Tall Fescue Rooting as Affected by Deficit Irrigation

Jinmin Fu

Postdoctoral Research Associate, Department of Plant Science and Landscape Architecture, University of Maryland, College Park, MD 20742

Jack Fry¹

Professor, Department of Horticulture, Forestry and Recreation Resources, Kansas State University, Manhattan, KS 66506

Bingru Huang

Professor, Department of Plant Biology and Pathology, Rutgers University, New Brunswick, NJ 08901

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Abstract. Deficit irrigation is increasingly used to conserve water, but its impact on turfgrass rooting has not been well documented. The objective of this study was to examine the effects of deficit irrigation on 'Falcon II' tall fescue (*Festuca arundinacea* Schreb.) root characteristics in the field using a minirhizotron imaging system. The experiment was conducted on a silt loam soil from the first week of June to mid-Sept. 2001 and 2002 using a mobile rainout shelter under which turf received applications of 20%, 60%, or 100% of actual evapotranspiration (ET) twice weekly. Neither soil water content (0 to 25 cm) nor tall fescue rooting between 4.1- and 50.1-cm depths was affected by irrigation at 60% compared with 100% ET. Despite consistently lower soil water content, tall fescue irrigated at 20% ET exhibited an increase in root parameters beginning in July or August. Tall fescue subjected to 20% ET irrigation had greater total root length and surface area on two of five monitoring dates in 2002 compared with that receiving 100% ET. Evaluation of tall fescue rooting by depth indicated that root proliferation at 20% ET was occurring between 8.7- and 36.3-cm depths. As evaluated under the conditions of this experiment, turfgrass managers using deficit irrigation as a water conservation strategy on tall fescue should not be concerned about a reduction in rooting deep in the soil profile, and irrigation at 20% ET may result in root growth enhancement.

Researchers have found that turfgrasses require water in amounts less than evapotranspiration (ET) to maintain acceptable visual quality (Feldhake et al., 1984; Fry and Butler, 1989; Fu et al., 2004; Qian and Engelke, 1999). Deficit irrigation is defined as supplying water in amounts less than actual ET measured under well-watered conditions and has become an increasingly popular conservation technique in turfgrass maintenance (Feldhake et al., 1984; Fry and Butler, 1989; Qian and Engelke, 1999). Irrigation deficits can be achieved by lengthening periods between irrigations or applying water more frequently at levels less than actual ET, which has been the approach of the aforementioned researchers.

Deficit irrigation in the transition zone of the United States is often practiced on tall fescue, a turfgrass that is popular in the transition zone of the United States as a result of its heat tolerance and ability to avoid

drought with deep rooting. However, under well-watered conditions, tall fescue has a higher ET rate when compared with most cool-season turfgrasses (Fry and Huang, 2004). In an earlier Kansas study, we found that tall fescue watered twice weekly maintained acceptable quality between June and September at deficit irrigation levels of 40% or 60% ET, assuming the turf manager could tolerate a period of slight decline in quality (Fu et al., 2004). When deficit irrigation is practiced in most turf situations, soil is wetted to a shallower depth than traditional deep, infrequent irrigation. Periodically wetting the surface few centimeters of soil could influence growth and distribution of roots. Roots deeper in the soil profile, however, could be exposed to drying soil, which may influence their development. Despite the positive water-saving benefits of deficit irrigation, effects of this practice on tall fescue root development have not been well evaluated.

Soil drying, but not deficit irrigation, has been evaluated for its effects on turfgrass rooting. Bennett and Doss (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% versus 70% of available water content. During a dry down after irrigation treatments, soil under zoysia-

grass (*Zoysia japonica* Steud.) watered at the onset of wilt had roots extracting water at depths greater than 50 cm, whereas soil under turf previously watered daily did not exhibit a similar drying pattern (Qian and Fry, 1996).

