Reprinted from *Agronomy Journal*
Vol. 84. No. 3

Iron Fertilization Effects on Shoot/Root Growth, Water Use, and Drought Stress of Creeping Bentgrass

D. S. Glinski, R. N. Carrow,* and K. J. Karnok

ABSTRACT

Creeping bentgrass (*Agrostispalustris* Huds.) golfgreens in the U.S. Southeast are subjected to summer drought and heat stresses. This study was initiated to determine the effects of foliar Fe on Fe-suffkient bentgrass shoot responses, root growth, and responses to drought stress. Ferrous sulfate (FS), Lawn-Plex (LP), and Sequestrene 330 (Seq. 330) iFcS0$_4$ 7H$_2$0; Fe phosphate-citrate; and sodium ferric diethlenetriamine-pentaacetate, respectively) were applied to a golf green at 1.12 kg Fe ha ' per month for a 17-mo period. AJI Fe sources improved color and visual quality throughout the year; summer color improved 5.9% compared to 8.6 to 9.5% for all other seasons. Total extractable tissue Fe was not well correlated with color \r < t.54). Iron carriers had different effects on growth, especially between late summer and winter. Lawn-Plex increased cool-season clipping yields while Seq. 330 reduced verdure in the summer by 18% compared to the control. Root growth (weight and length) was equal to, or less than the control for all Fe treatments. In August, FS-treated plants exhibited a 31% decrease in root length density (RLD) in the 0 to 10 cm zone. In October, 10- to 20-cm depth RLDs were reduced relative to the control by 31% for FS and 28% LP for treatments. While LP tended to reduce rooting, it was the only Fe carrier to exhibit consistently better (15-40%) soil moisture extraction than the control. Iran had no apparent effect on canopy temperature as a stress indicator. Since shoot growth, root growth, and water extraction responses dam varied with Fe carrier, many reported Fe effects are probably due to the carrier rather than Fe. Exceptions would be the color and visual quality improvements observed for all Fe carriers.

D.S. Glinksi and K.J. Karnok, Dcp. of Agronomy, Univ. of Georgia, Athens, GA 30605; R.N. Carrow, Dep. of Agronomy, Griffin Exp. Stn., Griffin, GA 30223-1797; **Received 24 Aug. 1990.** **• Corresponding author.**

Published in Agron. J. 84:496-503 (1992).

CREEPING BENTGRASS provides an excellent surface for golf greens and is often used for this purpose in mid- to northern areas of the Southeast. Close mowing and heavy traffic subject bentgrass greens to severe summer stress. Managers in hot, humid climates often find bentgrass, a cool-season species, a challenge to maintain.

Under Fe-deficient conditions, Fe has been applied to turfgrasses for color enhancement and improved growth (Deal and Engel, 1965; Minner and Butler, 1984). Foliar Fe application to creeping bentgrass golf greens on a biweekly to monthly schedule is a routine practice even in Fe-sufficient regions. In the Southeast, an Fe-sufficient area, foliar Fe is purported to enhance rooting and drought stress, as well as improve shoot quality. Evidence is limited to support these responses, and if they occur, their magnitude and duration are not clear.

A dark green color is a major component of visual shoot quality on turfgrass. Iron has been applied to promote a darker green color for cool-season turfgrass grown on Fe-sufficient soils (Carrow, 1983; Schmidt and Snyder, 1984; Snyder and Schmidt, 1974; Wehner and Haley, 1990; Yust et al., 1984). In Virginia, Snyder and Schmidt (1974) reported the greatest Fe color enhancement on bentgrass during cool, dry periods. The magnitude of color improvement that may occur under more warm, humid climatic conditions has not been reported, however.

Shoot growth responses to foliar Fe applications under Fe-sufficient soil conditions remain unclear.

Abbreviations: CT, canopy temperature; FS, ferrous sulfate; LP, Lawn-Plex; RLD, root length density; Seq. 300, Sequestrene 300; TDR, time domain reflectrometry.

Snyder and Schmidt (1974) and Schmidt and Snyder (1984) indicate that Fe fertilizers increase spring growth and decrease summer (June) growth of bentgrass. Goatley and Schmidt (1990) reported improved shoot growth of seedling Kentucky bluegrass *(Poa pratetisis* L.) in a winter greenhouse study. In contrast, Carrow el al. (19X8) found that centipedegrass *(Eremochloa ophiuroides)* summer growth was unaffected by Fe applications, as did Yust et al. (1984) for Kentucky bluegrass evaluated during Jury and August in Illinois. In a field study in Canada, Davidson and Sheard (1984) observed little or no effect of foliar Fe on creeping bentgrass shoot growth rate.

In Fe-sufficient situations, Snyder and Schmidt (1974) reported that Fe increased bentgrass summer root weight under high applied N when using Sequestrene 330[1] (Ciba-Geigy, Greensboro, NC). Similar results were observed in a growth chamber study simulating spring through summer conditions (Schmidt and Snyder, 1984). Recently, Goatley and Schmidt (1990, 1991) published rooting data on Kentucky bluegrass in Virginia showing no root response (1991) under summer field conditions but positive root response in a winter greenhouse study.

