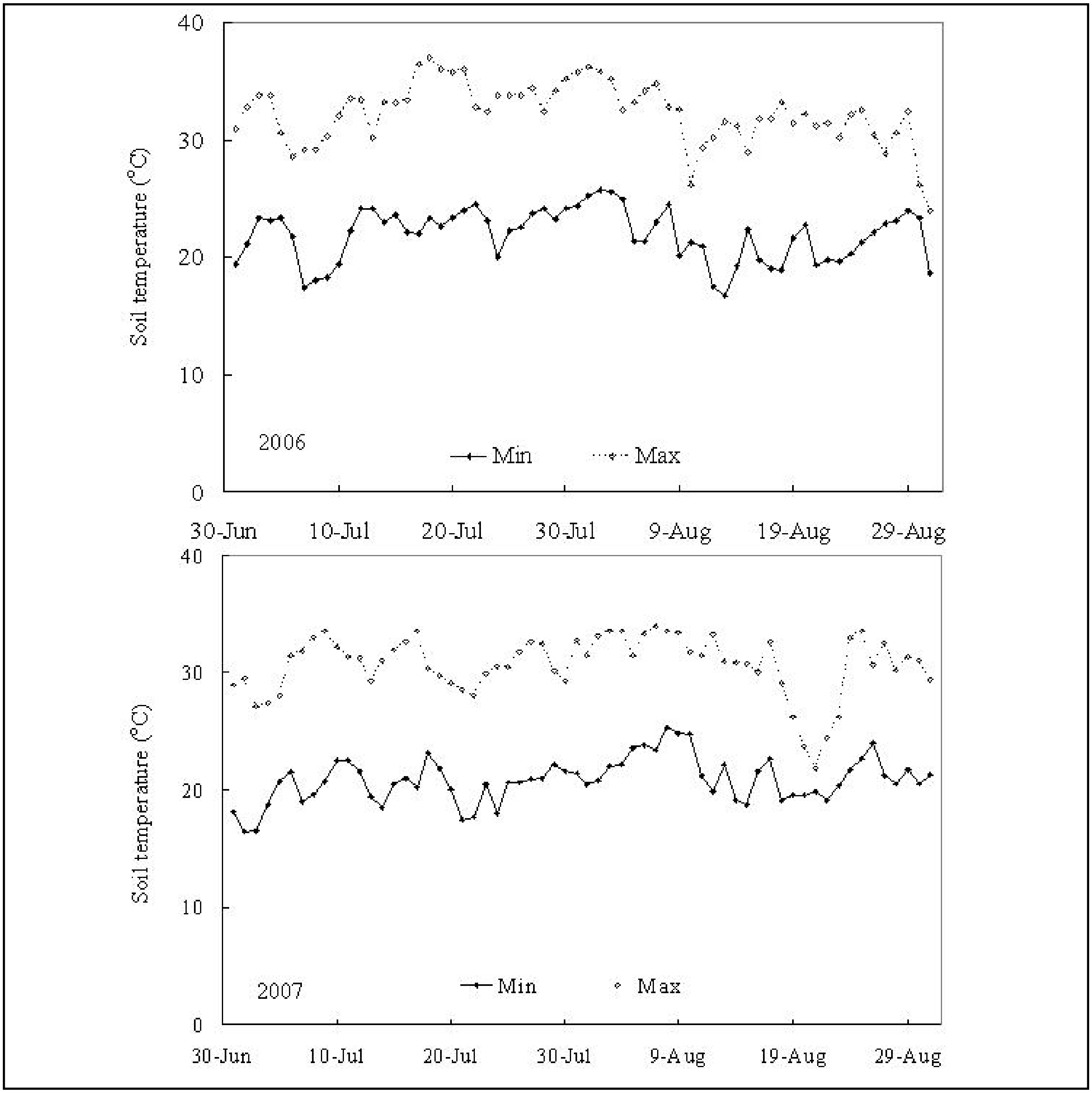

Figure 1. Minimum and maximum soil temperature at the 2.0 cm depth in July and August 2006 and 2007.

or mortality under field conditions, especially in the eastern U.S. Furthermore, we are not aware of any root studies that have taken into consideration soil temperature as influenced by summer irrigation in bentgrass greens.

