Growth and Carbon Metabolism of Tall Fescue and Zoysiagrass as Affected by Deficit Irrigation

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Abstract. Understanding turfgrass physiological responses to deficit irrigation will help explain potential effects of this practice on turf quality and subsequent stresses. The objective of this study was to investigate the influence of deficit irrigation growth and physiology of 'Falcon II' tall fescue (*Festuca arundinacea* Schreb) and 'Meyer' zoysiagrass (*Zoysia japonica* Steud). Turf was subjected to deficit irrigation levels of 20%, 40%, 60%, 80%, and 100% of actual evapotranspiration (ET) from June to Sept. 2001 and 2002 in Manhattan, Kans. In an earlier study, minimum deficit irrigation levels required to maintain acceptable quality (MDIL) were determined. We compared growth and physiological parameters at these MDIL with turf irrigated at 100% ET. Tall fescue had a lower canopy vertical growth rate (30% lower), canopy net photosynthesis (P_n , 14% lower), and whole-plant respiration (R_w , 11% lower) in 1 of 2 years when irrigated at the MDIL compared with 100% ET; tiller number was not reduced at the MDIL. Water use efficiency ($\mu\text{mol CO}_2$ per $\text{mmol H}_2\text{O}$) in tall fescue increased by 15% at the MDIL relative to turf receiving 100% ET in 1 of 2 years. In zoysiagrass, the MDIL had no effect on any of the growth or physiological parameters measured. Reductions in canopy vertical growth rate at the MDIL in tall fescue during deficit irrigation would likely reduce mowing requirements. Across all deficit irrigation levels, P_n was more sensitive to deficit irrigation in both grasses than was R_w , which could potentially contribute to declines in canopy vertical growth rate, tiller number, and turf quality. Zoysiagrass exhibited higher water use efficiency than tall fescue, particularly at irrigation levels 60% or more ET.

Water availability is becoming limited across many areas of the United States. In recent years, deficit irrigation, or application of water at levels less than maximum evapotranspiration (ET) demand, has been practiced as a strategy to minimize water, resulting in overall water savings. An irrigation deficit can be achieved by returning less water than would occur through actual ET. In some cases, this involves extending the time between irrigations and, in other cases, applying water amounts less than actual ET

on a more frequent schedule. Deficit irrigation has been successfully used on some turfgrasses for water conservation without significant loss of turf quality (Brown et al., 2004; DaCosta and Huang, 2005; Feldhake et al., 1984; Fry and Butler, 1989).

Growth and physiological changes of turfgrasses in response to deficit irrigation are not well understood. Growth rate and tiller density may be impacted as may carbon metabolism. Reductions in growth during water deficits are related to a negative whole-plant carbon balance that results from photosynthetic capacity declines during drought. Maintaining a balance between photosynthesis and respiration is particularly important for plants to survive a long-term water deficit, because each may be differentially affected (Pande and Singh, 1981).

Water use efficiency (WUE), expressed as the amount of water lost through ET relative to the amount of carbon fixed, may also be affected by deficit irrigation. Generally, higher water use rates in turfgrasses are associated with increased soil water avail-

ability (Beard, 1973). Turfgrass subjected to deficit irrigation or limiting soil moisture may use less water when compared with well-watered turfgrass (Qian and Engelke, 1999). Overall, the extent of allowable deficit irrigation may vary among species and cultivars with warm-season grasses typically being better able to withstand greater levels of deficit irrigation when compared with cool-season grasses (Carrow, 1995; Qian and Engelke, 1999).

In an earlier publication that presented turf quality responses to deficit irrigation in the same study area described here, we reported that tall fescue quality in Kansas was acceptable between June and September when irrigated at 60% and 80% of actual ET in 2001 and 2002 (Fu et al., 2004). However, if the turfgrass manager could tolerate 1 week of unacceptable quality, then a MDIL of 40% and 60% in 2001 and 2002, respectively, would have sufficed. Zoysiagrass quality was acceptable only when irrigated at 80% ET. Using the lower MDIL assumptions for tall fescue and 80% ET irrigation for zoysiagrass, tall fescue required 28% less water than zoysiagrass in 2001 and the same amount of water as zoysiagrass in 2002.

Our objective was to determine growth and physiological impacts of the previously reported MDIL on tall fescue and zoysiagrass, and also evaluate responses across all deficit irrigation levels.

Materials and Methods

Plant material and growing conditions.