Iron may improve bentgrass drought resistance. Snyder and Schmidt (1974) found foliarly applied Fe reduced bentgrass winter desiccation in Virginia. Currently, little evidence exists to explain the reported ability of Fe to improve drought resistance under Fe-sufficient conditions, but Snyder and Schmidt's (1974) research suggest Fe could alter drought resistance through its effects on root growth.

Since foliarly applied Fe is so widely used on Fe-sufficient golf greens under warm humid conditions, the purposes of this research were to (i) investigate the effects of foliar-applied Fe on shoot growth and quality of creeping bentgrass grown on a Fe-sufficient golf green under warm, humid conditions, and (ii) determine the effects of Fe on root growth and water relationships.

MATERIALS AND METHODS

The research was conducted on a 2-year-old 'Penncross' creeping bentgrass putting green at the Georgia Experiment Station, Griffin, GA. Green construction followed U.S. Golf Association specifications (Ferguson, 1965) and encompassed an area of 673 m^2 containing 24 separate plots (4.6 x 4.6 m each). The manufactured mix consisted of **96.7%** sand, 2.3% silt, and 1.0% clay. Soil pH was 5.50 and organic matter content 0.84%. The sand in the mix was predominately quartz and the mix exhibited a DTPA (diethylenetriaminepentaacetic acid) extractable Fe level of >8.5 mg Fe kg ha^{-1}, which may be considered high (Lindsay and Norvell, 1978).

The turf received 290-42-162 kg ha-' of N-P-K, respectively, in 1987 and 1988 using carriers that did not contain Fe. Preventative fungicide, insecticide, and preemergence weed control programs (Fe-free materials) were used throughout the study. Mowing was three times per week at 4 mm with clippings removed.

The original experimental design consisted of a 4-by-2 factorial (4 Fe treatments by 2 irrigation levels) in randomized complete block design with three replications. Irrigation treatments were (i) well watered (100%) and (ii) moderate drought stress (8()ʳj). Since very few significant irrigation treatment responses were noted, irrigation levels arc combined in this paper and data analyzed as a randomized complete block with six replications.

Iron treatments included (i) control, which did not receive any Fe, (ii) ferrous sulfate (FS)—Fisher Analytical Reagent FeSO, 7H,0 (Fair Lawn, NJ), 20% Fe. 12% S; (iii) Lawn-Plcx (LP) — R.G.B. Laboratories (Kansas City, MO), 8% Fe, 8% S; and (iv) Scq. 330, 19% Fe. Treatments were applied over a 17-mo period beginning March 1987 and continued to July 1988. Iron was foliarly applied with a CO, sprayer each month at a rate of 1.12 kg Fe ha⁻' in 1660 L water ha^{-1}. Application dates were 16 Feb., 19 Mar., 16 Apr., 21 May, 22 June, 15 July, 18 Aug., 16 Sept., 15 Oct., 18 Nov., and 15 Dec. 1987; and 29 Feb., 23 Mar., 2 May, and 1 June 1988. Applications were in the morning (before 1000 h), usually in the presence of dew. This rate and frequency is commonly used by growers.

To evaluate the influence of Fe carriers on turfgrass visual quality and color, plots were rated monthly, just prior to Fe application except for weekly ratings in the summer (July, August, and September 1987). All ratings were made between 1100 and 1500 h and 27 total ratings were made. Quality ratings ranged from 9 to 1 (9 = ideal shoot density, uniformity, texture, and color; 1 = no live turf). Color ratings ranged from 9 to 1 (9 = dark green, 1 = no green, all brown or yellow). Ratings were analyzed by individual dates and in groups (seasons). Due to the large number of individual readings, only seasonal results are reported.

Clippings were collected at least once a month. During the summer, collection occurred 1 to 2 d before, and 7 to 10 d after Fe applications. Using the two front reels of a tri-plex reel mower, a single pass (3.65 m long) through the center of a plot encompassed 3.72 m^2. Immediately after collecting clippings, samples were washed in a 1% soap solution, rinsed in distilled water and dried (80 ° for 24 h) for later weighing and Fe analysis. All samples were ground in a stainless steel Wiley Mill (0.425 mm, 40 mesh screen). Iron content was determined after wet digestion by atomic absorption spectrophotometry (Isaac and Kerber, 1977).

Verdure samples were collected on (18 July and 21 Aug. 1987). Three cores (5.7-cm diam by 3.0 cm deep) were removed from each plot. Live tissue was cut at the top surface of the thatch on each core and dried (1 h at 100°C, and 24 h at 70°C). Verdure content was evaluated on a weight basis.

During the study, plots were subjected to four drought-stress periods: July, August, and September 1987, and June 1988. The evening before stress initiation, plots received normal mowing and irrigation. During the stress periods, canopy temperature (CT), water use, and turfgrass quality parameters were monitored. As the turfgrass approached severe wilt (usually in the afternoon of the third stress day), plots were irrigated, ending the drought stress period. After this period, root samples were collected.

Canopy temperature was measured four times each day (around 1000, 1200, 1500, 1800 h with a Model 110 infrared thermometer (Everest Interscience, Tustin CA). Average plot temperature was determined under clear skies from measurements taken from two directions. Immediately after measuring CT, air temperature was recorded and data were analyzed as CT minus air temperature.