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 light frequent- and deep infrequent-irrigation practices. Soil temperatures were monitored in light frequent- and deep infrequent-irrigated plots to determine if either practice would greatly influence soil temperature in the region where bentgrass stems are located and consequently affect summer root decline.

MATERIALS AND METHODS

This study was conducted on a research green built using USGA recommendations (9) at

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

§ Means in a column within a rootzone depth followed by the same letter are not significantly different based on Fisher's protected least significant difference test (P=0.05).

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

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 of organic matter g^{-1} soil. In September 2005, the study site was treated with glyphosate (Round-up) and the sod was removed to expose bare ground. The area was seeded (1.0 lb/1000 ft^2; 50 kg seed ha^{-1}) with 'Providence' creeping bentgrass in September 2005. A total of 250 kg N ha^{-1} (5.0 lb N/ 1000 ft^2) was applied between September 20 and November 11, 2005. The bentgrass was fertilized biweekly with 4.9 kg N ha^{-1} (0.1 lb N/1000 ft^2) from urea between May 1 and June 7 and then weekly through August 24 for a total of 78.4 N kg N ha^{-1} (1.6 lb N/1000 ft^2) during the experimental period in 2006. The bentgrass was fertilized with 70 kg N ha^{-1} (1.4 lb N/1000 ft^2) between September 20 and November 17, 2006.

In 2007, the bentgrass was fertilized weekly with 4.9 kg N ha^{-1} (0.1 lb N/ 1000 ft^2) from urea between April 30 and August 27 to provide a total of 88.2 kg N ha^{-1} (1.8 lb N/1000 ft^2) during the experimental period. Mowing height was reduced to 4 mm (0.158 in.) on July 3, 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.

Two irrigation regimes were assessed in both years as follows: i) deep and infrequent (DI) irrigation and ii) light and frequent (LF) irrigation. Each plot measured 1.8 by 2.4 m and was bordered by fiber glass polymer edging set 10 cm deep in soil to minimize lateral movement of water. Individual plots also were separated by a

