Comparing Turfgrass Cumulative Evapotranspiration Curves

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Abstract. Twenty-five commercially available turfgrass cultivars were evaluated for cumulative evapotranspiration (ET_{cum}) attributes under progressive water stress for 0 to 21 and 0 to 24 days using the gravimetric mass balance method in two greenhouse studies. At the end of the water-stress treatment, the cultivars were scored visually for their green appearance on a 0 (no green) to 10 (100% green) scale. The Gompertz nonlinear model gave a best fit to ET_{cum} vs. days adjusted for pan evaporation variation in the greenhouse compared with monomolecular and logistic nonlinear regression models. Two ET_{cum} attributes—maximum evapotranspiration rates (ET_{max}) and inflection time (t_i) (the time when the change in ET becomes zero)—were estimated for each cultivar using the Gompertz model. Based on final ET_{cum} , ET_{max} , t_i , and greenness score, 'Bristol', 'Challenger', and 'Wabash' Kentucky bluegrass (*Poa pratensis* L.); 'Shademaster' creeping fescue (*Festuca rubra* L.); 'FRT-30149' fine fescue (*F. rubra* L.); and 'Aurora' hard fescue (*F. ovina* var. *duriuscula* L. Koch.) were identified as low water-use cultivars.

In arid and semi-arid regions, drought is a major turfgrass management problem. To maintain verdant turfgrass, frequent watering is required during the growing season. When well watered, turfgrass evapotranspiration (ET) is 2.5 to 7.5 mm·day⁻¹ (Beard, 1973). ET is a function of plant, soil, and climatic factors. Relationships between turfgrass ET rates and net solar radiation, water availability, air and soil temperatures, wind velocity, and vapor pressure deficit have been demonstrated (Feldhake et al., 1983; Kim and Beard, 1988). Identifying turfgrass cultivars that use little water and remain green during drought is of primary importance to turfgrass managers and homeowners.

Many investigations have compared ET rates among and within turfgrass species under nonlimiting soil moisture conditions (Bowman and Macaulay, 1991; Kim and Beard, 1988; Kopec et al., 1988; Shearman, 1986, 1989). Traditional water-use studies based on well-watered turfgrass measure only the initial phase of the turfgrass water-use curve. Kneebone and Pepper (1984) showed that bermudagrass [*Cynodon dactylon* (L.) Pers.] turf used 70% more water under high irrigation (52 mm·day⁻¹) compared with low irrigation (16 mm·day⁻¹). It is plausible that, as soil

moisture is depleted, there is a gradual reduction in water use even before turfgrass wilts. The water-use measurements under nonlimiting conditions are not good predictors of low water-use patterns under restricted water use, which may be appropriate to conserve water. Under progressive water stress, various turfgrass cultivars may show differential ET rates that may be related to their low water-use potential. Therefore, there is a need to assess comparative turfgrass ET rates under progressive water stress given a uniform cultural regime.

The cumulative evapotranspiration (ET_{cum}) pattern is controlled by many genetic and environmental factors. A plausible general pattern is an S-shaped curve for which asymptotic growth models (Tipton, 1984) should be evaluated. Maximum ET rate (ET_{max}) and inflection time (t_i) are components of ET_{cum} curves vs. time, where t_i is the time to reach ET_{max} , a measure of the delay in maximum water use. Final ET_{cum} (FET_{cum}) is an accumulated value over the experimental period. Therefore, the objectives of this study were to compare ET rates of 25 turfgrass cultivars under progressive water stress, estimate ET_{max} and t_i from the ET_{cum} curve, and identify cultivars with low water-use potentials using the ET_{cum} components.

Experiment 1. In Nov. 1989, 25 commercial turfgrass cultivars representing diverse genetic origins (Kentucky bluegrass, tall fescue, perennial ryegrass, fine fescue, chewings fescue, hard fescue, sheep fescue, and red top) were established in white cylindrical containers, 15 cm in diameter × 30 cm high, with a bottom drainage hole. Containers were filled with 2.5 kg fritted clay for its water retention properties (van Bavel et al., 1978). Seeds were sown evenly at 880 mg/container (50 g·m⁻²) for tall fescue, 140 mg/container (8 g·m⁻²) for Kentucky bluegrass, and 440 mg/container

(25 g·m⁻²) for other turfgrass cultivars. After germination, the turfgrass was established for 6 months in a greenhouse maintained at 23/18C day/night. During this period, the turfgrass was irrigated with half-strength Hoagland's solution (Hoagland and Arnon, 1950). The turf was mowed weekly to a height of 5 cm, as reported by Bowman and Macaulay (1991).