The experiment was conducted using an automated, mobile rainout shelter at the Rocky Ford Turfgrass Research Center at Manhattan, Kans., from 4 June to 14 Sept. 2001 and from 3 June to 13 Sept. 2002. The shelter, 12 m wide and 15 m long, was essentially a small building constructed of wood with an A-frame roof and metal siding. 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 min to move south on rails and completely cover the test area. One h after precipitation stopped, the shelter returned to its resting position. Turf was mowed twice weekly at 5.0 cm using a rotary mower. Nitrogen from urea (46–0–0) was applied at $49 \text{ kg} \cdot \text{ha}^{-1}$ to tall fescue on 3 May, 19 Sept., and 8 Nov. in 2001 and 3 May, 18 Sept., and 15 Nov. in 2002. Zoysiagrass received an equivalent level of nitrogen on 3 May and 29 June 2001 and 3 May and 5 Aug. 2002. 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, 27.8 and 31.1 °C; July, 34.4 and 35 °C; August, 32.8 and 32.8 °C; and September, 28.9 and 32.8 °C. Mean minimum air temperatures for each month of the study (2001 and 2002, respectively) were June, 16.1 and 17.8 °C; July, 21.1 and 20 °C; August, 18.3 and 18.6 °C; and September, 14.4 and 17.2 °C.

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The study was set up as a randomized split-plot design with turfgrass species as the main plots and irrigation levels as the subplots. The main plots measured 5.9×1.8 m and consisted of 'Meyer' zoysiagrass and 'Falcon II' tall fescue. All main plots were established by sodding on a river-deposited silt loam soil (fine, montomorillonitic, mesic Aquic Arquidolls with a pH 6.4 and phosphorus and potassium of 41 and 367 mg·kg⁻¹, respectively) in Spring 2000 into plot areas that were replicated three times. The subplots measured 1.2×1.8 m and consisted of irrigation levels of 20%, 40%, 60%, 80%, and 100% of ET. Each plot was bordered by metal edging (set 15 cm deep) to minimize lateral movement of water on application.

Plots were irrigated twice weekly using a metered, handheld hose with a shower nozzle and the appropriate amount of water was monitored using a flow meter. Deficit irrigation amounts were determined by taking the fraction of water use (ET_{100}) of lysimeter-grown turf receiving 100% actual ET. Evapotranspiration was measured using lysimeters and the water balance method (Qian et al., 1996b). Lysimeters, one in each plot, were constructed of polyvinylchloride pipe (10.1-cm diameter by 25-cm deep) that had a nylon screen on the bottom end attached with duct tape. An intact soil core with accompanying turf was collected from plots using a 10-cm diameter cup cutter and each was placed in a lysimeter. Lysimeters were then set into holes located in the center of each plot. The day before the study began each year, lysimeters were irrigated until water drained through the bottom of each. Twenty-four hours later, each was sealed on the bottom end with two-layer plastic, weighed to determine its reference weight, and then returned to respective holes in the plot area. To determine ET, lysimeters were removed from the field and weighed between 0100 HR and 0200 HR on Monday and Friday of each week. The mass of water lost from each 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 amount for field plots was calculated as: deficit irrigation level $\times$ ET_{100} $\times$ an area adjustment factor. Total water applied to turf receiving 100% ET during the study periods in 2001 and 2002, respectively, was as follows: tall fescue, 562 and 598 mm and zoysiagrass, 390 and 449 mm.

Measurements. Soil water content was measured using a time domain reflectometer (Soil Moisture Equipment Corp., Santa Barbara, Calif.). Two steel probes, 0.63-cm diameter by 25-cm long, were set into at an arbitrary location in each plot in April 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 for 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. Soil water content at the beginning of the experiment in 2001 averaged 35.7% (v/v) across all plots. At the end of the study, soil water content at each irrigation level for tall fescue and zoysiagrass, respectively, were: 20% ET (21.8%, 12.3%); 40% ET (24.0%, 15.9%); 60% ET (28.4%, 20.3%); 80% ET (30.7%, 26.5%); and 100% ET (29.4%, 25.6%). In 2002, beginning soil water content across all treatments was 29.7%. At the end of the study in 2002, soil water contents at each irrigation level for tall fescue and zoysiagrass, respectively, were: 20% ET (15.1%, 8.5%); 40% ET (20.4%, 12.0%), 60% ET (25.1%, 19.3%); 80% ET (27.7%, 22.5%); and 100% ET (27.1%, 27.0%).

Turf quality was visually assessed weekly on a 0 to 9 scale in which 0 = brown or dead turf; ≥ 6.0 = acceptable quality; and 9 = optimum greenness and cover.