Measuring root changes in the field often results in error, because measurements are commonly taken by destructively sampling soil cores and determining the total roots present. The root-washing process can result in loss of a significant number of roots. The minirhizotron imaging technique allows root growth and development at a particular depth and location to be monitored in situ without destructive sampling (Huang and Liu, 2003; Upchurch and Ritchie, 1983). Murphy et al. (1994) demonstrated that determination of root length density using field cores and minirhizotron root counts was correlated ($r^2 = 0.86$) in creeping bentgrass (*Agrostis palustris* Huds.) and annual bluegrass (*Poa annua* L.). The minirhizotron technique has also been used to effectively monitor creeping bentgrass root production, growth, and mortality under field conditions (Huang and Liu, 2003; Liu and Huang, 2002).

This is the third in a series of publications investigating turfgrass responses to deficit irrigation in the transition zone, the first reporting minimum deficit irrigation levels required to maintain turf quality (Fu et al., 2004) and the second investigating deficit irrigation effects on shoot growth and physiology (Fu et al., 2006). The objective of this experiment was to monitor rooting of field-grown tall fescue during deficit irrigation using the minirhizotron imaging technique.

Materials and Methods

Growing conditions and treatments. This experiment was conducted at the Rocky Ford Turfgrass Research Center at Manhattan, Kan. (lat. 39.14°N, long. 96.34°W) from 4 June to 14 Sept. 2001 and from 3 June to 13 Sept. 2002. An automated, mobile rainout shelter that covered a 180-m² area was used to prevent rainfall on experimental plots. During dry weather, the shelter rested just to the north of the study area. The shelter was triggered by a minimum of 0.38 mm precipitation and required ≈2 minutes to move south on rails and completely cover the test area. One hour after precipitation stopped, the shelter returned to its resting position. A weather station located ≈500 m from the rainout shelter monitored temperature. Mean maximum air temperatures during each month of the study (2001 and 2002, respectively) were: June, 28 and 31 °C; July, 34 and 35 °C; August, 33 and 33 °C; and September, 29 and 33 °C. Mean minimum air temperatures for each month of the study (2001 and 2002, respectively) were: June, 16 and 18 °C; July, 21 and 20 °C; August, 18 and 19 °C; and September, 14 and 17 °C.

Tall fescue was established by sodding in Spring 2000 on a river-deposited silt loam soil (fine, montmorillonitic, mesic Aquic Arguidolls), pH 6.8. Treatments consisted of irrigation levels of 20%, 60%, and 100%

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¹To whom reprint requests should be addressed; e-mail jfry@oznet.ksu.edu

of ET (also referred to as well-watered turf) applied to 1.18 m (east to west) $\times$ 1.83 m (north to south) plots. Plots were bordered by metal edging (set 15-cm deep) to minimize lateral movement of water during application. There were no indications based on turf appearance during the study period that any subsurface lateral flow of water occurred between plots. Irrigation levels were arranged in a randomized complete block design with three replications. Two root measurement locations in each plot were subsamples.

Water was applied on Monday and Friday each week using a metered, handheld hose with a fan spray nozzle attached. Deficit irrigation amounts were determined by taking the fraction of water use of lysimeter-grown turf. Lysimeters (10.1-cm diameter and 25-cm deep) were constructed of polyvinyl chloride (PVC). Individual cores were sampled from the study area in Apr. 2001 using a 10.1-cm diameter cup cutter to remove a 25-cm deep soil core and accompanying turf. Cores were then placed into PVC containers. Each lysimeter had a nylon screen on the bottom end that was secured with duct tape. After planting, lysimeters were placed in holes that had been dug in the center of each plot scheduled to receive 100% ET. The hole was only slightly larger than the lysimeter assuring no space between the turf in the lysimeter and the surrounding turf. Lysimeters were set such that the soil surface was even with the surrounding soil. Turf in lysimeters was maintained identically to that of the surrounding turf. Lysimeters remained in the field during the 2001 to 2002 winters and were used again during the 2002 study period.

The day before the study began each year, soil in lysimeters was soaked until water drained through the bottom of the container. Twenty-four hours later, two plastic bags were secured on the bottom of each lysimeter with duct tape to prevent leakage, and each lysimeter was weighed to determine its reference weight. Lysimeters were then returned to respective holes in the plot area. To determine ET, lysimeters were removed from the field and weighed with a balance providing accuracy to the nearest gram between 13:00 and 14:00 HR on Monday and Friday of each week. The mass of water lost from each lysimeter was recorded and converted to ET. Water was then added to lysimeters using a graduated cylinder to return each to its reference weight before returning to the field.