Progressive water stress was imposed by withholding water for 21 days in June 1990. To monitor evaporation variation in the greenhouse, 50 pans (25 cm in diameter) full of water were placed in rows on either side of the turf pots and positioned at the same height as the turfgrass canopy. Turfgrass water loss was measured by the gravimetric mass balance method (Bowman and Macaulay, 1991) 1, 2, 3, 5, 8, 10, 12, 14, 16, 18, and 21 days after withholding water. Concurrently, pan evaporation was measured by weighing the evaporation pans. The pans were refilled after each measurement. Both ET and pan evaporation were converted to millimeters. Twenty-one days after water stress began, the turfgrass cultivars were scored visually for green retention on a 0 to 10 scale, where 9 = 90% of the leaf tissue green and 1 = 90% of the leaf tissue scorched. The turfgrass was not mowed during the progressive water-stress period.

The design was a randomized complete block with four replications. A repeated-measures analysis (Fernandez, 1991) was performed on ET_{cum} on different days. For each ET_{cum} , the average pan evaporation on either side was used as the covariate in the analysis of covariance (Fernandez, 1990a) to adjust for ET microvariation in the greenhouse.

Experiment 2. The previous experiment was repeated using the same cultivars under the same greenhouse conditions. A 2-month recovery period was allowed between experiments to make sure that the stressed turfgrass recovered completely. During recovery, the pots were irrigated using half-strength Hoagland nutrient solution.

Progressive water stress was imposed on the turfgrass by withholding water for 24 days in Aug. 1990. To monitor ET variation in the greenhouse, six 25-cm-diameter pans full of water were placed, two at the center, and two each at the border of the bench. ET water loss from the turfgrass was measured 3, 6, 9, 12, 15, 18, 21, and 24 days after progressive water stress began. On these days, average pan evaporation was measured from the six pans. On day 24, the turfgrass cultivars were scored visually for the amount of greenness on the 0 to 10 scale noted.

The design was a 5 × 5 lattice with two replications. The objective of using incomplete blocks in this design was to reduce the microvariation in the greenhouse that might have influenced ET . A repeated-measures analysis (Fernandez, 1991) was performed on ET_{cum} on different days after adjusting for microvariation by the incomplete block adjustment in the lattice design analysis (Fernandez, 1990b).

Cumulative ET curves. Three commonly used asymptotic nonlinear growth models—monomolecular, logistic, and Gompertz

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(Tipton, 1984)—were evaluated for suitability in describing the ET_{cum} turfgrass pattern under progressive water stress. ET_{cum} data for 'Wabash' and 'Bonanza' were used to compare the models using Statistical Analysis System's (SAS's) PROC NLIN procedure (SAS, 1988). Because daily ET was influenced by daily environmental conditions in the greenhouse and the incremental effects of days were not equal, adjusted days were substituted for days in these nonlinear models:

Monomolecular model, $Y = a[1 - \text{bexp}(-kt)]$;
Logistic model, $Y = a/[1 + \text{bexp}(-kt)]$; and
Gompertz model, $Y = a\text{exp}[-\text{bexp}(-kt)]$;

where Y = predicted ET_{cum} , t = adjusted days (ET_{cum} at i^{th} day/mean pan evaporation/day); a = the asymptote, theoretical maximum value for Y ; and b and k are constants with different values for different cultivars.

ET_{cum} was a progressively accumulating process and produced an S-shaped curve (Fig. 1A), which indicated that ET rate is not constant but varies with time under progressive water stress. The parameter estimates and the residual sums of squares (RSS) for these three models using ET_{cum} data for 'Wabash' and 'Bonanza' from Expt. 1 are presented in Table 1. The Gompertz model resulted in smaller standard errors for the parameter estimates and a low RSS. Thus, the Gompertz model was chosen to describe the ET_{cum} data patterns of the 25 turfgrass cultivars under progressive water stress in these two experiments.

The Gompertz model is a sigmoid curve and is asymmetrical about the inflection point where the change in ET is zero. ET_{cum} components can be estimated from the Gompertz model parameters a , b , and k . ET rate is

Table 1. Parameter estimates, standard errors, and residual sums of squares (RSS) from three nonlinear regression models of turfgrass cumulative evapotranspiration (ET_{cum}) over days (t) for two cultivars in Expt. 1.