Water use, determined by monitoring soil moisture, was measured by time domain reflectrometry (TDR) (IRAMS Model 6000, Soil Moisture Equip. Corp., Santa Barbara, CA) (Topp et al., 1980). Prior to drought-stress initiation, two groups of TDR stainless steel rods (a group consisting of a 14 and 25 cm set) were inserted at a 60 degree angle (relative to ground) in each plot to depths of 10 and 20 cm.

'Listing of a product does not constitute endorsement or preference of the product over similar products.

Table 1. Color and visual quality responses during different seasons of a bentgrass golf green to monthly applications (April 1987 to June 1988) of various Fe fertilizers.

Fe Treatment†	1987 Spring 2 April-29 May	1987 Early summer 6 June-13 July	1987 Late summer 20 July-31 August	1987 Early fall 7 Sept.-20 September	1987 Late fall 17 October 28 December-	1988 Winter 15 January 11 March	1988 Spring 29 April 17 May	1988 Early summer 16 June
				Turfgrass color				
				9 = dark green, 1 = no green				
None	7.2a‡	6.9a	6.7a	6.9a	6.7a	6.4a	6.7a	7.1a
$FeSO_4$	7.8b	7.4b	7.2b	7.7b	7.5b	7.2b	7.5b	7.9b
Lawn-Plex	7.6b	7.4b	7.1b	7.5b	7.4b	7.2b	7.4b	7.7b
Seq. 330	7.6b	7.3b	7.0b	6.8a	7.4b	7.4b	7.4b	7.9b
CV (%)	2.4	2.1	2.5	3.0	3.5	3.0	3.1	4.3
				Turfgrass visual quality				
				9 = ideal, 1 = no live turf				
None	6.4a	6.5a	6.6	6.5a	6.4a	6.4a	6.4a	6.5a
$FeSO_4$	7.0b	6.8ab	6.7	6.5a	6.8b	7.2b	7.1b	7.3b
Lawn-Plex	6.9b	6.8ab	6.7	6.5a	6.7b	7.3b	7.0b	7.1b
Seq. 330	7.0b	7.0c	6.7	6.8b	6.8b	7.1b	7.1b	7.4b
CV (%)	4.2	4.1	3.8	4.3	3.1	2.2	4.3	3.8

† Fe carrier; foliar Fe applied monthly, 1.12 kg Fe ha^{-1}.
‡ Treatment means separated by LSD (0.05) within a column.

t Fe carrier; foliar Fe applied monthly, 1.12 kg Fe ha'[1].
* Treatment means separated by LSD (0.05) withaa a column.

respectively. Measurements were made three times a day (0800, 1200, and 1700 h). Water use equaled the difference between initial and subsequent readings. These values yielded water use per day, per dry-down period, and cumulative water use.

Immediately prior to the end of a stress period, plot appearance was evaluated. Wilt ratings were on the scale 0 • no wilt; 9 = 80 to 100% plot area exhibiting wilt. At the same time, plots were rated for turfgrass quality.

Root growth was characterized by root weight and length. Five (six in July 1987 and June 1988) soil cores (3.2-cm diam, 21.6 cm deep) were removed from a quadrant of each plot—a different quadrant for each stress period. After removing the top 1.3 cm (verdure and thatch), the cores were cut into two 10 cm sections. The upper sections (0-10 cm) were grouped together, as were the lower (10-20 cm). Cores were washed clean of sand by agitation as a 18 mesh (1.0 mm) screen. Hand cleaning removed organic matter. Root length was determined by the root intercept method and Newman's equation (Newman, 1966). Due to the large volume of roots, four sub-samples were measured per core. These sub-samples were grouped (within a plot) and dried (80°C, 24 h) along with bulk samples. Lengths of bulk samples were interpolated from weights and lengths of sub-samples. Root growth (weight, length) was analyzed at 0- to 10-, 10- to 20-, and 0- to 20-cm depths.

Data were analyzed using Statistical Analysis Systems procedures (SAS Institute, 1982). Least significant difference (LSD) test was used to separate treatment means based on a significant treatment F-test of 0.10*.

RESULTS AND DISCUSSION

Shoot Responses

Color and Visual Quality. Iron application enhanced the degree of green turfgrass color in all seasons (Table 1). Little difference occurred between Fe carriers except for FS and LP producing significantly darker color than Seq. 330 on one occasion. When significant color response to Fe application occurred compared to the control, the magnitude of response tended to be greater in the cooler seasons than the mid-summer months. When averaged over all Fe carriers and compared to the control, color improved from Fe applications by 8.6, 8.6, 9.6, and 5.9%, respectively, for the spring, early summer, fall/winter, and mid to late summer. These findings agree with reports of Fe fertilization improving turfgrass color under Fe-sufficient situations (Carrow et a!., 1988; Christians, 1984; Schmidt and Snyder, 1984; and Snyder and Schmidt, 1974; Yust et al., 1984).

The color differences observed in this study reflect differences at specific points in time. Other authors report differences in duration of color response. Snyder and Schmidt (1974) and Yust et al. (1984) found Fe enhanced spring color for approximately 2 wk, and enhanced fall/winter color for several months. In this study, monthly Fe applications precluded evaluating long-term color effects. However, short-term (less than a month) color effects could be observed. During the spring, color improvement persisted for at least 28, 21, and 37 d after Fe application (April and May 1987 and April 1988—data not presented for these dates). Color effect did not necessarily decrease after these times, instead, Fc applications occurred before another color rating. During the summer, the duration of color improvement was shortest. Three rating dates (6 July, 10 August, and 7 September) showed no Fe effect. These ratings occurred 30, 26, and 25 d after Fe applications.