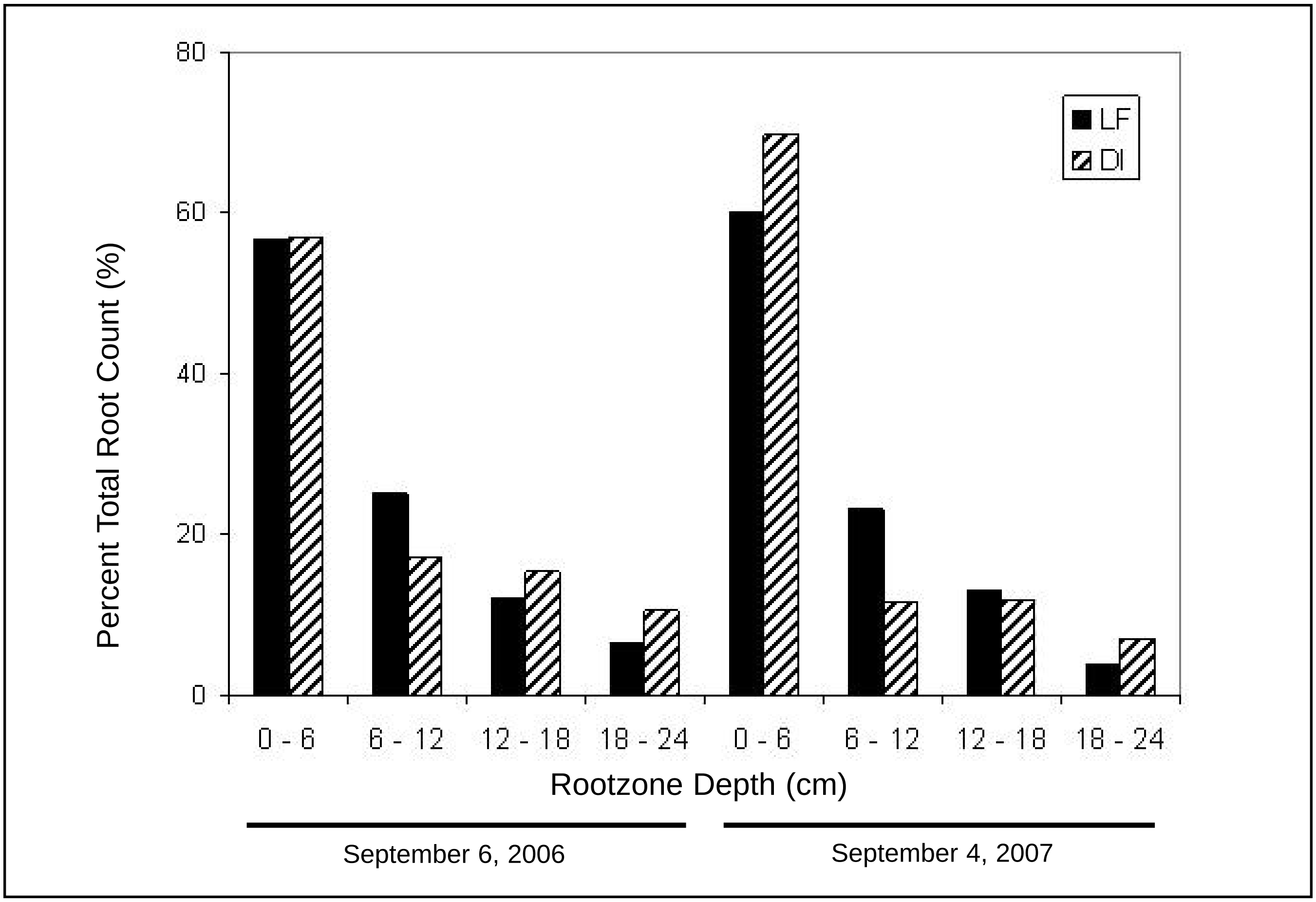

Figure 2. The percent of the total root count at four rootzone depths in response to light and frequent (LF) and deep and infrequent (DI) irrigation on September 6, 2006 and September 4, 2007.

60-cm perimeter border of creeping bentgrass. Each plot was individually irrigated between 7 and 8 AM using a hand-held hose equipped with a shower head nozzle.

The quantity of water applied was monitored with a digital flow meter attachment having a 5% inaccuracy. In the light frequent irrigation regime, water was applied daily to replace moisture lost due to evapotranspiration (ET). This ensured that soil was maintained in a moistened state to a depth of about 4 to 6 cm (1.6 to 2.4 in.) each morning. Evapotransporation was estimated using an atmometer located within 10 m of the center of the study site. In the deep infrequent-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 deep infrequent irrigation was variable and depended on weather conditions, which could be as often as every 3 days or as infrequently as 7 days. Since soil was dried to about the same level at wilt, about 50 liters (11.6 mm) of water was applied to each deep infrequent-irrigated 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 (2.4 to 3.1 in.) within 5 minutes and water penetrated to a depth > 24 cm (approximately 9.5 in.) within 20 minutes after irrigation ceased.

On sunny days, plots were hand-syringed depending on weather conditions. When syringed, the canopy was moistened, but little or no water wet the thatch-mat layer. To minimize the impact of rain, tarps were used to cover all eight plots prior to the onset of rain between May 22 and August 31 in 2006 and 2007. Six rain events in 2006 (total 16.3 mm; 0.64 in.) and five events in 2007 (21.6 mm; 0.85 in.) occurred before plots could be covered. On those days, light frequent-irrigated plots were not irrigated. An additional 59.7 mm (2.4 in.) of rain inadvertently fell on uncovered plots on August 20 and 21, 2007. Tarps usually were removed within 15 minutes after weather had cleared.

Soil temperature was measured by installing a temperature sensor in each plot about 2.0 cm (0.8 in.) 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, Logan, Utah) and programmed to measure soil temperature at 15-minute intervals. Soil temperature data were averaged over four replicates in deep infrequent- and light frequent-irrigated plots for statistical analysis. Air temperature was obtained from a USDA weather station located 3 km (1.8 miles) from the experimental site.