Nonlinear regression model	Cultivar	
	Wabash	Bonanza
Monomolecular ^a		
a	252.3 (45.2) ^b	204.3 (23.1)
b	1.0 (0.007)	1.03 (0.014)
k	0.024 (0.0056)	0.043 (0.007)
RSS	18.11	39.79
Logistic ^a		
a	104.7 (4.52)	119.19 (4.5)
b	11.12 (1.30)	11.39 (1.52)
k	0.238 9 (0.018)	0.264 (0.020)
RSS	68.01	106.40
Gompertz ^a		
a	119.8 (5.0)	131.5 (4.51)
b	3.6 (0.11)	3.1 (0.13)
k	0.132 (0.008)	0.154 (0.009)
RSS	24.65	39.44

^a $Y = a[1 - \text{bexp}(-kt)]$.

^bNumbers in parentheses represent standard error.

^c $Y = a/[1 + \text{bexp}(-kt)]$.

^d $Y = a\text{exp}[-\text{bexp}(-kt)]$.

$kY\log_e(aY^{-1})$. ET_{max} in the Gompertz model occurs when the rate of change in ET is 0 at the curve, $t_c = (\log_e b)/k$ and its value is $ET_{max} = (ka)e^{-1}$ (Tipton, 1984).

In the absence of a significant cultivar (C) $\times$ experiment (E) interaction, a combined analysis of variance (genotypic means over two experiments) was performed to detect significant cultivar effects in the Gompertz model parameters and the ET_{cum} components (t_c , ET_{max} , FET_{cum}) using $C \times E$ as the error term. The multiplicative basis for the $C \times E$ interaction was determined ($P \leq 0.05$) by Tukey's test for nonadditivity (Tukey, 1949); thus, mean comparisons among cultivars on the Gompertz model parameters k and t_c were not performed. For the other components, mean comparisons were performed using the Waller-Duncan k ratio, t test (SAS, 1988).

In Expt. 1, results of the analysis of covariance indicated that the covariance adjustment was significant ($P \leq 0.05$) in adjusting for microvariation in greenhouse pan evaporation. In Expt. 2, significant blocks within replicates ($P \leq 0.05$) in the lattice design analysis also indicated the presence of significant microvariation in the greenhouse. The lattice design seemed to be more effective than the covariance analysis, because the additional covariate measurements (pan evaporation measurements for every turfgrass pot) were not needed in the lattice design.

In both experiments, cultivar and the cultivar $\times$ days interaction were highly significant (Wilks' Lambda $P \leq 0.0001$) in the repeated-measures analyses. Cultivar effects also were significant for the visual score and the FET_{cum} 21 and 24 days after progressive water stress ($P \leq 0.001$).

The mean nonlinear Gompertz model parameters (ET_{cum} vs. adjusted days) for each cultivar in the two experiments are given in Table 2. The Gompertz model parameter a for

Table 2. Average parameter estimates from the Gompertz^a model for the turfgrass cumulative evapotranspiration (ET_{cum}) (in millimeters) over days (t) in two greenhouse studies.

Cultivar ^b	a	b	k ^c
Bristol (KB)	121 a ^w	2.9 a	0.124
Challenger (KB)	124 bc	3.0 a	0.122
Aurora (KB)	124 a-c	3.0 a	0.127
Mecklenburger (SF)	122 c	3.0 a	0.130
MX86 (SF)	123 bc	3.1 a	0.130
Wabash (KB)	132 a-c	3.1 a	0.123
Shademaster (CF)	125 a-c	3.1 a	0.133
FRT-30149 (FF)	129 a-c	3.1 a	0.133
Saturn (PR)	129 a-c	3.0 a	0.129
Omega (PR)	122 c	3.0 a	0.138
Charger (PR)	127 a-c	3.1 a	0.128
Citation (PR)	128 a-c	3.0 a	0.134
She (Fine F)	126 a-c	3.1 a	0.139
Accolade (PR)	130 a-c	3.0 a	0.131
Murieta (TF)	132 a-c	3.1 a	0.141
Shadow (HF)	129 a-c	3.1 a	0.141
Olympic (TF)	131 a-c	3.1 a	0.145
Streaker Red Top	141 a-c	3.1 a	0.148
Monarch (TF)	136 ab	3.0 a	0.136
Chesapeake (TF)	130 a-c	3.0 a	0.142
Silverado (TF)	133 a-c	3.0 a	0.146
Syn GA (TF)	129 a-c	3.2 a	0.149
Arid (TF)	132 a-c	3.1 a	0.150
Bonanza (TF)	135 a	3.0 a	0.151
Apache (TF)	136 a	3.2 a	0.154

^aGompertz model: $ET_{cum} = a\text{exp}[-\text{bexp}(-kt)]$.

^bKB = Kentucky bluegrass, SF = sheep fescue, CF = creeping fescue, FF = fine fescue, PR = perennial ryegrass, TF = tall fescue, HF = chewings fescue.