Deficit irrigation amounts for field plots were calculated as: deficit irrigation level $\times$ actual ET of well-watered turf in lysimeters $\times$ 267 (a plot area adjustment factor).

Before and after study periods in each year, turf was allowed to receive natural precipitation. When drought stress was imminent, turf was watered with an in-ground irrigation system that had been installed in the study area before establishment. The plot area was watered thoroughly a few days before the beginning of the study in each year to ensure soil was at field capacity. Throughout the growing season, turf was mowed twice weekly at 5 cm using a walk-behind rotary mower, and clippings were collected. Nitrogen was applied at 49 kg-ha⁻¹ on 3 May, 19 Sept., and 8 Nov. 2001 and 3 May, 18 Sept., and 15 Nov. 2002.

Measurements. Soil water content at a 0- to 25-cm depth was measured weekly using a time domain reflectometer (TDR; Soil Moisture Equipment Corp., Santa Barbara, Calif.). Two steel probes, 0.63-cm diameter by 25-cm long, were set vertically into the soil at a random location in each plot in Apr. 2001 and remained in place until removal at the end of the study period in Sept. 2002. Approximately 1 cm of each probe remained exposed at the soil surface to allow attachment to the TDR handle and periodic measurements of soil water content. A 1-cm wide block of wood, with appropriate holes drilled to accommodate probes, was used to protect the probes in the period between measurements.

Root growth and production were monitored from 4 June to 11 Sept. 2001 and from 3 June to 10 Sept. 2002 using a minirhizotron imaging technique (Upchurch and Ritchie, 1983). In May 2001, two cores (5-cm in diameter by 90-cm long) were removed from each plot at a 45° angle from the soil surface. Clear butyrate tubes were plugged with a black rubber stopper at the bottom end, sealed with waterproof silicon sealant, and manually forced into holes. On the upper side of each tube were etched frames (1.3-cm long by 1.8-cm wide) that extended along the length of the tube allowing the camera to return to the exact location when repeated measurements were taken. Each tube was positioned in the ground with the upper end plugged toward the north (to minimize any light infiltration in the tube) with a black rubber stopper $\approx$ 1 cm above the soil surface such that tubes did not interfere with mowing. Within each plot, the top of one tube was positioned 40 cm from the east border and the

top of the other $\approx$ 40 cm from the west border. Each of the tubes was $\approx$ 45 cm from the north border in each plot. Video images of roots visible against the surface of the tubes were recorded using a high-magnification minirhizotron camera (BTX-100; Bartz Technology Co., Santa Barbara, Calif.) and a camcorder (Sony Electronics, Park Ridge, N.J.). Root images were taken every 2 weeks through 43 d of irrigation treatments and then every 4 weeks until the end of the experiment in each year.

Video root images were recorded beginning at the fifth frame (3.7 to 4.6 cm in vertical depth) from the soil surface through to the 55th frame (49.6 to 50.6 cm in vertical depth). Root distribution is reported in tables as the soil depth at the midpoint of each frame.

Root images were captured as bitmap files onto a personal computer. All visible roots were traced manually in each image frame and analyzed using an image analysis program (RooTracker; Duke University, Durham, N.C.) that determines root number, length, and diameter on each image. Root surface area and volume were also calculated based on the length and diameter of roots.

Data analysis. Treatment effects were determined by analysis of variance according to the mixed procedure of Statistical Analysis System (SAS Institute, 2001). Variation was partitioned into deficit irrigation level, soil depth, and date. Differences among treatment means were separated by Fisher's least significant difference mean separation test ($P < 0.05$). Initial number, length, and surface area of roots were considered as covariants to analyze covariance effects according to the general linear models of the Statistical Analysis System. The initial root images were taken on 1 June 2001 and 31 May 2002. Then, initial root numbers, lengths, and surface areas were adjusted as if each treatment had the same initial value.

Results and Discussion

Total water applied to turf receiving 100% ET during the study period in 2001 and 2002 was 562 mm and 598 mm, respectively. Water applied to turf receiving 60% ET in 2001 and 2002, respectively, totaled 337 mm and 359 mm. Turf irrigated at 20% ET received 112 mm in 2001 and 120 mm in 2002.