Results show Fe fertilizer improved turfgrass visual quality in all seasons of 1988 and spring and late fall of 1987 (Table 1). Seq. 330 improved visual quality in all seasons except late summer 1987. In general, the improved visual quality from foliar Fe was due to better color, a component of visual quality. As with color enhancement, visual quality improvement was not great in magnitude.

Shoot Growth and Leaf Iron Content. Iron treatment analysis showed that Fe influence clipping yields on some dates (Table 2) and Fe carriers differed in their influence on clipping yields. Lawn-Plex produced significantly higher yields than the control on only two out of 11 occasions. Most significant yield differences among Fe carriers occurred in the fall period.

Previous research results conflict as to whether Fc

Table 2. Leaf Fe content and clipping yield during different seasons in 1987 of a bentgrass golf green receiving monthly applications of various Fe fertilizers.

Fe Treatment†	18 May 31§	19 June 29	29 June 7	14 July 22	23 July 8	11 August 27	25 August 12	9 September 27	17 September 7	17 October 2	13 October 29
							Leaf Fe Content				
							$mg\ kg^{-1}$				
None	613‡	182a	184a	130	208a	153	165a	198	114a	340	769
$FeSO_4$	743	457b	478b	146	314b	151	292b	285	233c	410	753
Lawn-Plex	1295	229ab	351ab	148	317b	184	369c	308	246c	416	1079
Seq. 330	706	179ab	205ab	132	261ab	141	335bc	163	181b	325	704
CV (%)	85	100	72	21	27	19	52	71	15	22	48
							Clipping Yield				
							$g\ m^{-2}$				
None	5.28	4.21	5.23ab	2.40	4.64	6.30	3.24ab	3.34	1.90a	5.62a	8.25
$FeSO_4$	5.36	4.62	5.18ab	2.69	4.57	6.27	3.33ab	3.00	2.01ab	6.26ab	7.31
Lawn-Plex	5.55	4.63	6.09b	2.66	4.75	6.26	3.64b	3.66	2.68b	6.86b	11.12
Seq. 330	4.74	3.86	4.54a	2.19	4.40	6.20	2.80a	3.37	2.28ab	5.86a	7.08
CV (%)	27	21	18	28	17	19	16	18	24	13	43

† Fe carrier; foliar Fe applied monthly, 1.12 kg Fe ha^{-1}.
‡ Treatment means separated by LSD (0.05) within a column.
§ Days after Fe application.

influences turfgrass clipping yield. Horst (1984) reported Fe increased top growth in an Fe deficient situation during bermudagrass *[Cynodon dactylon* (L.) Pers.] establishment. Carrow et al. (1988) (centipedegrass), Deal and Engel (1965) and Yust et al. (1984) (Kentucky bluegrass) found Fe had no effect on top growth under Fe-sufficient conditions. On bentgrass greens, Snyder and Schmidt (1974) reported monthly fall-winter Fe applications (FeDTPA) tended to increase spring top growth, while spring application under a high N regime decreased June top growth. In a follow-up investigation, Schmidt and Snyder (1984) found FeDTPA increased growth during cool ambient conditions (growth chamber) and decreased growth as temperature increased.

Verdure measurements, another indicator of shoot growth, showed that Seq. 330 reduced turfgrass shoot growth (Table 3). Relative to the control, Seq. 330 decreased verdure by about 18%. Comparing this data with clipping data of others (Carrow, 1983; Schmidt and Snyder, 1984), it "appears that, Seq. 330 may at times reduce turfgrass shoot growth. Since other Fe treatments did not decrease verdure, the carrier and not the Fe probably contributed to the effect. Schmidt and Snyder (1984) suggested FeDTPAs influence on shoot growth depended on temperature and growth rate; during warm temperatures and fast growth, succulent leaf tissue absorbs more FeDTPA. The FeDTPA may then act as a minor growth regulator (Burstrom, 1963; Wallace et al., 1957). Our results indicate the most significant growth effects of FeDTPA tend to occur in late summer through early winter (August-November 1987), rather than spring. Variation in results probably reflects differences in experiment design. We concentrated on summer effects, neglecting some winter-spring clipping collections. Schmidt and Snyder (1984) concentrated on fall/winter/spring effects, disregarding summer clipping collections and summer Fe applications.

The variance in influence of Fe carrier on clipping yield and verdure ranged from no apparent effect for FS, a tendency for somewhat greater clipping yields for LP, to a tendency for reduced verdure for Seq. 330. These results imply that care must be exercised in attributing a particular response to Fe, especially when using a single carrier. Components other than Fe in the carrier may cause certain plant responses.

Table 3. Verdure of a bentgrass golf green in 1987 as influenced by monthly applications of various Fe fertilizers.

Fe Treatment†	Verdure 24 July	19 August
	$g\ m^{-2}$	
None	568b‡	543b
$FeSO_4$	530ab	457ab
Lawn-Plex	596b	483ab
Seq. 330	468a	440a
CV (%)	21	20

† Fe carrier; foliar Fe applied monthly, 1.12 kg Fe ha^{-1}.
‡ Treatment means separated by LSD (0.05) within a column.

