

Reprinted from *Agronomy Journal*
Vol. 77, May-June 1985

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ABSTRACT

An understanding of the natural variation in heat tolerance of Kentucky bluegrass is needed to develop predictive models for stress tolerance. The variation in heat tolerance of 'Adelphi' Kentucky bluegrass (*Poa pratensis* L.) over the growing season and the effect of recovery environment on the perceived heat tolerance of the plants was determined. Field-grown plants (Chillum silt loam, fine-silty, mixed, mesic Typic Hapludults) were exposed to heat stress on 11 dates over two growing seasons by immersion in a water bath for 30 min at either 42, 44, or 46 °C and then placed in either a greenhouse, or one of two growth chamber environments (35/22 or 22/15 °C day/night temperature) for a 2-week recovery period. The dry weight of the stressed plants expressed as a percentage of the controls (recovery weight) was used as a measure of heat tolerance. Heat tolerance increased from May to July and then decreased from August to October. A significant relationship existed between heat tolerance, daylength (D) and average low temperature (LT) for the sampling dates ($y = 128.65 \cdot D - 5.67 \cdot D^2 - 14.46 \cdot LT - 0.49 \cdot LT^2 + 2.21 \cdot D \cdot LT - 743.86$, $R^2 = 0.95$, $P = 0.003$). Recovery weights for plants in the greenhouse were not significantly different from recovery weights for plants in either of the other two recovery environments on 10 of the 11 sampling dates.

Additional index words: 'Adelphi', *Poa pratensis* L.

GOALS of a research program on heat tolerance of cool-season turfgrasses should be the development of heat-tolerant cultivars or elucidation of management practices that promote a more stress-tolerant turfgrass stand. The first step toward either goal is to evaluate the nature of the high temperature response.

Previous research, utilizing 30-min exposures to temperatures in the range of 40 to 50 °C as the stress test, showed that Kentucky bluegrass (*Poa pratensis* L.) was more heat tolerant than perennial ryegrass (*Lolium perenne* L.) and annual bluegrass (*Poa annua* L.), however, there was no difference in heat tolerance between the latter two species (Wehner and Watschke, 1981). It was also found that plants grown under high soil moisture and high N conditions were less heat tolerant than plants grown under low soil moisture and low N conditions. Later research (Minner et al., 1983) revealed that field-grown Kentucky bluegrass and perennial ryegrass responded in a similar manner to high temperature as did greenhouse and growth chamber-grown plants. A good correlation was found between the recovery of the plants from heat stress and either average high temperature or amount of precipitation at the field site for the 2-day period immediately preceding the stress test.

To achieve the goal of developing management strategies to increase heat tolerance requires a knowledge of the natural variation in heat tolerance of the plants during the growing season. The potential to influence heat tolerance through management has been well documented (Carroll, 1984; Julander, 1945; Lange,

Table 1. Nitrogen application schedule for 1979 and 1980.

Total N per year	Fall	Spring	Summer	Fall	Spring	Summer	
	9-27-78	4-11-79	6-13-79	9-15-79	9-30-79	4-18-80	6-27-80
	kg ha ⁻¹						
98	49	49	0	49	0	49	0
196	49	49	49	49	49	49	49

1965; Levitt, 1980; Wehner and Watschke, 1981). Hence, short-term changes in management programs could be implemented when there is a prediction that the stand is susceptible to heat damage.

In previously reported research, heat-stressed plants were placed in a greenhouse for recovery (Minner et al., 1983; Wehner and Watschke, 1981, 1984). Information is needed on the effect of post-stress environment on the recovery of heat-stressed plants.

The purpose of this research was to evaluate, through the growing season, the heat tolerance of 'Adelphi' Kentucky bluegrass fertilized at two different N levels. A secondary objective was to determine the effect of post-stress environment on the recovery of plants from heat stress.

MATERIALS AND METHODS

An Adelphi Kentucky bluegrass stand was established in the fall of 1978 on a Chillum silt loam (fine-silty, mixed, mesic Typic Hapludults) with a pH of 6.0 in Silver Spring, MD. At the time of establishment, 49 kg N, 22 kg P, and 41 kg K ha⁻¹ were incorporated into the seedbed. In the spring of 1979, the area was divided into 6.7 × 3.7 m plots using a randomized complete block design with three replications. Two fertility treatments were imposed of either 98 or 196 kg N ha⁻¹ year⁻¹ from urea (46-0-0) and applied in either two or four applications of 49 kg N ha⁻¹ (Table 1). Plots were mowed at 3.2 cm and clippings were collected. Irrigation was provided during establishment, and subsequently only to prevent severe moisture stress of the turf. Weather records were collected from a standard weather station located on site.