An irrigation level by date irrigation occurred in both years (Table 1). In 2001,

Table 1. Analysis of variance with mean squares and treatment significance levels.

Source of variation	2001			2002		
	No.	Length (mm)	Surface area (mm)	No.	Length (mm)	Surface area (mm)
Irrigation level	21.21	930.39	1713.28	69.24**	3091.41**	858.87
Date	93.72**	6566.48**	63408.69**	65.14**	14137.86**	72732.10**
Soil depth	159.83**	9751.24**	12640.99**	104.99**	10626.16**	13193.40**
Irrigation level by date	22.91*	1339.45	3121.50	31.92**	1407.41**	3024.71**
Irrigation level by soil depth	17.93*	1385.38	1680.57	12.57*	1966.43**	3293.93**
Date by soil depth	6.65	1111.55	696.16	7.43	411.57	1037.72
Irrigation level by date by soil depth	10.52	1183.35	1117.70	7.03	365.51	618.47

**Significant at $P \leq 0.05$ and 0.01, respectively.

an increase in root number occurred at all irrigation levels from 21 June to 3 July (Table 2). Root number declined between 17 July and 14 Aug. at 60% and 100% ET irrigation levels, but not at 20% ET, which contributed to the irrigation-by-date interaction. Tall fescue receiving 20% ET had more roots on 14 Aug. and 11 Sept. compared with turf receiving 60% and 100% ET.

In 2002, an increase in root number, length, and surface area occurred between 13 Aug. and 10 Sept. at the 20% ET irrigation level, but only a slight increase or decrease between the two measurement dates at 60% and 100% ET irrigation levels (Table 3). Tall fescue subjected to 20% ET had higher root numbers than turf irrigated at 60% ET on 10 Sept.; greater root length than turf receiving either 60% or 100% ET on 2 July, 13 Aug., and 10 Sept.; and greater surface area than turf receiving 100% ET on 2 July and 10 Sept.

Evaluation of the irrigation level by soil depth interaction (Table 1) indicated that tall fescue irrigated at 20% ET had more roots at a 17.9-cm soil depth than that receiving 60% or 100% ET in 2001 (Table 4). Irrigation at 20% ET also resulted in higher root numbers than turf receiving 60% or 100% ET at 8.7-cm, 13.3-cm, 17.9-cm, and 36.3-cm soil depths in 2002. Similarly, root surface

areas were greater at the 20% ET irrigation level compared with turf receiving 60% or 100% ET at 8.7- and 13.3-cm depths. Root surface area was also greater at a 17.9-cm soil depth when tall fescue was irrigated at 20% ET compared with 100% ET but was inexplicably lower at a 22.5-cm depth compared with turf irrigated at 100% ET, which contributed to the significant interaction observed.

One of the concerns regarding deficit irrigation, as defined here, is the potential to restrict deep rooting because the surface is periodically wetted. Soil water content at 0 cm to 25 cm was lower under tall fescue receiving 20% ET than under well-watered turf beginning after 8 d of irrigation in 2001 and after 7 d in 2002 (Fig. 1). Average irrigation amount for the 20% ET irrigation regime was 3 mm to 4.5 mm, which typically wetted the soil to a depth 3 cm or less. Soil drying under the 20% ET regime enhanced tall fescue root development between 8.7 cm and 36.3 cm. The TDR probe measures average water content over its entire 25-cm length; as such, there were periods when the surface few centimeters were likely more wet than the rest of the profile for a short period after irrigation. This soil surface wetting could not be detected by the TDR measurement, however.

Irrigation at 60% ET had no effect on tall fescue rooting or soil water content in either year compared with turf irrigated at 100% ET. Irrigation at this level was, on average, 13 mm and resulted in soil wetting to a depth of ≈ 10 cm. The lack of effect of irrigation at 60% ET irrigation compared with 100% ET irrigation on soil water level likely resulted from lower ET rates in this treatment than in turf receiving 100% ET. In an earlier study, irrigation at 60% ET resulted in an ET rate that was 35% lower than in well-watered turf (Fu et al., 2002). Hence, although less water was applied to these plots, ET was also lower. Also of importance is that rooting did not proliferate at 4.7- or 8.1-mm depths under a 60% ET irrigation regime, depths to which the soil wetting front reached twice weekly.