Another implication of the shoot growth data for Seq. 330 is that reduced verdure production could increase the potential for wear injury and reduce recovery rate. Increased verdure provides a cushioning effect to reduce wear, while adequate clipping production furnishes the primary means of recovery from wear.

On five of 11 sample dates, a significant increase in leaf Fe content occurred for at least one Fe carrier relative to the control (Table 2). No single Fe carrier was consistently better than the others, but Seq. 330. tended to result in the least increase in leaf Fe content. Ferrandon et al. (1988) found greater foliar uptake for inorganic than for chelated Fe, but chelated Fe displayed greater translocation. This may explain why Seq. 330 treatments could maintain lower tissue Fe content, but manifest similar color to FS treated turf.

Tissue Fe content did not correlate well with color. The highest correlations occurred in 1987 on 17 September *(r* = 0.54) and 13 November (r = 0.49). The wet digestion removes total plant Fe, but evidence indicates quantification of chloroplast lamellae bound Fe (active Fe) correlates best to chlorophyll content (Terry and Low, 1982).

Duble (1977) reported leaf Fe contents of 0 to 50 (deficient) and 51 to 200 mg Fe kg^{-1} (low) for turfgrasses in general. Summer month values of leaf Fe

Table 4. Shoot responses of creeping bentgrass to Fe fertilizers immediately following 3-d dry-down periods.

	Wilt				Color				Quality			
	1987			1988	1987			1988	1987			1988
Fe Treatment†	19 July	22 August	19 October	16 June	19 July	22 August	19 October	16 June	19 July	22 August	19 October	16 June
	% plot				9 = dark green, 1 = no green				9 = ideal, 1 = no live turf			
None	13	14	52b‡	3	7.0a	6.8a	5.7a	7.1a	6.6a	6.4a	6.2a	6.5a
$FeSO_4$	14	10	8a	5	7.6b	7.1ab	6.6b	7.9b	7.0b	6.5ab	6.5ab	7.3b
Lawn-Plex	6	8	8a	3	7.6b	7.3b	6.7b	7.7b	6.9ab	6.5ab	6.8b	7.1b
Seq 330	13	13	6a	3	7.1a	7.2b	6.7b	7.9b	6.8ab	6.7b	6.8b	7.4b
CV (%)	107	73	200	112	5	5	8	4	5	4	7	4

† Fe carrier; foliar Fe applied monthly, 1.12 kg Fe ha^{-1}.
‡ Treatment means separated by LSD (0.05) within a column.

in the control treatment often were within the low range. Iron applications raised tissue Fe contents into the moderate range (201-1000 mg Fe kg^{-1}). With the recent emphasis on tissue analysis in golf course situations, these data on leaf Fe content will be useful in establishing normal baseline levels within the Southeast.

Shoot Responses After Stress. Table 4 contains shoot responses immediately after the 3-d stress periods when water use data were collected. Shoot responses to water stress following drought stress periods were negligible in terms of color and quality. The most dramatic differences to stress response appeared as wilt. In June, July, and August no treatment differences occurred. In October, control plots wilted more than Fe treatments. Several factors could influence wilt: CT, water use, and root growth. None of these appeared to explain the October wilt responses when comparing control versus Fe carrier data, however.

While Fe application on creeping bentgrass in the stressful summer months is a common grower practice, these research results indicate color and quality responses are minimal. Some color improvement may occur in the summer, but they are of such a small magnitude that they have little or no influence on overall visual quality. The small improvement in color and sometimes quality could be important on areas that are maintained to meet high quality expectations.

Verdure was reduced to some extent by Seq. 330, but this appears to be a carrier rather than true Fe response. Clipping yield responses occurred but primarily in the fall and were not of great magnitude.

Root Responses

Root Growth. In this study, Fe application decreased root growth or had no effect (Table 5). Iron did not affect root growth in early to mid-summer (July 1987 and June 1988). Creeping bentgrass rooting is greatest in the spring to early summer. Thus, the July 1987 and June 1988 dates should represent maximum seasonal rooting. Apparently, Fe application did not influence the magnitude of spring root growth.

From late June/early July until August should be a period of overall root decline for cool-season grasses. In late-summer (August), FS treated turf had 22% lower RLD than the control at 0 to 10 cm (Table 5). Seq. 330 and LP tended to cause a lower *(P* < 0.15%) RLD than the control at both depths.

In fall (October), Fe carriers had their most significant influence on root growth (Table 5). All Fe sources yielded less total root weights than the control. Total root weights (0-20 cm) were 17, 27, and 25% less than the control for FS, LP, and Seq. 330, respectively. Root length density in the 10 to 20 cm zone was reduced 31% by FS, while unaffected in the 0 to 10 cm depth. Lawn-Plex treated turf exhibited reduced RLD at 0 to 10 cm (26%) and 10 to 20 cm (28%) relative to the control, while Seq. 330 significantly reduced RLD by 21% in the surface 10 cm only. Thus, Fe treatments did not enhance rooting and actually seemed to result in greater root growth decline, especially from August into mid-fall. Only after mid-fall would new root initiation occur.