Soil moisture was measured at 0 to 6.5 cm (0 to 2.6 in.) and 0 to 15 cm (0 to 5.9 in.) rootzone depths. Measurements were taken in the 0 to 6.5 cm rootzone depth since light frequent-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 deep infrequent-irrigated plots.

Roots were monitored using the minirhizotron imaging technique as described by Fu and Dernoeden (8). Before treatments were imposed, two cores were removed from each plot at a 30 degree 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. 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' 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. Images (1.35 by 1.8 cm) were taken incrementally at 0 to 47 cm diagonal soil length (actual depth 0 to 23.5 cm) for a total of 35 images per tube. Root number and length data represent the total number or length of all observed roots in an image. All visible roots in each image were traced and analyzed using image-analysis software. 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 May 22 and ended in early September in both years. Root data were collected on three dates in 2006 and 2007.

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. These depths represent the vertical rootzone. The partitioned 6-cm soil depths are hereafter referred to as rootzones. Data were analyzed statistically. For full details on methodology and statistical procedures see Fu and Dernoeden (8).

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 deep infrequent-irrigated plots (data not shown). Deep and infrequent-irrigated plots had an average soil moisture of 10.5% and light frequent-irrigated plots had an average of 19.4% in the 0 to 6.5 cm rootzone in 2006 and 2007. Similarly, the deep infrequent-irrigated plots (11.2% average in 2006 and 2007) had lower soil moisture levels than light frequent-irrigated plots (17.5% average in 2006 and 2007) in the 0 to 15-cm rootzone.

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^{o} C in July and 31.6 and 18.2^{o} C in August 2006, respectively. Mean maximum and minimum air temperatures were 31.0

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

§ Means in a column within a rootzone depth followed by the same letter are not significantly different based on Fisher's protected least significant difference test (P=0.05).

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

and 17.5° C in July and 31.5 and 20.2° C in August 2007, respectively. When data were averaged over each 24-hour period in July and August, soil temperature at the 2.0 cm soil depth was only 0.2° C higher in light frequent- versus deep infrequent-irrigated 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 light frequent- and deep infrequent-irrigated plots (Figure 1). Across both years, the average maximum air temperature (31.4° C), maximum soil temperature of light frequent-irrigated plots (31.4° C), and soil temperature of deep infrequent-irrgated plots (31.5° C) were nearly identical. The largest significant difference in soil temperature between irrigation regimes in July and August of both years occurred between 18:00 and 22:00 hours. Average soil temperatures in July and August ranged from 0.3 to 1.4° C and 0.1 to 0.9° C higher between 18:00 and 22:00 hours in light frequent-irrigated plots compared to plots that received deep infrequent-irrigation in 2006 and 2007, respectively.

Total Root Count

_2006_

In 2006, deep infrequent-irrigated bentgrass had a greater total root count (TRC) in the 0 to 6 cm rootzone on all three measurement dates compared to light frequent-irrigated bentgrass (Table 1). Deep and infrequent irrigation resulted in a greater total root count in the 6 to 12 cm rootzone on June 14 versus light frequent irrigation.

No differences in total root count, however, were found between irrigation regimes in the 6 to 12 cm rootzone on July 12 or September 6. Bentgrass subjected to deep infrequent irrigation had greater total root counts in the 12 to 18 cm rootzone on June 14 and September 6, 2006 compared to light frequent-irrigated bentgrass. Bentgrass in deep infrequent-irrigated plots had greater total root counts in the 18 to 24 cm rootzone on two (June 14 and September 6) out of three dates compared to light frequent-irrigated bentgrass. When total root count data were summed over the 0 to 24 cm rootzone, greater total root counts were observed on all three measurement dates in deep infrequent- versus light frequent-irrigated bentgrass.

On the last measurement in September 2006, 57, 25, 12, and 6% of roots in light frequent-irrigated plots were found in the 0 to 6 cm, 6 to 12 cm, 12 to 18 cm, and 18 to 24 cm rootzones, respectively (Figure 2). For deep infrequent-irrigated 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. Percent of total root counts within light frequent and deep infrequent treatments in the 0 to 6 cm rootzone were similar, but were greater for light frequent bentgrass in the 6 to 12 cm rootzone. Conversely, the percent of total root counts in the 12 to 18 cm and 18 to 24 cm rootzones were greater in deep infrequent-irrigated bentgrass compared to light frequent-irrigated bentgrass.