Canopy vertical growth rate and tiller density were determined every 4 weeks. Canopy vertical growth rate was the difference in turf canopy height before and after cutting on 3-d intervals. A sheet of paper was rested on the canopy surface to measure canopy height as the distance from the paper to the soil surface at eight locations in each subplot. Tiller density was determined by counting numbers of tillers in a 5.1-cm diameter template at two locations in each subplot.

Canopy net photosynthesis (P_n) and whole-plant respiration (R_w) were measured every 4 weeks beginning on 4 June 2001 and 3 June 2002 using a LI-6400 portable gas exchange system (LI-COR Inc., Lincoln, Neb.). Measurements were made between 0900 and 1500 h. Canopy net photosynthesis was measured by enclosing the turf canopy in a transparent Plexiglas chamber ($15 \times 10 \times 10$ cm) attached to the CO₂ analyzer on a sunny day. The chamber was pressed into the ground ≈ 3 cm to provide an adequate seal for canopy gas exchange measurement. Whole plant respiration was determined in the dark by covering the Plexiglas chamber. Data for P_n and R_w were expressed as CO₂ uptake and evolution per unit turf area.

Water use efficiency ($\mu\text{mol CO}_2$ per mmol H₂O) was calculated as the photosynthetic rate ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ CO₂) over ET rate ($\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ H₂O).

Data analysis and presentation. Treatment effects were determined by analysis of variance according to the mixed model of Statistical Analysis System (SAS Institute, Cary, N.C.). To remove the effect of year and sampling date, data were analyzed separately for each year and variation was partitioned into grass species, deficit irrigation level, and corresponding interactions. Results indicated a significant species $\times$ deficit irrigation level interaction; therefore, results and discussion focus on responses to deficit irrigation within each turfgrass species. Where multiple measurements were made on an individual plot (e.g., for canopy vertical growth rate and tiller density), measurements were averaged

before analysis. Treatment means were separated by a Fisher protected least significant difference test ($P \leq 0.05$). To clarify presentation and discussion, only comparisons between the MDIL and 100% ET are presented in tables; where additional discussion across all deficit irrigation levels is included, those values are presented in the text.

Results and Discussion

At MDIL, growth and physiology of only tall fescue was affected. Zoysiagrass growth and physiology was affected at deficit irrigation levels lower than the MDIL.

Canopy vertical growth rate was reduced at the MDIL in tall fescue in both years (Table 1). Irrigation at levels lower than the MDIL resulted in lower canopy vertical growth rate in both grasses in each year relative to grasses receiving the MDIL (Tables 1 and 2). For example, in 2002, canopy vertical growth rate of tall fescue receiving 20% ET ($1.2 \text{ mm}\cdot\text{d}^{-1}$) was 40% lower than that irrigated at 100% ET ($2.0 \text{ mm}\cdot\text{d}^{-1}$). In zoysiagrass in 2002, turf irrigated at 20% ET had a canopy vertical growth rate three times lower than that receiving 100% ET (1.0 versus $3.0 \text{ mm}\cdot\text{d}^{-1}$, respectively). Maintenance of turf quality with a concomitant reduction in canopy vertical growth rate would be beneficial for the turf manager, because mowing would also likely be reduced.

The reduction in canopy vertical growth rate with increasing irrigation deficits may reflect in the influence of a water deficit on cell expansion. Biran et al. (1981) reported that delaying irrigation until the onset of temporary wilting caused a significant decrease in clipping production in most of the 11 warm and cool-season turfgrasses evaluated. In a greenhouse study with tall fescue conducted by Huang and Fu (2001), withholding irrigation from the upper 20 cm of a 40-cm soil profile reduced canopy vertical growth rate by 79% after 16 d of treatment. A similar reduction in shoot extension rate was observed when Kentucky bluegrass was subjected to drying in the surface 20 cm of soil (DaCosta et al., 2004). Tiller density was not reduced at the MDIL in tall fescue or zoysiagrass in either year (Tables 1 and 2). Lowest tiller numbers were counted in tall fescue and zoysiagrass subjected to deficit irrigation levels of 20% and 40%, with reductions in tall fescue of up to 16% and in zoysiagrass up to 25% (data not shown).

Canopy net photosynthesis was lower at the MDIL relative to turf receiving 100% ET in tall fescue in 2002 (Table 1). The P_n in tall fescue was consistently lower ($P \leq 0.05$) at $\geq 60\%$ ET deficit irrigation levels than in zoysiagrass in both years. For example, in 2002, P_n in tall fescue at 40% and 80% ET were 8.2 and $10.5 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ CO₂, respectively; zoysiagrass P_n at 40% ET was $10.4 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ CO₂ and at 80% ET, $17.2 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ CO₂. These results indicate that zoysiagrass is able to fix more carbon under moderate water deficits when compared with tall fescue.