Under Fe-sufficient situations, Snyder and Schmidt (1974) found fall to early winter Fe applications increased spring root weight of bentgrass compared to treatments receiving a single application of only N in October. May and June applications of Fe + N increased July root weight (relative to low N, high N, or low Fe + N). Also, they found increased frequency of Fe applications (fall to winter) tended to increase July root growth under a late fall N regime but with no difference under an early spring N regime. They mentioned that Fe effects seem greatest during water-stress years. In a follow-up study, under greenhouse conditions, Schmidt and Snyder (1984) noted a tendency for Seq. 330 (FeDTPA) to increase root growth. Recently, Goatley and Schmidt (1990) reported better root growth from Fe treatments on Kentucky bluegrass seedlings in a greenhouse study. Since shoot growth and gross CO_2 exchange rate increased from Fe application, the improved rooting of the seedling may have been as a result of these responses and not a direct influence of Fe on rooting. In a field study using mature Kentucky bluegrass sod, Goatley and Schmidt (1991) did not observe any influence of Fe on rooting.

The root growth enhancement in summer months reported by Snyder and Schmidt (1974) and Schmidt and Snyder (1984) was not observed in our study. Although several of the Fe application and root sampling dates in our study do not coincide with theirs, our June to August results should coincide with their fall to winter application and July sampling. Differences in climate, and/or levels of available soil Fe may contribute to the lack of agreement. Since Seq. 330 was the sole Fe source used in their studies, root responses may reflect the potential shoot growth regulation responses of the carrier more than a true Fe

Table 5. Root growth of creeping bentgrass sampled in July, August, and October 1987 and June 1988 as affected by Fe fertilizers.

	Root weight			Root length density	
	depth, cm				
Fe Treatment†	0-10	10-20	0-20	0-10	10-20
	$mg \cdot cm^{-2}$			$cm \cdot cm^{-3}$	
			July 1987		
None	19.31‡	4.58	23.90	47.3	11.6
$FeSO_4$	18.16	4.37	22.53	43.3	9.7
Lawn-Plex	17.12	4.52	21.64	41.9	10.9
Seq. 330	17.98	3.89	21.88	47.4	9.1
CV (%)	22	21	22	29	29
			August 1987		
None	18.76	3.19	11.95	52.3b	12.4
$FeSO_4$	15.69	2.88	11.26	41.0a	11.0
Lawn-Plex	16.60	2.53	10.82	44.6ab	9.0
Seq. 330	17.48	3.12	10.94	47.9ab	9.6
CV (%)	22	36	23	21	31
			October 1987		
None	15.09b	2.42c	17.50c	42.6b	7.4b
$FeSO_4$	13.02ab	1.47a	14.49b	40.2b	5.1a
Lawn-Plex	11.06a	1.63a	12.70a	31.9a	5.3a
Seq. 330	11.42a	1.76b	13.18a	33.5a	5.8ab
CV (%)	20	32	23	23	30
			June 1988		
None	19.43	2.87	22.30	51.1	9.3
$FeSO_4$	15.57	2.43	18.00	40.6	9.4
Lawn-Plex	19.62	3.00	22.62	48.5	7.4
Seq. 330	16.93	2.51	19.45	46.7	7.6
CT (%)	16	34	18	15	41

† Fe carrier; foliar Fe applied monthly, 1.12 kg Fe ha^{-1}.
‡ Treatment means separated by LSD (0.05) within a column.

response. Burstrom (1963) and Wallace et al. (1957) noted that FeDTPA can cause growth regulatory responses.

Current literature contains few explanations of how Fe may influence turfgrass root growth under Fe-sufficient growing conditions. In addition to the potential effects discussed above, another explanation could relate to color—darker color resulting from more chlorophyll per unit area which in turn results in increased photosynthesis (PS). Schmidt and Snyder (1984) provide some support for this possibility; under Fe-sufficient conditions, Fe increased PS under low N regime, while also increasing total non-structural carbohydrate content under warm temperatures (27° C day/18° C night). However, under a high N regime, PS decreased. Thus, existing evidence for improved turfgrass rooting from foliar Fe suggests an indirect, secondary response (via influencing shoot growth and/or carbohydrate status) or due to plant response to compounds in Fe carriers other than the Fe.

Water Use. We viewed higher water use as beneficial under the conditions of this study: a sandy soil media with low water-holding capacity; a limited depth of root system; a grass with high water use; and a condition requiring the turf to maintain turgor for wear resistance. A turf that absorbs water quickly would have better drought avoidance capabilities. One of our objectives was to determine if Fe enhanced the ability of bentgrass to extract water for the first 1 to 2 d after an irrigation event, which could reflect enhanced summer-stress tolerance.

During the July 1987 stress period, LP plots used 24% more water than the control (Table 6). All differences occurred in the first 2 d of the period and were from the 10- to 20-cm zone. Turf treated with Seq. 330 used 11% less total water than the control with the difference attributed to 55% lower water extraction from the 10 to 20 cm soil zone on day 2. No differences in water use or extraction patterns were observed in the FS treatment relative to the control.

All treatments had similar total water use for the complete August stress period, but on the second day, LP treated turf extracted more total (0-20 cm) and deep (10-20 cm) water than the control (25 and 31%, respectively) and Seq. 330 treated plots (35 and 56%, respectively). At 0 to 20 cm, LP plots increased in water use from the first to second day by 15%, while the control and Seq. 330 treatments decreased (13 and 15%, respectively).