2007

There were fewer numbers of roots observed in 2007 compared to 2006. In 2007, bentgrass subjected to deep infrequent irrigation had a greater total root count in the 0 to 6 cm, 12 to 18 cm, and 18 to 24 cm rootzones on all three measurement dates compared to light frequent-irrigated bentgrass (Table 1). Deep and infrequent irrigation resulted in a greater total root counts in the 6 to 12 cm rootzone on July 20, but not on May 23 or September 4. When total root count data were summed over the 0 to 24 cm rootzone, a greater total root count was observed on all three measurement dates in deep infrequent- versus light frequent-irrigated bentgrass.

On September 4, 60% (LF) and 70% (DI) of the total root counts were observed in the 0 to 6 cm rootzone (Figure 2). In light frequent-irrigated 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 deep infrequent-irrigated 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. Percent of total root counts were greater in 0 to 6 cm and 18 to 24 cm rootzones in deep infrequent- versus light frequent-irrigated bentgrass. In the 6 to 12 cm rootzone, the percent of total root counts was greater in light frequent-irrigated bentgrass, but the percent of total roots counts were 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 deep infreqent- versus light frequent-irrigated bentgrass (Table 2). Bentgrass subjected to deep infrequent irrigation had longer total root lengths in the 6 to 12 cm rootzone on June 14, but no differences were observed on July 12 or September 6. Greater total root length was observed in deep infrequent- versus light frequent-irrigated bentgrass in the 12 to 18 cm and 18 to 24 cm rootzones on June 14 and September 6, but there were no differences on July 12. When data were summed over the entire 0 to 24 cm rootzone, deep infrequent-irrigated bentgrass had a greater total root length on all three 2006 measurement dates compared to light frequent-irrigated bentgrass.

2007

Root length declined between 2006 and 2007. Total root length was greater in deep infrequent-irrigated than light frequent-irrigated bentgrass in the 0 to 6 cm rootzone on all three measurement dates in 2007 (Table 2). Deep and infrequent irrigation resulted in an increase in total root

Rootzone depth (cm)	Irrigation	2006			2007		
		June 14	July 12	Sept 6	May 23	July 20	Sept 4
		Root surface area (mm²)					
0 to 6	LF †	540.4 b§	412.3 a	375.4 a	189.3 b	111.4 b	115.2 b
	DI ‡	668.5 a	417.8 a	395.3 a	291.3 a	369.0 a	191.7 a
6 to 12	LF	177.4 b	204.1 a	198.1 a	117.9 a	83.2 b	63.3 a
	DI	256.3 a	222.7 a	160.2 a	122.3 a	116.2 a	56.1 a
12 to 18	LF	166.6 b	222.8 b	9 0.3 b	71.8 b	72.1 b	25.5 b
	DI	291.8 a	285.2 a	147.2 a	97.2 a	104.3 a	52.9 a
18 to 24	LF	71.6 b	110.6 b	47.8 b	14.9 b	12.0 b	13.3 b
	DI	137.3 a	142.9 a	107.8 a	43.2 a	56.2 a	30.8 a
Total	LF	956.0 b	949.8 b	711.6 b	393.9 b	278.7 b	217.3 b
(0 to 24)	DI	1353.9 a	1068.6 a	810.5 a	554.0 a	645.7 a	331.5 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 approximately 24 cm.

§ Means in a column within a rootzone depth followed by the same letter are not significantly different based on Fisher's protected least significant difference test (P=0.05).