Table 1. Growth and physiological responses of tall fescue at the minimum level of deficit irrigation needed to maintain quality (MDIL) and at 100% evapotranspiration (ET) in 2001 and 2002 at Manhattan, Kans.

	Value at MDIL	Value at 100% ET	Significance ($P \leq 0.05$) ^a
2001			
MDIL = 40% ET ^z			
Parameter measured ^y			
Canopy vertical growth rate (mm·d ⁻¹)	1.8	2.1	No
Tillers (no./m ²)	16,890	17,537	No
P _n (μmol·m ⁻² ·s ⁻¹ CO ₂)	6.2	6.8	No
R _w (μmol·m ⁻² ·s ⁻¹ CO ₂)	10.5	11.8	Yes
WUE (μmol CO ₂ per mmol ⁻¹ H ₂ O)	1.32	1.15	Yes
2002			
MDIL = 60% ET			
Parameter measured			
Canopy vertical growth rate (mm·d ⁻¹)	1.4	2.0	Yes
Tillers (no./m ²)	16,294	16,992	No
P _n (μmol·m ⁻² ·s ⁻¹ CO ₂)	9.6	11.2	Yes
R _w (μmol·m ⁻² ·s ⁻¹ CO ₂)	8.7	9.0	No
Water use efficiency (μmol CO ₂ per mmol H ₂ O)	1.74	1.84	No

^aMinimum deficit irrigation level required to maintain acceptable turf quality taken from Fu et al. (2004). Irrigation was applied Mondays and Fridays from 4 June to 14 Sept. 2001 and 3 June to 13 Sept. 2002. Total irrigation applied to the 100% ET treatment was 562 mm in 2001 and 598 mm in 2002. The MDIL was 225 mm in 2001 and 359 mm in 2002.

^yCanopy vertical growth rate, tillers, canopy net photosynthesis (P_n), whole plant respiration (R_w), and water use efficiency are averages of five measurement dates and four replicates in each year.

^zDifference between respective parameters measured at the minimum irrigation level and 100% ET determined using Fisher mean separation test ($P \leq 0.05$).

The decline in P_n at the MDIL in tall fescue and likely occurred because g_s is usually reduced in the early stages of a water deficit, which would consequently reduce P_n. DaCosta and Huang (2005) reported that P_n of colonial bentgrass (*Agrostis tenuis* Sibth.) and velvet bentgrass (*Agrostis canina* L.) irrigated at 60% and 40% ET was lower than turf irrigated at 100% ET. Huang and Fu (2000) also observed a decline in tall fescue P_n beginning 9 d after stopping irrigation in a 40-cm deep root zone in the greenhouse. Decline in P_n in turfgrass during deficit irrigation may be the result of a loss of leaf area attributable to lower canopy vertical

growth rates and, in some cases, a reduction in turf density.

Whole plant respiration was lower at the MDIL compared with irrigation at 100% ET in tall fescue in 2001 (Table 1). Canopy photosynthesis of tall fescue and zoysiagrass was inhibited more than respiration across all deficit irrigation levels. For example, in 2002, tall fescue irrigation at 20% ET caused a 45% reduction in P_n (6.2 μmol·m⁻²·s⁻¹CO₂) compared with turf irrigated at 100% ET (11.2 μmol·m⁻²·s⁻¹ CO₂). At the same time, however, tall fescue receiving 20% ET exhibited only a 21% decline in R_w (7.1 μmol·m⁻²·s⁻¹ CO₂) compared with turf

irrigated at 100% ET (9.0 μmol·m⁻²·s⁻¹ CO₂). In zoysiagrass, the decline was even more dramatic, with turf irrigated at 20% ET exhibiting a 70% decline in P_n (5.6 μmol·m⁻²·s⁻¹ CO₂) compared with turf irrigated at 100% ET (18.5 μmol·m⁻²·s⁻¹ CO₂). Respiration in zoysiagrass receiving 20% ET was 38% lower than in turf receiving 100% ET. Others have also reported that respiration was less affected by drought stress than photosynthesis (Saradadevik, 1994). The imbalance between P_n and R_w could lead to limited carbohydrate availability (Huang and Fu, 2000; Huang and Gao, 2000; Schmidt and Blaser, 1967) and exacerbate the declines in canopy vertical growth rate and tiller density. An extended period with such an imbalance between photosynthesis and respiration could also potentially influence resistance of both zoysiagrass and tall fescue to abiotic and biotic stresses, because carbohydrate reserves may be reduced (Fry and Huang, 2004).