During the October 1987 measurement period, total water use at the end of the 3-d period was not affected by treatment (Table 7). However, on Day 2 LP treated turf exhibited 30% greater total water use and 40% greater water extraction from the 10- to 20-cm zone, while FS treatment resulted in 16% kss total water use compared to the control. On 14 to 16 June 1988, the only significant difference in water extraction was 19% more water extracted on day 2 from the surface 10 cm for Seq. 330 versus the control (data not presented).

Based on these results, it appears that when Fe application had an effect only LP had any consistent influence on water extraction. Yet, this was not related to rooting. Deep prolific root systems are commonly considered to enhance water absorption. In this study, poor correlations existed between water use and rooting. Water use tended to decrease as rooting increased, especially in June ($r = -0.54$, $P < 0.07$),

Table 6. Soil water extraction and water use of a bentgrass golf green during dry down periods in July and August 1987 as affected by Fe fertilizers.

	Day 1†			Day 2			Day 3			Total		
	depth, cm											
Fe Treatment‡	0-10	10-20	0-20	0-10	10-20	0-20	0-10	10-20	0-20	0-10	10-20	0-20
	mm extracted water											
	17 to 19 July 1987											
None	1.85	2.04a§	3.89	2.08	3.85b	5.93b	0.51	0.73	1.24	4.44	6.62	11.06b
$FeSO_4$	1.82	1.69a	3.50	2.37	4.55bc	6.92bc	1.24	−0.06	1.18	5.43	6.17	11.60b
Lawn-Plex	1.67	2.99c	4.66	2.01	5.70c	7.70c	0.96	0.38	1.34	4.63	9.07	13.70c
Seq. 330	1.76	2.52ab	4.28	2.65	1.75a	4.40a	1.20	−0.07	1.13	5.60	4.20	9.81a
CV (%)	44	35	26	29	41	26	77	492	65	24	42	22
	20 to 22 August 1987											
None	4.54	1.82	6.37	1.83	3.69b	5.52ab	0.55a	0.50	1.05	6.92	6.02	12.94
$FeSO_4$	5.50	0.81	6.31	1.63	4.71c	6.34b	1.15b	−0.07	1.08	8.28	5.45	13.74
Lawn-Plex	4.51	1.48	5.99	2.05	4.85c	6.90c	1.23b	0.92	2.15	7.79	7.25	15.05
Seq. 330	4.07	1.94	6.01	2.02	3.11a	5.13a	1.14b	0.69	1.83	7.24	5.73	12.97
CV (%)	36	139	23	33	27	16	50	301	95	30	55	21

† Turf irrigated at 0100 and 0500 hr on Day 1 and no further irrigation until Day 4.
‡ Fe carrier; foliar Fe applied monthly, 1.12 kg Fe ha^{-1}.
§ Treatment means separated by LSD (0.05) within a column.

July (r = −0.39, P < 0.06) and August (r = −0.33, P < 0.11). Shearman and Beard (1973) found a poor correlation (r = +0.48) between root organic matter and creeping bentgrass water use. Similar to shoot growth responses, the influence of Fe carriers on water use and water extraction does not appear to be due to the Fe but to other carrier components.

The unusually dense surface rooting of bentgrass may contribute to the poor correlation between roots and water use. The high RLD, especially between 0 to 10 cm, may cause soil water potential to control water uptake more than lack of roots. As RLD decreases with depth, water extraction may be more limited by RLD than soil water potential. This is supported by results that show the majority of daily differences appeared between 10 to 20 cm.

These results imply that, in studies investigating the influence of a factor (such as Fe) on bentgrass total root weights, modest changes in surface 0 to 10 cm rooting may have little influence on plant water use. Substantial changes in surface rooting, or changes in deeper rooting (10-20 cm) may be required before observing effects on water use. Accordingly, genetic improvements of bentgrass rooting should be directed towards deeper rooting and/or higher RLD in the deep soil zone. In research investigations where only total rooting is investigated, the high RLD in the surface for bentgrass may mask any changes in deeper rooting.

Canopy Temperature. Canopy temperature data was gathered as a stress indicator and to support water use data (high water use causing lower CT via evapotranspiration). Iron carriers had no significant or consistent influence on CT (data not presented). Correlation was low between canopy temperature and water use (none better than r = 0.45, or significant at P < 0.10%).

CONCLUSIONS

From the results of this study, it appears Fe can improve summer color and visual quality of Fe-sufficient bentgrass, but the degree of color response is less than at other times of the year. All Fe treatments resulted in rooting equal to or less than the control in the June to October period, while only LP provided better water extraction. Iron relationships to summer drought stress as measured by canopy temperature were not strong.

The fact that many turf responses can vary with Fe carrier (i.e., in this study only LP enhanced water uptake; only Seq. 330 reduced verdure) indicates a factor other than Fe influences some of the responses. In studies with only one Fe source, the results may be related to other chemicals in the source rather than Fe and care should be taken in attributing responses to Fe as a nutrient.

Table 7. Soil water extraction and water use of a bentgrass golf green during dry down period on 17 to 19 October 1987 as affected by Fe fertilizers.