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

length in the 6 to 12 cm rootzone on July 20 compared to light frequent-irrigated bentgrass. No significant effect of irrigation on total root length was observed in the 6 to 12 cm rootzone on May 23 or September 4. Total root length was greater in deep infrequent-irrigated than light frequent-irrigated bentgrass in the 12 to 18 cm and 18 to 24 cm rootzones on all three measurement dates. When total root length data were summed over the 0 to 24 cm rootzone, a greater total root length was observed in deep infrequent- versus light frequent-irrigated 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, deep infrequent-irrigated bentgrass had greater total root surface area in the 0 to 6 cm rootzone on June 14 and a similar total root surface area on July 12 and September 6 compared to light frequent-irrigated bentgrass (Table 3). Total root surface area was greater in the deep infrequent-irrigated bentgrass in the 6 to 12 cm rootzone on June 14, but there were no differences on July 12 or September 6 compared to light frequent-irrigated bentgrass. Deep and infrequent-irrigated bentgrass had a greater total root surface area in the 12 to 18 cm and 18 to 24 cm rootzones on all three measurement dates compared to light frequent-irrigated bentgrass. When total root surface area data were summed throughout the entire 0 to 24 cm rootzone, total root surface area was greater in deep infrequent-irrigated plots on all three measurements versus light frequent-irrigated bentgrass.

2007

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

Root Diameter

2006

Average root diameter (i.e., average of all root diameters at a specified soil zone, ARD) was smaller in deep infrequent-irrigated bentgrass in the 0 to 6 cm rootzone on two (June 14 and July 12) out of three 2006 measurement dates compared to light frequent-irrigated bentgrass (Table 4). Average root diameter also was smaller in deep infrequent-irrigated bentgrass in the 6 to 12 cm rootzone on June 14 compared to light frequent-irrigated bentgrass. Irrigation regimes had no effects on average root diameter in the 12 to 18 cm soil depth zone on all three measurement dates in 2006.

Bentgrass subjected to deep infrequent irrigation had a smaller average root diameter in the 18 to 24 cm rootzone on June 14 and July 12 compared to light frequent-irrigated bentgrass. When average root diameter data were averaged throughout the 0 to 24 cm rootzone, deep infrequent-irrigated bentgrass had a smaller average root diameter on only June 14 in 2006 compared to light frequent-irrigated bentgrass.

2007

Average root diameter data were similar between years. In 2007, average root diameter were smaller at 0 to 6 cm rootzone in deep infrequent-irrigated bentgrass on all three measurement dates compared to light frequent-irrigated bentgrass. A similar average root diameter 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 average root diameter data were averaged over the entire 0 to 24 cm rootzones, deep infrequent-irrigated bentgrass had a smaller average root diameter than was observed in light frequent-irrigated bentgrass on July 20 and September 4.

DISCUSSION

Soil moisture levels were invariably higher in light frequent-irrigated bentgrass (average = 19.4% in 0 to 6.5 cm and 17.5% in the 0 to 15 cm rootzones) plots versus deep infrequent-irrigated bentgrass (average = 10.5% in 0 to 6.5 cm and 11.2% in the 0 to 15 cm rootzones) plots. Data showed that light frequent-irrigated plots exhibited only a slightly higher, but not statistically different, soil temperature in July and August at a 2.0 cm depth compared to deep infrequent-irrigated bentgrass plots. In both 2006 and 2007, average maximum temperatures at the 2.0 cm soil depth ranged between 30.6 and 33.1^{o} 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^{o} C higher than ambient air temperature in the mid-Atlantic region (4). In this study site, water infiltration (49.8 cm h^{-1}) and percolation (approximately 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 air and water drainage factors may have helped preclude heat accumulation and retention

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

§ Means in a column within a rootzone depth followed by the same letter are not significantly different based on Fisher's protected least significant difference test (P=0.05).

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

in this sand-based rootzone. Therefore, the small increases in soil temperature observed in light frequent-irrigated plots probably had little or no impact on root survival or function.

Creeping bentgrass root growth ceases at temperatures above 25^{o} C, and plants are subjected to indirect heat stress at temperatures above 30^{o} C (6, 11). During July and August in the study site, the average maximum soil temperature at the 2.0 cm depth was approximately 31^{o} 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 two years following establishment. With few exceptions, data collected in 2006 and 2007 showed that creeping bentgrass subjected to deep infrequent irrigation produced more roots and longer root lengths at most rootzone depths on most measuring dates compared to light frequent-irrigated bentgrass. Exceptions included a few dates when there were no total root count and total root length differences between the 6 to 24 cm rootzone depths and light frequent irrigation and deep infrequent irrigation treatments in 2006.