Plant samples were removed from the field on 15 June, 29 June, 12 July, 26 July, 20 Aug., 9 Sept., and 24 Oct. 1979 and 27 May, 24 June, 29 July, 28 Aug., and 1 Oct. 1980 and exposed to high temperature stress. The procedure for exposing the plants to high temperature has been previously reported (Minner et al., 1983). Briefly, it involved placing plants in plastic bags and immersing them in a water bath for 30 min. at a specific temperature in the range of 40 to 50 °C and then replanting them in the greenhouse. Recovery was measured as the weight of the treated plants expressed as a percentage of the weight of the nonheated controls 2 weeks after the stress test (recovery weight). In our research, three sets (three replications per set) of plants representing all fertilizer and temperature treatment combinations were exposed to heat stress. After exposure to high temperature, one set was placed in each of three recovery environments i.e., greenhouse, high temperature growth chamber, and low temperature growth chamber. Growth chambers were identical with each providing 200 μmol m⁻² s⁻¹ photon flux density for 12 h. The high temperature chamber was set for a day/night combination of 33/22 °C and the low temperature chamber set for 22/15 °C. Average high and low temperatures for the greenhouse were 35 and 18 °C, respectively.

¹ Contribution of the Agronomy Dep., Univ. of Maryland as Scientific Paper no. A-3923 and Contribution no. 6906 of the Maryland Agric. Exp. Stn., College Park, MD 20742. Received 6 Aug. 1984.

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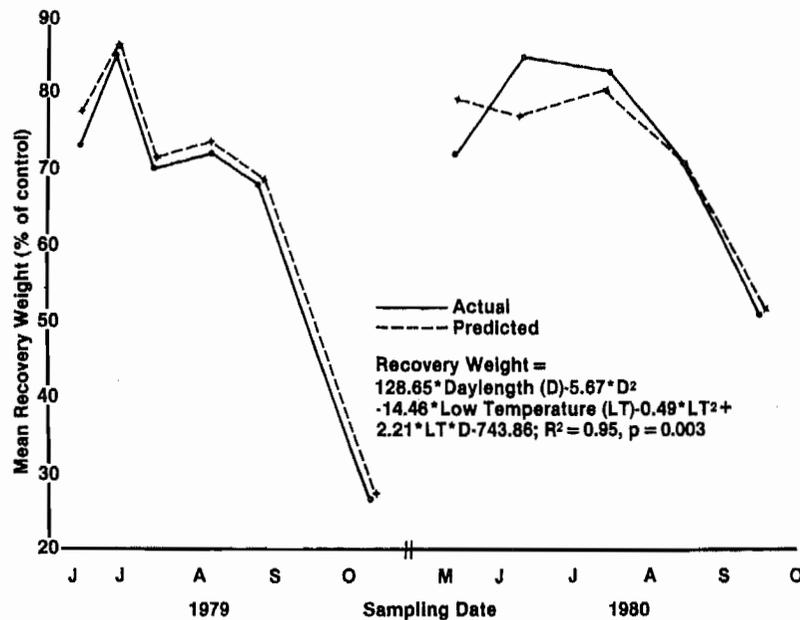


Fig. 1. Actual and predicted mean recovery weights for 11 sampling dates during 1979 and 1980.

Recovery weights for plants heated at 42, 44, and 46 °C were used for the analysis of variance (ANOVA). Recovery weights for these temperatures were from the linear portion of the sigmoidal recovery weight-temperature response curve determined from recovery weights of plants heated between 40 and 50 °C. Data were analyzed over all sampling dates as a split plot in time combined over recovery environments with fertility levels as main plots, waterbath treatment temperatures as subplots, and sampling date as the time factor. Because the sampling date by recovery environment interaction was significant, means were separated by sampling date.

RESULTS AND DISCUSSION

Recovery weights for plants heated at 42, 44, and 46 °C were used for the ANOVA because recovery weight showed a linear decline over this temperature range and this range allowed meaningful comparison between sampling dates where heat tolerance was high vs. dates where heat tolerance was low. Main effects of recovery environment and N level were not significant while effects of temperature, sampling date, and sampling date by recovery environment interaction were significant (Table 2).

With the exception of the 26 July 1979 sampling date, seasonal trends in heat tolerance for 1979 and 1980 were similar (Fig. 1). Heat tolerance increased with warm weather in mid-summer and decreased in late summer and early fall with the onset of cooler weather. Heat tolerance was lowest on 24 Oct. 1979 and highest on 24 June 1980. Average high and low temperatures for 24 Oct. 1979 and 24 June 1980 were similar, however there was a difference between the dates in the daylength and amount of precipitation (Table 3). The high temperature prior to the 26 July 1979 sampling date (mean recovery weight 70) was similar to the high temperature for the 29 July 1980 sampling date (mean recovery weight 83). However, average low for the 1979 sampling date was 3 °C higher than the low for the 1980 date suggesting a decrease in heat tolerance with higher night temperatures.

Table 2. Analysis of variance for recovery weight over all sampling dates.

Source	df†	Mean square
Recovery environment (E)	2	1 377
Rep (E)	6	341
Nitrogen (N)	1	89
N * E	2	580
N * Rep * E	6	236
Temperature (T)	2	65 781**
E * T	4	71
N * T	2	59
E * N * T	4	47
E * Rep * N * T	24	73
Sampling date (D)	10	15 649**
E * D	20	698*
E * Rep * D	60	329
N * D	10	350
E * N * D	20	193
E * Rep * N * D	60	199
T * D	20	1 755**
E * T * D	40	390**
N * T * D	20	258*
E * N * T * D	40	132
Rep * E * N * T * D	240	151

*, ** Significant at $P = 0.05$ and $P = 0.01$, respectively.