Water use efficiency was unaffected at the MDIL in tall fescue or zoysiagrass (Tables 1 and 2). At 100% ET irrigation, zoysiagrass had WUE values twice those of tall fescue, which was likely the result of the more efficient C₄ photosynthetic pathway used by zoysiagrass compared with the C₃ pathway in tall fescue (Fry and Huang, 2004). High WUE occurs when carbon fixation is maintained and the turfgrass uses relatively low amounts of water. Water use efficiency in zoysiagrass declined more rapidly than in tall fescue because irrigation was reduced. In 2002, for example, the range of WUE in tall fescue was 1.11 μmol CO₂ per mmol H₂O (20% ET irrigation) to 1.15 μmol CO₂ per mmol H₂O (100% ET irrigation), whereas the range in zoysiagrass was 1.32 μmol CO₂ per mmol H₂O (20% ET irrigation) to 3.82 μmol CO₂ per mmol H₂O (100% ET irrigation). This suggests that WUE in tall fescue is less sensitive to deficit irrigation than in zoysiagrass. A decrease in WUE with water availability has been observed in Kentucky bluegrass (Ebdon and Kopp, 2004). These results generally contradict crop (yield) studies in which WUE increases with water deficit (Starman and Lombardini, 2006). In yield studies, however, WUE is generally based on accumulative yield produced relative to the amount of water consumed.

As MDIL was defined by Fu et al. (2004), tall fescue required a total of 88 mm less water than zoysiagrass between June and September in 2001 and 2002. Nevertheless, zoysiagrass exhibited higher WUE than tall fescue, particularly at irrigation levels ≥60% ET. This reflects the drought resistance capability of tall fescue that is afforded by rooting more deeply than zoysiagrass (Qian et al., 1996a), despite having a higher water use rate than zoysiagrass (Qian et al., 1996b).

Here, relative to turf receiving 100% ET, tall fescue exhibited reduced canopy vertical growth rate, P_n, and R_w in 1 of 2 years at the MDIL. Tiller number was unaffected in tall fescue at the MDIL, whereas WUE increased by 15% in 1 of 2 years. Zoysiagrass growth and carbon metabolism were unaffected at

Table 2. Growth and physiological responses of Meyer zoysiagrass at the minimum level of deficit irrigation needed to maintain quality (MDIL) and at 100% evapotranspiration (ET) in 2001 and 2002 at Manhattan, Kans.

	Value at MDIL	Value at 100% ET	Significance ($P \leq 0.05$) ^a
2001			
MDIL = 80% ^z			
Parameter measured			
Canopy vertical growth rate (mm·d ⁻¹) ^y	2.9	2.8	No
Tillers (no./m ²)	29,652	29,832	No
P _n (μmol·m ⁻² ·s ⁻¹ CO ₂)	18.2	19.1	No
R _w (μmol·m ⁻² ·s ⁻¹ CO ₂)	9.7	9.9	No
Water use efficiency (μmol CO ₂ per mmol H ₂ O)	2.54	2.75	No
2002			
MDIL = 80%			
Parameter measured			
Canopy vertical growth rate (mm·d ⁻¹)	3.1	3.0	No
Tillers (no./m ²)	33,277	32,018	No
P _n (μmol·m ⁻² ·s ⁻¹ CO ₂)	17.2	18.5	No
R _w (μmol·m ⁻² ·s ⁻¹ CO ₂)	8.4	8.7	No
Water use efficiency (μmol CO ₂ per mmol H ₂ O)	3.79	3.82	No

^aMinimum deficit irrigation level required to maintain acceptable turf quality taken from Fu et al. (2004). Irrigation was applied Mondays and Fridays from 4 June to 14 Sept. 2001 and 3 June to 13 Sept. 2002. Total irrigation applied to the 100% ET treatment was 390 mm in 2001 and 449 mm in 2002. The MDIL was 312 mm in 2001 and 359 mm in 2002.

^yCanopy vertical growth rate, tillers, canopy net photosynthesis (P_n), whole plant respiration (R_w), and water use efficiency are averages of five measurement dates and four replicates in each year.

^zDifference between respective parameters measured at the minimum irrigation level and 100% ET determined using Fisher mean separation test ($P \leq 0.05$).

the MDIL in either year. Across all deficit irrigation levels, P_n was more sensitive to deficit irrigation in both grasses than was R_w , which could potentially contribute to declines in canopy vertical growth rate, tiller number, and turf quality.

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