These finding corroborate other studies showing that soil drying results in improved rooting in turfgrasses (7, 11, 13, 17). In the only other published investigation similar to the present study, Jordan et al. (13) reported that root length density (i.e., total root length divided by sample volume) to a 15-cm soil depth increased in response to irrigation every four days compared to irrigation every one or two days in the second year of a two-year study. In the first year of the study, differences in rooting were not observed due to frequent rain events. Jordan et al. (13), 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.

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 (2, 5). Using the minirhizotron imaging technique, Liu and Huang (14) 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% and 63% of the total root counts were found in the 0 to 6 cm rootzone in 2006 and 2007, respectively.

When considering the percent of total root counts within light frequent irrigation and deep infrequent irrigation plots in the 0 to 6 cm rootzone, a similar total root count percentage was found between regimes in 2006, but a greater percentage was found in deep infrequent irrigation versus light frequent irrigation plots in 2007. There were no significant total root count differences in the 6 to 12 cm rootzone between irrigation regimes, but a greater percentage of the total root counts was observed in light frequent irrigation versus deep infrequent irrigation plots in both years. Total root counts in the 12 to 18 cm and 18 to 24 cm rootzones generally were greater in deep infrequent irrigation plots on most rating dates compared to light frequent irrigation plots.

In September of each year, an average of 12 and 14% of total root counts were found in the 12 to 18 cm rootzone in light frequent-irrigation and deep infrequent-irrigation bentgrass, respectively. In the 18 to 24 cm rootzone, an average of 5 and 9% total root counts were observed in light frequent irrigation versus deep infrequent-irrigation bentgrass, respectively. When averaged over the entire 0 to 24 cm rootzone, total root counts, total root length, and total root surface area invariably were higher in deep infrequent-irrigation versus light frequent-irrigation bentgrass.

Water uptake from soil is a crucial function of the root system and determines the water status of shoots. Plants developing greater total root counts, total root length, and total root surface area in response to deep infrequent irrigation irrigation would likely to be able to survive longer periods of drought stress than those subjected to light frequent irrigation.

We are unaware of other studies in which total root surface area and average root diameter were quantified in creeping bentgrass grown on a sand-based rootzone. In general, deep infrequent-irrigation bentgrass had a similar or greater total root length and total root surface area in 2006 and 2007 compared to light frequent-irrigation bentgrass. A smaller average root diameter in deep infrequent- irrigation versus light frequent irrigation bentgrass, however, was observed June 14 2006, and July 20 and September 4, 2007.

Creeping bentgrass roots subjected to deep infrequent irrigation (average root diameter = 0.132 mm in 2006 and 0.123 mm in 2007) exhibited a 16% reduction in root diameter compared to light frequent irrigation (average average root diameter = 0.157 mm in 2006 and 0.146 mm in 2007). Similar effects of drought on root diameter in other crops have been reported (12, 18). 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 (12).

By retaining the tubes in ground over winter, rooting could be monitored and quantified between years. As expected, total root counts 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 total root counts in light frequent-irrigation and deep infrequent-irrigation bentgrass, respectively. Similarly, total root length was 69 and 52% less in light frequent-irrigation and deep infrequent-irrigation bentgrass between September of 2006 and 2007, respectively.

A large reduction in total root surface area in light frequent irrigation (30%) and deep infrequent irrigation (41%) irrigated 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 2005 during establishment versus 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 total root counts and total root length were greater in light frequent-irrigation bentgrass. While total root surface area was greater in deep infrequent-irrigation bentgrass, the reduction in total root surface area between 2006 and 2007 was greater in deep infrequent-irrigation (41%) than light frequent-irrigation (30%) bentgrass. A greater reduction in total root surface area occurred in deep infrequent-irrigation bentgrass because average root diameters were smaller in July and September 2007.

This investigation has shown that although a majority of roots reside in the upper 0 to 6 cm of soil regardless of how plots were irrigated, creeping bentgrass grown in a sand-based rootzone and deeply irrigated at visual signs of wilt stress will produce a greater root system than light frequent-irrigation bentgrass.

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