Visual quality of tall fescue subjected to deficit irrigation in this experiment was discussed in detail in an earlier publication (Fu et al., 2004). Irrigation at 20% reduced

visual quality below a level that was considered acceptable after 60 d in 2001 and ≈ 35 d after treatments were initiated in 2002. Irrigation at 60% ET was sufficient to maintain quality equivalent to turf receiving 100% ET throughout each summer of the experiment. Despite the reduction in visual quality at 20% ET, tall fescue rooting was concomitantly enhanced under this irrigation regime.

Moderate soil drying was reported to enhance tall fescue rooting in an earlier greenhouse study (Huang and Fu, 2001). Drying the surface 0 cm to 20 cm of soil under tall fescue in the greenhouse resulted in greater root mass at 0- to 20-cm and 20- to 40-cm depths compared with turf in which the entire 0- to 40-cm soil profile was consistently maintained near field capacity. The authors also reported greater carbon allocation to roots when the surface 0 cm to 20 cm was allowed to dry, which may have resulted from a reduction in vertical shoot growth rate and photosynthesis. The same tall fescue in this study subjected to 20% ET irrigation had a vertical growth rate $\approx 40\%$ lower, and a net photosynthesis rate 45% lower, than levels measured in well-watered turf (Fu et al., 2006). A similar reallocation of carbohydrates from shoots to roots resulting, in part, from a reduction in shoot growth may have contributed to root growth enhancement of tall fescue irrigated at 20% ET. A drier soil at the 0- to 25-cm depth at 20% ET irrigation in this field study also enhanced root numbers at a 36.3-cm depth, which is congruent with the observation of Huang and Fu (2001) who reported root enhancement deep in the soil (20 to 40 cm) as the surface (0 to 20 cm) dried.

This is the first study to report the effects of deficit irrigation on tall fescue rooting in situ. Of greatest importance to the turfgrass manager is that there are no detrimental effects on rooting of irrigating tall fescue at 20% or 60% ET from June to September, when irrigation requirements are highest and restrictions are most common. Irrigating tall fescue at 60% ET resulted in rooting patterns the same as those observed in well-watered tall fescue. It has been suggested that shallow applications of water will encourage a proliferation of root growth near the soil surface, which did not occur at the 60% ET irrigation level. Despite a drier soil in the surface 25 cm under the 20% ET irrigation regime, an

Table 2. Irrigation level by date interaction for root number in response to deficit irrigation on Falcon II tall fescue in 2001.

Date	Irrigation level (% of ET) ^z		
	20	60	100
	Root no. ^y		
21 June	43 a ^x	42 a	59 a
3 July	57 a	59 a	71 a
17 July	51 a	46 a	44 a
14 Aug.	50 a	34 b	34 b
11 Sept.	51 a	36 b	33 b

^zIrrigation was applied Monday and Friday from 4 June to 14 Sept. 2001.

^yRoot number represents the sum of roots counted in 11 1.3 $\times$ 1.8-cm frames at depths from 4.1 to 50.1 cm. Numbers represent the mean of three replicates.

^xMeans in a row followed by the same letter are not significantly different based on Fisher's least significant difference mean separation test ($P \leq 0.05$).

ET = evapotranspiration.

Table 3. Irrigation level by date interaction for root number, length, and surface area in response to deficit irrigation on Falcon II tall fescue in 2002.

Date	Irrigation level (% of ET) ^z								
	20	60	100	20	60	100	20	60	100
	Root no. ^y			Root length (cm)			Root surface area (cm ²)		
16 June	51 a ^x	50 a	64 a	68.2 a	64.6 a	82.4 a	9.7 a	9.6 a	12.6 a
2 July	64 a	50 a	53 a	56.8 a	48.5 ab	45.6 b	5.5 a	5.2 ab	4.7 b
16 July	54 a	40 a	47 a	45.6 a	38.1 a	40.2 a	4.6 a	4.3 a	4.0 a
13 Aug.	63 a	47 a	59 a	52.3 a	44.0 b	50.3 ab	5.1 a	5.0 a	5.1 a
10 Sept.	82 a	53 b	50 b	60.6 a	47.1 b	43.1 b	5.8 a	4.9 ab	4.7 b

^zIrrigation was applied Monday and Friday from 3 June to 13 Sept. 2002.