† df = Degree of freedom.

A regression equation was generated, using a step-wise multiple regression procedure (Statistical Analysis Systems, 1982), to relate recovery weight to the environmental parameters associated with each sampling date. Several different models were investigated using average high and low temperature, precipitation, and daylength of the period just prior to sampling in both linear and quadratic forms. The best equation generated was a quadratic utilizing daylength and average low temperature (Fig. 1) that had an R^2 value of 0.95 and was significant at the $p = 0.003$ level. The average high temperature showed little correlation ($r = 0.10$) to recovery weight in this study. Also, rainfall, which was sporadic, did not show a strong correlation with recovery weight ($r = -0.33$).

Table 3. Weather data and mean recovery weights for each recovery environment for each sampling date.

	Date										
	1979					1980					
	29 June	12 July	26 July	20 Aug.	9 Sept.	24 Oct.	27 May	24 June	29 July	28 Aug.	1 Oct.
Average low (°C)	14	18	23	19	13	12	14	14	20	18	11
Average high (°C)	25	28	31	24	31	29	26	30	32	34	24
Daylength (h)	14.9	14.9	14.4	13.5	12.7	10.9	14.6	14.9	14.3	13.2	11.8
Precipitation (mm)	4	0	0	21	0	15	18	0	0	0	0
	Recovery Weight (%)										
Low temp. recovery environment (22/15°C)	70	89	67	77	80	33	78	83	83	75	60
High temp. recovery environment (35/22°C)	72	84	71	66	69	17	72	85	82	70	42
Greenhouse recovery environment	77	82	73	73	54	27	67	87	86	68	53
LSD (P = 0.05)†	14.2	12.3	20.6	14.8	15.9	11.9	16.3	10.4	7.2	18.0	16.5
CV (%)	20.4	12	15.6	15.9	23	36.7	13.7	10.8	10.7	22.6	23.9

† LSD = Least significant difference; CV = Coefficient of variance.

The prediction equation showed excellent agreement with actual recovery weights for all but two of the sampling dates. Predicted values differed most from the actual values for the 27 May and 24 June 1980 dates. Rainfall (1.8 cm) preceded the 27 May 1980 sampling date and it is possible that the plants were less heat tolerant than expected because of a higher than normal moisture content. Research has shown that plant water status can influence heat tolerance (Julander, 1945; Lange, 1965; Sapper, 1935; Wehner and Watschke, 1981). The opposite situation may have occurred with the 24 June 1980 sampling in that no rainfall occurred during the week prior to sampling resulting in plants with a low moisture content and higher than expected heat tolerance.

Results of our study are useful for planning future research to develop a predictive model for heat tolerance. Information is needed, however, regarding the microenvironment of the plant including a direct or indirect measure of plant water status to develop a better prediction equation. In this research, the environmental parameters were measured with a standard weather station and may or may not reflect the plant environment. Furthermore, information is needed regarding the minimum conditioning time necessary to alter the heat tolerance of the plants. Levitt (1980) reviewed the literature on the effect of preconditioning on heat tolerance and indicated that with some species even a brief exposure to high temperature (heat shock) can increase heat tolerance. We used weather data for the period 2 days prior to sampling for the regression analysis because we have found the best correlation with heat tolerance using conditions for this time period as compared to conditions 3 to 7 days before sampling.

Another objective of our study was to determine if there was an effect on recovery weight due to the environment in which the plants were placed for the 2-week recovery period. Table 3 contains the mean recovery weights for each recovery environment on each sampling date. There were three sampling dates when the recovery environment affected the recovery weight: 9 Sept. 1979, 24 Oct. 1979, and 1 Oct. 1980. On these dates, plants in the low temperature recovery environment were probably favored by the cool environ-

ment (22/15 °C) that was closer to growing conditions in the field during these sampling periods and resulted in high recovery weights. Recovery weights for plants placed in the high temperature growth chamber were low for both October sampling dates. The high temperature recovery environment (35/22 °C) probably added additional stress to plants during a time when their heat tolerance was already at a minimum. In past research (Minner et al., 1983; Wehner and Watschke, 1981, 1984) a greenhouse was used as the recovery environment for heat-stressed plants. Results of our study support using a greenhouse as the recovery environment since differences in recovery weights among environments were minimal.

The N fertility programs did not significantly affect heat tolerance of plants on any sampling dates in spite of a twofold difference in N fertilization rate. This agrees with earlier findings (Minner et al., 1983) on which two cool-season species and a wider range of N fertilization levels were evaluated. This and previous research shows that moderate applications of N (49 kg ha⁻¹); the type usually employed by the turfgrass industry, do not reduce heat tolerance of cool-season grasses in the same manner as large single applications of N (245 kg N ha⁻¹) (Carroll, 1943).

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