^cThe genotype $\times$ experiment interaction was multiplicative ($P \leq 0.05$) based on Tukey's nonadditivity test; thus, mean separation among cultivars was not performed.

^wMean separation among cultivars within columns by Waller-Duncan k ratio, t test ($k = 100$).

'Bristol', 'Challenger', 'Mecklenburger', and 'MX86' were significantly smaller than that for 'Bonanza' and 'Apache', based on Waller-Duncan's minimum significant difference (SAS, 1988). The cultivars were not statistically significant for the Gompertz model parameter b (Table 2).

The relationship between ET_{cum} and ET and adjusted days for 'Challenger', 'Wabash', 'Arid', 'Bonanza', and 'Apache' are shown in Fig. 1A. In the Gompertz model, ET_{max} is expressed at t_c . ET_{cum} was higher for 'Arid', 'Bonanza', and 'Apache' than for 'Wabash' and 'Challenger' during the experiments. Lower ET rates and delayed were observed for 'Wabash' and 'Challenger' than for 'Arid', 'Bonanza', and 'Apache' (Fig. 1B). Beyond 14 days, ET rates seemed to be constant in both sets of cultivars. Similar ET_{cum} and ET curves can be constructed for the other cultivars used in the study by using the mean Gompertz model parameters reported in Table 2.

Longer t_c , lower ET_{max} and FET_{cum} , and higher visual scores are desirable attributes that can be used to identify the low water-use turfgrass cultivars. Three Kentucky bluegrass cultivar—Bristol, Challenger, and Wabash—expressed desirable low water-use attributes: delayed t_c (>8.5 days), lower ET_{max} (5.5 to 6.0 mm-day⁻¹), lower FET_{cum} (<112 mm), and higher greenness score (>7) (Table 3).

In addition to the three Kentucky bluegrass

Fig. 1. Gompertz nonlinear model curves for (A) cumulative evapotranspiration (ET) vs. days and (B) ET rate curves for five turfgrass cultivars evaluated in greenhouse study 1. The cubic spline option was used to connect the points in these plots.

cultivars, 'Shademaster' creeping fescue, 'FRT-30149' fine fescue, and 'Aurora' hard fescue also expressed desirable water-use efficiency attributes (Table 3). Tall fescue cultivars had a higher FET_{cum} (>115 mm) and ET_{max} (>6.5 mm·day⁻¹) and shorter t_i (<8 days) than

the perennial ryegrass cultivars (Table 3). However, the greenness score for tall fescue cultivars Monarch, Murieta, Olympic, and Arid were higher than those of perennial ryegrass cultivars Citation, Omega, and Accolade.

These results indicate that the nonlinear

Table 3. Mean inflection time (t_i), maximum evapotranspiration (ET_{max}) (in millimeters per day) estimated from the Gompertz model, mean final cumulative ET (FET_{cum}) (in millimeters), and greenness score (0 = no green, 10 = 100% green) under progressive water stress in two greenhouse studies.

Cultivar ^a	t_i	ET_{max}	FET_{cum}	Greenness score
Bristol (KB)	8.59 ^y	5.485 j ^x	102 h	7.8 ab
Challenger (KB)	9.02	5.530 j	103 gh	7.5 ab
Aurora (KB)	8.81	5.770 ij	112 b-f	7.0 a-c
Mecklenburger (SF)	8.39	5.810 ij	105 f-h	6.3 b-d
MX86 (SF)	8.70	5.835 ij	105 f-h	5.8 c-e
Wabash (KB)	9.17	6.005 hi	109 d-h	8.4 a
Shademaster (CF)	8.57	6.075 hi	107 e-h	8.0 a
FRT-30149 (FF)	8.81	6.085 hi	112 b-g	8.3 a
Saturn (PR)	8.75	6.155 g-i	110 b-h	4.0 f-h
Omega (PR)	7.88	6.265 gh	108 e-h	3.0 ij
Charger (PR)	8.88	6.045 hi	108 e-h	3.8 g-i
Citation (PR)	8.26	6.345 gh	111 b-h	1.5 j
She (FF)	8.05	6.445 f-g	110 b-h	5.3 d-g
Accolade (PR)	8.40	6.335 g-h	111 b-h	3.25 h-i
Murieta (TF)	8.18	6.640 d-e	115 a-d	4.5 e-h
Shadow (HF)	8.00	6.950 ef	118 a-c	4.3 e-h
Olympic (TF)	7.84	6.980 c-e	117 a-d	4.5 e-h
Streaker Red Top	7.58	6.855 d-e	113 a-f	5.3 d-g
Monarch (TF)	8.05	6.790 d-f	118 a-c	5.5 c-f
Chesapeake (TF)	7.77	7.035 c-e	116 a-e	3.3 h-i
Silverado (TF)	7.52	7.150 cd	119 a-c	3.8 g-i
Syn GA (TF)	7.78	7.130 cd	116 a-e	3.8 g-i
Arid (TF)	7.47	7.395 bc	119 ab	4.5 e-h
Bonanza (TF)	7.30	7.630 ab	122 a	2.3 ij
Apache (TF)	7.44	7.685 a	117 a-d	3.3 h-i