^yRoot number, length, and surface area represent the sum of each in eleven 1.3 $\times$ 1.8-cm frames at depths from 4.1 to 50.1 cm. Numbers represent the mean of three replicates.

^xMeans in a row for each parameter and date followed by the same letter are not significantly different based on Fisher's least significant difference mean separation test ($P \leq 0.05$).

ET = evapotranspiration.

Table 4. Irrigation level by soil depth interaction for root number, surface area, and length in response to deficit irrigation on Falcon II tall fescue in Manhattan, Kan., in 2001 and 2002.

Soil depth (cm)	2001			2002								
				Irrigation level (% of ET) ²								
	20	60	100	20 ³	60	100	20	60	100	20	60	100
	Root no. ¹			Root no.			Root surface area (mm ²)			Root length (mm)		
4.1	1.7 a ^x	1.9 a	2.2 a	2.1 a	1.9 a	2.1 a	25.9 a ^x	23.3 a	19.1 a	19.3 a	16.6 a	11.6 a
8.7	5.4 a	4.9 a	4.7 a	5.7 a	3.1 b	2.4 b	62.3 a	39.3 b	38.6 b	52.4 a	31.2 b	24.7 b
13.3	6.1 a	5.3 a	5.7 a	8.1 a	4.8 b	3.9 b	91.4 a	62.2 b	58.3 b	76.9 a	44.3 b	42.0 b
17.9	8.8 a	6.6 b	5.8 b	10.1 a	5.6 b	5.6 b	89.8 a	71.6 ab	62.8 b	80.0 a	62.2 b	55.8 b
22.5	5.8 a	4.9 a	5.0 a	5.8 a	6.1 a	6.1 a	52.9 b	78.6 ab	86.0 a	54.4 a	62.8 a	62.3 a
27.1	4.9 a	3.8 a	4.5 a	4.6 a	5.1 a	5.9 a	38.2 a	61.6 a	57.7 a	44.5 a	47.0 a	52.8 a
31.7	4.1 a	4.3 a	4.3 a	5.4 a	5.0 a	5.7 a	46.8 a	63.5 a	58.0 a	48.0 a	49.5 a	53.7 a
36.3	3.7 a	3.8 a	4.4 a	7.2 a	4.5 b	6.0 ab	68.2 a	47.0 a	55.5 a	63.1 a	43.4 a	53.4 a
40.9	5.2 a	4.1 a	5.2 a	4.3 a	3.9 a	6.1 a	43.7 a	48.7 a	58.9 a	42.2 a	43.9 a	53.2 a
45.5	3.3 a	3.5 a	2.1 a	4.9 a	4.6 a	5.7 a	49.8 a	52.4 a	69.6 a	46.0 a	52.9 a	58.4 a
50.1	2.5 a	2.8 a	3.1 a	4.2 a	3.1 a	5.2 a	43.2 a	32.2 a	57.5 a	40.3 a	30.8 a	55.6 a

¹Irrigation was applied Monday and Friday from 4 June and 14 Sept. 2001 and 3 June to 13 Sept. 2002.

²Root number, surface area, and length represent means from 1.3 × 1.8-cm frames across three replicates and five measurement dates.

³Means in a row followed by the same letter are not significantly different based on a Fisher's least significant difference mean separation test ($P \leq 0.05$). ET = evapotranspiration.

Fig. 1. Change in soil water content at a 0- to 25-cm depth under 'Falcon II' tall fescue receiving 20%, 60%, and 100% of actual evapotranspiration under a rainout shelter at Manhattan, Kan., in 2001 and 2002. Bars represented least significant difference values ($P \leq 0.05$).

increase in tall fescue root number, length, and surface area was observed to a 17.3-cm depth, and root number enhancement occurred to a 36.3-cm depth. As such, although quality declined under the 20% ET irrigation level, as previously reported, rooting was stimulated.

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