	Day 1†			Day 2			Day 3			Total		
	depth, cm											
Fe Treatment‡	0-10	10-20	0-20	0-10	10-20	0-20	0-10	10-20	0-20	0-10	10-20	0-20
	mm extracted water											
None	0.24a§	1.22	1.47	0.55	1.16a	1.72b	−0.01	0.67	0.66	0.79	3.06	3.85
$FeSO_4$	0.47b	0.88	1.36	0.15	1.30ab	1.45a	0.62	−0.02	0.59	1.25	2.16	3.41
Lawn-Plex	0.41ab	1.70	2.11	0.61	1.62b	2.23c	0.61	0.00	0.61	1.63	3.32	4.95
Seq. 330	0.28a	1.58	1.86	0.93	1.02a	1.94b	0.13	0.57	0.71	1.35	3.17	4.52
CV (%)	107	90	72	90	45	28	246	246	78	69	68	31

† Turf irrigated at 0100 and 0500 hr on Day 1 and no further irrigation until Day 4.
‡ Fe carrier; foliar Fe applied monthly, 1.12 kg Fe ha^{-1}.
§ Treatment means separated by LSD (0.05) within a column.

REFERENCES

Burstrom. H. 1*163. Growih regulations by metals and chelates. Adv. Bot. Res. 1:73-99.

("arrow, R.N. 19X3. Turfgrass Field Day Resort. Kansas Stale Univ., Manhattan. KS.

Carrow. R.N., B.J. Johnson, and G.W. Landry, Jr. 1988. Centipede response to foliar applications of Fe and N. Agron. J. 80:746-750.

Christians. N. 1984. Eagle iron studies. 1984 Iowa Turfgrass Research Report, Cooperative Extension Service, Iowa State University, Ames, Iowa.

Davidson, D.B. and R.W. Sheard. 1984. Iron-nitrogen interactions on bentgrass. Turf. Res. Report 1984. Ontario Agric. Coll., Univ. of Guelph, Canada.

Deal, E.E. and R.E. En gel. 1965. Iron, manganese, boron and zinc: effects on growth of 'Merion' Kentucky bluegrass. Agron. J. 57:553-555.

Dublc, R.L. 1977. Leaf analysis - A backup to soil testing. Turf-Grass Times 11(1): 14-17.

Ferguson, M.H. 1965. After five years: The Green Section specifications for a putting green. USGA Green Section Record. 3(4): 1-7.

Ferrandon, M. and A.R. Chamel. 1988. Cuticular retention, foliar absorption and translocation of Fe, Mn, and Zn supplied in organic and inorganic forms. J. Plant Nutr. 11(3), 247-263.

GoatTey, J.M., Jr. and R.E. Schmidt. 1990. Seedling Kentucky bluegrass growth responses to chelated iron and biostimulator materials. Agron. J. 82:901-905.

Goatley, J.M., Jr. and R.E. Schmidt. 1991. Biostimulator enhancement of Kentucky bluegrass sod. HortScience 26:254-255.

Horst, G.L. 1984. Iron nutrition for warm-season grasses. Grounds Maintenance. 19:44-48, 70.

Isaac, R.A., and J.D. Kerber. 1971. Atomic absorption and flame photometry: techniques and uses in soil, plant, and water analysis, p. 17-37. *In* L. M. Walsh (ed.) Instrumental methods for analysis of soils and plant tissue. SSSA Madison, Wl.

Lindsay, W.L. and W.A. Norvell. 1978. Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Sci. Soc. Am. J. 42:421^*28.

Minner, D.D. and J.D. Butler. 1984. Correcting iron deficiency of Kentucky bluegrass. Hon Science 19:109-110.

Newman, E.I. 1966. A method of estimating the total length of root in a sample. J. Appl Ecol. 3:139-145.

SAS Institute. 1982. SAS User's Guide. 1982 ed. SAS Inst., Inc., Cary, NC.

Schmidt, R.E.. and V. Snyder. 1984. Effect of N, temperature, and moisture stress on the growth and physiology of bentgrass and response to chelated iron. Agron. J. 76:590-594.

Shearman, R.C. and J.B. Beard. 1973. Environmental and cultural preconditioning effects on the water use rate of *Agrostis palustris* Huds., cultrvar Penncross. Crop Sci. 13:424—427.

Soyder, V., and R.E. Schmidt. 1974. Nitrogen and iron fertilization on bentgrass. p. 176-185. *In* E.C. Roberts (ed.) Proc. 2nd Inter. Turf. Res. Conf. VPI, Blacksburg, VA. 15-20 June 1973. ASA, Madison, WL

Terry, N. and G. Low. 1982. Leaf chlorophyll content and its relation to the intracellular localization of Fe. J. Plant Nutr. 5(4-7):301-310.

Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic determination of soil water content: measurements in transmission lines. Water Resources Research 16.3:574-582.

Wallace, A., L.M. Shannon, O.R. Lunt, and R.L. Imply. 1957. Some aspects of the use of metal chelates and micronutrient fertilizer sources. Soil Sci. 84:27-41.

Wehner, D.J. and J.E. Haley. 1990. Iron fertilization of Kentucky Bluegrass. Commun. Soil Sci. Plant Anal., 21(7 and 8):629-637.

Yust, A.K., D.J. Wehner, and T.W. Fermaaian. 1984. Foliar applications of N and Fe to Kentucky bluegrass. Agron. J. 76:936-938.