^aKB = Kentucky bluegrass, SF = sheep fescue, CF = creeping fescue, PR = perennial ryegrass, FF = fine fescue, TF = tall fescue, HF = chewings fescue.

^yThe cultivar × experiment interaction was multiplicative ($P < 0.05$) based on Tukey's nonadditivity test; thus, mean separation among cultivars was not performed.

^xMean separation among cultivars within columns by Waller-Duncan k ratio, t test ($k = 100$).

Gompertz growth model describes the ET_{cum} pattern for turfgrass under progressive water stress and, therefore, should be considered as a model for describing ET_{cum} data. ET_{cum} attributes ET_{max} and t_i were especially useful, because they associated linearly with greenness score while FET_{cum} did not (Fig. 2). The correlation between FET_{cum} and greenness score was not statistically significant (Fig. 2). Thus, ET_{cum} attributes from Gompertz growth model (ET_{max} and t_i) could be used effectively to select low water-use turfgrass cultivars that have the additional advantage of having consistent drought symptoms.

Literature Cited

- Beard, J.B. 1973. Turfgrass science and culture. Prentice-Hall, Englewood Cliffs, NJ.
- Bowman, D.C. and L. Macaulay. 1991. Comparative evapotranspiration rates of tall fescue cultivars. *HortScience* 26:122-123.
- Feldhake, C.M., R.E. Danielson, and J.D. Butler. 1983. Turfgrass evapotranspiration. I. Factors influencing evapotranspiration rate in urban environment. *Agron. J.* 75:824-830.
- Fernandez, G.C.J. 1990a. Evaluation of moving mean and border row mean covariance analysis for error control in yield trials. *J. Amer. Soc. Hort. Sci.* 115:241-244.
- Fernandez, G.C.J. 1990b. Analysis of lattice design using PC-SAS. *HortScience* 25:1450.
- Fernandez, G.C.J. 1991. Repeated measure analysis of line-source sprinkler experiments. *HortScience* 26:339-342.
- Hoagland, D.R. and D.I. Arnon. 1950. The water culture method for growing plants without soil. *Calif. Agr. Expt. Sta. Circ.* 347.
- Kim, K.S. and J.B. Beard. 1988. Comparative turfgrass evaporation rates and associated morphological characteristics. *Crop Sci.* 28:328-332.
- Kneebone, W.R. and I.L. Pepper. 1984. Luxury water use by bermudagrass turf. *Agron. J.* 76:999-1002.
- Kopec, D.M., R.C. Shearman, and T.P. Riordan. 1988. Evapotranspiration of tall fescue turf. *HortScience* 23:300-301.
- SAS Institute. 1988. SAS/STAT user's guide. release 6.03. SAS Institute, Cary, N.C.
- Shearman, R.C. 1986. Kentucky bluegrass cultivar evapotranspiration rates. *HortScience* 21:445-457.
- Shearman, R.C. 1989. Perennial ryegrass cultivar evapotranspiration rates. *HortScience* 24:767-769.
- Tipton, J.L. 1984. Evaluation of three growth curve models for germination analysis. *J. Amer. Soc. Hort. Sci.* 109:451-454.
- Tukey, J.W. 1949. One degree of freedom for non-additivity. *Biometrics* 5:232-242.
- van Bavel, C.H.M., R. Lascano, and D.R. Wilson. 1978. Water relations of fritted clay. *Soil Sci. Soc. Amer. J.* 42:657-659.

Fig. 2. Scatter plots of mean greenness score and cumulative evapotranspiration attributes: (left) final cumulative ET (FET_{cum}) (in millimeters), (center) mean inflection time (t_i), and (right) maximum ET rate (ET_{max}) (in millimeters per day) in two greenhouse studies. Other F = other fescue, TF = tall fescue, KB = Kentucky bluegrass, Redtop = 'Streaker Red Top', PR = perennial ryegrass. ns,***Nonsignificant or significant at $P \leq 0.001$.